Europa-Universität
Flensburg

Addressing global coal supply for climate change mitigation

Modeling and policy analysis of the global coal sector

vorgelegt von
M.Sc.
Christian Hauenstein
geboren in Tübingen-Weilheim
ORCiD: 0000-0001-9077-2220

an der Europa-Universität Flensburg
zur Erlangung des akademischen Grades

Doktor der Wirtschaftswissenschaften
– Dr. rer. pol. –

genehmigte Dissertation

Promotionsausschuss:

Vorsitzende:	Prof. Dr. Anke Wischmann
Gutachter:	Prof. Dr. Pao-Yu Oei
Gutachter:	Prof. Frank Jotzo, PhD (Australian National University)
Gutachter:	Prof. Dr. Christian von Hirschhausen (Technische Universität Berlin)

Tag der wissenschaftlichen Aussprache: 03. Mai 2023

Zweite Betreuerin:
Prof. Dr. Franziska Holz (Norwegian University of Science and Technology)

Flensburg 2023

Abstract

This thesis focuses on global coal supply and how thermal coal extraction can be reduced in order to mitigate climate change. Using quantitative modeling techniques, as well as qualitative research methods, it assesses economic, technical, and political drivers and barriers for phasing out coal mining. The analysis in this thesis is divided into three general parts. First, prospects of global coal supply under climate policy and energy sector trends are studied, including the effects of the COVID-19 pandemic. This serves to understand what a 1.5°C pathway would imply for coal producers, as well as where current developments would lead coal supply. Second, the effects of changes in market conditions due to economic, political, and structural factors on coal supply are assessed, studying the cases of Australia and the USA. This aims at understanding how these different factors can contribute to a decline in coal supply. Third, the political process of the German coal phase-out decision is analyzed in order to improve understanding on how to overcome political stalemates on coal transitions.

Applying an enhanced version of the coal sector model COALMOD-World (CMW), this thesis shows that for a 1.5°C pathway more than half of the cumulative production capacities in currently operating coal mines need to remain unused. Based on an extensive scenario building exercise and the use of an earlier version of CMW, it shows that the COVID-19 pandemic hit an already struggling coal sector. However, its further development is largely dependent on the choice of economic recovery policies. Without additional climate policies, coal supply would remain well above a 1.5°C compatible pathway. Zooming in on the Galilee Basin in Australia, this thesis shows that investments in new coal mines in this basin are not following economic rationales, while new coal mines in other regions are only economically feasible if demand remains high. For the USA it shows how domestic demand for coal is dwindling due to lower cost alternatives in the power sector and an ageing fleet of coal plants, while high coal production and transport costs constrain export opportunities. An analysis of the German decision process on phasing out coal shows how the implemented stakeholder commission was able to overcome the previous stalemate situation and to initiate a coal transition.

By assessing the coal supply sector from these different perspectives, this thesis contributes to a better understanding of coal supply side dynamics and possible levers for phasing out coal. Furthermore, this thesis advances open source coal sector modeling, contributing to promote collaborative analysis of the coal supply sector and policies. Although coal supply side measures and policies alone will most likely not suffice to phase out coal fast enough to achieve 1.5°C, they can help to build momentum for the necessary coal transitions.

Keywords: Climate change mitigation, climate policy, coal market modeling, coal phase-out, energy economics, just transition, political economy, supply-side policy

Zusammenfassung

Die vorliegende Arbeit befasst sich mit Möglichkeiten zur Reduzierung der weltweiten Kohleförderung. Mithilfe quantitativer Modellierungstechniken und qualitativer Forschungsmethoden werden wirtschaftliche, technische und politische Trieber und Hindernisse für den Ausstieg aus der Kohle untersucht. Die Analyse in dieser Arbeit gliedert sich in drei allgemeine Teile. Erstens werden die Aussichten für die globale Kohleversorgung im Fall ambitionierter Klimapolitik, sowie unter gegenwärtiger Trends im Energiesektor, einschließlich Auswirkungen der COVID-19-Pandemie, untersucht. Dies dient dem besseren Verständnis der Auswirkungen eines 1,5°C-Pfades auf Kohleproduzenten, sowie aktueller Trends der Kohleversorgung. Zweitens werden die Auswirkungen von Veränderungen der Marktbedingungen und deren Einfluss auf die Kohleproduktion an Hand der Beispiele Australien und USA untersucht. Drittens wird der politische Prozess des deutschen Kohleausstiegsbeschlusses analysiert, um zu untersuchen, wie politische Blockaden beim Kohleausstieg überwunden werden können.

Diese Arbeit zeigt mithilfe einer weiterentwickelten Version des Kohlesektormodells COAL-MOD-World (CMW), dass für einen 1,5°C-Pfad mehr als die Hälfte der kumulativen Produktionskapazitäten in den derzeit betriebenen Kohleminen ungenutzt bleiben muss. Basierend auf einer umfangreichen Szenarienentwicklung und der Verwendung einer früheren Version von CMW wird gezeigt, dass die COVID-19-Pandemie einen bereits angeschlagenen Kohlesektor getroffen hat. Die weitere Entwicklung des Kohlesektors hängt stark von der Wahl der Konjunkturpolitik ab. Ohne zusätzliche klimapolitische Maßnahmen würde das Kohleangebot deutlich über einem 1,5°C kompatiblen Pfad bleiben. Mit Blick auf das Galilee-Becken in Australien zeigt diese Arbeit, dass Investitionen in neue Kohleminen dort nicht wirtschaftlich sind. In anderen Regionen sind sie dies nur in Szenarien mit kontinuierlich hoher Nachfrage. Für die USA zeigt diese Arbeit, dass die Inlandsnachfrage nach Kohle aufgrund kostengünstigerer Alternativen im Stromsektor und eines alternden Kohlekraftwerksparks zurückgeht, während die hohen Kohleförder- und Transportkosten kaum Exportmöglichkeiten bieten. Die Analyse des deutschen Entscheidungsprozesses zum Kohleausstieg zeigt, wie es der eingesetzten Stakeholder-Kommission gelungen ist, die vorherige Patt-Situation zu überwinden und den Kohleausstieg einzuleiten.

Diese Arbeit trägt zu einem besseren Verständnis der Dynamik auf der Kohleversorgungsseite und möglicher Hebel für den Ausstieg aus der Kohle bei. Darüber hinaus trägt diese Arbeit zur Open-Source-Modellierung des Kohlesektors und der gemeinschaftlichen Analyse desselben bei. Obwohl angebotsseitige Maßnahmen allein höchstwahrscheinlich nicht ausreichen werden, um einen 1,5°C kompatiblen Kohleausstieg zu erreichen, können sie dazu beitragen, die Abkehr von der Kohle zu beschleunigen.

Schlüsselwörter: Klimaschutz, Klimapolitik, Kohlemarktmodellierung, Kohleausstieg, Energieökonomie, Just Transition, Politische Ökonomie, angebotsseitige Politik

Acknowledgements

First of all, I want to thank Prof. Pao-Yu Oei, who gave me the idea and opportunity to come to Berlin and later Flensburg and to go into science in the first place with his exciting research. During my doctoral studies under his supervision, he was always open, even to unconventional ideas, yet never lost sight of the big picture. Both scientifically and as a person, I have found in him a mentor and a role model.

A special thanks also goes to Prof. Franziska Holz, who accompanied my work from the beginning as a second supervisor and mentor. Thank you for the very pleasant and productive collaborations, that resulted in multiple joint papers, and all the wonderful skills I was able to learn from you. I thank Prof. Frank Jotzo for reviewing my work. I have high regard for his leading scientific work in the field of climate change mitigation economics and policy. I would also like to thank Prof. Christian von Hirschhausen, with whom every meeting offered new surprises, and who always had uncomfortable questions at the ready. His chair has become another home for me.

Many thanks also to Dr. Roman Mendelevitch, who was not my twin in the WIPian tradition, but rather my “big brother”, and without whom I am sure COALMOD-World would not have opened up to me so quickly. And to Isabell Braunger, with whom I shared much of the journey from joining CoalExit the same day to introducing new ideas and formats in written and practical form, to defending almost simultaneously. Muchísimas gracias también al Team Global/International, particularly to Paola Yanguas Parra and Felipe Corral-Montoya, with whom I shared a (virtual) office, many fruitful debates, and who have become close friends to me. I am extremely grateful also to the entire further CoalExit, later FossilExit, and WIP team! Without you, Alexandra, Andrea, Ben, Catharina, Franziska, Hanna, Imane, Jens, Jonathan, Karlo, Konstantin, Marina, Marius, Nora, Paula, Petra, Philipp, Thorsten, and so many more, these years would not have been such a creative, productive and good time.

Further, I would like to thank the Heinrich-Böll-Stiftung, which has supported my doctoral studies financially and made it possible in this form, as well as its research cluster Transformation Research and its fellows for many inspiring events and exchanges. Thank you also to Prof. Claudia Kemfert and the Energy, Transportation, Environment team at DIW Berlin, where I was always welcome as a guest.

Finally, this thesis would not have been possible without the support and motivation of my friends and family, who were always there with and for me, both in the good, as well as in the difficult times. And most importantly, thank you Carola, for your enduring patience, limitless support, and all the joy you bring to my life!

Rechtliche Erklärung

Ich erkläre hiermit an Eides Statt, dass ich die vorliegende Arbeit selbstständig verfasst und andere als in der Dissertation angegebene Hilfsmittel nicht benutzt habe; die aus fremden Quellen (einschließlich elektronischer Quellen, dem Internet und mündlicher Kommunikation) direkt oder indirekt übernommenen Gedanken sind ausnahmslos unter genauer Quellenangabe als solche kenntlich gemacht. Zentrale Inhalte der Dissertation sind nicht schon zuvor für eine andere Qualifikationsarbeit verwendet worden. Insbesondere habe ich nicht die Hilfe sogenannter Promotionsberaterinnen bzw. Promotionsberater in Anspruch genommen. Dritte haben von mir weder unmittelbar noch mittelbar Geld oder geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt. Auf die Bedeutung einer eidesstattlichen Versicherung und die strafrechtlichen Folgen einer, auch fahrlässigen, falschen oder unvollständigen eidesstattlichen Versicherung und die Bestimmungen der §§ 156, 161 StGB bin ich hingewiesen worden.

Christian Hauenstein
Flensburg, 30.09.2022

Overview

Contents

List of Figures

List of Tables

List of Abbreviations

ACE	Affordable Clean Energy rule.
CCS	carbon capture and storage.
CCTS	carbon capture, transport, and storage.
CG	collaborative governance.
CGE	computable general equilibrium.
CGR	collaborative governance regime.
CHP	combined heat and power.
CMW	COALMOD-World.
CO_2	carbon dioxide.
Coal Commission	Commission on Growth, Structural Change and Employment.
CPP	Clean Power Plan.
CSAPR	Cross-State Air Pollution Rule.
EIA	Energy Information Administration.
EMF34	Energy Modeling Forum 34.
EPA	Environmental Protection Agency.
FERC	Federal Energy Regulatory Commission.
FIDs	Final Investment Decisions.
FoC	Friends of Chair.
GHG	Greenhouse gas.
$GtCO_2e$	gigaton carbon dioxide equivalents.
GW	gigawatt.
IAM	integrated assessment model.
IEA	International Energy Agency.
IFCG	integrative framework for collaborative governance.
IMF	International Monetary Fund.
JETP	just energy transition partnership.
MATS	Mercury and Air Toxic Standards.
Mt	megaton.

Mtpa	million tons per year.
MW	megawatt.
MWh	megawatt hour.
NDCs	nationally determined contributions.
NSR	New Source Review.
PPCA	Powering Past Coal Alliance.
PRB	Powder River Basin.
RES	renewable energy sources.
SDS	Sustainable Development Scenario.
SO_2	sulfur dioxide.
STEPS	Stated Policy Scenario.
U.S.	United States of America.
WEO	World Energy Outlook.

Chapter 1

Introduction

1.1 Motivation and research objective

Assessment Report 6 of the Intergovernmental Panel on Climate Change (IPCC 2022) stresses once more the urgency to drastically reduce greenhouse gas (GHG) emissions within the next few decades to uphold the chance of limiting global warming in line with the *Paris Agreement* to well below 2°C, aiming for 1.5°C. Decarbonizing the energy system is a key element to this end. Out of all major fossil fuels, coal, one of the most emission-intensive energy sources, needs to be reduced the fastest. For the 1.5°C target to be met, coal consumption needs to drop to well below 50 % of today's level by 2030 (IPCC 2022, 2018a).

Politically, the phase-down and phase-out of coal is receiving increased attention. In 2017, the Powering Past Coal Alliance (PPCA) was founded, which contains an increasing number of countries and regions committed to phasing out coal consumption (PPCA 2017). Several countries, including Germany, the world's largest lignite producer and consumer, have announced the phasing out of coal within the next one to two decades (Ritchie 2021). At the UN Climate Change Conference in Glasgow (COP26) in 2021, coal was at the heart of many discussions about how to ratchet up climate change mitigation efforts. The conference produced the first international agreement with the explicit global target to cut the use of a particular fossil fuel, namely coal (UNFCCC 2021). Furthermore, several initiatives were announced at the conference to cease permissions and funding for new unabated coal-fired power plants, and to support transitions away from coal (e.g., UN Climate Change Conference UK 2021).

Coal currently accounts for approximately 27 % and 36 % of the total global primary energy supply and global power generation, respectively (BP 2022, 9, 51).[1] It is responsible for approximately 40 % of global fossil fuel CO2 emissions (Friedlingstein et al. 2022, 1933). Global coal consumption peaked in 2014 and after a slight decline in the following two years, it rebounded to a level only slightly below the record high by 2018 (BP 2022). In 2020, the first year of the COVID-19 pandemic, global coal consumption dropped significantly. However, in 2021 it surpassed the pre-pandemic level and, overall, shows no declining trend so far, at most signs of a stabilization at its currently high level (IEA 2021a, 2022a).

---

[1] The share of coal in total primary energy supply and CO_2 emissions from coal refer to the use of all types of coal. Generally, coal is divided into two categories based on its type of use, thermal coal and metallurgical (or coking) coal. Thermal coal is used mainly for power and (commercial) heat generation, accounting for about two-thirds of primary coal use. Thermal coal can be subdivided further into two general subcategories, lignite and steam coal, based on the energy content of the coal (differences exist depending on the classification schemes). Metallurgical coal refers to coal used for making coke, which is used in steelmaking. For further details, see Section 1.2.1. In the following, coal usually refers to thermal coal.

As of July 2022, 193 countries have signed the Paris Agreement and committed to take action on climate change (UNFCCC). One often considered instrument to achieve climate change mitigation is carbon pricing (Carbon Pricing Leadership Coalition 2017; Strefler et al. 2021). In 2021, 64 carbon pricing instruments were implemented globally and the share of global GHG emissions covered under some form of carbon pricing instrument reached 21.5 % (The World Bank 2021, 21). However, studies on the effectiveness of such instruments to reduce emissions show mixed results (Best, Burke, and Jotzo 2020; Green 2021), and additional measures are required to achieve short-term emission reductions (Kriegler et al. 2018). To address the roll out of renewable energy sources (RES), around 150 countries have created RES power regulatory policies and targets (REN21 2022, 44). As a result, the share of RES (excl. hydro power) in global power generation has risen from about one to 13 % in the last 20 years (BP 2022, 6), and studies find that a 100 % RES-based power system would be technically feasible and economically efficient (Hirschhausen et al. 2018; Jacobson et al. 2017; Löffler et al. 2017).

While coal production and consumption decreased to some extent in recent years in countries such as Germany and the United States (Diluiso et al. 2021), it is on the rise mainly in Asian countries (IEA 2021a; Edenhofer et al. 2018; Tong et al. 2019). Current projections of countries' and companies' coal production and consumption plans do not provide much hope for a fast turnaround towards a global coal phase out (SEI et al. 2021; UNEP 2021). Thus, scholars stress the necessity to increase the attention on suppressing the use of coal and other fossil fuels more directly (Asheim et al. 2019; Piggot et al. 2020; Turnheim and Geels 2012; York and Bell 2019). This requires governments to restrict and phase out the consumption of fossil fuels within their jurisdiction on the one hand (David 2017; Diluiso et al. 2021; Vinichenko, Cherp, and Jewell 2021), and to end the supply of fossil fuels on the other hand (Erickson, Lazarus, and Piggot 2018; Faehn et al. 2017; Green and Denniss 2018; Jakob et al. 2020).

Policies to actively phase-out the use of coal have been largely missing so far in attempts to reduce GHG emissions (Nascimento et al. 2022). The target to reduce and phase out the use of coal has only gained traction in recent years on the international level. More concretely, among others, Canada, Chile, South Korea and 23 European countries have so far announced a coal phase out within the next two decades (Ritchie 2021; Europe Beyond Coal). These countries, as well as the members of the PPCA mostly have limited domestic coal production and consumption, with electricity demand not growing strongly, and relatively old power plants (Blondeel, Van de Graaf, and Haesebrouck 2020; IEA 2019a; Jewell et al. 2019). Germany, as one of the world's largest lignite producers and consumers, is somewhat of an exception.

In many parts of the world, coal is still an abundant resource (BGR 2019). Not considering the societal and environmental costs caused by coal's production and combustion (Cardoso 2015; Muller, Mendelsohn, and Nordhaus 2011; Rauner et al. 2020; Sovacool, Kim, and Yang 2021), it is falsely perceived as a low-cost energy source (Diluiso et al. 2021; Jakob and Steckel 2022). Often coal is considered to contribute to energy security, particularly in countries of the Global South (Jakob et al. 2020; Jakob and Steckel 2022; Kalkuhl et al. 2019). Furthermore, the coal industry, particularly coal mining, is an important economic factor in many regions, with coal rents contributing about 0.2 % to global GDP (The World Bank). Locally, regions can be highly dependent on the coal industry, which provides jobs and tax income in otherwise often disadvantaged regions (Hanto et al. 2021; Oei and Mendelevitch 2019; Spencer et al. 2018; Zhou et al. 2022).

An incumbent system has evolved around these diverse dependencies, including coal mining and power industries, profiting from, and locking-in, the status quo (Erickson et al. 2015; Seto et al. 2016; Unruh 2000). Additionally, coal-fired power plants and coal mines are long-lasting infrastructures (Fisch-Romito et al. 2021). A 1.5°C compliant global coal phase-out would require the writing off of significant coal-fired power plant asset values (Edwards et al. 2022; Löffler et al. 2019; Pfeiffer et al. 2018) and the majority of current coal reserves would have to remain unmined (McGlade and Ekins 2015; Welsby et al. 2021). Thus, incumbent actors in the mining and power sector, including workers and dependent communities, often oppose a transition away from coal (Fisch-Romito et al. 2021; Johnstone, Stirling, and Sovacool 2017; Kalt 2021; Kungl and Geels 2018; Leipprand and Flachsland 2018). Scholars find that considering these political economy dimensions of coal transitions and addressing a just transition for affected regions is key to enabling the phasing out of coal (Diluiso et al. 2021; Brauers and Oei 2020; Hanto et al. 2022; Hermwille and Kiyar 2022; Jakob and Steckel 2022; Muttitt and Kartha 2020; Stognief, Walk, and Oei 2022).

Depending on the political system and the power of the incumbents and affected stakeholders, political stalemate situations can occur that prevent policy change (Brisbois and Loë 2016; Leach, Scoones, and Stirling 2010; Sabatier and Weible 2007), such as a decision to phase out coal (Furnaro 2022; Hermwille and Kiyar 2022). In order to find compromises and gain support for policy changes, several countries, such as Canada, Chile, the Czech Republic, Spain, and South Africa have initiated participatory stakeholder process to provide policy recommendations on coal phase-outs and just transitions (Brauers et al. 2022). In Germany, the stakeholder commission *Wachstum, Strukturwandel und Beschäftigung* (engl. Growth, Structural Change and Employment, also called the Coal Commission), was implemented in 2018 to overcome the stalemate of the German coal transition (Furnaro 2022; Hermwille and Kiyar 2022). The commission completed its work in 2019 with the recommendation to end coal-fired power generation and related coal (lignite) production in

Germany by 2038 at the latest (BMWi 2019), which was thereafter enacted.[2] While a phase-out by 2038 falls short of Germany's required climate mitigation obligations (Climate Analytics 2016; Yanguas Parra et al. 2019), it is the first binding phase-out decision of a major coal-producing country (Ritchie 2021). How to successfully govern and accelerate coal phase-out and other energy system transformation processes remains a pressing question (Köhler et al. 2019; Wolff et al. 2020).

Policies addressing coal supply could be effective measures to reduce coal consumption and related emissions (Lazarus and Asselt 2018). Mendelevitch (2018) finds that a moratorium on new coal mines could effectively reduce coal consumption by limiting global coal supply. A different avenue for reducing coal supply and consumption could be a coal production tax, which would raise prices of coal while generating additional income for coal-producing countries (Richter, Mendelevitch, and Jotzo 2018). A major coal-producing country that intended to implement such coal supply constraining measures in the past was the U.S. under the Obama administration, which introduced, for example, a moratorium on new mines on federal land (Erickson, Lazarus, and Piggot 2018). Under the Trump administration, however, the political agenda was reversed and fossil fuels were actively supported again (Jotzo, Depledge, and Winkler 2018), not at last with the promise to bring back coal mining jobs (Houser, Bordoff, and Marsters 2017), and a fueling of the hope of U.S. coal miners to continuously export coal to the international market (NCC 2018). However, despite the support for the coal sector under the Trump administration, coal production and consumption has continued its downward trend in the U.S. (EIA 2022a; Wamsted, Feaster, and Cates 2020). The Biden administration has announced the goal of reaching a carbon emission-free electricity supply by 2035 (The White House 2021), implying a significantly faster decline of U.S. coal consumption than previously envisioned, for example, by the U.S. Energy Information Administration (EIA 2020).

For many coal-producing countries, such as the U.S., coal production is also influenced by export opportunities, as about one fifth of the consumed coal is traded internationally, mostly seaborne (IEA 2021a; Holz et al. 2018). For major coal-exporting countries such as Australia, Colombia, Indonesia and Russia, coal rents contribute up to 0.7 % to national GDP, and for Mongolia and South Africa even some two to five percent (The World Bank). Previous assessments of the global coal market show that climate policies addressing coal demand could lead to shifts in regional coal production and trade (Haftendorn, Kemfert, and Holz 2012; Holz et al. 2018), which could lead to significant losses of coal rents and jobs (Ansari and Holz 2020; Auger et al. 2021; Le Billon and Kristoffersen 2019; Oei and Mendelevitch 2019). To limit GHG emissions from coal to Paris Agreement compatible levels, a significant share of the currently operating global coal-production capacities would

---

[2] The Federal Government: "Ending coal-generated power", https://www.bundesregierung.de/breg-en/news/kohleausstiegsgesetz-1717014, last accessed July 25, 2022.

have to be decommissioned early (Trout et al. 2022), which could lead to further coal mining job and rent losses, as well as stranded assets (Auger et al. 2021; Ploeg and Rezai 2020a).

Despite this asset-stranding risk, many countries see a continued development of new coal mining capacities. One of them is Australia, which has the largest amount of proposed coal mining capacities after China (Driskell Tate, Shearer, and Matikinca 2021). Despite the economic risks and increasing public debates about climate change, a wide range of actors, including politicians, continue to support new coal projects in Australia (Christoff 2022; Curran 2021; Stutzer et al. 2021). With domestic coal demand continuously declining, most of these new capacities are supposed to produce coal for the export market (AEMO 2021; Jotzo, Mazouz, and Wiseman 2018). However, these future export opportunities are uncertain as it is doubtful whether new coal projects are economically feasible (Gosens, Turnbull, and Jotzo 2022; Holz et al. 2018). Furthermore, they bring with them the risk of locking in further GHG emissions from coal (Trout et al. 2022; Unruh 2019).

Research gap and objective:

In order to reduce emissions from coal at the speed required to keep the Paris Agreement targets within reach, it is necessary to not only address coal demand but also its supply, and to manage an orderly and timely phasing out of coal production (Asheim et al. 2019; Diluiso et al. 2021; Erickson, Lazarus, and Piggot 2018; Jakob et al. 2020). However, so far only a few studies have addressed the global coal supply sector and its transition in the wake of climate change mitigation (i.a., Haftendorn, Kemfert, and Holz 2012; Mendelevitch 2018), and knowledge on how global coal supply can be reduced in a timely and equitable manner remains limited.

A 1.5°C-compatible decline in coal consumption would certainly impact all coal producers in the global coal market, yet, when and how this is felt by individual coal producing regions is unclear. Also financial and other implications, like early coal mine closures, are likely to differ highly among regions. Knowledge of sustainable pathways for coal supply can inform policymakers about what levels of coal supply might still be acceptable, and when it might be necessary to address excessive coal supply. This knowledge can also help to prepare early on for economic structural changes caused by ending coal mining activities in many regions.

Other open questions include, how climate policies, as well as general economic and structural developments of the energy sector affect coal production, and what this implies for individual coal producing regions. Knowledge on barriers and drivers for a decline of coal supply can help to find leverage points for polices addressing excessive coal supply. During the COVID-19 pandemic, coal production and consumption declined in many countries, while other energy sources where affected significantly less. The question arises whether this situation could mark a turning point for coal and initialize its global decline.

However, if the political objective to phase out coal is met by the resistance of incumbent actors, effectively preventing coal phase-out policies, ways to overcome this political stalemate need to be found. Knowledge of how to overcome such stalemate situations stalling coal transitions is still very limited.

With this thesis, I intend to further close these research gaps and contribute to the overarching research objective of finding out how to phase out coal supply in line with global climate targets. To do so, this thesis addresses four overarching research questions (RQs):

- RQ1: What would a 1.5°C-compatible global coal phase out imply for coal producers, in terms of the temporal course of the decline of production volumes, investments in new coal supply, and the utilization and retirement of existing coal supply infrastructure?
- RQ2: How might global coal supply evolve under current policy and energy sector trends, also as a result of the COVID-19 pandemic and the subsequent economic recovery programs?
- RQ3: What effect have current economic, political and structural factors each on coal supply and how might they contribute to a decline in coal supply?
- RQ4: How can a political process be designed and managed to achieve a coal phase-out in the event of incumbent actors blocking coal phase-out policies?

Research approach and methodology:

To answer these questions, this thesis takes into account the global coal sector, yet it puts an additional focus on coal production and supply for countries of the Global North, as coal sector transitions in these countries are already under way to some extent (Diluiso et al. 2021; Jewell et al. 2019; Nascimento et al. 2022), and these countries are considered to be required to phase out coal production and consumption earlier than countries of the Global South (Climate Analytics 2016; Yanguas Parra et al. 2019). RQ1 and RQ2 are primarily studied from a global perspective, however, taking into account regional specifics and assessing regional effects. To answer RQ3, the coal supply sectors in Australia and the U.S. were studied. Australia is a major coal exporting country with a large number of new coal projects under development. The U.S. is the only major coal producing, exporting and consuming country with significant decline in both, production and consumption, over the last few years, and multiple policies addressing the coal sector were implemented and rolled back over the last years. For RQ4, Germany and its stakeholder commission process was studied. In Germany, the first coal phase-out law in a major coal producing and consuming country was implemented after the stakeholder commission managed to overcome the previous stalemate (Brauers et al. 2022).

To study the context of global coal supply, and the effect of climate policies and market developments on it, I used mathematical modelling techniques. COALMOD-World (CMW) is an established model of the global coal market (Haftendorn, Holz, and Hirschhausen 2012; Holz et al. 2016), which I updated and employed to conduct scenario analyses (Chapters 3, 5 and 6). Furthermore, I developed a new version of CMW, CMW v2.0 (Hauenstein 2022b), to enable the detailed assessment of investments and stranded assets in the coal supply sector (Chapters 2 and 4). I complement these quantitative approaches with qualitative approaches to study actors' behaviors and influences in the policy-making process (Chapter 7). This interdisciplinary approach allows for the study of the multidimensional and complex issue of coal supply phase outs from different perspectives to gain a more comprehensive understanding of drivers and barriers for phasing out coal. The applied methods are presented and discussed in more detail in Section 1.4.

This thesis contributes to the literature on supply side climate change mitigation and coal phase-out debates in five main ways: (1) It improves the understanding of coal supply in line with global climate targets and of possible effects on the coal supply sector; (2) It improves the understanding of current trends in global coal supply and of the effect of different coal supply and demand policies, as well as market and energy sector developments on reducing coal supply; (3) It contributes to more comprehensive projections of possible coal sector developments by building coal demand scenarios based on bottom-up coal sector data; (4) It advances open source coal sector modelling by introducing a more comprehensive version of the global coal sector model COALMOD-World, considering coal mine lifetimes and retirements, and by making it more accessible via code and data publications; and (5), it contributes to a better understanding of governance processes to overcome incumbent actors' resistance to achieve coal transition policies.

The remainder of this chapter introduces the global coal sector (Section 1.2), as well as the literature and previous approaches of supply side policies and coal phase-out processes (1.3). It continues by presenting and discussing the research approach and chosen methodology applied in this thesis (1.4). Section 1.5 provides the thesis outline, as well as an overview of Chapters 2-7 and the most important findings from these chapters. Section 1.6 concludes and gives an outlook of further research needs. Chapter 2 focuses on implications of 1.5°C coal consumption pathways on global coal supply. Chapter 3 deals with the effects of economic policies and energy sector trends and on global coal supply. Chapter 4 assesses economic prospects for export-oriented coal supply and coal mine investments. Chapter

5 focuses on the effects of pro coal policies versus economic drivers on coal production. Chapter 6 assesses the impacts of structural and economic coal sector developments on coal production. And finally, Chapter 7 studies governance processes to achieve political feasible coal phase outs.

1.2 The global coal sector: status quo and current developments

1.2.1 Coal supply and the global steam coal market

In 2019, about 7,740 million tons (Mt) of coal were produced worldwide (IEA 2022b), providing about 4.7 million direct jobs (Ruppert Bulmer et al. 2021, 34). Coal rents contribute some 0.2 %, or USD 170 billion, to global GDP (The World Bank). The bulk of global coal production is geographically highly concentrated, with ten countries responsible for 94 % of global coal supply in 2019 (BP 2022). About 86 % (mass based) of the globally produced coal is thermal coal, which can further be divided into steam coal (89 %) and lignite (11 %) (IEA 2022b). Steam coal and lignite are differentiated based on their energy content. Lignite has an energy content of less than 20 GJ/t, steam coal of 20 GJ/t or more (IEA 2019a). Due to its low energy content, lignite is usually not transported over large distances but mostly used for power and heat generation in the close vicinity of the mines. In contrast, steam coal is an internationally traded good, with some 18 % (2019) of the produced steam coal consumed outside of the country of origin (IEA 2022b).

The major producing countries of thermal coal are also the largest consumers (Figure 1.1). The major exporting countries of steam coal, in descending order, are Indonesia, Australia, Russia, Colombia, South Africa, the U.S., and Kazakhstan. Together they were responsible for about 90 to 95 % of all steam coal exports in the last ten years. Over the same time, China, India, Japan, South Korea, and Taiwan where constantly the five largest importers, importing together some 60 % of all internationally traded steam coal (IEA 2022b).

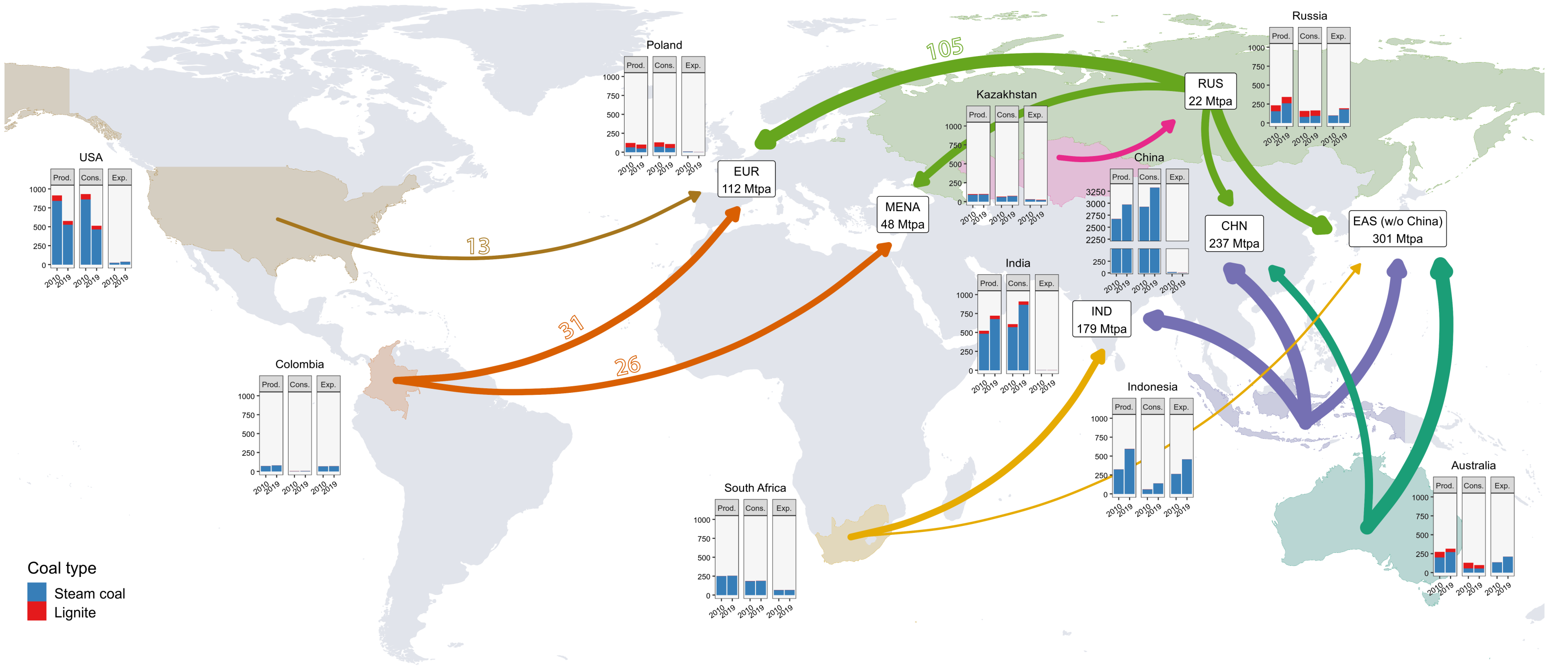


Figure 1.1: Steam coal and lignite production and consumption in major coal producing countries in 2010 and 2019, and major steam coal trade flows and total steam coal imports of major importing regions in 2018.

Note: Total imports based on export statistics. Actual total imports might deviate. Comprehensive steam coal trade data only available for 2018.
Source: Data from IEA (2019a).

While from a global perspective thermal coal production and consumption, as well as the annual amount of steam coal internationally traded, has remained relatively constant over the last decade, some significant changes have occurred on a regionally level. Particularly China, India and Indonesia, but also Australia and Russia increased their steam coal production significantly. China and India, globally the two largest producers, consumers and net importers of steam coal, almost solely produce for their domestic demand each (IEA 2022b). Thus, developments in these countries are important to consider as they can highly influence demand for seaborne coal (Holz et al. 2018) (see also Chapters 2 to 4). Australia, Indonesia and Russia produce for their domestic demand as well, however, increases in production resulted mostly from significantly raised annual exports of steam coal in these countries.

On the other end, in the U.S., in 2010 still the second largest coal producer after China, coal production dropped by about one third between 2010 and 2019 (IEA 2022b). The development of the U.S. coal sector is a very interesting case, not only because it represents the largest decline of coal in a single country in absolute terms so far (Diluiso et al. 2021), but also because a multitude of influencing factors can be observed for this case. Politically, the U.S. coal sector was addressed within the last decade with both, measures to decrease, as well as to support the use of coal (Erickson and Lazarus 2018; Houser, Bordoff, and Marsters 2017). Furthermore, domestic coal-fired power generation is increasingly competing with other power sources and struggling due to the old age of many of its power plants. And last but not least, U.S. coal production also depends on export opportunities to the international market (Coglianese, T. D. Gerarden, and Stock 2020; Culver and Hong 2016). Without a coal phase-out policy in place, it is interesting to observe how the different factors have contributed to the decline of U.S. coal production so far, and how this might develop in the future (see Chapter 5 and 6).

Germany, Poland, Ukraine and the United Kingdom (UK) are other countries with (previously) large coal sectors, which experienced a significant decline in coal production in the past (Diluiso et al. 2021). For the Eastern European countries Poland and Ukraine, as well as the former German Democratic Republic (GDR) region of Germany, the economic restructuring in the wake of the collapse of the Soviet Union largely contributed to the decline of coal production (Brauers, Oei, and Walk 2020; Diluiso et al. 2021; Stognief et al. 2019). The decline of coal mining in the UK and the Western parts of Germany was largely driven by its high costs and the availability of cheaper import coal (Oei, Brauers, and Herpich 2020; Brauers, Oei, and Walk 2020). In the UK, also coal consumption has been replaced almost completely by other power sources in the meantime, while Germany and Poland have remained highly reliant on coal in the power sector (Brauers and Oei 2020; Brauers, Oei, and Walk 2020).

Germany remains the largest lignite producer worldwide, although its annual production has started to decrease in recent years. Turkey and Russia show an opposing trend in lignite production, however, each reaching only about half the quantity produced in Germany in 2018 (IEA 2022b). With Germany's decision to phase-out coal production by 2038 the latest (see Chapter 7), this order is likely to change soon. Furthermore, China and Indonesia, both do not show up in IEA statistics on lignite production due to their reporting schemes, however, they are likely to be among the world's major lignite producers (IEA 2019a).

Despite some single phase-out policies, new coal mining projects with a total capacity of about 2,300 Mt per annum (Mtpa) are currently under development in a range of countries. China leads the list of new capacities under development, yet it is closely followed by Australia and India. About 75 % of these new capacities are thermal coal mines (Driskell Tate, Shearer, and Matikinca 2021). Despite having new coal mines under development, China plans, like Germany and the U.S., to gradually reduce coal production over the next decades. However, Australia and India are still on a coal production expansion path.[3] If all countries realize future coal production as currently planned and projected, total global coal production would remain at today's level throughout 2040 (SEI et al. 2021). If all these planned new coal mines will be realized is another question though. For example, in Australia the in May 2022 newly elected government has raised climate change mitigation ambitions, and doubts about the economic feasibility of proposed new coal projects exist (e.g., Buckley and Nicholas 2017). Prospects for new export oriented coal projects, as in Australia and Russia, are highly dependent on import demand developments of major coal importers, such as China, and could be among the first projects to come under economic stress in case of a global decline in demand (Holz et al. 2018) (see also Chapter 4).

Different studies estimate that up to 90 % of global coal reserves need to remain unmined in order to limit global warming to 1.5°C, or at least to well below 2°C (McGlade and Ekins 2015; Meinshausen et al. 2009; Welsby et al. 2021). Regionally, large differences exist, depending on existing reserves and remaining regional coal consumption, with the lowest shares of unextractable coal reserves in Asia (Welsby et al. 2021). Emissions from coal reserves in operating mines and mines under development alone would exhaust almost 80 % of the remaining 1.5°C GHG emission budget (Trout et al. 2022, 7). Thus, achieving the international climate target could require to retire large coal mining capacities early, which could lead to the stranding of assets also in the coal mining sector (Auger et al. 2021). Limiting the commissioning of new coal mining capacities could significantly reduce the

---

[3] Before summer 2022, also Russia was planning to continue expanding its coal production and export capacities (IEA 2021a; Fortescue 2021; SEI et al. 2021). However, sanctions and import bans imposed by the EU and other countries on Russian coal, following Russia's escalation of the war against Ukraine, have led to Russian coal companies suspending new coal mine projects. (Global Energy Monitor, Coalwire issue 434, September 15, 2022, https://mailchi.mp/791e6df7de74/insurance-evaporating-for-coal-utilities-russian-companies-suspend-new-mines-adani-fails-to-find-external-finance-for-australian-coal-port?e=48a7230869; last accessed September 22, 2022.

total amount of assets at risk of becoming stranded (Trout et al. 2022; Driskell Tate, Shearer, and Matikinca 2021) (see also Chapters 2 and 4).

1.2.1.1 Effects of Russia's invasion of Ukraine on the global coal market

On February 24, 2022, Russia escalated the ongoing military conflict in Ukraine by invading large parts of Ukrainian mainland. As a response, the EU, the U.S., and other countries significantly tightened and introduced new sanctions on Russia, including a ban on Russian coal imports. Russia responded by significantly reducing natural gas and oil deliveries to Western countries, in particular the EU (Hauenstein, Hainsch, et al. 2022; Yanguas Parra et al., in preparation). This has led to significant changes in global energy markets.

Natural gas supply shortages and overall market insecurity have led to natural gas prices rising significantly, from already high levels in the second half of 2021.[4] Many countries therefore have turned to replace natural gas with coal, particularly in the power sector, which is expected to lead to a growth in global annual coal demand by almost one percent in 2022 compared to 2021 (IEA 2022a). In combination with reduced Russian coal exports,[5] as well as supply shortages elsewhere, for example, due to flooding of coal infrastructure in Australia, this has led to historically high coal prices. While prices for internationally traded thermal coal lay in the range of about 50 to 130 USD/t between 2010 and mid of 2021, they reached more than 400 USD/t in the summer of 2022.[6] While coal prices are expected to decline again, they might very well remain above 200 USD/t over the next two years (IEA 2022a).

This will most likely also continue to affect global coal production, trade, and demand. While, for example, China and India have increased imports of Russian coal, which sells with a discount due to the ban by other countries, European and other Asian countries are looking for alternative coal supplies, mainly from Australia, Colombia, USA, and South Africa (IEA 2022a). For coal exporting countries, the currently high coal prices and the hope for a renaissance of coal demand also in European and other countries might trigger new investments in coal supply infrastructure, or delay previously planned coal mine closures (Yanguas Parra et al., in preparation). In Section 1.6, I briefly discuss what these new developments might imply for previous findings on coal supply developments and policies.

---

[4] Trading Economics: Natural gas; https://tradingeconomics.com/commodity/natural-gas, last accessed September 22, 2022.

[5] Russian coal exports to the Asian market, in particular to Japan, South Korea, and Taiwan, have declined as well (Global Energy Monitor: Coalwire Issue 433 (September 08, 2022), https://mailchi.mp/d018af8b79b4/hawaiis-only-coal-plant-closes-russian-coal-sanctions-bite-protests-hit-glencores-colombian-mine?e=48a7230869, last accessed September 22, 2022.

[6] Newcastle free on board (FOB) thermal coal (6000 kcal/kg) spot prices. Trading Economics: Coal; https://tradingeconomics.com/commodity/coal, last accessed September 22, 2022.

1.2.2 Coal demand and future coal consumption

Coal supply developments cannot be assessed without taking into account the demand for coal. For thermal coal supply it is in particular the coal demand in the power sector that is relevant. The power sector (including electricity and heat production) is responsible for about 75 % of thermal coal consumption, while the remainder goes mostly to industrial sectors like iron and steel production, the chemical industry, and the non-metallic minerals industry (IEA 2019a, II.17–18). Figure 1.1 above shows that thermal coal demand has remained relatively constant within the last decade. Again, regional differences apply. As already mentioned, particularly in the U.S. thermal coal demand declined significantly, reducing the market for U.S. coal producers drastically. Outside of the U.S., thermal coal demand declined most significantly in Canada and a number of European countries. This decline was, however, more than compensated by the growth in demand mostly in Eastern, Southern, and South-eastern Asian countries (IEA 2019a, 2021a).

Power generation from coal accounts for about 36 % of global power generation, followed by natural gas (23 %), hydro (15 %), RES (excl. hydro; 13 %), and nuclear (10 %) (BP 2022, 51). While the relative share of coal has slightly decreased from around 40 % in 2010, the absolute amount of coal-fired power generation has continued to increase (BP 2022; IEA 2021b). In contrast, the share of RES increased rapidly, with an average annual growth rate in power generation (excluding hydro) of about 15 % over the last ten years (BP 2022, 44). RES have experienced significant technological developments with high cost reductions over the last years (IRENA 2021). Furthermore, RES can provide numerous co-benefits, such as improved air quality or increased energy security (Karlsson, Alfredsson, and Westling 2020). Hydro power, already established for a long time, had a significantly lower average annual growth rate of 1.5 % over the last decade (BP 2022, 42, 51).

Power generation from natural gas increased by 35 % between 2010 and 2021, while nuclear energy power generation has remained relatively flat (BP 2022; IEA 2021b). Considering the future role of these two power sources, climate change mitigation scenarios show mixed outlooks. In many scenarios for limiting global warming to well below 2°C by the end of the century, the use of natural gas (in combination with carbon capture (transport) and storage; CCTS or CCS) and nuclear energy further increases (Byers et al., AR6 Scenarios Database). Yet, doubts remain, that GHG emissions from natural gas production and natural gas-fired power generation can be controlled effectively (Brauers 2022; Kemfert et al. 2022), and nuclear energy so far remains an expensive and high risk power source, without an existing solution for its waste disposal (Mendelevitch et al. 2018). In the year 2022, with the escalation of the Russian war against Ukraine, there is, at least in Europe, additional attention on the geopolitical and security risks and challenges of these two power sources (Hausmann et al. 2022; Hirschhausen 2022).

An important factor for the increasing deployment of RES is the significant reduction in generation costs per unit of electricity produced for PV and wind power (REN21 2022). While the global average levelized cost of electricity (LCOE), for example, of PV dropped by almost 90 % over the last ten years, the LCOE of coal remained flat, and that of nuclear even increased (Lazard 2021, 8). RES have become in many regions of the world the power source with the lowest LCOE, not considering subsidies. In some regions, the LCOE of new build RES even undercut the LCOE of existing fossil fuel-fired power plants (REN21 2022; L. Clarke et al. 2022; Lazard 2021). However, not included in the calculations of the LCOE of RES are factors like dispatch ability. Nevertheless, also when taking these system services into account, up to 100 % RES-based energy systems can offer economic alternatives to fossil based systems (L. Clarke et al. 2022; Jacobson et al. 2017; Löffler et al. 2017).

Yet, RES are more capital intensive than coal and natural gas power plants (which have higher operating costs), which can favor investments in fossil power plants in case of high cost of capital (Hirth and Steckel 2016). In many countries of the Global South, the cost of capital for RES is significantly higher than in countries of the Global North (Steffen 2020), which is a major obstacle for investments in RES in many of these countries (Jakob and Steckel 2022). This situation might change in the future, with financial institutions increasingly considering sustainability criteria in their lending policies (see Section 1.3.1.2 below).

Related to the question of costs of existing versus new power generation capacities, is the question of the availability and age structure of coal-fired power generation units. Many new coal-fired power plants have been built in recent years in Asian countries, most dominantly in China and India (Edwards et al. 2022). In contrast, only very few or no new plants were built, for example, in Europe and the U.S. The U.S. provide a prominent example of an aging coal-fired power plant fleet with a large number of plants around its retirement age, and an eventually quickly declining coal-fired power generation capacity (see Chapter 5 and 6). While the construction of new coal plants continues, the amount of worldwide completed new builds has decreased significantly since 2015, as well as the amount of new capacities under development. Yet, the annual capacity additions still outpace annual retirements, driven mostly by additions in China (Global Energy Monitor et al. 2021). GHG emissions from currently operating and being planned coal-fired power generation capacities would exceed remaining GHG budgets of climate targets by far, if the capacities would be fully utilized until the end of their expected lifetime (Pfeiffer et al. 2018; Edwards et al. 2022).

However, techno-economic factors, such as LCOE for different power sources and existing power generation infrastructure, rarely are the sole influences on power systems. All of the above depends on political decisions regarding power market designs, and further regulations and policies, such as carbon pricing or feed-in schemes for RES, increasing the relative costs of coal-fired power generation (REN21 2022; Strefler et al. 2021). Furthermore, coal-fired power generation can cause, beyond GHG emissions, substantial adverse environmental impacts like air and water pollution (Cardoso 2015; Sovacool, Kim, and Yang 2021). To address these impacts, environmental regulations have been put in place to limit coal-fired power generation or to enforce the installation of emission control technologies, increasing costs for coal-fired power plants (Diluiso et al. 2021). On the other hand, coal is still explicitly and implicitly subsidized in many countries (Coady et al. 2017; Gençsü et al. 2020; Mendelevitch 2018; Parry, Black, and Vernon 2021), due to political economic considerations, for example, to support local economies, energy security or serve vested interests (Diluiso et al. 2021; Jakob and Steckel 2022; Montrone, Steckel, and Kalkuhl 2022).

The idea of equipping coal-fired power plants with devices to capture CO_2 and thereby making continued coal-fired power generation compatible with climate targets might also stem to some extent from the latter considerations (Hirschhausen, Herold, and Oei 2012; Marshall 2016; Mohn 2020). The idea of abating emissions of fossil fuel-fired power generation with CCTS started to gain traction in the beginning of this century (IPCC 2005). However, despite high hopes, CCTS still does not play a role in the power sector, with only one coal-fired power plant currently equipped and running with CCTS (GCCSI 2020). Due to high costs and technical difficulties, significant doubt remains if CCTS can be deployed on coal-fired power generation units in time and to sufficient extent in order to allow for continued use of significant amounts of coal (Budinis et al. 2018; Grant et al. 2021; Martin-Roberts et al. 2021; Mendelevitch et al. 2018) (also see Chapter 5). Furthermore, aimed for CO_2-capturing rates of coal-fired power plants with CCTS usual leave out of consideration GHG emissions along the coal production chain, which could be particularly critical in case of methane emissions from coal mines (Saunois et al. 2020). Taking into account methane emissions of coal production, the CO_2-capturing efficiency per unit of power produced could be well below 80 % (Schlissel and Wamsted 2022).

Carbon dioxide removal (CDR) technologies, also called negative emission technologies (NET), are other mitigation options that could affect future demand for coal in case of stringent climate change mitigation pathways (Byers et al., AR6 Scenarios Database; Pradhan et al. 2021; Yanguas Parra et al. 2019). CDR technologies, like bioenergy combined with CCTS (BECCS), direct air capture with carbon storage (DACCS) and CO2 removal on managed land, are envisioned to actively withdraw CO2 from the atmosphere (Minx et al. 2018). In many well-below 2°C scenarios these technologies play an essential role to limit or bring back atmospheric GHG concentration to levels in line with climate targets (Braunger and Hauenstein 2020; Riahi et al. 2022; Rogelj et al. 2018). This removal of

CO2 from the atmosphere could increase the remaining GHG emission budget also for coal-fired power plants and allow for a slower and later decline of coal-fired power generation (Pradhan et al. 2021). However, many CDR technologies remain unproven at industrial scale so far and doubt about the possibility of their large-scale implementation, as well as concerns of adverse impacts exist (Bednar, Obersteiner, and Wagner 2019; Braunger and Hauenstein 2020; Bui et al. 2018; Creutzig et al. 2021; Fuss et al. 2018; Heck et al. 2018; Minx et al. 2018; Peters and Geden 2017). Also the issue is raised that such measures and technologies are rather intended to enforce the carbon lock-in and have little potential to mitigate climate change (e.g., CIEL 2019; Marshall 2016). For a detailed discussion of CDR technologies and potential reasons for their prominent role in climate change mitigation scenarios also see Braunger and Hauenstein (2020).

Chapters 2 to 6 take up these different factors for future coal demand when choosing and building own coal demand scenarios. Chapter 2 covers the range of 1.5°C scenarios without or limited overshoot. In Chapter 4, a range of scenarios is build, considering techno-economic and political developments in the Asia-Pacific region, the region where future coal demand will most likely be concentrated. In Chapter 5, scenarios include effects of climate and environmental policies on coal demand, as well as considerations of the availability of CCTS for coal-fired power plants. Chapter 6 includes additionally a scenario, which takes into account plant level data for coal-fired generation unit's age and geographical location, as well as a 1.5°C scenario based on mitigation pathways with limited deployment of CDR. All these considerations also feed into the scenario building process in Chapter 3, where additionally the most recent developments during the COVID-19 pandemic and their possible effects on coal demand are taken into account.

1.3 Climate policies to phase-out coal supply

Generally two different routes can lead to a politically desired change in the use of coal: either policies addressing coal consumption, or, as introduced in more detail in the following, policies addressing coal supply. Past climate policy discussions and incentives have mostly focused on limiting the consumption, and in particular the combustion of fossil fuels (Asheim et al. 2019; Lazarus and Asselt 2018; Piggot et al. 2020; Piggot et al. 2018). Limiting fossil fuel combustion with global and stringent demand-side policies could theoretically be sufficient to meet this target (Asheim et al. 2019). However, despite countries' ratification of the Paris Agreement, national ambitions and contributions to limit GHG emissions have not been sufficient so far (IPCC 2022; UNEP 2021).

Scholars argue that complementing demand-side approaches with measures to limit fossil fuel supply could help achieving climate targets, and at the same time reduce overall costs of climate change mitigation and risks of asset stranding (Asheim et al. 2019; Collier and Venables 2014; Green and Denniss 2018; Faehn et al. 2017; Lazarus and Asselt 2018). Addressing fossil fuel consumption only, but not fossil fuel supply, furthermore bears the risk of carbon leakage, meaning that a local reduction in demand can lead to overall lower prices, and hence to higher consumption elsewhere in case of transregional markets (Harstad 2012; Sinn 2008). A mix of demand- and supply-side measures instead could help to prevent such leakage effects. Furthermore, expectations of increasing fossil fuel prices due to constraint demand could trigger investments in, for example, RES and efficiency measures, as well as disincentivize investments in fossil fuel consuming infrastructure (Asheim et al. 2019; Green and Denniss 2018). If fossil fuel supply would be restricted widely enough, it could also ensure against a failure of demand-side policies (Asheim et al. 2019). Additionally, supply-side policies that lead to increased prices could benefit incumbent fossil fuel producers and thus gain their support (Asheim et al. 2019; Collier and Venables 2014; Green and Denniss 2018; Richter, Mendelevitch, and Jotzo 2018). Beyond economic arguments, past efforts to constrain fossil fuel supply have shown to create significant societal mobilization potential and public support for mitigation measures (Erickson, Lazarus, and Piggot 2018; Green and Denniss 2018; Piggot 2018).

However, as laid out in Section 1.1, restricting fossil fuel production will lead in the long-run to the disappearance of the fossil fuel sector's current business model, and hence to opposition by incumbent actors (Erickson, Lazarus, and Piggot 2018; Piggot et al. 2020) (also see Chapter 2). Thus, addressing and moderating these negative effects, for example, for workers in coal mines, can lower resistance and contribute to the political feasibility of supply-side measures (Green and Denniss 2018; Gürtler, Löw Beer, and Herberg 2021; Jakob et al. 2020) (also see Chapter 7). In case supply-side policies are enacted only locally, similar to limited demand-side measures, mitigation effects could be small due to increased production elsewhere (Richter, Mendelevitch, and Jotzo 2018). Yet, effects may vary depending on the specific case (Erickson, Lazarus, and Piggot 2018), and global effects ultimately depend on the overall set of implemented measures (Asheim et al. 2019).

Supply-side policies can be of various types and forms. In the literature generally three different categories are mentioned: i) economic instruments; ii) regulatory approaches; and iii) government provision of goods and services (Lazarus and Asselt 2018; Somanathan et al. 2014; SEI, IISD, ODI, et al. 2019). The three categories are explained and illustrated in more detail in the following sub-sections. A clear classification of individual measures and policies into the three categories is not always possible, as described below. For example, providing access to public finance or compensation payments could be considered as economic instrument, but also as a governmental goods provision. Furthermore, not only public actors like governments might implement such policies, but also private actors like banks or asset owners (see Section 1.3.1.2). A relatively new approach to address fossil fuel supply by civil society groups and others is climate litigation, which aims at holding fossil fuel producing companies accountable for climate change induced damages (Setzer and Byrnes 2020; Stuart-Smith et al. 2021). Climate litigation can increase the economic risk for fossil fuel companies and projects (Solana 2020; Zhou, Wilson, and Caldecott 2021). I therefore add it to the category of economic instruments below.

To successfully phase out the supply of fossil fuels, it will most likely need more than one isolated economic or regulatory policy, at least if the idea of a just transition is to be realized (Jakob et al. 2020; Piggot et al. 2020; SEI, IISD, ODI, et al. 2019). This can also be observed in current coal phase-out processes in, for example, Canada or Germany (Brauers et al. 2022). An important component in these cases is the governance process to find a politically legitimate and feasible policy package for the phase-out itself. Section 1.3.4 therefore dives deeper into these national coal phase-out processes.

1.3.1 Economic instruments

Economic instruments include the taxation of fossil fuel supply or the levy of fees and royalties, the removal of previously granted subsidies, the restriction of finance and insurance for fossil fuel projects, the divestment of funds from companies in the fossil fuel supply sector, and tradable allowances for production rights and compensations for non-extraction. All these instruments aim at increasing the costs or opportunity costs of fossil fuel production and supply (Lazarus and Asselt 2018; SEI, IISD, ODI, et al. 2019). In case of public finance and funds, this could also be considered as (curtailment of) governmental provision of goods and services. Two examples for economic instruments, which currently are also politically discussed and I therefore want to briefly introduce here, are coal supply taxes, and the removal of coal production subsidies and restrictions to finance.

1.3.1.1 Coal supply taxes

In line with the thought of creating incentives for coal producing countries to restrict coal production, Richter, Mendelevitch, and Jotzo (2018) study the theoretical case of introducing coal export and production taxes by coal producing countries. Just as of August 2022, Colombia, one of the major global coal exporting countries, is planning the introduction of such a coal (and oil) export tax.[7] Richter, Mendelevitch, and Jotzo (2018) find that a coal export tax introduced by a single exporting country could very well raise

---

[7] Bocanegra and Vargas (August 08, 2022): "New Colombian tax bill aims at oil exports to fund social spending", https://www.reuters.com/world/americas/new-colombian-government-proposes-576-billion-tax-reform-congress-2022-08-08/ (last accessed August 11, 2022).

substantial tax revenues, as it is the motivation in the case of Colombia, however, overall emission reductions would most likely be marginal due to compensatory effects in the global coal market. Yet, if a coalition of the major coal exporters would jointly introduce a coal export tax, a significant, but still small reduction of global coal consumption could be achieved. The effect could be increased significantly, and possible trade law violations could be avoided, if instead of an export tax, a tax on coal production would be introduced. However, domestic welfare increases in exporting countries could be reduced compared to the case of an export tax, as also domestic coal consumption would become more expensive. To reduce global coal consumption sufficiently to achieve global climate targets, the tax would have to be expanded to all coal producers and reach a sufficiently high level, which again raises the question of political feasibility of such a global approach. Nevertheless, in line with Faehn et al. (2017) they find that there could be very well economic incentives for fossil fuel producers to limit production.

1.3.1.2 Removing coal mining subsidies and restricting finance for coal projects

Despite global climate targets, the use of coal is still subsidized around the world and public and private investment in the coal sector continues (Gençsü et al. 2020; Parry, Black, and Vernon 2021; Urgewald et al. 2022). In recent years, attention to address these behaviors that directly oppose climate policy targets has increased. In 2009, G20 governments pledged to phase out fossil fuel subsidies (Rentschler and Bazilian 2017), and the UN Sustainable Development Goal (SDG) 12 includes the target to "[r]ationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions (…)" (UN 2015, 23). Targeting the moral side of investments in fossil fuel projects, a global fossil fuel divestment movement has evolved (Braungardt, Bergh, and Dunlop 2019; Piggot 2018). In particular, also financial actors and analysts are increasingly taking into account the financial and moral risks of continued investments in coal. Analysts have warned that similar to the housing bubble in the U.S., which triggered the global financial crisis in 2008 when it burst, a financial "carbon bubble" could exist, considering the market valuation of fossil fuel assets that is based on assumptions of continuous fossil fuel consumption (CTI 2011; CTI and GRI 2013). And most recently, at the COP26 in Glasgow in 2021, governments agreed to end fossil fuel subsidies and international financing of coal projects.

Mendelevitch (2018) finds that removing all explicit subsidies to steam coal producers worldwide would reduce global GHG emissions only marginally. This can be explained by the relative small amount by which explicit subsidies reduce unit production costs of coal. According to Parry, Black, and Vernon (2021), subsidies to coal are largely of implicit nature, that is, for example, not charging coal producers and consumers for induced environmental costs. An example of a case where the removal of explicit subsidies ended coal mining is the German hard coal sector, which was not competitive without subsidies anymore and ended in 2018 (Oei, Brauers, and Herpich 2020).

Less studied so far, but increasingly mentioned also by actors of the coal sector, is the restriction of finance (and insurances) for coal projects. More and more major banks, insurance companies, and investment firms are adopting self-imposed regulations to exclude coal projects as their customers and from their portfolios. But also investors that still consider investing in coal projects start to demand higher risk premiums for investments in coal (Fattouh, Poudineh, and West 2019). As a consequence, loan spreads for coal mining projects have significantly increased (Zhou, Wilson, and Caldecott 2021). This increasingly challenges the economics of new coal projects and project expansions (see also Chapters 3 and 4).

An additional financial risk for coal projects starts to evolve in the form of climate and environmental litigation (Solana 2020). Based on increasing capabilities of climate attribution research, climate litigation is gaining traction (Setzer and Byrnes 2020; Stuart-Smith et al. 2021). With an increase in likelihood for extreme weather events due to climate change (B. Clarke et al. 2022), also the financial risk for GHG intensive assets, such as coal mines, could increase.

1.3.2 Regulatory approaches

Regulatory approaches include moratoria, bans, or quotas on fossil fuel exploration, extraction and transport, the limitation or repeal of production licenses, as well as the establishment or tightening of environmental performance standards for fossil fuel supply facilities (Lazarus and Asselt 2018; SEI, IISD, ODI, et al. 2019). A relatively often discussed, and already temporarily implemented, regulatory approach addressing coal production is a moratorium on new coal mines (Blondeel and Van de Graaf 2018; Dong, Qi, and Nemet 2021; Erickson and Lazarus 2018; Mendelevitch 2018), which I therefore introduce here in more detail. Regulating transport infrastructure, for example, coal export terminals at the U.S. West coast, are another example of restricting coal supply (see below and Chapters 5 and 6). Many countries also already limit exports and imports of coal with quotas or bans, however, in most cases not due to climate mitigation reasons but, for example, to support domestic coal production, as in China, or to ensure domestic supply with coal, as in Indonesia (IEA 2021a; Gosens, Turnbull, and Jotzo 2022) (see also Chapters 3 and 4).

1.3.2.1 Coal mine moratoria

The basic idea behind a moratorium on new coal mines is to limit coal supply to the remaining production from reserves in operating mines. To estimate the effects of a global moratorium for steam coal mines, Mendelevitch (2018) estimated coal reserves in operating mines and used the COALMOD-World model to analyze future coal supply and consumption. A moratorium implemented in 2020 could reduce global coal supply and consumption sufficiently to limit emissions from coal to a 2°C budget. However, results are highly sensitive to estimates of reserves in operating mines. If reserves, particularly in China and India, tend towards the upper end estimate, supply exceeds levels compatible with the 2°C target. In both cases, coal prices would increase significantly (Mendelevitch 2018), which could eventually increase the coal sector's acceptance of such a global measure.

China and the U.S. both implemented (partial) moratoria for new coal mines in 2015 and 2016, respectively. While these cases of partial and temporary coal mine moratoria in major coal producing countries offered reason for optimism to constrain global coal supply, both moratoria were implemented not because of climate considerations, but as a form of industrial policy (Blondeel and Van de Graaf 2018). The moratorium in China addressed domestic coal mining overcapacities and effectively reduced Chinese coal mining capacities, yet only as far as needed to stabilize the desired coal supply and demand equilibrium (Dong, Qi, and Nemet 2021). The moratorium in the U.S., if sustained permanently, could have reduced GHG emissions from coal significantly (Erickson and Lazarus 2018). However, it was repealed by the Trump administration only one year after it was introduced (also see Chapter 5).

1.3.2.2 Restricting coal supply infrastructure

The production and distribution of coal as a bulk good is dependent on adequate transport infrastructure (Gosens, Turnbull, and Jotzo 2022; Haftendorn, Holz, and Hirschhausen 2012). Thus, regulating coal transport infrastructure, like coal export terminals, can be an effective measure to limit coal supply. One prominent case of sub-national authorities regulating coal transport infrastructure is the West of the U.S., where in the past a large number of coal ports were planned to export coal from the Powder River Basin (PRB), located in central U.S., to Asia (Power and Power 2013; Cornot-Gandolphe 2015). These plans raised public concern over environmental impacts and led to local regulations limiting or excluding coal exports from ports along the U.S. West coast, which restricts the option to export U.S. coal to Asia (see Chapters 5 and 6). Such regulatory measures could be, for example, emission and other environmental performance standards, which are also widely used to regulate power plants (Diluiso et al. 2021).

1.3.3 Government provision of goods and services

To achieve political goals, governments cannot only tax or regulate the applicable economic activities, but can also provide incentives for changes. One idea is that governments provide compensation payments for forgone production (also considered an economic instrument), or put in other words, pay for reserves to be left in the ground. Furthermore, to ease the transition process away from fossil fuel production, they can assist affected regions in structural change processes, often considered as just transition measures (Lazarus and Asselt 2018; SEI, IISD, ODI, et al. 2019; SEI et al. 2021). Both could be at national, but also international level. These approaches are also interesting from a global justice and equity perspective, considering, for example, that resource-rich countries in the Global South should now refrain from fossil fuel production and consumption because of climate change, while countries of the Global North have exploited and built their economic development on the consumption of fossil fuels for many decades and thereby are responsible to a large degree for global climate change (Bos and Gupta 2019; Kartha et al. 2018; Muttitt and Kartha 2020). The concept of just transition has its focus more directly on workers, communities and consumers that could be adversely affected by a transition away from fossil fuels (Atteridge and Strambo 2020; ILO 2015; UNFCCC 2015, 2016). Capturing the broader context, including actors up to the level of states, Green and Gambhir (2019) speak of transitional assistance policies that are required for a global just and equitable transition.

1.3.3.1 Compensation payments for leaving coal in the ground

Harstad provocatively titled his article in 2012 with the advice “Buy Coal!”, showing that economically “the best climate policy [could be] to purchase fossil-fuel deposits and preserve them”, or, to prevent nationalization and exploitation of the bought reserves by the state where they are located at a later point in time, “pay the owner for not exploiting it right now” (Harstad 2012, 106–107). Collier and Venables (2014) argue that simply buying foreign coal reserves to avoid their exploitation would probably be met with societal and political resistance in the target countries, but other international compensation mechanisms could improve the feasibility of such an approach. A prominent real-world example of such a compensation for non-extraction scheme was the Yasuní-ITT initiative proposed by Ecuador in 2007. Ecuador offered to not exploit a large oil reserve in an ecologically sensitive region in return for international payments. Ultimately, the initiative collected less than 0.5 % of the hoped for funds from the international community, was met by high political pressure, and could not exclude carbon leakage, which led to its failure (Sovacool and Scarpaci 2016). While the Yasuní-ITT initiative was more successful than other attempts to raise money to deliberately strand fossil fuel reserves, it also shows that, at least at that time, the international community was not willing to pay significant amounts of money for stranding fossil fuel reserves. One reason was the fear that this would set an example leading to prohibitively large compensation demands in the case of significantly larger reserves in other fossil fuel producing countries (Sovacool and Scarpaci 2016).

Compensation for non-extraction, however, is also part of national coal phase-out processes, for example, in the Czech Republic and Germany (Brauers et al. 2022). For example in Germany, private lignite mining companies, which also operate the lignite-fired mine-mouth power plants, receive compensation payments based on calculations of possibly forgone profits in return for ending lignite mining and lignite-fired power generation earlier than approved in previously (Gürtler, Löw Beer, and Herberg 2021). While these compensation payments eventually smooth the transition process, they are not uncontested, as some argue that early closures could also take place alone due to economic market effects and paid compensations could be received as a “golden handshake” to incumbent fossil fuel companies (Furnaro 2022; Gürtler, Löw Beer, and Herberg 2021; Hermwille and Kiyar 2022) (also see Chapter 7).

Lifting the idea of a comprehensive coal phase-out process as part of an energy and just transition to the international level, at COP26 in Glasgow, a just energy transition partnership (JETP) between South Africa and several countries of the Global North was announced. It includes the provision of funds by countries of the Global North for an energy transition away from coal in South Africa, and aims at enabling a just transition for people and communities impacted by this transition of the energy sector (UN Climate Change Conference UK 2021). This offers hope for the case of the highly coal-dependent South Africa. However, the notion of receiving financial assistance by countries of the Global North in turn for increasing coal phase-out ambitions, might have been also one reason for China and India to enforce a watering down of the agreement on coal at the COP26 (“phase down” of coal power instead of “phase out”), to later increase ambitions in turn for compensation. Only seven months later, at the G7 summit in June 2022 in Germany, the G7 countries pledged to work on further partnerships in line with the JETP with India, Indonesia, Senegal, and Vietnam (G7 2022), including with India and Indonesia the second and third largest global coal producers.

1.3.3.2 Just transition and transitional assistance policies

The call to ensure a just transition away from the fossil fuel based system is stated prominently, for example, in the Paris Agreement (UNFCCC 2015). Many scholars argue that it is essential to take into account the concept of a just transition when aiming to phase-out coal, in order to decrease resistance by affected stakeholders and communities, as well as from a moral point of view to achieve an inclusive and equitable transition process (i.a., Diluiso et al. 2021; Brauers and Oei 2020; Gürtler, Löw Beer, and Herberg 2021; Jakob et al. 2020; Muttitt and Kartha 2020).

The concept of just transition itself goes back to the 1980s and a trade union movement in the U.S. in the wake of industry closures due to environmental regulations (Jenkins et al. 2020). While still also focusing on workers and jobs, just transition in the context of climate policy is understood now more broadly as the goal to involve and to address the needs of all stakeholders that might by adversely affected (Atteridge and Strambo 2020; ILO 2015; UNFCCC 2015, 2016). Just transition principles and objectives in the context of coal phase-outs include, beyond the imperative of a timely decarbonization, support for affected workers and their communities, diversification and reorientation of (local) economies, support to achieve societal equality and well-being, environmental remediation of mining sites, as well as the effort for inclusive and transparent planning processes (Atteridge and Strambo 2020; Furnaro et al. 2021). Speaking of transitional assistance policies, these objectives might also be expanded to transitions at the national level, including support not only by a national entity, but by other states of the international community (Green and Gambhir 2019), as it is the concept of the JETPs.

Transitional assistance policies and just transition measures can take a large variety of forms and target different actor and institution levels. Measures can include, for example, financial compensations, exemptions from climate laws, and structural adjustment support. These can be targeted at workers, corporations, consumers, communities, and states (Green and Gambhir 2019; Spencer et al. 2018). The applied measures are very case specific and transition processes can be lasting for several decades, yet without a guarantee that the objectives can always be fulfilled (Atteridge and Strambo 2020; Diluiso et al. 2021; Furnaro et al. 2021; Green and Gambhir 2019; Muttitt and Kartha 2020; Oei, Brauers, and Herpich 2020). Nevertheless, transitional assistance policies seem to have played a key role in recent processes of nationally coordinated and implemented coal phase-out decisions (Brauers et al. 2022; Gürtler, Löw Beer, and Herberg 2021; Hermwille and Kiyar 2022) (see also Chapter 7). Thus, current intentions to provide transitional assistance also on an international level (see Section 1.3.3.1 above) could promote phasing out coal also in countries with limited economic capacities.

1.3.4 Coordinated national coal phase-out processes and governance

Several coal producing countries have engaged in nationally coordinated processes in recent years to address a national coal phase-out. These include Canada, Chile, the Czech Republic, and Germany, which set up stakeholder commissions in the years 2018 and 2019 to find a way forward for a national coal phase-out and just transition each (Brauers et al. 2022). In all four cases, a wide spectrum of stakeholders were included and participated, from industry to environmental nongovernmental organizations. However, the scope, extent and outcome differed in each case.

In Canada, the government had already decided to phase out coal-fired power generation by 2030 prior to setting up the commission. The commission was then tasked to provide recommendations for a just transition for affected workers and communities (Gürtler, Löw Beer, and Herberg 2021). Not part of this process in Canada was the decision about the future of coal mining.[8] The commission concluded its work with recommendations and demands for a just transition, and a proposal of a just transition plan. However, a promised "Just Transition Act" is still not realized (Brauers et al. 2022).

In Chile, issues of coal mining were also not part of the commission process, as coal mining was already at very low levels and ended in 2020 (Hauser et al. 2021). The commission was tasked to assess potential effects of a phase-out of coal-fired power production. Based on these assessments, the Chilean government together with the private power utilities decided on a coal phase-out plan for the remaining coal-fired power plants until 2040. However, a later adopted plan did not set closure dates for all coal plants. Yet, due to economic, political and societal developments, the closure of the Chilean coal plant fleet might as well come earlier than 2040 (Hauser et al. 2021).

In the Czech Republic, lignite mining still plays a substantial role, with production levels around 40 Mtpa prior to the COVID-19 pandemic (IEA 2022b). In 2019, the stakeholder commission was tasked to propose a coal phase-out date and to identify measures for an energy transition, as well as to identify economic and social impacts of such a transition. The commission concluded with a proposal for a coal phase-out by 2038. However, several members of the commission did not support this proposal and the work of the commission was criticized as biased and supporting vested interests (Ocelík et al. 2022). The government

---

[8] At the COP26 in Glasgow, Canada announced a possible end of thermal coal exports by 2030. Thus, with an end to domestic use of thermal coal by 2030, this would imply also a phase-out of thermal coal mining. However, no end date to metallurgical coal mining has been announced so far. (Husser, November 04, 2021: "Canada is weaning itself off thermal coal but keeps shipping it elsewhere"; https://www.cbc.ca/news/science/thermal-coal-canada-ban-exports-1.6236441, last accessed August 15, 2022.)

rejected the proposed phase-out date and finally decided to phase out coal by 2033 (Europe Beyond Coal).

The case of Germany is particularly interesting, as Germany is still highly reliant on coal in its power sector and is the world's largest lignite producing country (IEA 2019a; Jewell et al. 2019). Several earlier attempts to limit coal production and coal-fired power generation failed due to resistance by powerful incumbents and their high influence in the political processes (DIW Berlin, Wuppertal Institut, and Ecologic Institut 2019; Furnaro 2022; Oei et al. 2015). However, societal pressure to reduce coal consumption and production in Germany also increased, as well as the pressure to reduce coal consumption to achieve Germany's climate targets (Blondeel, Van de Graaf, and Haesebrouck 2020; Gürtler, Löw Beer, and Herberg 2021; Leipprand and Flachsland 2018; Rinscheid and Wüstenhagen 2019). The in 2018 implemented stakeholder commission was tasked to propose a pathway and final date for phasing out coal mining and power generation in Germany, as well as recommendations on how to enable a just transition for affected regions. The commission concluded with recommendations on how to implement the coal phase-out in Germany by 2038, with an option for 2035, and how to support a just transition in the affected regions and the energy system (BMWi 2019). These recommendations have since been implemented to a large extent by the German Federal Government (Gürtler, Löw Beer, and Herberg 2021). After a further ratcheting-up of EU and national emission reduction targets, the German Federal Government now aims for a coal phase-out in Germany already by 2030.

While not necessarily delivering a coal phase-out in line with the Paris Agreement, these collaborative coal phase-out governance processes are interesting study objects, considering the limited progress on phasing-out coal in some of the cases prior to these national stakeholder processes. Furthermore, they adhere to the notion articulated by many scholars that taking into account just transition objectives and stakeholder involvement could contribute to successful coal phase-outs (Diluiso et al. 2021; Jakob et al. 2020; Muttitt and Kartha 2020). Furthermore, the process of how to arrive at a political feasible decision for an intended phase-out of, for example, coal, is still a very recent and highly relevant question (Jewell and Cherp 2019; Kern and Rogge 2018; Köhler et al. 2019). In case of such highly contested decisions, like a coal phase-out, with numerous competing objectives of powerful incumbent stakeholders, policy decisions can be stalled or are at risk to create further lock-ins of fossil fuel dependencies (Leach, Scoones, and Stirling 2010; Johnstone, Stirling, and Sovacool 2017; Newell 2018; Sabatier and Weible 2007). As a means to overcome such stalemate situations and to achieve consent for sustainability transitions by incumbent actors, collaborative (or participatory) governance (CG) approaches, as in the case of the above coal phase-out processes, are receiving increased attention (Ansell and Gash 2007; Emerson, Nabatchi, and Balogh 2012; Newig et al. 2018). At the same time, also these collaborative approaches have to deal with the political economy boundary conditions of each individual case and incumbent actors might still be able to prevent ambitious coal phase-out pathways, or even could capture these processes to legitimize the continued use of fossil fuels (Breetz, Mildenberger, and Stokes 2018; Brisbois and Loë 2016, 2017; Dutterer and Margerum 2015; Kallis, Kiparsky, and Norgaard 2009; Krick 2013).

1.4 Research approach, frameworks and methodology

The assessment of global energy markets, their market dynamics, and their behavior under changing policy and boundary conditions is traditionally of quantitative nature (Edmonds and Reilly 1985; Gabriel et al. 2012; Huntington, Weyant, and Sweeney 1982). Such quantitative approaches can be very helpful to understand the macro dynamics of the studied systems and to illustrate possible system developments, as well as to approximate the effect of economic and regulatory policies, like the introduction of a coal production tax or moratorium on new coal mines (Holz 2015; Mendelevitch 2018; Richter, Mendelevitch, and Jotzo 2018). Model-based quantitative analysis is an established assessment method for studies of (global) coal supply and markets (Auger et al. 2021; Gosens, Turnbull, and Jotzo 2022; Holz et al. 2015; Paulus and Trüby 2011).

Quantitative modelling approaches of energy systems and markets are usually focusing on techno-economic aspects, while other influences, like political economic factors are often left out (Krumm, Süsser, and Blechinger 2022; Oei, Burandt, et al. 2020). However, agency and power of the different actors and institutions involved can be highly influential when determining the course of sustainability transitions (Markard, Suter, and Ingold 2016). Thus, the assessment of energy transitions and related policies requires to consider the socio-technical and political perspectives in addition to the techno-economic perspective (Cherp et al. 2018). As the literature shows, particularly the political economy, as part of the political perspective, can play a key role in the policy-making process and policies addressing coal supply and demand (Diluiso et al. 2021; Jakob and Steckel 2022). To assess the influence of different actors and institutions in these processes in depth, qualitative research methods like semi-structured interviews are more appropriate (Sovacool, Axsen, and Sorrell 2018).

Studying the multifaceted and complex dynamics and interrelations of the global coal supply sector and related policy processes require a multi-method research approach. In this thesis, I therefore chose an interdisciplinary research approach to assess the phase-out of coal supply holistically, taking into account different perspectives, particularly the techno-economic and political perspective. For the assessment of research questions one and two, I focus on economic and structural effects and developments at the macro scale of the coal supply sector, taking into account political factors and technical details (Chapters 2 to 6). I employ a mathematical modelling framework to conduct scenario analyses for the global and regional coal sector, which I explain in more detail in Section 1.4.1 below. I complement these largely quantitative studies with an analysis of coal phase-out policy-making processes, based on political decision making and governance theory and qualitative research methods. The applied theoretical framework and applied methods are described in Section 1.4.2.

1.4.1 Mathematical modelling framework

Mathematical models can be used as simplified representations of real world systems to assess and help understand complex processes with many interrelated elements and study, for example, the effect of climate policies on energy markets (Huntington, Weyant, and Sweeney 1982). Assessing global energy systems and markets, a wide variety of models are employed to assess different questions. For example, energy system models aim at a detailed technical representation of the energy system and are often used to assess scenarios for future energy supply systems (Auer et al. 2020; Löffler et al. 2017). In contrast, computable general equilibrium models (CGE) are representations of the economy and used to assess market equilibria of supply, demand and price under specified conditions (Wing 2009), usually with significantly less detailed technical representation of, for example, the energy system, and instead representing all economic sectors. Combining these and other modelling approaches, integrated assessment models (IAM) intend to capture dependencies and feedbacks of different systems, like the economic and the energy system, as well as natural systems and the climate, to enable, for example, the assessment of potential climate change mitigation pathways (Nordhaus 2013; Riahi et al. 2022).

What all these modelling approaches have in common is the large extent of the represented system(s), which usually comes with the limitation of limited details of individual sectors, like the coal sector, and the lack of representation of individual actors' strategic behaviors and interactions. Reducing the complexity of the problem by only representing a specific sector, partial equilibrium models can be used to model individual sectors with a high level of details and at the same time the actors' behaviors (Gabriel et al. 2012; Holz 2015). This model type is widely applied to study sectoral energy markets and, for example, the effects of climate policies on energy supply (Huppmann and Holz 2012; Egging, Holz, and Gabriel 2010; Mendelevitch 2018; Mendelevitch and Oei 2018).

Haftendorn, Holz, and Hirschhausen (2012) present the COALMOD-World model, a dynamic partial equilibrium model of the global steam coal sector. The model represents the supply chain of steam coal, with producers and exporters as profit-maximizing players. The model has been used widely for assessments of the global coal market (Haftendorn, Kemfert, and Holz 2012; Holz et al. 2018; Mendelevitch 2018), and adapted to study specific market and policy implications (Richter, Mendelevitch, and Jotzo 2018). Other models of the global coal sector have been developed by Paulus and Trüby (2011) and Trüby and Paulus (2012). The latter is also the basis for the model used in Auger et al. (2021). Rioux et al. (2015) and Gosens, Turnbull, and Jotzo (2022) developed models focusing on the Chinese coal sector.

In this thesis, I use and extend the open source COALMOD-World model to assess the global coal supply and effects of different market and policy conditions. For Chapters 3, 5 and 6, an updated model version of CMW, based on Holz et al. (2016), is employed. Figure 1.2 shows the now represented coal producing, exporting and importing countries. Extending this model version by a detailed representation of the retirement of coal mines, I present CMW v2.0 in Chapter 2. CMW v2.0 allows for the detailed assessment of investments in new coal mining capacities and potential stranding of coal mining capacities under different demand scenarios. This model version is also applied in Chapter 4.

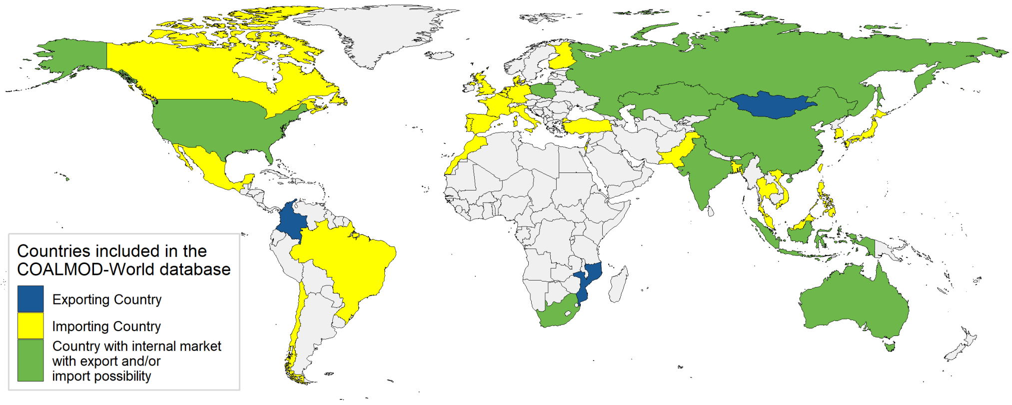


Figure 1.2: Coal producing, exporting, and importing countries represented in COALMOD-World. Reproduced with permission from Holz et al. (2016).

Source: Adapted from Holz et al. (2016) and updated.

CMW is used for scenario analyses to test for the effects of different supply and demand side policies, and to study the coal supply sector under different market and policy conditions. Scenario analysis is a commonly used method to assess, for example, climate change mitigation pathways (Söderholm et al. 2011). However, the design and scenario choices can be highly political and have to be considered carefully and communicated transparently, as the selection of the represented scenario range can influence the perception of possible futures and their likelihood. For a detailed discussion, see Braunger and Hauenstein (2020), as well as Chapter 5.

1.4.2 Theoretical framework and methodology to assess policy-making of coal phase-outs

A wide array of theoretical frameworks exist to assess energy transitions, the involved actors and institutions, and their influences (Markard, Raven, and Truffer 2012; Köhler et al. 2019). These include, for example, the multi-level perspective framework (Geels 2011), the "triple embeddedness framework" (Geels 2014), and the "meta-theoretical energy transitions framework" (Cherp et al. 2018). Focusing on political economy aspects, Jakob et al. (2020) develop the "actors, objectives, context" framework to assess policy outcomes in the context of energy and climate policies, which is applied to assess the political economy of coal in a wealth of country cases, such as Colombia (Puerto-Chaves and Corral-Montoya 2022), Germany (Hermwille and Kiyar 2022), South Africa (Hanto et al. 2022), and the UK (Stognief, Walk, and Oei 2022). These studies highlight the influence of powerful actors and institutions on coal policies and confirm the findings of other studies, that in case of powerful incumbent actors, or coalitions of actors, these can prevent policy changes or influence policies for their benefit (Johnstone, Stirling, and Sovacool 2017; Seto et al. 2016).

While these frameworks aim to assess the political arena in which policies are made, they are not focusing on specific situations of policy-making processes and how a policy change might be achieved in these situations. The "advocacy coalition framework", developed by Sabatier and Jenkins-Smith (1988), focuses on policy processes in the case of large interest conflicts with a high number of involved stakeholders. Major policy changes might occur if policy beliefs and objectives of actors change over time, which can be long-term processes though. Leading to major policy change much faster might be external shocks, such as the Fukushima nuclear accident (Markard, Suter, and Ingold 2016). A different pathway to a major policy change might also be a negotiated agreement (Sabatier and Weible 2007). In a case of a "hurting stalemate" situation, when the continuation of the status quo is not an acceptable solution for any of the major actor coalitions, but also none of the actor coalitions has the power to achieve a policy change by itself, actor coalitions might have the incentive to negotiate seriously about a policy change (Sabatier and Weible 2007, 206). A rich strand of literature has evolved around the broader topic of collaborative governance (CG) (Ansell and Gash 2007; Emerson, Nabatchi, and Balogh 2012; Koebele 2019), which describes the process of negotiating a policy agreement such a hurting stalemate situation (Emerson and

Nabatchi 2015). Emerson, Nabatchi, and Balogh (2012, 2) define *collaborative governance* as:

> *"the processes and structures of public policy decision making and management that engage people constructively across the boundaries of public agencies, levels of government, and/or the public, private and civic spheres in order to carry out a public purpose that could not otherwise be accomplished."*

In Chapter 7, the integrative framework for collaborative governance (IFCG; Emerson, Nabatchi, and Balogh 2012) is used to guide the empirical analysis of the stakeholder commission and policy-making process for a coal phase-out in Germany. The IFCG enables the assessment of the elements and dynamics that lead to the policy output of a GC process. In this study, the IFCG is used to study how the compromise for a phase-out of coal in Germany was achieved and what can be learnt from this case for other similar cases. For details on the IFCG, see Chapter 7.

To gather data for this empirical analysis, semi-structured interviews were conducted. Semi-structured interviews are of inductive and exploratory nature and can be used to assess specific processes and perspectives in depth. They form a common method for qualitative data collection in the field of energy social science (Sovacool, Axsen, and Sorrell 2018), and in case written accounts of the required information is missing (Mosley 2013). For the analysis of the gathered interview data, qualitative content analysis is applied, following the approach proposed by Gläser and Laudel (2010). Qualitative content analysis enables a theory- and rule-guided assessment of contents, without orienting the analysis on the quantification of information, but on the complexity of information and understanding. Theory guided categories are defined in the beginning of the analysis, which guide the extraction of information from the transcribed interviews. Following the approach by Gläser and Laudel (2010), categories can be added or adapted during the information extraction process, in case the gathered interview information contains new insights that require to reconsider the initially defined categories. This makes this approach particularly useful for exploratory assessments of causal relationships (Gläser and Laudel 2010), such as the mechanisms that led to the coal phase-out agreement in Germany.

1.5 Outline, findings and contributions

The outline of this thesis can be divided into three general parts, apart from the introductory chapter (see Figure 1.3). The first part consists of Chapters 2 and 3, and primarily addresses the overarching research questions RQ1 and RQ2 (see Section 1.1). It focuses on possible developments for global coal supply, differentiating between the case of global coal consumption following 1.5°C compatible pathways (Chapter 2), and the case of no specific additional policies targeting coal supply and demand but taking into account current energy sector and economic developments in the aftermath of the COVID-19 pandemic (Chapter 3). Part two consists of Chapters 4 to 6, addressing the various aspects of RQ3. It assesses the effects of changes in market conditions due to economic, political and structural factors on coal supply in major coal producing countries, and how these factors might contribute to a decline in coal supply. Part three, consisting of Chapter 7, turns to the political process of achieving coal phase-out policies in case of incumbents' resistance, addressing RQ4. It assesses the stakeholder commission process in Germany and its contribution to overcoming the political stalemate situation and to achieving a coal phase-out law in Germany.

Chapter 1: Introduction – Addressing global coal supply
General introduction of the global coal sector and policies addressing coal supply, the research approach of this thesis and its contributions to the greater question of how to phase out global coal supply

Prospects of global coal supply: climate policy pathways and energy sector developments

Chapter 2: Stranded Assets and Early Closures in Global Coal Mining under 1.5°C
Implications of 1.5°C coal consumption pathways on global coal supply

Chapter 3: The Death Valley of Coal – Modelling COVID-19 Recovery Scenarios for Steam Coal Markets
Effect of economic policies and energy sector trends and on global coal supply

Effects of market conditions on coal supply: economic, political and structural factors

Chapter 4: Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin
Australia: Prospects for export oriented coal supply and coal mine investments

Chapter 5: The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?
U.S. I: Effect of pro coal policies versus economic drivers on coal production

Chapter 6: The U.S. Coal Sector between Shale Gas and Renewables: Last Resort Coal Exports?
U.S. II: Impact of structural and economic coal sector developments on coal production

Political processes to phase out coal

Chapter 7: Overcoming political stalemates: The collaborative governance experience of the German Coal Commission
Germany: Governance of coal phase-out

Figure 1.3: Outline of the dissertation.

In the following, I give an overview of the research in Chapters 2 to 7, and present the most important findings related to the research questions. Table 1.1 shows the chapters' origins and the authors' contributions to each chapter.

Table 1.1: Chapter origins and own contributions

Chapter	Pre-publications and own contribution
2	Stranded assets and early closures in global coal mining under 1.5°C
	Under review in *Environmental Research Letters* under the same title. Revised version submitted September 16, 2022. Pre-print published as: Hauenstein, Christian. (2022). ‘Stranded assets and early closures in global coal mining under 1.5°C’ (Version v1). Zenodo. https://doi.org/10.5281/zenodo.6473733 (July 2023: revised version published in *Environmental Research Letters* 18 (2): 024021. https://doi.org/10.1088/1748-9326/acb0e5)
	Single author original research article.
3	The Death Valley of coal - Modelling COVID-19 recovery scenarios for steam coal markets
	Published as: Yanguas Parra, Paola, Christian Hauenstein, and Pao-Yu Oei. 2021. ‘The Death Valley of Coal –Modelling COVID-19 Recovery Scenarios for Steam Coal Markets’. *Applied Energy* 288 (April): 116564. https://doi.org/10.1016/j.apenergy.2021.116564
	Joint work with Paola Yanguas Parra and Pao-Yu Oei. C. H., P. Y. P., and P.-Y. O. carried out conceptualization, scenario building, investigation, visualization, writing - original draft, writing - review & editing. P. Y. P. and P.-Y. O. carried out the expert survey. C. H. carried out the model adaptations and model runs. P. Y. P. provided the project administration.
4	Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin
	Under review in *One Earth* under the same title. Pre-print published as: Hauenstein, Christian, Franziska Holz, Lennart Rathje and Thomas Mitterecker. 2022. ‘Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin’ *DIW Berlin Discussion Paper* 2003, Berlin: German Institute for Economic Research (DIW Berlin). (July 2023: revised version accepted for publication in *One Earth*)
	Joint work with Franziska Holz, Lennart Rathje and Thomas Mitterecker. C. H., F. H., L. R., and T. M. carried out writing –original draft. C. H. and F. H. carried out conceptualization and methodology. C. H., L. R. and T.M. carried out formal analysis and data curation. C. H. and T. M. carried out visualization. C. H. provided the project administration.
5	The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?
	Published as: Mendelevitch, Roman, Christian Hauenstein, and Franziska Holz. 2019. ‘The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?’ *Climate Policy* 19 (10): 1310–24. https://doi.org/10.1080/14693062.2019.1641462
	Joint work with Roman Mendelevitch and Franziska Holz. C. H., F. H., and R. M. carried out conceptualization, methodology, investigation, writing - original draft, writing - review & editing. C. H. carried out the literature review and data curation. C. H. and R. M. carried out the model runs and visualization. R. M. provided the project administration.
6	The U.S. coal sector between shale gas and renewables: Last resort coal exports?
	Published as: Hauenstein, Christian, and Franziska Holz. 2021. ‘The U.S. Coal Sector between Shale Gas and Renewables: Last Resort Coal Exports?’ *Energy Policy* 149 (February): 112097. https://doi.org/10.1016/j.enpol.2020.112097
	Joint work with Franziska Holz. C. H. and F. H. carried out conceptualization, methodology, data collection, investigation, writing - original draft, writing - review & editing. C. H. carried out the data curation, model runs, validation, visualization of results, and project administration.
7	Overcoming political stalemates: The collaborative governance experience of the German Coal Commission
	Under review in *Climate Policy* under the same title. Revised version submitted September 26, 2022. (July 2023: revised version accepted for publication in *Energy Research & Social Science*)
	Joint work with Isabell Braunger, Alexandra Krumm, Hanna Brauers and Pao-Yu Oei. C. H., I. B., A. K., H. B. and P.-Y. O. carried out conceptualization, methodology, validation, investigation, data curation, writing –original draft. C. H., A. K. and P.-Y. O. carried out writing –review. C. H. provided the project administration.

1.5.1 Prospects of global coal supply: climate policy pathways and energy sector developments (Chapters 2-3)

Chapters 2 and 3 focus on global coal supply under varying scenarios to address research questions RQ1 and RQ2:

- RQ1: What would a 1.5°C-compatible global coal phase out imply for coal producers, in terms of the temporal course of the decline of production volumes, investments in new coal supply, and the utilization and retirement of existing coal supply infrastructure?
- RQ2: How might global coal supply evolve under current policy and energy sector trends, also as a result of the COVID-19 pandemic and the subsequent economic recovery programs?

In Chapter 2, I introduce a new version of CMW, CMW v2.0, which enables the assessment of early retirements and stranded assets in coal mining. A global phase-out of coal, politically deliberate or driven by market forces, implies ending coal production globally. Depending on the speed of such a phase-out, operating mines could have to close before they reach their initially intended retirement age and coal mine asset values could become stranded. Based on the new model version, I analyze regional early coal mine closures and coal mine asset values at risk of becoming stranded for 1.5°C mitigation pathways.

Results show that global coal production would have to decline by some 75 to 93 % by 2030 compared to 2020 levels, and be phased-out by 2035 to 2040, if global warming is to be limited to 1.5°C. This implies that more than half of the cumulative coal mining capacity for 2020 through 2050 from currently operating coal mines would have to remain unused globally. The asset value at risk of becoming stranded, only considering unrecovered overnight capital costs of coal mines, sums up to some USD_{2015} 140 billion until 2050. This value would increase by another USD_{2015} 100 billion in case currently proposed new coal mining projects are realized. Coal supply capacities from currently operating mines would suffice in all regions to cater for remaining demand in 1.5°C pathways, thus, any investments in additional coal mining capacities would be redundant. To the contrary, in all coal regions coal mines would retire early due to eroding demand. By the end of this decade, in most coal regions more than three-fourths of the remaining coal mining capacities would retire early. The asset values at risk are relatively small compared, for example, to the asset stranding risk of coal-fired power plants. However, massive early retirements of coal mines could lead to significant amounts of job losses and economic distortions in affected regions. Regionally, the remaining coal production would be concentrated even more on the three largest coal producers, China, India and Indonesia. The global steam coal trade, outside of the Southeast Asian region, would come largely to a halt by 2030, leaving very limited export opportunities for traditional steam coal exporters like Australia, Colombia, Russia, South Africa, and the U.S. Particularly in the U.S., with already large excess coal mining capacities today, a high share of existing cumulative production capacities, of up to 85 %, would have to remain unused.

Chapter 3 focuses on how global coal supply and trade is affected by the COVID-19 pandemic and assesses its medium and long-term perspectives in the aftermath of the pandemic. In the year 2020, the outbreak of the COVID-19 pandemic also heavily impacted the global coal sector. While a slowdown in economic activities reduced demand for coal-fired power generation, regional lockdowns, boarder closures, and COVID-19 infections among employees interrupted coal supply chains. The coal sector already started to feel increasing pressure in many countries prior to the pandemic, for example, due to strengthened climate and environmental policies, and increasing weariness of financial institutions to lend money to projects in the coal sector. Thus, the question arose, if the pandemic could be a tipping point accelerating the decline of coal production and consumption, or if the coal sector could return to its previous output levels after the pandemic. To assess these questions, a range of stylized global coal demand scenarios based on an expert survey and a document analysis are developed. For this, regional economic recovery stimuli options, regional coal sector characteristics and specific coal sector policies are taken into account. Using CMW, supply and trade implications of these scenarios for the global coal sector are assessed.

Results indicate that a return to pre-pandemic levels of coal production and consumption in the mid to long-term are rather unlikely. Yet, prospects of the coal sector are highly dependent on the choice of economic recovery stimuli by national and regional governments. In case of predominantly climate and environmental friendly stimuli, the use of coal could be more than halved globally by 2040 compared pre-COVID-19 levels (not considering any additional climate policies). However, if economic recovery stimuli favor fossil-fuel consuming carbon-intensive industries, global coal use would decline only slightly until 2040. In both cases, consumption of coal is increasingly concentrating in Asian countries leading to decreasing export opportunities for producers distant to this market, like the U.S. or Colombia. In case China and India, the two largest consumers of coal, would restrict coal imports to boost their domestic coal production, the volume of seaborne traded coal would shrink significantly, affecting all major coal exporters. Independent of the scenario, the decline of coal would not be fast enough to be in line with global climate targets.

Chapters 2 and 3 show that current trends in global coal supply and demand are still far from a 1.5°C path. To keep the 1.5°C target within reach, and to prevent the further lock-in of new coal supply capacities, any expansions of coal mining capacities need to be stopped. Early on credible climate policies might prevent investors from continuing to invest in new coal projects. Economic recovery programs after the COVID-19 pandemic could offer the opportunity to steer energy supply and consumption away from coal and take advantage of an already struggling coal sector to commence a global decline of coal. However, building on coal as power source for renewed economic growth (as currently observed, for example, in China) increases the risk of further locking in new coal supply capacities and a continued high use of coal. In any case, additional efforts would be required to limit the use of coal to 1.5°C compatible levels and excess coal mining capacities would need to be addressed. The comparatively limited amount of asset values (considering unrecovered overnight capital costs) at risk in the coal supply sector, compared to coal power plant asset values, could make this a leverage point for climate policies to limit coal supply. However, market values of coal production assets might be higher and early mine closures would affect workers and communities.

1.5.2 Effects of market conditions on coal supply: economic, political and structural factors (Chapters 4-6)

In Chapters 4 to 6, it is zoomed in on specific coal producing countries to assess RQ3:

- RQ3: What effect have current economic, political and structural factors each on coal supply and how might they contribute to a decline in coal supply?

In Chapter 4, the CMW v2.0 is used to investigate the economics of proposed new coal mine projects. Results in Chapter 2 clearly show that no new coal mines are needed to supply the remaining demand in case of 1.5°C coal consumption pathways. Nevertheless, new coal mines and mine additions are broad forward globally. In this chapter, the economics of new coal mining projects in the Galilee Basin, Australia, are assessed. These receive great international attention due to the large amount of GHG emissions that could be emitted from the extracted coal, and at the same time continuous doubt about their economic viability exists. Data for the most advanced of these projects, the Carmichael coal mine project, is used to parameterize this potential new mining site in CMW v2.0 and the model is run for different coal demand scenarios. To construct these scenarios, bottom-up coal sector data and policy information for the major coal consuming countries in the Asian coal market is used.

Results show that even in a high demand scenario new coal mines in the Galilee Basin are economically not viable in the long-run. In case the initial investment costs are considered as sunk, the then available new production capacities would be utilized in a high demand scenario. However, already in a moderate decline scenario for global coal demand, these additional coal capacities would not produce at full capacity throughout their entire lifetime. The continuation of the development of new coal mining capacities in the Galilee Basin seems to be driven rather by political-economic reasons than by financial project characteristics. Investments in new coal mining capacities in other Australian coal mining regions and other countries, situated closer to remaining coal demand centers or with more favorable cost structures, would still be economically viable to some extent in the scenario with the highest remaining demand. However, in all other scenarios, no additional investments are economically feasible.

Chapters 5 and 6 investigate how evolving political, economic and structural drivers are impacting coal supply in the short- to long-term. These drivers might act independently from – and in addition to – climate policy. In both chapters, the assessment is focusing on the U.S., one of the largest coal producers worldwide and with a significant decline in coal production and consumption in the past decade. Methodologically, both chapters are based on literature and data driven scenario building and quantitative scenario analyses, which are performed with CMW. In Chapter 5, it is analyzed how coal supply in the U.S. and globally is affected by political efforts of the Trump administration to stop the ongoing decline of U.S. coal production, such as revoking environmental policies passed during the Obama administration. Furthermore, the access of coal exporters to the Asian market and the availability of Carbon Capture, Transport and Storage technology are taken into account. Chapter 6 continues the work of Chapter 5 as part of round 34 of the Energy Modeling Forum (EMF) on "North American Energy Trade and Integration". Here, a new coal demand scenario for the U.S. power sector is build, based on plant-level data of U.S. coal-fired power plants, taking into account lifetime and capacity factors, as well as recent power market trends. CMW is soft-coupled in this study with the Integrated Assessment Model GCAM (Global Change Assessment Model; Calvin et al. 2019) to assess coal supply implications of future coal demand scenarios stemming from GCAM model runs. These are compared to the results for the new bottom-up coal demand scenario and the effects on coal production in the individual U.S. coal basins are analyzed.

Results indicate that the decline in U.S. coal production in recent years was caused largely by general domestic energy sector developments, and less by environmental and climate policies targeting coal use. Particularly the availability of relatively cheap natural gas, as well as the build out of RES capacities on the one hand, and an old and costly coal-fired power plant fleet on the other hand led to a decline of domestic coal demand. The revoking of environmental and climate policies under the Trump administration thus could ease the situation for coal producers only marginally and only when considering a scenario without additional climate policies in the future. Furthermore, a continuously high U.S. coal consumption, as projected in many system-wide analyses of the EMF 34, as well as by the U.S. Energy Information Administration (EIA) in their reference cases of future

U.S. power supply, would depend on significant refurbishments in the aging U.S. coal plant fleet or new builds. However, neither of these are currently under way. Thus, chances are high that even without additional climate policies, U.S. coal demand in the power sector will continue its downward trend. Also an increasing availability of CCTS would most likely not save U.S. coal producers, as a CCTS rollout would be dependent on sufficiently strong incentives to address climate change and would thus lead to an overall unfavorable environment for coal. Until CCTS would be widely available, most coal plants in the U.S. and worldwide would have been retired already or would be too old to be considered for an economic refurbishment with CCTS. With declining domestic coal demand in the U.S. coal could be increasingly exported. Coal export harbors along the U.S. West Coast could boost U.S. coal exports to Asia, however, societal resistance against such new ports is high and most projects have been canceled in the last years.

Chapters 4 to 6 show that the economic risk for coal producers, and in particular for new coal supply projects, is increasing in countries without continuously high domestic demand. Particularly for export oriented coal projects, but also for new coal mining capacities meant to supply domestic demand, the risk of asset stranding is high in case coal consumption as projected in the upper bound coal demand scenarios does not realize. In countries with an aging coal power plant fleet and limited or no investments in new coal power plants on the one hand, and limited export opportunities to the remaining coal demand centers in Asia on the other hand, prospects for coal producers are dim. The example of the U.S. shows that the production of coal can decline very rapidly in such a case and pro-coal policies are unlikely to prevent the further decline once the economics in the power sector have turned against coal-fired power generation. Also CCTS technology is not likely to change the picture for coal. Continued political support for coal, for example, by increasingly subsidizing coal consumption or new coal mine projects, might only temporarily delay the decline of coal production, however, at the same time risking to strand further capital and to increase societal costs.

1.5.3 Political processes to phase out coal (Chapter 7)

In Chapter 7, the coal phase-out process in Germany is assessed to address RQ4:

- RQ4: How can a political process be designed and managed to achieve a coal phase-out in the event of incumbent actors blocking coal phase-out policies?

In Germany, a stakeholder commission was set up by the government in 2018 to propose how to go about organizing the German coal phase-out after different previous political attempts to reduce Germany's use of coal had failed. This so called Coal Commission achieved to overcome the previous stalemate situation and passed a catalogue of recommendations for a coal phase-out in Germany, which were implemented to large extent thereafter, including a coal phase-out for Germany by 2038 at the latest. In this Chapter, the process of the Coal Commission is analyzed. The focus of the analysis is on how this commission achieved to breach the previous stalemate situation and how the final recommendations were formed. To assess this collaborative governance process, the integrative framework for collaborative governance (Emerson, Nabatchi, and Balogh 2012) is applied and data in 18 semi-structured interviews with participants of the Coal Commission collected.

Results show that the Commission helped to find joint recommendations and overcome the long standing stalemate situation by providing a safe space to build up trust and understanding, which was important considering the previous highly contentious situation. Key for the willingness of actors to participate and engage in this process was the absence of other alternatives to enforce their interests on the one hand, and the opportunity to influence future German energy and structural change policies, provided by the comprehensive mandate of the Commission, on the other hand. The willingness of incumbent (pro-coal) actors to participate and agree on a phase-out was influenced significantly by the possibility to offer high compensation payments to affected regions and companies. In the work of the Commission, existing power imbalances influenced the way members could participate, resulting in a domination of the decision-making process by certain members. Stakeholders representing local interests found it relatively more difficult to participate effectively in the Commission process, due to their limited negotiation experience and equipment with other resources, like professional staff. While the bandwidth of represented stakeholders was perceived as relatively comprehensive by most participants, younger generations, and perspectives from countries most affected by the climate crisis, were barely represented.

Germany managed to overcome with this collaborative governance approach a decade-long stalemate that several other attempts by the government had failed to resolve. Having shifted discussions from “if” to “how” to phase out coal eventually enabled the next German government to further advance the aimed for coal phase-out date from 2038 to 2030. The question remains to what extent this approach can advance coal transitions also in other countries in less economically privileged positions, or if the same could have been achieved also differently. Nevertheless, this chapter offers valuable insights for one option to approach coal transitions in case of incumbent actors stalling the policy-making process.

1.6 Conclusions and outlook

Achieving global climate targets requires to drastically reduce emissions from the use of coal within the 2020s. Policies addressing the consumption of coal have proven insufficient so far to initiate the needed decline. Thus, scholars argue that it is necessary to also address the supply of coal and to manage an orderly and timely phase-out of coal production. In this thesis I set out to assess how a phase-out of coal supply in line with global climate targets could look like, which drivers and barriers exist, and how these could be overcome. In the following, I will present the main conclusions I draw from the findings of this thesis, presented in the previous section. I point out limitations of the research conducted in this thesis, before ending with an outlook for further research.

To limit global warming to 1.5°C, global annual thermal coal production needs to be reduced by at least three quarters until 2030, and phased out almost completely by 2035. This implies a radical change to coal supply compared to previous trends in global coal production. This thesis shows that in none of the world's major coal producing regions investments in additional coal mining capacities are needed to cover remaining demand under the premise of reducing the use of coal to a 1.5°C compatible path. Furthermore, almost two thirds of the remaining production capacity of operating global coal mines need to remain unused. Thus, it is necessary to stop not only the addition of new mining capacities, but also to end coal production from operating mines before these reach the end of their economic lifetime.

In this thesis, I discuss how market forces and already introduced climate policies are creating an increasingly challenging economic environment for the coal sector. Particularly coal mining projects under development are facing economic difficulties. The uncertain market outlook, finance and insurance providers excluding coal from their portfolios, and calls by the international community to not support new fossil fuel projects, make it difficult to secure finance and insurance for new mines. Furthermore, local resistance because of expected adverse health, climate and environmental impacts, and tightened regulations are delaying or stopping new coal projects. Climate litigation, to hold coal producers accountable for induced climate change and thereby caused damages, is a further newly arising risk, which might become increasingly significant if catastrophic climate change advances.

I find that for operating coal mines an even greater challenge is a slowing demand. Coal producers, including in Europe and the USA, are already experiencing this. Coal is increasingly replaced by more economic energy sources in the power sector. In many European countries, coal power plants are also deliberately closed down based on climate politics. Without incentives to invest in new coal power plants, the average age of the existing fleet steadily increases, and more and more plants retire, creating further momentum for a transition away from coal. In such environments, further tightened regulations and increasing costs, as for example rising CO_2 prices, can impact a dwindling coal sector significantly.

This, however, requires the availability of affordable alternative power sources, namely sufficient capacities of renewable energy sources (RES), and energy market designs that can deal with up to a 100 % share of RES in the system.

However, it is more than questionable, if a continuation of these trends will suffice to achieve the required rapid decline of coal supply until the end of the 2020s. In particular, as these trends apply mostly to a limited number of countries, such as Australia, USA, and to countries in the EU. In other parts of the world, namely China, new coal plants are still added, although also this trend has slowed in recent years. The renewed increase in coal demand in 2021 and the first half of 2022 due to increased economic activity after the economic slowdown caused by the COVID-19 pandemic, as well as in the wake of the Russian invasion of Ukraine, casts doubt on the robustness of previous signs and trends of a declining coal supply and demand, including in countries of the Global North.

Considering the very short time span to reduce coal output globally by more than half until 2030, timely political action is required. Preventing the addition of new mines could be a comparatively low hanging fruit, as these projects already face difficult economics and a significant risk of becoming stranded assets, particularly export oriented coal projects. Furthermore, new projects have not yet created such high economic and socio-economic dependencies as operating projects.

Addressing coal supply from operating mines and achieving early mine closures might be substantially more difficult, due to the existing economic and socio-economic dependencies. Overcoming resistance of stakeholders profiting from the status quo is a key challenge for coal transition politics. Although Germany has enacted a coal phase-out only by 2038, the stakeholder commission that led to this compromise managed to break the previous stalemate in German coal politics. In this thesis, I explain that a prerequisite for this process was the clear political signal that a transition away from coal was inevitable, and that it was only a question of how the pathway should look like. Otherwise, powerful incumbents would most likely not have considered to give up on their position stalling the transition. Similar approaches as in Germany might help to initiate a coal phase-out pathway also in other countries with contested futures of coal. International cooperation and finance might ease these processes, providing funds to support just transition measures.

The new German government elected in 2021 even aims to move the coal phase out forward to 2030, a development eventually only possible due to the earlier agreement on a coal phase-out in general. The U.S. are another example of what momentum might evolve once a general decline of the coal sector has set in. For such a momentum to build up, it is required to send clear political and economic signals that disincentivize investments in new coal infrastructure. Solutions proposed by pro-coal actors for alternative outlets for coal, including carbon capture, transport, and storage (CCTS) retrofits of coal plants, are not likely to turn the tide for coal miners, as they usually only worsen the economics of coal further. While not able to prevent the general decline of coal, they might only delay necessary investments in the transformation process and efforts to achieve a relatively smooth transition, in particular also for local communities and workers in the coal sector.

In summary, reducing the use of coal to mitigate climate change will most likely need to build on both, coal supply and demand side policies. Taking into account supply side dynamics and using leverage points to cut additional coal supply can contribute to reduce overall economic costs and reduce political barriers to climate change mitigation. Coordinated supply and demand side approaches can possibly create momentum for accelerated coal transitions to achieve the required speed of emission reductions from coal. Involving affected stakeholders in policy processes, and considering socio-economic dependencies and necessary structural change early on, can contribute to overcome stakeholders' resistance to inevitable transformative changes in the coal industry and help to achieve timely and just transitions away from coal.

Limitations and research outlook

Assessments of topical developments in the highly dynamic field of energy and climate economics and policy will always be dependent on the circumstances at the time of the investigation. During the time of my thesis, the global coal market was first strongly influenced by the COVID-19 pandemic. Then, while still "recovering" from these exceptional developments, Russia invaded Ukraine, possibly leading to even more extensive disturbances of global energy and coal markets and politics. While I was able to integrate the assessment of possible effects from the new situation caused by the COVID-19 pandemic directly in my thesis, the Russian invasion of Ukraine and its repercussions are not covered in the assessments of this thesis. If considered, results would certainly look different in some instances, including global coal trade flows. Current high coal prices, as of mid of 2022, might also change the economics of new coal mine investments, as studied in Chapter 4. Yet, these price effects might only prevail for a limited time, not significantly affecting the long-term economics of coal projects. Coal demand might be affected as well, yet effects could be mixed. While in the short term coal is used to replace natural gas, for example, in Europe, the increased awareness for the risk of fossil fuel import dependencies and volatile prices might as well lead to additional impetus for the energy transition.

Using a sectoral model implies that effects studied in the model are detached from developments in other sectors. Developments in these other sectors are implicitly covered by scenario assumptions or specific constraints applied in the model. Yet, feedback mechanisms are largely excluded (e.g., effects of changes in coal supply on other energy sources).

Limited data availability is another issue for assessments of the coal sector. While data for the coal sector is offered, in particular for industry customers, access usually is very costly. However, the availability of openly accessible data is improving, potentially allowing for more accurate assessments of local coal supply situations in the near future. So far, the assessment on a country, or at best coal basin level, with the applied model allows for the description of aggregated developments only. Results for individual coal mines within the same basin, for example, could differ significantly. A different model setup, using a social-welfare optimization approach, can reduce model run-times significantly and would allow for the consideration of a significantly higher number of nodes in the model. In combination with an improved data availability, this offers the possibility of more comprehensive assessments on the individual mine level to provide mine-specific insights for local politicians and societal actors. This could help to design tailored supply side and transition policies.

While this thesis zoomed in on a few country cases, the elephants in the room of global coal, China and India, were only assessed as part of global studies with some additional details on country specifics. Also coal transitions in countries of the Global South, such as Colombia, Indonesia and South Africa, were not studied in particular. While many of the results in this thesis are also applicable to these countries, coal transitions in these countries might face additional challenges. Thus, extending the study on coal supply developments and policies to address coal supply in these countries could contribute valuable insights on how to deal with coal supply and advance coal transitions also in these major coal producing countries.

The same goes for the study of coal transition governance processes. Stakeholder commissions as a means to address coal transitions currently receive wide attention. Studying also stakeholder commissions in other countries and contexts than Germany, as well as other political instruments, could substantially enhance the understanding of chances and limitations of governance instruments for coal transitions. A comparative assessment of stakeholder commission processes in various countries, including Canada, Chile, and the Czech Republic, could yield valuable insights on how to design similar processes in the future, and how to achieve timely and just coal transitions.

This thesis shows that phasing out coal remains challenging around the world and coal transitions still have a long way to go. Yet, recent developments related to coal also offer signs of hope for initiating and accelerating the departure from coal. Addressing coal supply and its phase-out deliberately can contribute to increase the momentum of coal transitions and to ensure that implied adverse effects are mitigated. How this can best be achieved remains to be conclusively answered and requires further input also from the scientific community.

Chapter 2

Stranded assets and early closures in global coal mining under 1.5°C

This chapter is based on the manuscript with the same title currently under review in *Environmental Research Letters.*

2.1 Introduction

In the first major international agreement of its kind, the COP26 Glasgow Climate Pact explicitly seeks to phase-down (unabated) global coal-fired power generation. This goal is urgently needed in order to limit global warming to 1.5°C, which requires a phase-out of most coal use within the next two to three decades (IPCC 2022; Rogelj et al. 2018). Yet the coal supply sector and national energy planning in many countries still seem oblivious to the need to cut future coal production (Global Energy Monitor et al. 2021; SEI et al. 2021). Annual global investments in coal supply have remained continuously high in recent years (IEA 2020d), and are set to remain at current levels for the coming decades (Driskell Tate, Shearer, and Matikinca 2021; SEI et al. 2021).

The decoupling of coal supply capacities from future admissible levels of coal consumption could place coal mines at an increased risk of becoming stranded assets (Auger et al. 2021; Ploeg and Rezai 2020a). While it is well known that coal-fired power plants face a substantial risk of asset stranding (Edwards et al. 2022; Löffler et al. 2019; Pfeiffer et al. 2018), the potential asset stranding of coal mines has received limited attention so far (Fisch-Romito et al. 2021). Compared to oil and gas production, capital expenditure costs make up only a minor share of the total production costs for coal mining (Spencer et al. 2018). Nevertheless, in the past coal miners have experienced large asset value write-downs due to excess investments and coal price drops (Mendelevitch, Hauenstein, and Holz 2019). Apart from the financial risks they pose to owners and investors, early closures of coal mines affect coal workers and local the economies of coal-producing regions (Auger et al. 2021; Diluiso et al. 2021).

Moreover, excess long-lasting coal supply infrastructure can cause lock-in effects, hindering the transition away from coal (Erickson et al. 2015; Fisch-Romito et al. 2021; Unruh 2019). Trout et al. (2022, 7) find that the emissions from developed coal reserves alone -that is, the coal stored in running mines and those under development -would exhaust almost 80 % of the remaining 1.5°C emission budget. In order to keep the 1.5°C target within reach, approximately 88 % of the total global coal reserves need to remain unextracted until the end of the century (Welsby et al. 2021, 233). Actively limiting coal supply could serve as an important complement to demand-side climate policies (Asheim et al. 2019; Erickson, Lazarus, and Piggot 2018).

This is the first study to offer a detailed assessment of the implications of 1.5°C mitigation pathways for the global coal mining sector. This analysis focuses on investments, premature mine closures, and the stranding of production assets in coal regions. Identifying misaligned coal supply developments that contradict mitigation efforts can help governments to address these and reduce lock-in risks. A better understanding of future regional coal production developments can also enable national and regional governments to address inevitable structural changes in affected regions early on, thereby reducing the negative socio-economic impacts of coal phase-outs (Diluiso et al. 2021; Jakob et al. 2020).

This study also provides a new version of the open partial equilibrium model of the global steam coal sector COALMOD-World (CMW). The model uses data from the open-source coal mine database 'Global Coal Mine Tracker' (GCMT) provided by Global Energy Monitor (2021b) to approximate and consider lifetimes of existing and new coal mines. This new version of CMW now also allows for the assessment of remaining coal supply capacities, investments, and asset stranding. Previous model versions either entirely overlooked or only partially considered the retirement of existing infrastructure (Haftendorn and Holz 2010; Haftendorn, Holz, and Hirschhausen 2012; Holz et al. 2016).

The focus of the study is on steam coal -that is, thermal coal excluding lignite. Worldwide, steam coal comprises approximately 3/4 of current total coal consumed, and about 90 % of thermal coal consumed (IEA 2019a). The 1.5°C compatible coal demand scenarios are based on the IPCC (2022) mitigation pathways, representing coal consumption in scenarios of the category “C1: limit warming to 1.5°C (>50 %) with no or limited overshoot” (Byers et al., AR6 Scenarios Database). To illustrate recent production planning in coal sector (compare SEI et al. 2021), a coal demand scenario, based on the IEA (2019b) 'Stated Policy Scenario' (STEPS), is added.

2.2 Methods and data

To assess the global coal supply sector in a 1.5°C world, a scenario analysis using a new version (v2) of the open COALMOD-World model is performed. CMW is a comprehensive model of the global steam coal market, covering about 90 % of global steam coal production and consumption (see Appendix A.1). It represents coal producers and exporters as profit-maximizing players with model-endogenous decisions on new capacity investments. Previous model versions have been widely used for academic studies, assessing international coal market dynamics and various climate policy implications for the supply, trade, and consumption of coal (cf., Haftendorn and Holz 2010; Haftendorn, Holz, and Hirschhausen 2012; Hauenstein and Holz 2021; Mendelevitch 2018; Richter, Mendelevitch, and Jotzo 2018; Yanguas Parra, Hauenstein, and Oei 2021). CMW and related model data is openly available for use and adaptation (Holz et al. 2016). Few other models of the global coal market exist. These include the EIA (2022b) National Energy Modeling System (NEMS) with its Coal Market Module (CMM), which can be used to calculate coal flows and prices. The CMM can be used to calculate annual coal production, trade and consumption volumes, as well as coal prices. Auger et al. (2021) develop a model based on Paulus and Trüby (2011) and Trüby and Paulus (2012), which covers investments and retirements of coal mines, however, relies on proprietary data to be run. The new version of CMW applied here is based on openly available code and data. It considers the limited lifetimes of existing and new coal mines, which makes it possible to assess investments, remaining capacities, and stranded assets in the coal mining sector. The data on coal mines’ lifetimes comes from the GCMT (Global Energy Monitor 2021b), the first comprehensive open-access database to provide worldwide data on coal mines.

2.2.1 Lifetime of coal mines

New (proposed) coal mines have an average lifetime of 29 years, according to the GCMT (where data is available, and excluding China).[1] The reported lifetimes are generally in the range of six to 50 years per mine. In contrast, Baruya (2018, 75) assumes an amortization time of 20 years for coal mine projects. However, according to coal sector experts, major mines rarely operate for fewer than 20 years due to the high end-of-life costs for such mines (personal communication, March to May 2021). Based on this information, average lifetime of new mines is set here as 25 years. This is a rather conservative estimate for the technical lifetime of a mine; however, it is meant to represent the entire techno-economic lifetime of coal mine assets.

The GCMT also provides limited information on remaining lifetimes of operating coal mines. The GCMT covers approximately 800 (540 outside of China) operating steam coal mines (excluding lignite and pure met coal mines), with a total annual production of about 4.3 Gt (2.7 Gt outside of China). However, a value for 'Reported Life of Mine (Remaining)' is only given for 99 mines outside of China. By contrast, a 'Reserve to Production Ratio (R/P)' value is available for 388 mines. However, while R/P values provide information on available physical resources, the technical lifetime of a mine also depends -among other things -on the available infrastructure and physical accessibility of reserves. To improve the representation of regionally disaggregated remaining lifetime estimates, the relationship of remaining mine lifetime to R/P for operational thermal coal mines is estimated with a logarithmic regression function and applied to GCMT entries, providing only R/P values (for details and resulting estimates of regional remaining lifetimes, see Appendix A.1.2).

---

[1] According to industry experts, lifetime and reserve data for Chinese coal mines is very inaccurate, tending to overestimate the remaining exploitable reserves and mine lifetimes (Source: personal communication with coal industry experts, March to May 2021).

2.2.2 New features of the COALMOD-World version 2.0

The latest version of CMW features a new retirement mechanism for coal production capacities, which yields an improved representation of available mining capacity and necessary investments. In CMW, a coal production asset comprises all equipment and capital stock at coal mines that enable the extraction of a certain amount of coal per year. The investment in coal production capacity represents the initial investment needed to make available the new coal mining capacity. The previous model version allowed mine capacities to be idle for indefinite times and be restarted without additional costs. However, as experts noted, keeping inactive mines in operational conditions is very costly and is rarely done for more than 1-1.5 years. Thus, the new retirement mechanism is based on coal mine ages and lifetimes, not prior production (for details, see Appendix A.1.1).

2.2.3 Coal demand scenarios

To increase the robustness of results and to represent the uncertainty of 1.5°C compatible coal demand scenarios, a *lower bound*, a *central*, and an *upper bound* 1.5°C coal demand scenario are included. These three *1.5°C* coal demand scenarios represent 0.25, 0.5 (median), and 0.75 percentile values for annual coal consumption in the power sector of IPCC (2022) scenarios that limit global warming to 1.5°C (>50 %) with no or limited overshoot. In the baseline 1.5°C scenarios presented in this study, coal consumption of power plants with Carbon Capture, Transport and Storage (CCS) is excluded, as the availability of CCS and its application to coal-fired power plants remains uncertain (cf. Budinis et al. 2018; L. Clarke et al. 2022; Martin-Roberts et al. 2021; Grant et al. 2021). In Appendix A.3, results for scenarios including coal demand of power plants with CCS are included for comprehensiveness, and to assess possible effects of CCS for stranded assets.

To illustrate current coal production plans in the coal sector (SEI et al. 2021) and allow for the comparison of the *1.5°C* scenarios with such a scenario, the *WEO19-STEPS* scenario is added. The latter represents a state of continuous high global coal demand throughout the year 2050. Coal demand growth rates for this scenario are based on the IEA (2019b) STEPS scenario. Further details on the scenarios are provided in Appendix A.2 and all scenario input data files are available in Hauenstein (COALMOD-World 2.0 data, results, figures for: Stranded assets and early closures in global coal mining under 1.5°C).

2.2.4 Excess capacities, early closures, and stranded assets in coal mining

Excess coal production capacities and stranded assets in the case of 1.5°C pathways are calculated for the period 2020-2050 in this study. These ex-post calculations are based on CMW data for the lifetimes and investment costs (overnight capital cost, OCC) of capacities, and on CMW results for available mining capacities ($PCap_{af}$) and realized production ($Prod_{af}$) in year a in production node f. Early closures are calculated for the year 2030, representing general trends towards the end of the current decade. The share of early closures in year a is defined here as the share of idle capacities in year a that also do not resume production in later model years.

Excess capacities are calculated as the difference between available capacity and realized production over the considered time period (2020-2050) for the production node f (Eq. 2.1).

$$\text{Excess capacity}_f = \sum_{2020}^{2050} \text{PCap}_{af} - \sum_{2020}^{2050} \text{Prod}_{af} \tag{2.1}$$

In this study the monetary value of stranded assets is calculated based on the non-recovered share of initial overnight capital cost (OCC; Eq. 2.2), following an approach similar to that of Edwards et al. (2022). A full recovery of the OCC is assumed when the mine produces at full capacity for 25 years (lifetime of new mines). For coal production capacities that started production before 2020, a total lifetime of 25 years and production at full capacity for the time prior to 2020 is assumed. Thus, only the share of OCC that is assigned to the remaining lifetime from 2020 on (RL) can potentially become stranded. Node specific OCC figures are taken from the CMW input data (cf. Hauenstein, COALMOD-World 2.0 data, results, figures for: Stranded assets and early closures in global coal mining under 1.5°C; Holz et al. 2016).

$$\text{Stranded Assets}_f = \text{OCC}_f \cdot \text{PCap}_{2020,f} \cdot \frac{\text{Excess capacity}_f}{\sum_{2020}^{2050} \text{PCap}_{af}} \cdot \frac{\text{RL}}{25} \tag{2.2}$$

Calculating stranded assets based on recovered OCC of initial investments over an assets lifetime is a widely used approach (Edwards et al. 2022; Fisch-Romito et al. 2021). However, financial asset devaluation can be significantly higher than just the value of unrecovered

OCC, as the asset's value also depends on expected future cash flows (Mendelevitch, Hauenstein, and Holz 2019; Spencer et al. 2018). Thus, the stranded asset values calculated in this study are relatively low-end estimates.

2.3 Results

2.3.1 New coal mines redundant globally under 1.5°C

Global steam coal consumption drops by 88 % (central *1.5°C* scenario; values for the upper and lower bound *1.5°C* scenarios given in brackets, here 75-93 %) in the *1.5°C* scenario between 2020 and 2030 (Figure 2.1, top panel). With CCS available, this rapid decline is slowed down only slightly, with consumption dropping by 85 % (70-91 %; see Appendix A.3 for results on scenarios with CCS). This is in stark contrast to the *WEO19-STEPS* scenario, with coal consumption even slightly increasing until 2030, and only decreasing marginally thereafter. For all major producing regions, a 1.5°C demand path means drastically reduced output compared to a scenario with continuously high demand (lower three panels of Figure 2.1). However, the speed of the decline varies among producing countries. Of the remaining global coal production in 2030, 86 % (85-92 %) come from only three countries: China, Indonesia, and India. China and India produce exclusively for their domestic markets, which are the last two remaining major consumers in 2030, while Indonesia continues to produce for both domestic and export use. The amount of internationally traded steam coal is reduced by three-fourths (57-82 %) between 2020 and 2030, eroding export opportunities for most traditional exporting countries (see Figure A.5 in Appendix A.3). Only Indonesia remains as major exporter in 2030 due to its low production costs and its central position in the Asian market, where consumption is increasingly concentrated.

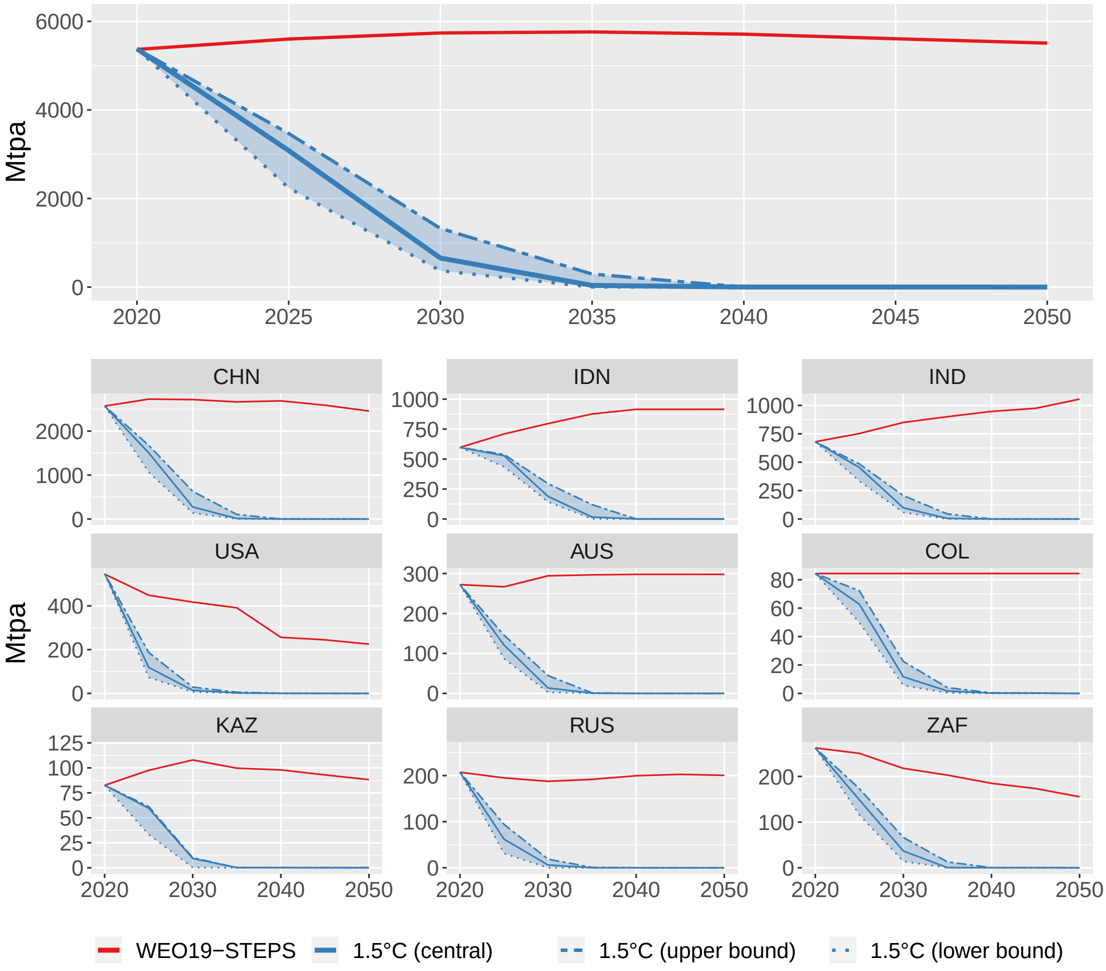


Figure 2.1: Global annual steam coal consumption (Mtpa) in all scenarios (top panel) and annual steam coal production (Mtpa) in major producing countries.

Note: Shaded blue area shows range of *1.5°C* scenarios. For detailed nodal production results see Appendix A.3.

Investments in coal mine additions become redundant in the *1.5°C* scenarios (Figure 2.2). In all coal-producing regions the operating coal mining capacities suffice to meet the remaining demand until 2050. Additional sensitivity runs show that these results are robust also in case of reducing the assumed remaining lifetimes of existing coal mines, and in case of most *1.5°C* scenarios including CCS (see sensitivity analysis in Appendix A.3.3). By contrast, in case of continuously high global coal demand the cumulative global capacity (about 5,500 Mtpa) needs to be replaced about once before 2050 (*WEO19-STEPS* scenario in Figure 2.2), with some regional shifts in capacity, mostly towards Indonesia and India.

The currently proposed new steam coal mining capacities amount to about 1,400 Mtpa, with large shares in traditional coal exporting countries (Australia, Russia, and South Africa). However, if coal consumption is reduced to 1.5°C-compatible levels, all of these new projects face a substantial risk of asset stranding, as there is no demand for additional coal supplies. The asset value at risk of stranding -the overnight capital cost (OCC) of all proposed new mine projects -sums up to about USD$_{2015}$ 100 billion (Figure 2.2). If capacity investments continue to follow the *WEO19-STEPS* path, cumulative OCC spending on new coal mines amounts to USD$_{2015}$ 380 billion by the year 2050. However, not only new coal mines are at risk of stranding, as the following section shows.

Figure 2.2: Investments in new steam coal mine capacities: cumulative capacity additions and related overnight capital costs (OCC) in major coal producing countries, 2020-2050, in the *1.5°C* and *WEO19-STEPS* scenarios, as well as proposed capacity additions as of June 2021. Capacity additions in Mtpa, OCC in billion USD$_{2015}$. Available coal mine capacity in 2020 shown for comparison. Zero capacity additions in all three *1.5°C* scenarios.

Sources: Proposed capacity in Mtpa based on data from (Global Energy Monitor 2021b). Proposed capacity OCC based on (Global Energy Monitor 2021b) and CMW OCC data. All other results from CMW.

2.3.2 1.5°C requires the premature retirement of existing coal mines

The remaining cumulative production capacity from existing steam coal mines amounts to roughly 87 Gt between 2020 and 2050. However, the remaining coal production between 2020 and 2050 in the *1.5°C* scenarios amounts to 32 Gt (26-39 Gt) only (Figure 2.3). More than half of the remaining global cumulative capacity would need to remain unused. This would affect all major coal-producing countries, yet with some variation, for example, due to remaining domestic demand and access to the remaining demand centers in Asia.

Russia and the USA would incur the largest shares of excess capacities, with 78 % (73-83 %) and 83 % (79-85 %), respectively. The USA already have large excess capacities today, due to continued investments in new coal mining capacities and at the same time collapsing domestic demand in recent years (Mendelevitch, Hauenstein, and Holz 2019). Domestic U.S. coal demand continues to decline rapidly under 1.5°C scenarios, and exporting U.S. coal to the remaining demand centers in Asia is not competitive due to limited export infrastructure along the U.S. West Coast (Hauenstein and Holz 2021; Yanguas Parra, Hauenstein, and Oei 2021). Russia has adopted the political objective to become one of the largest coal exporting countries and has significantly expanded its coal exports and related infrastructure in the last years (Fortescue 2021; IEA 2021a). However, Russian coal mines are mostly far from the coast, which implies high transportation costs to reach export markets and makes Russian coal exports noncompetitive in case of low global coal prices.

Indonesia would face the lowest overall capacity stranding of all major producing countries (47 %, 36-55 %) due to its low production costs and proximity to the remaining demand centers. However, with Indonesian exports mostly going to China, capacity stranding in Indonesia could increase as well, in case China succeeds to increase its level of self-sufficiency (cf. Gosens, Turnbull, and Jotzo 2022). China and India -the two countries with the highest remaining demand, and currently the largest producers of coal worldwide, both of which serve only their domestic markets -would be affected by their domestic demand declining faster than their coal mining capacities are depleting.

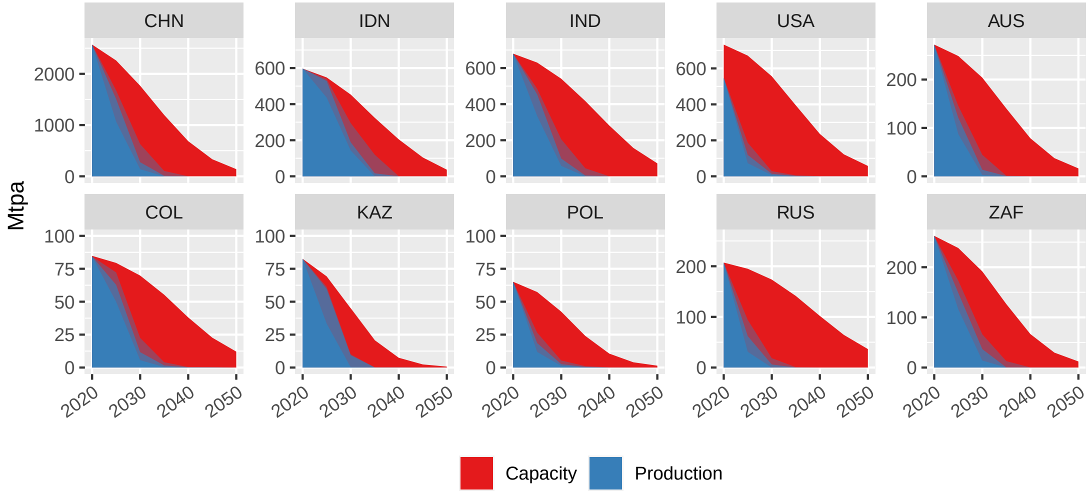


Figure 2.3: Stranded coal capacity: Countries' annual steam coal production capacity (red) vs. production in *1.5°C* scenarios (blue, with shaded area representing the range of the *1.5°C* scenarios).

Large shares of the existing coal mines in all major coal producing regions would have to close before reaching their retirement age (Figure 2.4a). Only in Indonesia would fewer than 60 % of mines have to close early by 2030. About one third of Indonesia's current coal mining capacity will have reached its retirement age or exhausted reserves by 2030 and therefore will retire anyways. Other regions with an aging coal mining fleet and decreasing capacities due to regular retirements of mines include Kazakhstan and some Chinese and Indian regions. In all other coal mining regions, three-fourths or more of the remaining mining capacities would have to close prematurely by 2030. Exports of all major exporting countries, except Indonesia, would drop by more than 80 % between 2020 and 2030. Remaining exports would almost exclusively go to the Asian market, where Indonesia is situated best to outcompete other coal exporting countries like Colombia and the USA, which are far from this market, but also Australia, Russia, and South Africa, which can supply coal only at higher costs than the low-cost Indonesian mines.

Thus, currently operating capacities are also at risk of becoming stranded assets. Early closures of steam coal mines between 2020 and 2050 could lead to stranded assets of some USD_{2015} 140 billion (USD_{2015} 120-150 billion) (Figure 2.4b). Considering absolute asset volumes, asset stranding of existing mines would be highly concentrated in China and the USA. In China it is the sheer size of the coal sector that leads to these large volumes. The coal mine fleet in the USA is still relatively large, and at the same time would lose its market shares comparatively quickly. Furthermore, OCC for coal mines are rather high in some Chinese and U.S. coal mining regions with high shares of underground mines (e.g., in Appalachia) (cf. Holz et al. 2016), thus, also the asset value per unit of production capacity is higher. In India and Indonesia OCC of coal mines are generally lower, but also less production capacities would be stranded. Of the currently proposed new coal mines a relatively large share is situated in the coal exporting countries Australia, Russia, and South Africa (see Figure 2.2). If realized, these capacities could face a particularly high risk of stranding due to the collapsing export market.

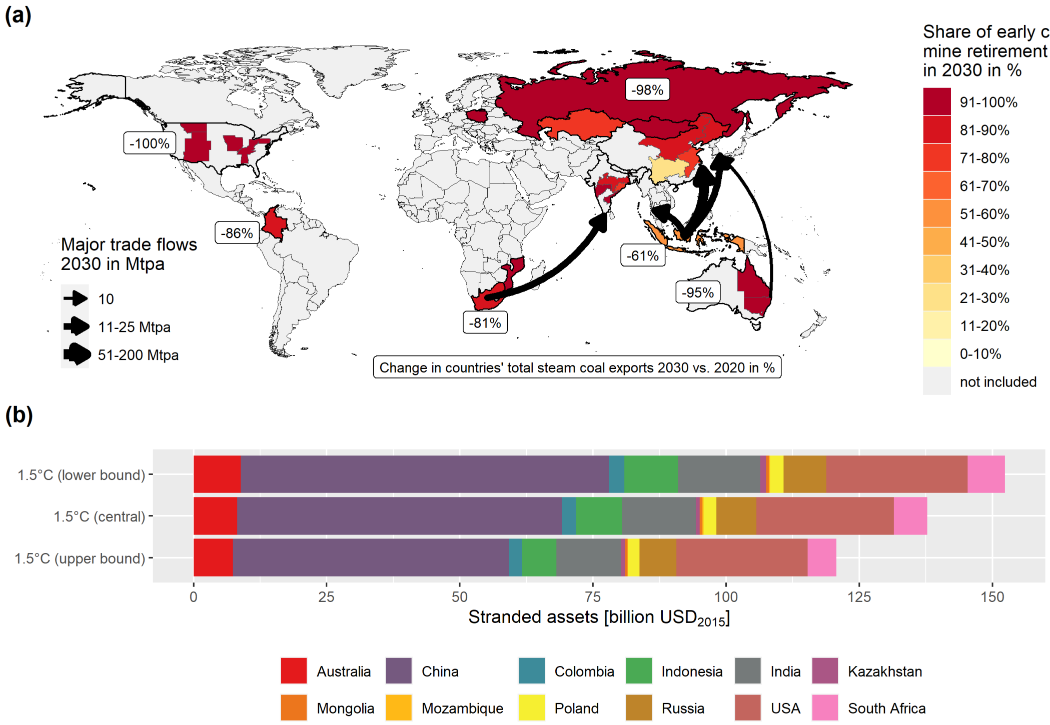


Figure 2.4: Early coal mine closures in 2030, trade flows, and stranded assets from operating mines under 1.5°C: (a) share of coal mine capacity that will retire early by 2030 in the central *1.5°C* scenario, remaining major trade flows in 2030, as well as change in total national steam coal exports compared to 2020, and (b) value of stranded coal mine assets (2020-2050) across the *1.5°C* scenario range. Source: Own illustration. Geographical data from (Becker et al. 2021; ABS 2016; OCHA-ROAP 2020; Runfola et al. 2020; Census 2019).

2.4 Discussion

Trout et al. (2022) have shown that, in order to limit global warming to 1.5°C, a substantial share of developed coal reserves would have to remain unused. This study further fleshes out that analysis, assessing the implications of a 1.5°C policy environment for the steam coal mining sector and its exposure to the risk of asset stranding. Global coal consumption in line with the 1.5°C target would lead to a significant reduction of coal output and cause excess capacities across all major coal producing regions. The finding that any new coal mining capacities after 2020 would be redundant is in line with IEA (2021d). Also for scenarios with continuously high coal consumption, results for investments in new coal mines in this study align with the results of other studies (cf. Auger et al. 2021; IEA 2019b).

Not only new coal projects but also currently operating mines would be significantly impacted by a required rapid reduction in coal demand. About 63 % (56-70 %) of their cumulative capacity until 2050 would have to remain unused, and more than three-fourths of all operating capacities in almost all coal mining regions would need to retire early by 2030. This is about three times the amount of capacities affected by premature retirements Auger et al. (2021) find in case of gradually declining coal consumption (-60 % by 2040 compared to today's consumption). Global coal consumption is already largely phased-out by 2035 in 1.5°C scenarios due to coal's high emission intensity and the relatively good subsitutability of coal, particularly in the power sector (IPCC 2022). If CCS would become generally available for coal-fired power plants, it could only prevent early coal mine closures and asset stranding to limited degrees due to its relatively late and limited deployment on existing coal-fired power plants in most 1.5°C scenarios (Byers et al., AR6 Scenarios Database). This could change, if CCS is rolled out very fast (Fan et al. 2018; McJeon et al. 2021), however, past experiences with CCS cast doubt on its near-term large-scale deployment on coal-fired power plants due to high costs and technical difficulties (Wang, Akimoto, and Nemet 2021; Grant et al. 2021; Martin-Roberts et al. 2021).

The stranded asset value (unrecovered OCC) from currently operating coal mines alone could represent about USD$_{2015}$ 140 billion. If all of the currently proposed new coal mines were to be built, this could add another USD$_{2015}$ 100 billion of stranded asset value. So far, few assessments of stranded assets in the upstream coal sector exist (Fisch-Romito et al. 2021; Curtin et al. 2019), and used definitions for stranded assets vary. For 2°C scenarios, CTI (2015) and IRENA (2017, 26) estimate coal supply capital expenditure costs (capex) and asset values at risk of stranding to amount to some USD 220 and 250 billion, respectively, including the value of maintenance capex (CTI 2015) and coal reserves (IRENA 2017). Assessing differences in financial values, the cumulative value of stranded coal supply assets until 2035 in 2°C scenarios could amount to USD$_{2016}$ 300 billion to one trillion, depending on the applied discount rate (Mercure et al. 2018). This reflects that the financial value of coal supply assets (based on expected future cash flows) can be significantly higher than the capex of new coal mine capacities (Spencer et al. 2018). Thus, results of this study should be considered a lower end estimate for the value of stranded coal supply assets under 1.5°C. In the downstream coal power sector, asset values at risk of stranding are significantly larger than for upstream coal supply, with around USD 900-1,400 billion (unrecovered OCC only) in 1.5°C scenarios (Edwards et al. 2022). Long lifetimes (around 50 years) and relatively high capex of coal-fired power plants (1,300-3,000 USD/kW) (Saygin et al. 2019) compared to coal mine assets cause these higher asset values at risk.

Although the value of possible stranded assets in the upstream and downstream coal sector differ, they are strongly linked by their dependence on future global coal-fired power generation pathways, with coal-fired power plants being the largest consumers of coal. However, regional differences arise. Net exporters of coal, like Australia or Indonesia, have a high risk of asset stranding in the upstream coal supply sector, while net importers, like the EU or Japan, could be affected mostly by asset stranding in the coal power sector (cf. Edwards et al. 2022). For China and India, with their large coal mining capacities and power plant fleets, up- and downstream asset stranding risk is high, and more than 50 % of all coal assets at risk of stranding are located in these two countries. In both countries, coal supply is largely in the hand of state-owned or controlled companies, while in countries, like Australia and the USA, private companies dominate (CTI 2015; Heede and Oreskes 2016).

For both, up- and downstream coal sector, the volume of assets at risk of stranding can be significantly reduced if immediate action is taken and investments in additional capacities are prevented (cf. Edwards et al. 2022; Auger et al. 2021). Introducing moratoria on new coal mines could be one option (Mendelevitch 2018; Blondeel and Van de Graaf 2018). Particularly, for coal exporting countries with a high amount of proposed new capacities, like Australia or Russia, this could be an effective measure to limit stranded assets. Additionally, restricting access to finance and insurance could increase project costs and eventually limit the realization of new coal projects (Zhou, Wilson, and Caldecott 2021). Beyond reducing the risk of asset stranding, limiting coal supply could complement demand side climate policies, aiming to reduce coal consumption, by increasing the relative cost of coal and by contributing to prevent carbon leakage (Asheim et al. 2019; Collier and Venables 2014; Green and Denniss 2018).

However, the coal mine asset value at risk of stranding is only one side of the medal. Coal mine closures can lead to significant economic downturns in affected regions due to deindustrialization, unemployment and outmigration (Nel et al. 2003; Harfst 2015; Diluiso et al. 2021). Globally, there are currently around 4.7 million direct jobs in coal mining, concentrated in China and India, and possibly even more informal and dependent indirect jobs (Ruppert Bulmer et al. 2021). And coal rents contribute about 0.2 %, or USD 160 billion (year 2019) to global annual GDP (The World Bank).

This highlights the importance of adequate measures to compensate for economic and socio-economic effects of coal mine closures. Renewable energy and other energy transition related industries could offer alternative employment and economic development opportunities (Pai et al. 2020; Zhou et al. 2022). National and international funds to provide structural change assistance to affected regions, as well as stakeholder integration in policy processes can furthermore contribute to increase stakeholder consent to phasing out coal production (Brauers et al. 2022; Gürtler, Löw Beer, and Herberg 2021).

Limitations to this study include the meager availability of coal sector data. Although Global Energy Monitor (2021b) provides the first comprehensive open database for coal mines with the GCMT, the data on coal mine lifetimes is still quite limited -even more so on OCC for coal mines. While the results obtained for required capacity additions across the *1.5°C* scenarios are robust to further reductions of remaining lifetimes, the amount obtained for stranded assets is sensitive to assumptions on OCC values. Furthermore, the results of this study are based on intertemporal optimization with perfect foresight. In contrast, real-world coal markets are characterized by cyclical effects, with periods of excess investment in mining capacities when coal prices rise, and early write-offs of uneconomic capacities when coal prices dip (Mendelevitch, Hauenstein, and Holz 2019). Thus, the volume of stranded coal supply assets could turn out even higher.

2.5 Conclusion

While previous studies have shown that the majority of global coal reserves need to stay in the ground if global warming is to be limited to 1.5°C, this is the first study to assess the effects on the operative global steam coal mining sector. A 1.5°C compatible coal demand would lead to a global slump of coal production. Any coal mine capacity additions from 2020 on would be redundant and at risk of becoming stranded assets. Furthermore, almost two-thirds of the current global cumulative production capacity needs to remain unused and the majority of coal mines need to be retired early. The value of stranded assets in the coal mining sector from operating mines alone would amount to some USD_{2015} 140 billion by 2050. If all of the currently proposed new coal mines and coal mine additions were to be built, this would almost double the amount of stranded assets. While this value is comparatively small (about one-sixth of stranded coal power plant assets' value), local economic dependencies on coal mining mean that declining coal production and early closures of coal mines can have severe local effects.

Stopping currently proposed coal mine capacity expansions, for example, by introducing moratoria on new capacities, could reduce the risk of coal mine asset stranding significantly.

However, also excess operating coal mine capacities need to be addressed urgently in order to limit global warming to 1.5°C. Combined coal phase-out and structural change policy packages can cushion adverse socio-economic effects and increase legitimacy for early coal mine closures.

Chapter 3

The Death Valley of coal - Modelling COVID-19 recovery scenarios for steam coal markets

---

This chapter is based on joint work with Paola Yanguas Parra, and Pao-Yu Oei published in *Applied Energy* 288 (April): 116564 under the title: “The Death Valley of coal - Modelling COVID-19 recovery scenarios for steam coal markets”. DOI: 10.1016/j.apenergy.2021.116564; published open access under CC BY NC ND 4.0.

3.1 Introduction: Prospects for coal markets during and after COVID-19

Coal accounts for around a third of global primary energy supply and is responsible for 40 % of global CO_2 emissions (IEA 2020b). There is a broad consensus within science that a fast coal phase-out is needed to limit global heating and prevent related catastrophic consequences (IPCC 2018b). Still, uncertainty prevails about the actual pathway that coal countries will take -with scenarios projecting a rapid global coal phase-out within the next 30 years while others announce a renaissance of coal considering that many countries - mostly in the Global South -are still planning to expand coal use in the coming decades (Audoly et al. 2018; Burandt et al. 2019; Jewell et al. 2019; Spencer et al. 2018; Steckel, Edenhofer, and Jakob 2015).

Since the signing of the Paris agreement in 2015, however, additional financial, and political pressures on coal businesses can be observed. This includes climate and air pollution regulation, local resistance to projects, climate litigation, trade restrictions, and reduced operational margins of coal companies due to competition with alternative fuels (Yanguas Parra et al. 2019). This resulted in key indicators showing early signs of decline of the global coal industry, such as coal use peaking in 2014 (IEA 2020b), a 75% shrinking of the global coal power plants pipeline (Shearer et al. 2020), accelerated retirement of operating coal fleets in many countries, low international coal prices, and a bleak financial performance for a large share of coal-related businesses in many countries (Bond, Vaughan, and Benham 2020; Mendelevitch, Hauenstein, and Holz 2019; Oei and Mendelevitch 2019). On top of this, the COVID-19 pandemic and the local to global responses to it have led to a sudden drop in economic activity, resulting in drastic reductions of energy demand (IMF 2020). With numbers of infections still increasing, no cure or vaccine available yet, the end of the pandemic is still not in sight. While as a consequence Greenhouse gas (GHG) emissions have declined (Forster et al. 2020; Le Quéré et al. 2020), the economic consequences of the pandemic and its further impacts on energy markets are highly uncertain (Baker et al. 2020). First assessments of the COVID-19 pandemic indicate that resulting direct and indirect effects will hit the coal industry hard in the short-term (Oei, Yanguas-Parra, and Hauenstein 2020).

The International Energy Agency (IEA) has published an assessment for the short-term future of global coal demand incorporating the effects of the pandemic (IEA 2020c). The assessment shows that coal will be severely affected due to the global lockdown measures, and projects global coal demand to fall by an unprecedented 8 % by the end of 2020, with coal power generation declining by more than 10 % (IEA 2020c). Similarly, recent 2020 projections for seaborne coal exports have been revised downward considerably to account for the impacts of COVID-19 (Argus 2020a, 2020b; O. o. t. Chief Economist 2020). These absolute declines in trade, combined with decreases in benchmark prices, will have a strong impact in the forecasted earnings from coal exports, as updated national forecasts from coal exporters confirm (O. o. t. Chief Economist 2020; A. O. o. t. Chief Economist 2020; Modi 2020b).

While the COVID-19 pandemic will likely have a strong negative impact on the short-term outlook for steam coal markets, the longer-term outlook is much more uncertain. For instance, the downward trend in coal investments (IEA 2020d), and growing number of restrictions for coal financing by financial institutions,[1] will likely be accelerated by COVID-19 due to the capital scarcity resulting from the global economic recession. Decreasing capital availability for coal businesses make the prospects for new coal power plants look much worse than before (Bloomberg 2020a; IEEFA 2020b; Moody's 2020). See Figure B.1 in the Appendix mapping various (in-) direct impacts of COVID-19 on the international steam coal market.

However, it is important to note that a large part of the coal power plant pipeline relies on public investment (End Coal 2020; IEEFA 2019; Chen 2018). This could still be available in the post-COVID-19 period, and could end up being used for "brown-recovery" (favouring fossil-fuels based and carbon-intensive industries) measures as it happened after the 2009 financial crisis, when only 16 % of all fiscal measures (520 USD billion) were allocated to "green stimulus" (favouring climate-friendly and low-emissions industries) (ILO 2011).

In this regard, public investments for projects abroad are of critical importance. China (as largest public investor) has not made any announcements regarding its intentions to continue financing large amounts of new coal power plants abroad in the post-COVID-19 period. Japan and South Korea (second and third largest public investors in new coal power plants (End Coal 2020; IEEFA 2019; Chen 2018)), on the other hand, have presented steps in the direction of limiting or suspending their lending for new coal projects (CIB 2020; IEEFA 2020a), but with loopholes and exceptions that would allow some planned projects to go ahead (Bloomberg 2020b; Japan 2020).

Therefore, key policy and economic developments in the next years, driven largely by the evolution of the pandemic and governments' responses to it, nationally and internationally, will be determinant for the medium and long-term future of coal markets and global warming mitigation efforts (Oei, Yanguas-Parra, and Hauenstein 2020; Cherp and Jewell 2020). Pointing towards increasing pressure on coal, "green recovery" issues have taken on

---

[1] Since the global pandemic was declared, over 30 significant financial organizations (with Assets under management >US$10billion) have either announced or strengthened their anti-coal lending/investment/insurance policies, bringing the total or organizations to 142 as of September 2020. Full overview available at https://ieefa.org/finance-exiting-coal/.

a prominent role in the policy, advocacy, diplomatic, and academic discussions around the pandemic and post-pandemic world (Forster et al. 2020; Hainsch et al. 2020; Hepburn, O' Callaghan, et al. 2020; New Economic Thinking 2020; Economist 2020; Wright and Fenton 2020; Hepburn, O'Callaghan, et al. 2020; Rosenbloom and Markard 2020; Barbier 2010; Lahcen et al. 2020; McKibbin and Fernando 2020; Mukanjari and Sterner 2020; Hanna, Xu, and Victor 2020).

Within this context, this paper examines the medium and long-term perspectives of the global steam coal demand and production considering the potential impacts of the COVID-19 pandemic and its aftermath. A key question in this regard is the speed and geographical distribution of the global decline of coal use and production (Muttitt and Kartha 2020; SEI, IISD, Climate Analytics, et al. 2019). Main uncertainties hereby prevail with respect to (i) the severity of the short-term demand shock in 2020/21 as well as (ii) to the shape/characteristics of recovery packages -resulting in a range of post-COVID-19 scenarios that shed light on the speed and geographical distribution of coal decline in the next decades.

The difficulty of projecting the medium and long-term future of coal can be seen in the failure of most organizations in doing so in the past (Mohn 2020), with mainstream energy projections persistently underestimating the deteriorating outlook for coal demand (and the uptake of renewable energy) in the last years (Brown et al. 2018; Metayer, Breyer, and Fell 2015; Muttitt, Scott, and Buckley 2018). Such overoptimistic projections are used as reference for investment and policy decisions resulting in unnecessary investments in long-term infrastructure that can create or perpetuate a carbon lock-in for many decades, or will become stranded once the carbon bubble bursts (Caldecott et al. 2016; Caldecott 2017; Löffler et al. 2019; Pfeiffer et al. 2016).

To assess energy markets, such as global coal markets, sectoral models using a partial equilibrium approach have been used (Gabriel et al. 2012; Trüby and Paulus 2012). Equilibrium modelling allows to study energy market development that is subject to individual actor behaviour under constraints, and considering market and investment mechanisms. The partial equilibrium model framework COALMOD was developed to assess the global steam coal market, focusing on steam coal supply and trade (Haftendorn and Holz 2010; Haftendorn, Holz, and Hirschhausen 2012; Holz et al. 2015). The model COALMOD-World is used in a number of studies to investigate the implications of different coal demand and market configuration scenarios for coal producing regions and international coal trade in a pre-COVID-19 world (Mendelevitch, Hauenstein, and Holz 2019; Hauenstein and Holz 2020; Holz et al. 2018). In most of the assessed scenarios in these studies, results fall into two different groups. One representing a relatively stable consumption and production around 2015-2020 levels, and the other one, based on 1.5-2°C pathways, leading to drastic changes for all coal producers.

The above literature review shows that there is an urgent need of alternative scenarios that reflect the most recent trends in coal markets, in particular related to the COVID-19 pandemic. In this paper, we therefore examine plausible recovery scenarios for the global steam coal market subject to different political decisions. To do so, this paper presents an interdisciplinary approach to develop a range of stylized coal demand scenarios up to 2040 as described in more detail in Section 3.2. These scenarios' implications for steam coal international trade and coal producing countries are investigated using the partial equilibrium model COALMOD-World (CMW) (Holz et al. 2015; Holz et al. 2016). Additional insights are gained by assessing effects of coal trade restrictions of key actors in further scenarios. Results of these scenarios for thermal coal production and trade are shown and discussed in Section 3.3. Section 3.4 focuses on broader policy and political economy issues of these results. Finally, Section 3.5 presents our conclusions as well as key issues that require further research.

3.2 Methods and scenario building

Within the uncertainty context explained in the previous section, in this article, we conduct a scenario analysis taking pre-COVID-19 trends in the energy and coal sectors into account, to assess the influence of the COVID-19 pandemic and resulting recovery stimuli on the global steam coal market. Scenario analysis (responding to "what if" questions) exploring the joint impact of various uncertainties which stand side by side (Ansari, Holz, and Kuhlani 2020) is much more appropriate for answering our research questions than a forecasting or other prediction-oriented exercises, which focus on "probability" rather than on "plausibility" (Schoemaker; Notten 2005; Mietzner and Reger 2005). Scenario building exercises must balance qualitative and quantitative information inputs to be able to assess a plausible range or a 'scenario cone' (Amer, Daim, and Jetter 2013) of outcomes and telling "a story of how various elements might interact under uncertain conditions" (Schoemaker). With this aim, as other recent studies looking at the longer-term implications of the 2020 pandemic on important sectors, we build narratives about possible futures (e.g. brown vs green recovery) based on qualitative research techniques, and build quantitative estimates of the potential range of outcomes, making use of established models in the research field.

Our scenario building process of six different scenarios can be divided into three steps, which are summarized in Figure 3.1, and explained in more detail in the following sub-sections.

First, we determine the plausible range of short-term impacts of the COVID-19 shock (2020-21) on coal demand. Second, we adjust pre-COVID long-term national and/or regional projections (up to 2040) for coal demand based on a plausible range of post-pandemic recovery strategies ("brown" vs. "green" recovery). Third, we consider additional (COVID-19 related) coal supply-side policies and add exemplary scenarios taking these coal market influencing measures into account.

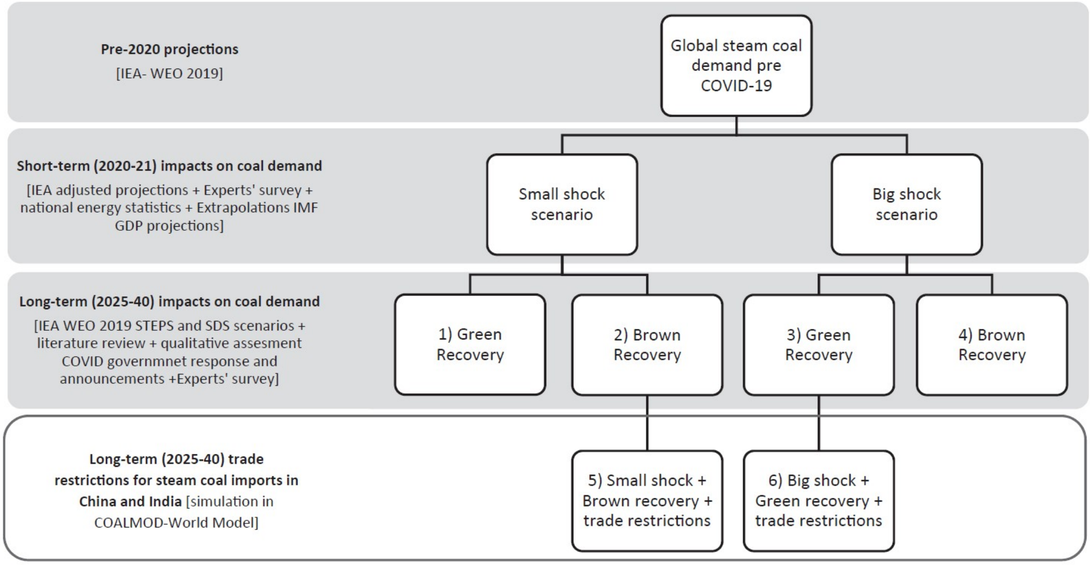


Figure 3.1: Schematic scenario building approach and scenario mapping. Boxes on light grey contain scenarios where only changes and assumptions were made to coal demand, the last box with blue framing shows scenarios where an additional version of the scenarios were run in model simulations with changes and assumptions on coal supply. Text within square brackets shows the main sources used at each analytical step to build the final set of scenarios.

For this scenario building process, we derive information from a triangulation of data sources:

(i) Pre COVID-19 projections based on the IEA[2] World Energy Outlook (WEO) 2019 (IEA 2019b); and quantitative assessments of the short-term impact of COVID-19 in coal demand based on the 2020 adjusted Energy projections by the IEA (IEA 2020c)).

(ii) For the qualitative research on the narratives, we follow a similar approach to Hepburn, O'Callaghan, et al. (2020) and base part of our narrative building exercise on surveys of

---

[2] The IEA was chosen as reference projection scenario due to its wide use in the energy and policy areas, and to increase consistency in model inputs and regional resolution between pre and post-COVID scenarios. However, it was supplemented with additional quantitative assessments (see sections below for further details).

national experts in the coal sector, for the main coal producing and consuming countries. This expert survey (conducted in May and June 2020)[3] provides both qualitative and quantitative assessments of the updated trends for coal demand and supply in key coal consuming and producing countries as well as expert judgement of the IEA projections.[4]

(iii) For general economic trends, non-sector specific information on recovery plans, as well as global climate action narratives related to the storylines behind our scenarios, we examine the scarce academic literature available on the topic, and complement it with non-academic sources (e.g. news articles and press releases,[5] policy monitors (Economics; Brief 2020b; OECD 2020b), and grey literature (BARCLAYS 2020; ILO 2020; OECD 2020a; Climate Action Tracker; IMF) examining recovery packages) focusing on publications since the outbreak of COVID-19 until September 2020.

Our intention is not to forecast coal demand for individual countries with high accuracy, but rather to map the existing range of uncertainty in the global steam coal market under plausible post-COVID-19 scenarios. This allows us to reflect on strategies major coal-producing countries could adopt to prepare for a highly uncertain future of their coal industries, and how these strategies could be integrated in COVID-19 related policy interventions.

3.2.1 Demand scenarios –short term

In our upper bound scenario, we assume a short-term reduction of 8 % in global coal-fired power generation (“small-shock”; for national/regional reductions see Appendix B.2). This is based on a combination of the projected decline by the IEA (2020c) Global Energy Review 2020 (when available), and independent assessments by international experts or review of national energy statistics (when IEA individual forecast were not available or for

---

[3] The survey included 20 coal sector experts (with a complete response rate of 50 %) covering all the ten largest coal consuming countries, as well as experts in international energy markets (without a concrete country emphasis). The main question was around the short-term impact of COVID-19 in their respective countries, as well as a personal assessment of the projections of this impact by the International Energy Agency and the probability of recovery packages to support (or not) the coal industry.

[4] At the moment of the analysis, the latest version of the IEA World Energy Outlook (WEO) available was the WEO 2019. All analysis therefore refers to these values. During the process of peer-review and publication of this paper, the WEO 2020 became available. This version is supposed to have been corrected for the COVID-19 shock in their energy sector projections, and reduced both short-term and long-term projections for coal generation. However, compared to our scenarios coal demand in the updated 2020 STEPS scenario is still higher than our highest post-COVID-19 scenario (see Appendix B for further information on the differences between the two World Energy Outlooks). Therefore, our criticism of the WEO results not sufficiently representing the upcoming downturn of coal is still valid also for the WEO 2020.

[5] This included a qualitative assessment of over 270 documents, including a selection of relevant news articles, public statements, and press releases related to different combinations of the search terms “COVID-19”; “climate”; “recovery”; “policy” –See Table B.1 in the Appendix for overview of number or sources considered for individual countries/regions.

divergent reasoned opinions from various regional experts). As a result of this approach our "small-shock" scenario is more conservative compared to the IEA forecast for coal power generation in 2020 (globally at least -10 %), with the main difference between this scenario and the IEA projection being lower reductions forecasted by national experts for China (-4 % instead of -5 %) and India (-5 % instead of -6 to -9 %). Arguments for these differences were mostly potentially faster uptakes of coal utilization than assumed by the IEA. Still, all experts confirmed high uncertainty about the evolvement of the national coal industries, which we try to reflect in our scenario range.

The calculations of the IEA Global Energy Review 2020 (used for the small shock scenario for several regions) are consistent with the reference scenario of the International Monetary Fund (IMF) World Economic Outlook from April 2020, assuming an overall reduction of 3 % GDP for 2020 (IMF 2020). The IMF, however, has also provided alternative scenarios, covering a range of possible developments regarding the uncertain spread and severity of COVID-19. This includes calculations for a "longer outbreak in 2020" or a "longer outbreak in 2020 with a second wave in 2021", which would result in global GDP growth estimates of -5.8 % for 2020 (IMF 2020).

Based on an extrapolation of these GDP growth forecasts from the IMF to coal demand forecasts by the IEA, together with alternative forecasts provided by the surveyed experts, we create a second lower bound or "big-shock" scenario resembling a 16 % short-term global reduction in coal power generation –twice as steep as the "small-shock" scenario.[6] A summary of reductions in coal demand in 2020 for key countries and regions is presented in Table 1 below. A full overview of the reductions for all regions under the different scenarios is available in the supplementary information (Appendix B.2).

Table 3.1: Reductions in coal electricity generation in 2020 for selected regions and countries. Reductions indicated with a * are the same as in the IEA Global Energy Review 2020 projection.

Coal Electricity generation	USA	Europe	South Africa	Russia	China	India	Japan	South East Asia	Other Asia Pacific
Small shock	-25 %*	-20 %*	-15 %	-10 %	-4 %	-5 %	-5 %	-5 %	-5 %
Big shock	-50 %	-40 %	-30 %	-20 %	-8 %	-10 %	-10 %	-10 %	-10 %

---

[6] Our lower bound resembles the "longer outbreak in 2020" scenario of IMF (2020) and does not extend the shock beyond 2020. Therefore, it could even underestimate the shock for coal in the case that COVID-19 does not get under control globally by the end of 2020.

3.2.2 Demand scenarios –medium and long term

Longer-term estimates for global steam coal demand will depend largely on two drivers:

(i) speed of coal phase-out in countries concentrating the majority of the operating coal fleet (China, India, USA and EU); and

(ii) new investment decisions in China, and other few countries (e.g. India, Turkey, Vietnam and Indonesia) which concentrate the large majority (>75 %) of planned coal power capacity additions.

Regarding the first aspect, our analysis of relevant literature and our expert survey shows that the coal phase-out will accelerate in most developed economies due to the COVID-19 pandemic, with medium uncertainty level about the extent and speed of the acceleration. On one hand, the pandemic reduces the profitability of the coal industry. On the other, it might also delay retirement decisions in some countries due to factors like delays in capacity replacements, or concerns about employment in a shrinking economy. Considering this uncertainty, our scenarios do not include an explicit assumption on targeted policy interventions on the coal power generation sector.

Even more uncertainty, however, prevails for the second aspect regarding developing and emerging economies and their investments in new coal capacity: Global Final Investment Decisions (FIDs) for coal-fired generation are on a steep downward trend, reaching in 2019 a 40-year historic low at around 17 GW (IEA 2020d). Nonetheless, around 130 GW of new coal-fired power generation capacity are in the planning phase. Their realization would more than compensate for expected retirements in the next three years, resulting in a net growth in the global coal fleet of around 40 GW in this period (IEA 2020d).

Based on conflicting visions about these important drivers, we build two medium-to-long-term post-COVID-19 steam coal demand scenarios, resembling “green” and “brown” recovery scenarios (see Figure 3.2). These scenarios are based upon a combination of pre-COVID-19 reference values of the Stated Policy Scenario (STEPS) and Sustainable Development Scenario (SDS) of the IEA (2019b) WEO. For each post-COVID-19 pathway, we determine a demand spread for each of the WEO regions, which ranges between entirely brown (resembling STEPS growth rates for coal –e.g. in Russia) and entirely green (resembling a SDS trajectory for coal generation –e.g. in Europe).

To determine this range, based on the experts’ survey and our own desk research, we calculate a compound index for each region considering the following variables:

(i) accuracy of STEPS coal capacity projections based on updated information on current retirement schedules and new additions planned in 2019/20 (classified into three categories: unlikely low, likely, unlikely high);

(ii) a qualitative assessment of the overall climate policy environment in the region (classified into three categories: high, medium, and low); and

(iii) degree of discussion on “green recovery” packages for stimuli packages affecting the coal industry (classified into three categories: high, medium, and low) based on mapping media coverage of COVID-19 related measures and policy announcements from March to June 2020.

Results for the individual compound indexes resulting from this method for key countries and regions are presented in Table 3.2, a full overview of the ranges for each region are available in the supplementary information (Appendix B.2).

Table 3.2: Overview parameters green and brown recovery scenarios for selected regions and countries.

		USA	Europe	South Africa	Russia	China	India	Japan	South East Asia	Other Asia Pacific
Compounded green recovery factor (1=STEPS / 0=SDS)	Min	0,0	0,0	0,2	0,5	0,2	0,1	0,4	0,3	0,3
	Max	0,5	0,5	0,7	1,0	0,8	0,6	0,9	0,8	0,6
Accuracy of STEPS coal projections		unlikely high	unlikely high	likely	likely	unlikely high	unlikely high	likely	unlikely high	unlikely high
Overall climate policy environment		low	high	medium	low	high	high	low	medium	medium
References to Green Recovery		low	high	medium	low	medium	medium	low	medium	low

The first criteria (assessment of the STEPS capacity projections) is in particular important for countries where without additional new coal power plants (beyond the ones announced, planned or under development in 2019), the installed capacity assumed by the STEPS scenario would require a significantly increased retirement age for operating coal power plants than what is observed in historical averages or even higher than average technical lifetimes of coal power plants (around 40 years). For these countries, we have lowered the probability of going into a STEPS growth rate post-COVID-19 scenario to account for this miss-match.

A clear example of this is the USA, where despite low overall climate policy environment, and hardly any active attempt from the federal government to design “green recovery” plans, the current investment and closure decisions are far away from the assumptions of the STEPS scenario. While the STEPS scenario assumes coal generation capacity to remain relatively stable throughout the 2030s for the USA, a large number of coal generation units have already announced to retire over the next years, without any new units under construction or planned, and a remaining fleet with an average age higher than 40 years (Hauenstein and Holz 2020).

For the second and third criteria, there is a higher degree of uncertainty on the assessment (reflected on higher spreads in the "brown to green" scale). This results mainly from: (i) the regional aggregation in the IEA (2019b) WEO, which combines groups of countries with very mixed policy and political environments for climate policy (e.g. Australia and South Korea are grouped under the same region), (ii) the uncertainty about the stability of policy regimes with regards to climate in the medium and long-term in a large number of countries; and (iii) the lack of specific references to the coal sector in most of the "green recovery" announcements or media reports. Therefore, the width of the range of "green" and "brown" post-COVID-19 scenarios increases substantially (and proportionally to this uncertainty) after 2025.

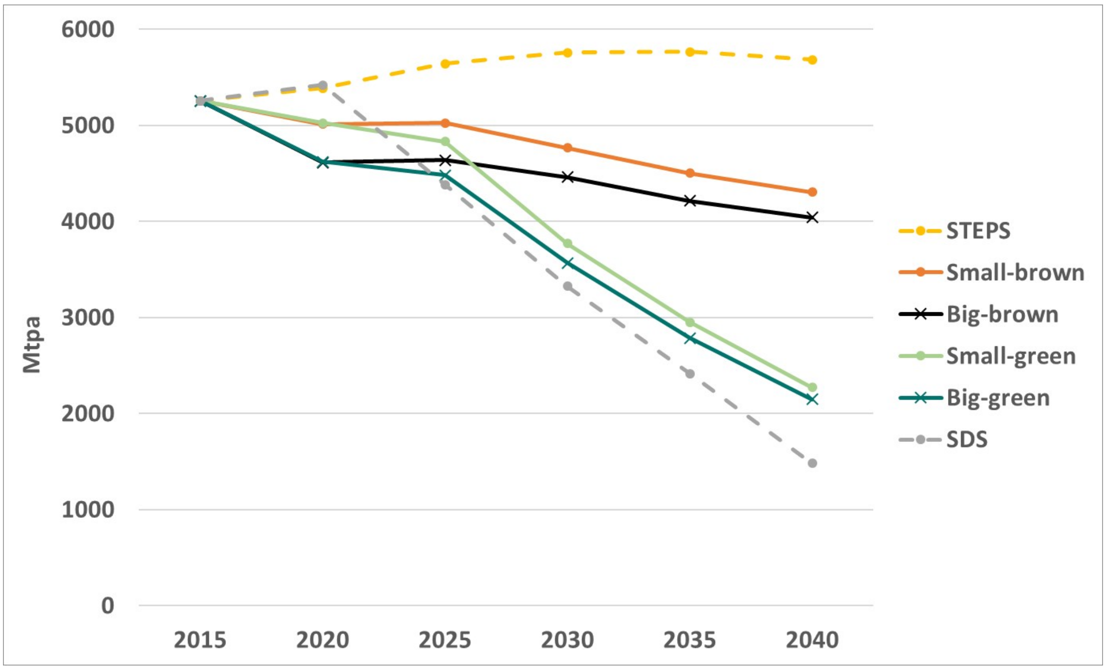


Figure 3.2: Steam coal global demand projections under selected pre and post-COVID scenarios.

Note: STEPS and SDS scenarios from the IEA WEO 2019 are only presented in the figure for reference - but do not incorporate the effects of the COVID-19 pandemic.

All resulting demand scenarios are depicted in Figure 3.2 and the underlying numerical assumptions are available in the supplementary information. For the rest of this article, we will mostly focus on the two extreme cases for post-COVID scenarios, namely small-brown and big-green scenarios, since they cover the full uncertainty range of our projections and by reducing the number of combinations, we reduce the complexity of results interpretation. Results for the other scenarios are included in the Appendix B.

3.2.3 Trade restriction scenarios

In 2020, China and India will be collectively responsible for around 70 % of global coal consumption and around 60 % of global coal production, as well as a large part of global coal imports. China, in addition, has also become a major investor in many international coal projects (End Coal 2020; IEEFA 2019; Chen 2018). Our analysis on the supply side therefore focuses on trends in these two countries, as they constitute a dominating force in the international steam coal markets. If for instance, China and India encourage both production and use of coal, then international coal prices could remain stable or even increase. However, if they impose import restrictions, or end up with a national production surplus, then global coal prices could plummet rapidly, with significant impacts in large coal producing countries (Cornot-Gandolphe 2014, 2015).

India has been pursuing to reduce its dependency on coal imports in the last years, and has recently announced its intention to cut imports drastically with the aim of incentivizing national production and promoting employment options for infrastructure build-up considering the new scenario for energy demand during and after the pandemic (Chaturvedi 2020; Modi 2020a; Peh 2020). Preliminary analysis based on announcements by the Chinese government, on the other hand, suggest that China might attempt to use investments into the coal industry (in combination with the steel industry) to restart its economy and while reducing coal imports (Peh 2020; Hume and Smyth 2020). This would come in addition to already ongoing infrastructure improvements and expansions (e.g. Haoji railway) as part of the domestic coal industry restructuring aimed at boosting production and decreasing dependency on imports (Bloomberg 2019).

To investigate the implications of different post-COVID-19 coal demand scenarios on coal producing countries, we run a simulation of the demand scenarios presented in the previous sections with the COALMOD-World (CMW) model under two modalities: a “competitive market” scenario, without additional constraints imposed on global coal trade in the model; and a “limited market” scenario, with policy driven import bans in China and India from 2025 onwards, representing the attempt to prop-up their national coal industry as an economic recovery measure. While it is unlikely that all Indian and Chinese coal imports end in 2025, implementing these extreme trade restrictions in the model allows us to observe more clearly the main implications of these countries implementing trade restrictions for coal, in comparison with a “competitive market” scenario.

3.2.4 Model description

We run a simulation of the above described demand scenarios with a holistic model of the world steam coal market, COALMOD-World (CMW). The model calculates steam coal production, trade, and prices for the world' s regions. It features a detailed representation of domestic and international steam coal supply with a forecasting horizon until 2050 and includes endogenous investment decisions in production, land transport, and export capacity, as well as an endogenous mechanism that updates production costs due to resource depletion (Holz et al. 2015; Holz et al. 2016).

Mathematically, COALMOD-World is a perfect foresight complementarity model that collects the profit maximization problems of the major player types in the global steam coal market, producers and exporters, and balances their supply with demand in the coal consumption regions. The model specification has a focus on the supply side of coal (coal extraction, coal transport) and includes extraction costs and extraction constraints, transport costs and transport constraints, investments in mining and transport. Both the seaborne and the overland international trade as well as the national markets are included, with large countries split in regional nodes.

In our six base scenarios, all input parameters remain unchanged, except the scenario specific, exogenously defined coal demand for the year 2020 and onwards. In the two scenarios with trade restrictions, the option of coal imports is excluded in the model for China and India starting in 2025. This is operationalised in CMW as an arbitrarily high import tax for all Chinese and Indian demand nodes (200 USD per tonne), from 2025 onwards -which, due to model characteristics, is equivalent to an import ban.

In the next section, results of our simulations are presented and discussed regarding its implications for international steam coal trade and for the largest coal exporting countries.

3.3 Results: A dim mid- and long-term outlook for steam coal markets

3.3.1 COVID-19 recovery: Avoid false hopes for a “V” or “U” shaped coal demand curve

Our results show that - regardless of the scale of the short-term shock of COVID-19 - medium and long-term global coal demand (Figure 3.2) will be far below levels of the outdated reference scenario (STEPS in WEO2019) of the IEA. While the IEA has corrected short-term decline in coal demand resulting from the COVID-19 pandemic, it still misses to account sufficiently for fundamental pre-COVID trends that affect the long-term coal demand and have been strengthened by the crisis (e.g. scarcity of capital for new coal projects, acceleration in retirements of old coal fleet).[7] Our scenarios show that the developments in China, India, and the USA are hereby the biggest drivers influencing the slope of the overall decline (see Figure B.3 in the Appendix B for regional demand developments). Following the decline in demand, global production volumes will observe a contraction of -20 to -60 % by 2040 (compared to values of 2015) (see Figure 3.3).[8]

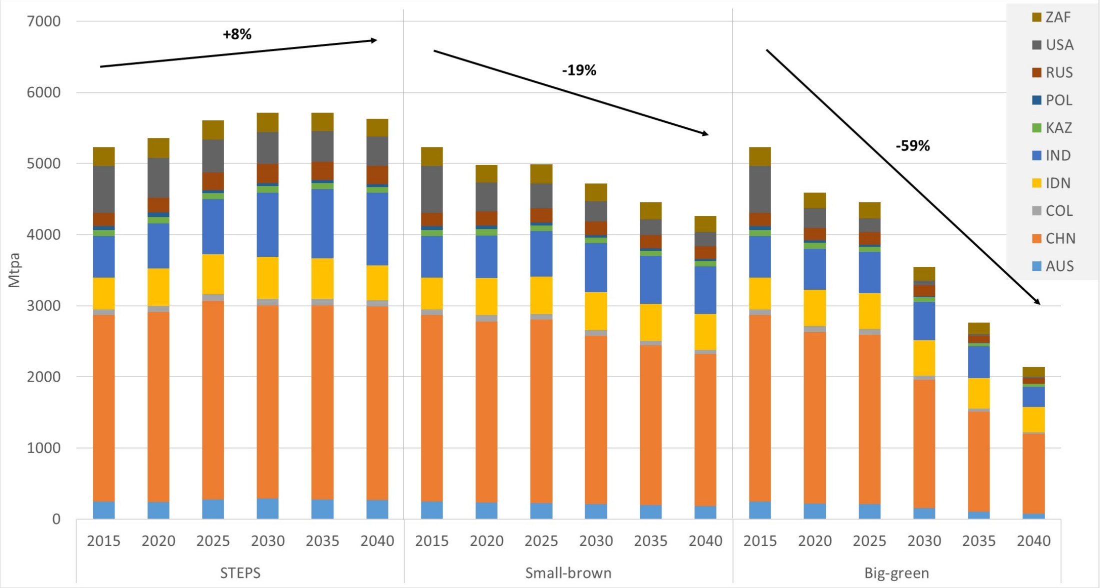


Figure 3.3: Steam coal production by major steam coal producing countries 2015-2040 in two selected scenarios accounting for the COVID-pandemic –compared to the outdated STEPS forecast.

False hopes for a “V” or “U” shape of the demand curve (assuming a recovery) consequently have to be replaced by an “L” or “\” shape comparison. At best, global demand, and thus production, after the pandemic stays flat at 2020 levels throughout 2025 in case of broad recovery measures supporting coal-fired power production (brown recovery scenarios).

---

[7] A comparison between the STEP 2019 and STEPS 2020 scenario of the IEA (see Appendix B.3) shows a strong short-term correction for global coal demand, but a much more moderate long-term adjustment, with the two scenarios for coal demand having a very similar long-term slope. This shows that structural changes in coal markets that could follow the COVID-crisis (e.g. strong green recovery policies) have not been taken into account in the revised long-term projections, and the short-term shock is just seen as temporary, which strands in strong contrast with the scenarios we have developed in this paper.

[8] Results for global production volumes in the other scenarios are provided in Figure B.2 in the Appendix B.

However, even in the most optimistic scenarios from a coal perspective, demand starts to decline further after 2025.

3.3.2 The Atlantic market dries out first, causing shifts in trade patterns

The results of trade patterns show that effects vary across regions –and especially in between the two different markets (see Figure 3.4): The Atlantic coal market is being reduced at a much faster pace than the pacific market (for details see Figure B.5 in the Appendix B). This is due to the shrinking demand in the EU and the USA across all scenarios. As a result, especially the USA and Colombia see shrinking volumes of coal exports within the next two decades (for details see Figure B.6 in the Appendix B). Instead of U.S. American export volumes increasing to new heights by 2040 (STEPS scenario: 122 Mt), calculated exports range from 35 Mt (small-brown) to 0 Mt (big-green) by 2040. Colombia' s production volumes, having nearly no domestic consumption, shrink in parallel with their exports from 89 Mt in 2020 to a range of 54 Mt (small-brown) to 21 Mt (big-green) in 2040.

China is and remains the biggest consumer of coal in the world and one of the largest importers throughout all scenarios (without import restrictions). A faster decline of demand in China therefore increases the pressure on all major coal producers. Dominating actors such as China (or India) might in addition implement policies to protect and subsidize their domestic coal industries. Similar dynamics were observed in the past when China implemented new coal policies (i.e. affecting coal imports and Chinese coal production (IEA/OECD 2016a)). This will consequently increase the pressure on other export regions economically dependent on their sales. The scenarios also show that South Africa loses its last shares in the Atlantic market and therefore becomes fully dependent on its trade to the Pacific market and especially to India - competing with (relatively cheap) Indonesian exports. This dependency becomes evident in the scenarios that limit coal imports for China and India resembling their aim to protect domestic coal production (see Figure 3.5). Introducing trade restrictions in India would lead to an increase of domestic production to meet continuous demand for coal within the country. This would reduce South African exports in 2040 by around 50 % compared to scenarios without import restrictions in China and India. Indonesia and Australia, currently the two largest thermal coal exporters in the Pacific market would also be hit by reductions of around 20-40 % and 50-80 %, respectively, by 2040 (scenario dependent) due to such trade restrictions.

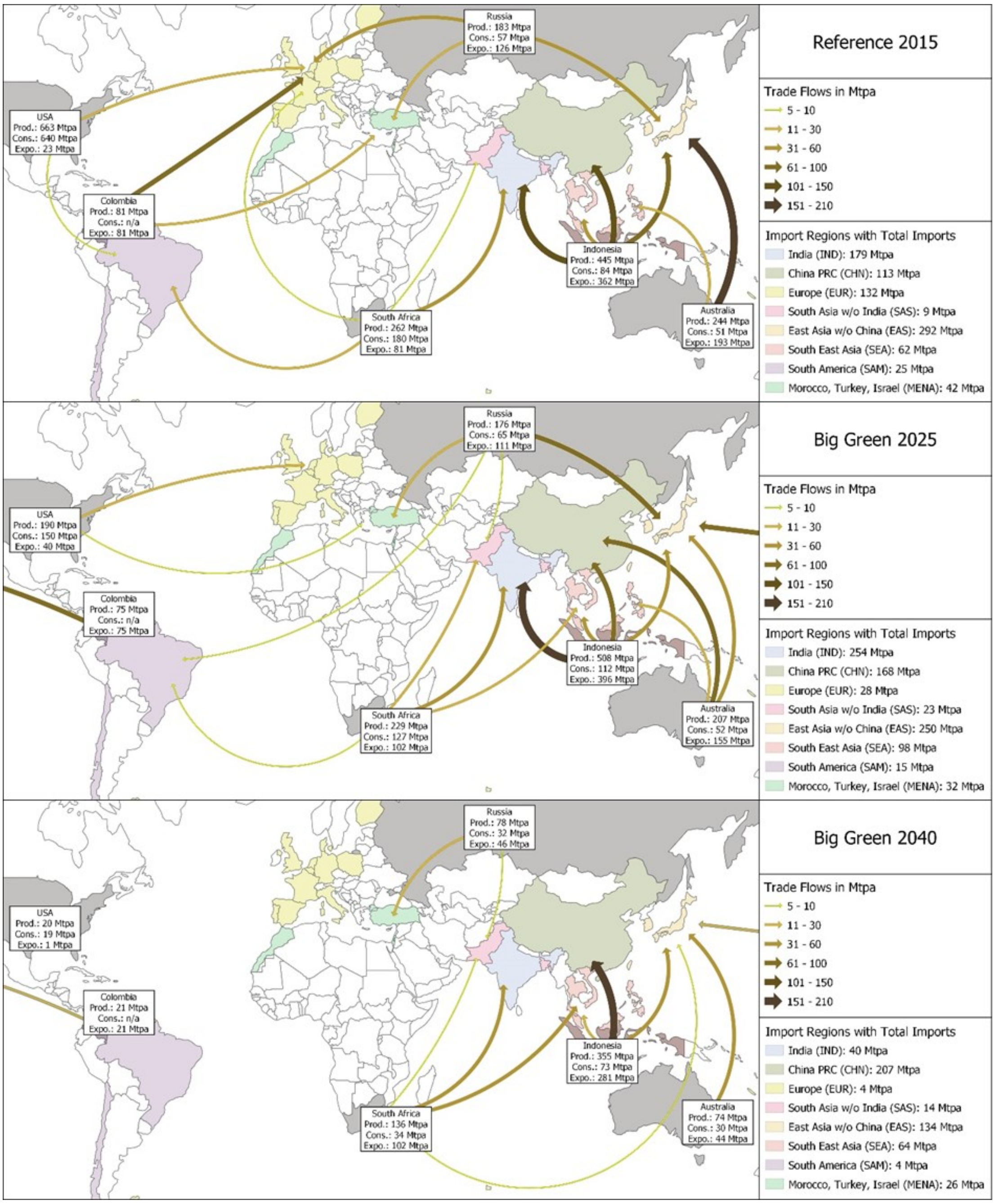


Figure 3.4: Major steam coal trade flows, and values for production, consumption and exports in 2015 (reference), 2025 and 2040 (model results of the scenario Big-Green).

Note: Values for 2015 are model results of a 2015 benchmark run (with slight deviations from historical values).

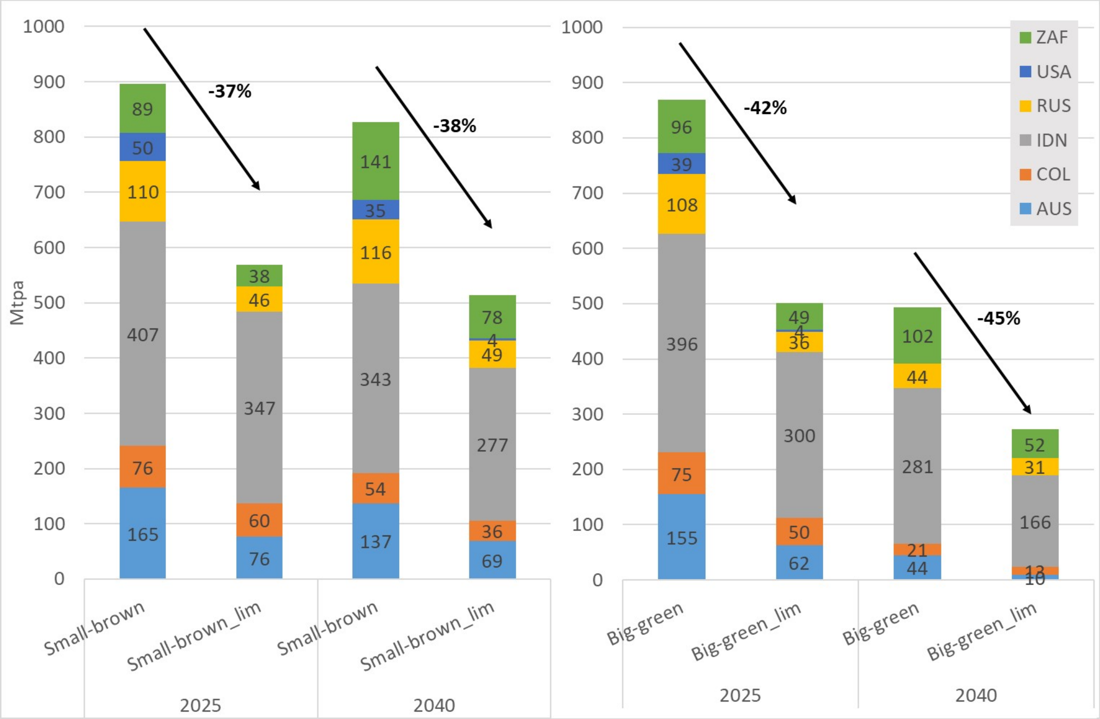


Figure 3.5: Steam coal exports by major exporters 2025 and 2040 in scenarios with and without Chinese and Indian import restrictions.

These results illustrate the risk for coal exporting regions such as in Australia, Colombia, Indonesia or South Africa - being dependent on coal policies in India and China. This highlights the importance and urgency of just transition policies in these regions, described in the following section.

3.4 Discussion

An important insight from our analysis is that the scale of the short-term shock (2010-2021) of COVID-19 on coal demand and the choice of recovery strategy will have considerable repercussions for the longer-term coal demand outlook ranging between -20 to -60 % (compared to 2015 values).

The importance of the short-term shock effect can be explained by the reaching of tipping points in 2020 for some key players in national and international coal markets, which are not sufficiently considered by mainstream global energy outlooks such as the IEA WEO. Considering the weak economic position of many coal generation operators and mining companies already in 2019, a big-shock could significantly accelerate the retirement or sale (at a depreciated value) of their assets, with considerable long-term implications for national and international coal markets. This is amplified by the difficult economic outlook of finance for the global coal industry, which already was characterised by restricted private finance before COVID-19.

Regarding the post-pandemic recovery strategies, our results show that their design has long-term implications for the future of coal demand and supply. Thus, when designing these policies, decision makers should consider lessons learned from past economic recovery schemes (e.g. following the last global financial crisis) and previous experiences with coal transitions in coal-dependent regions.

Based on the literature review and our scenario results, we believe there are reasons for optimism regarding the "green" nature of post-COVID-19 recovery packages. A key difference between the 2008 crisis is that in 2020 most countries in the world have ratified the Paris Agreement, and have enacted national GHG emissions reduction targets. This will make it much more difficult for countries to opt for recovery strategies centred around carbon intensive industries. This is exemplified by the recent announcements of China and the European Union (among the largest GHG emitters) about increasing the ambition of their GHG reduction targets.

Another key difference is that considerably less private capital is available for coal related businesses than in the aftermath of the 2008 crisis, and the risk profile of the commodity is much larger. With reduced capital available and interest rates primes compared to other industries, it is unlikely that coal businesses will be able to ensure large amounts of capital for business expansion in the aftermath of the COVID-19 crisis. Moreover, the currently observed currency depreciation and private capital flight in developing countries will make it more difficult for new projects in capital intensive industries (e.g. mining) to take-off unless heavily subsidised by public finance. Therefore, it is much more likely that the capital attracted by coal businesses in the aftermath of the COVID-19 crisis is merely destined to keep current operations on board.

Under these new circumstances, it is likely and highly beneficial that countries and multilateral organisations focus much more on green investment recovery packages than in the aftermath of the 2008 crisis, where despite its modest size, "green stimuli" had a significant impact on green industries. In particular innovations in renewable energies were very successful, pushing many technologies beyond their inception phase and improving the overall financial outlook for green industries (Geels 2013). However, a careful classification of "green" investments is needed, to avoid the fossil fuel industry capturing a large part of the subsidies to subsidize continuation of their business (e.g. investments in marginal production efficiency) or using it as a fig leaf (e.g. investments into carbon capture (CCS) technologies) to protect their business.

Within this context, investment and policy decision by China, the world largest user and importer of steam coal, could have important international and global consequences, however, large uncertainty remains in this regard. Preliminary analysis based on announcements by the Chinese government suggest that China is willing to relax regulations that limited the expansion of national coal power capacity in the past with over 100 GW of new capacity possibly coming online in the next 10 years (GEM and CREA 2020; Myllyvirta, Zhang, and Shen 2020; Meidan, n.d.). Analysis of the provincial post-COVID-19 stimuli plans reveal that coal dependent provinces are planning large sums of investment in rail and coal-to-chemicals projects with the aim of promoting the local coal industry (Brief 2020a). This stands in stark contrast with the recent announcement of the Chinese government about its intention to peak emissions in 2030 at the latest, and aim for carbon neutrality by 2060. Thus, the central government might turn around provincial energy plans and the next-five-year plan preparation process, to ensure a “green recovery” that can move the country quickly to its emissions peak and then to a carbon-neutrality pathway (Myllyvirta 2020).

Moreover, as our results show, special attention needs to be out on coal-export dependent countries, where strong to extreme reductions are expected for coal exports. The global steam coal market is characterised by a few producing (and exporting) countries, which have local regional economies that heavily rely on coal in terms of economic activity, fiscal revenue, and employment (Pai et al. 2020; Sartor 2018). The political economy of these regions is strongly linked to coal. Thus, the future of this fuel can have big repercussions on local policy making, which traditionally aims to slow and water-down climate policy efforts (Cardoso and Turhan 2018; Edenhofer et al. 2018; Isoaho and Markard 2020; Svobodova et al. 2020).

Considering the strong social and economic impacts that coal decline has had in heavily coal-dependent regions and countries in the past, already existing negative trends in coal markets have brought renewed interest from policy makers and researchers on the strategies and instruments needed to ensure the existing and upcoming coal transitions are achieved in a just and socially acceptable manner (Sartor 2018; Brauers et al. 2018; Caldecott, Sartor, and Spencer 2017; Campbell and Coenen 2017; Herpich, Brauers, and Oei 2018; Ocelík et al. 2019; Rečková, Rečka, and Ščasný 2017; Wehnert et al. 2019). The extreme reductions on coal exports in some coal exporting countries that our scenarios show, confirm previous findings of the literature on just transitions regarding the importance of focusing recovery and transition efforts on vulnerable coal-dependent countries and regions to develop alternative sustainable development perspectives. In absence of such policies, these countries might become international roadblocks for climate action, while local economies and communities might result highly affected.

3.5 Conclusion

This paper has analysed the influence of the COVID-19 pandemic and resulting recovery stimuli on the mid and long-term outlook for the global steam coal market. Results show that the short-term impact of COVID-19 on coal power demand will be significant and unprecedented. The pandemic mostly reinforces already existing trends and market effects negatively affecting the coal sector. Consequently, false hopes for a “V” or “U” shape of the coal demand curve (assuming a recovery) will have to be replaced by an “L” or “\” shape demand outlook. Our results for mid- and long-term coal demand and production trends are significantly lower than in the IEA reference scenario STEPS, independently of possible pro-coal COVID-19 recovery attempts. This is in-line with recent analyses of the coal sector and its future development (Bond, Vaughan, and Benham 2020; Mendelevitch, Hauenstein, and Holz 2019; Oei and Mendelevitch 2019).

The fact that future coal demand in the IEA STEPS lays far above plausible volumes in any post-COVID scenario is an important finding considering that investment decisions (in particular on the supply side), as well as some policy decisions, rely on mainstream reference scenarios for coal demand, which are still depicting outdated trends (Mohn 2020). These predictions were already too high before COVID-19, but now after the pandemic have become even more unrealistic. This increases the risk of misleading short-term decision making in many coal regions and highlights the need for further independent research. However, our research shows that there are reasons for optimism regarding the post-COVID-19 recovery packages when it comes to the impacts of the “green recovery” packages in the energy sector and its alignment with climate targets.

The economic crisis following the COVID-19 pandemic will most likely result in a dying coal industry, unless substantial support through national subsidies and public financing is provided to this sector. In this regard, China’ s potential support for new coal power generation units, both domestically and internationally, is a critical factor regarding the future coal demand trajectory. The question arises if this support for coal can be aligned with agreed on climate targets, calling for additional research.

Depending on the extent of the pandemic, we find that it could also open the door for the world to get into a trajectory of decline in coal power generation that is more in line with scenarios limiting global heating to tolerable levels. Post-COVID-19 economic recovery packages should therefore be designed in a way that promotes clean energy, moves away from new investments on coal infrastructure, stays away from subsidies that prolong artificially the life of coal assets, and delivers a just transition to the most affected.

Nonetheless, neither the SDS of the IEA, nor our (slightly higher) lowest post-COVID-19 coal demand scenario are in line with the Paris Agreement (Yanguas Parra et al. 2019). Existing market trends triggered by the pandemic, together with “green recovery” plans for a big number of coal consuming countries therefore will not be enough to achieve the reductions needed in the coal sector under low warming scenarios. Additional targeted climate policy interventions aimed at the coal sector are therefore needed in addition to “green recovery” policies. These include the acceleration of already existing coal retirement schedules, much stricter air pollution and emissions standards, the early retirement of coal power plants that have been built in the last 20 years, and the shelving of the large majority of new coal power plants currently in construction or planning stage.

Our results and approach highlight the importance of further interdisciplinary work that provides the foundations for evidence-based policy making on these important issues (McCauley et al. 2019). Limitations of our methodology, which can be addressed by further research, include developing scenarios with more detailed projections and information for individual non-OECD countries with ongoing discussion about the future of coal. These are under-represented in our literature research and scenario sampling (e.g. Indonesia, Pakistan, Bangladesh, Turkey, etc.). Furthermore, to close the quantitative bias towards the global energy demand projections from the IEA, a larger sample of scenarios should be added as soon as other relevant global energy outlooks start providing COVID-19-adjusted projections. To improve coverage of regional specifics and details, modelling and analysis of the consequences of global demand scenarios should be carried on with a higher resolution and deeper level of analysis for individual coal exporters (e.g. impact for specific coal basins, regions, or companies; impacts on fiscal revenues and national accounts; coal supply assets at risk of stranding; etc.). Our analysis does not consider additional targeted climate policies and therefore only covers parts of the scenario cone. Scenarios taking into account additional policies aimed at reducing the use of fossil fuels could significantly worsen the outlook for coal producers and should be assessed in further studies.

Chapter 4

Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin

---

This chapter is based on joint work with Franziska Holz, Lennart Rathje and Thomas Mitterecker currently under review in *One Earth.* Pre-print published under the same title as DIW Berlin Discussion Paper 2003, Berlin: German Institute for Economic Research (DIW Berlin). URL: https://www.diw.de/.

4.1 Introduction

Limiting global warming to 1.5°C of pre-industrial levels requires the rapid decline of coal use over the next decades (IPCC 2018a). The climate conference COP26 in Glasgow in November 2021 has heralded the end of coal in the next decades as political objective. However, the late end date leaves room for different interpretations by coal suppliers and consumers as to the trajectory in the very next years.

Indeed, the coal industry does not seem ready to comply with climate targets. According to Global Energy Monitor et al. (2022), there are proposals for new steam coal mining projects with a cumulative capacity of some 1300 million tons per annum (Mtpa).[1] Some 380 Mtpa of these planned capacities are expansion projects, but almost 900 Mtpa are in greenfield projects. About 2/3 of the proposed capacities are in Australia, China, and India. These mining expansion plans reflect that coal demand, in particular in Asia, is expected to remain high for the next decades (Chen and Mauzerall 2021; Global Energy Monitor et al. 2021). Australia, one of the major coal exporting countries (IEA 2021a), is one example of a country that so far has shown little intention to reduce coal production, but rather plans to continue exporting large coal quantities over the next decades (SEI et al. 2021).

However, investments in coal supply capacities are at risk of becoming stranded if not aligned with climate targets (Ploeg and Rezai 2020b). McGlade and Ekins (2015) and Welsby et al. (2021) find that Australia will have to leave the overwhelming majority of its coal reserves in the ground if the world is to limit global warming to 2°C or 1.5°, respectively. They find 93-95 % unburnable coal reserves in Australia until 2050 which is in the same range as the stranded coal reserves of the other two high-profile exporters that are losing their markets, the USA and Russia (Former Soviet Union). Of Australia's existing coal mining capacities, around half would have to remain unused in scenarios with ambitious climate policies (Hauenstein 2022c). Even though Auger et al. (2021) assume less stringent climate policy, they also find that Australia risks to see around 140 Mtpa of yearly capacity – a third of today's capacity – as stranded. Australia will be among the hardest hit coal exporters, next to the United States. Caldecott, Tilbury, and Ma (2013) point out the particularly high risk of stranding for greenfield coal projects in Australia if the industries' expectations for a continuously high coal demand growth in China do not materialize.

Despite the risk of asset stranding, the Australian government has continued to support coal and to forecast further increase in Australian coal production (Christoff 2022; Stutzer et al. 2021; SEI et al. 2021). This perpetuation of the coal lock-in increases the risk for asset

---

[1] In this paper, we use the term steam coal to denominate thermal coal. This includes mostly bituminous coals, but also sub-bituminous coals from Indonesia. We exclude lignite from our analysis.

stranding (Unruh 2019). Taking into account the large share of the national workforce in the coal sector, SEI et al. (2020) apprehend difficulties for Australia to accomplish a just transition. Australian coal miners are at risk of losing their jobs even in moderately ambitious climate policy scenarios (Auger et al. 2021). However, Mercure et al. (2018) show that Australia might actually gain in total in terms of cumulative GDP in a 2°C scenario compared to a high fossil fuel consumption scenario, whereby losses (stranding) of cumulative fossil fuel value in the country would be outweighed by gains in other sectors.

In this context, we assess the economic viability of the famous Carmichael project by Adani in the Galilee Basin. We use this notorious project to study the economic prospects of investments in the export oriented steam coal sector today and their risk of becoming stranded assets.

The Galilee Basin is a steam coal basin in central Queensland in Northeastern Australia and until recently was one of the world's largest known untapped coal basins (Geoscience Australia 2021). With rising coal prices in the 2000s, interest in this remote basin increased and a number of coal mine projects were announced, one of them the Carmichael Coal Mine and Rail Project, with an initially proposed coal production capacity of 60 Million tons per year (Mtpa) (DAWE 2018). With this size, it would have been one of the largest coal mines of the world. Developed by a subsidiary of the Indian Adani Group, Adani Mining/Bravus Mining,[2] it was supposed to boost coal supply for growing Indian coal demand, and supported by the Indian government's economic development program (Rosewarne 2016). Support has also come from the federal Australian and the regional state government of Queensland, which have been intertwined with the domestic coal industry for many decades (Baer 2016). Carmichael is the first mine developed in the Galilee Basin and could possibly pave the way for other mining projects in the basin.

However, the Carmichael project's economic viability has been questioned ever since its development started in 2010. On a global level, long periods of low steam coal prices, growing global efforts to reduce greenhouse gas emissions, as well as unfavourable physical conditions have put a question mark on the project's viability (Buckley and Sanzillo 2013; Buckley and Nicholas 2017; Quiggin 2017). By 2021, over 40 financial institutes and banks, including major international investment banks, have ruled out financing Adani's mine or the Abbot Point coal terminal. Due to the economic challenges and difficulties to acquire sufficient funding, the project was downsized several times and, as of early 2022, envisages an initial production capacity of 10 Mtpa. Beyond economic doubts, Carmichael and

---

[2] Due to the negative publicity around the Carmichael mine and to weaken the opposition's "Stop Adani" slogan, several subsidiaries of the Adani Group as well as the Adani Abbot Point Terminal changed their names and removed all references to the parent company. Adani Abbot Point Terminal became North Queensland Export Terminal (NQXT); Adani Mining became Bravus Mining; Adani's new coal rail haulage company is now called Bowen Rail Company.

the Galilee Basin projects have been criticized for their potentially severe environmental impacts, including harmful effects on the Great Barrier Reef, and for being located on indigenous peoples' sacred land (Meinshausen 2015; Foxwell-Norton and Lester 2017).

Despite the criticism, Adani obtained all the required state and federal approvals until 2021 and started the construction of the mine in June 2019 and of the rail line in June 2020. After many years of sinking investment expenditures - combined with strong political support in Australia and Queensland - the project is on the verge of starting commercial extraction in 2022. The global post-COVID-19 recovery with unusually high coal prices have turned the project's economics favorable for a moment.

In this paper, we use the partial equilibrium model COALMOD-World of the global steam coal market (Hauenstein 2022c; Holz et al. 2016) to assess prospects for coal production from the Galilee Basin and Australia in general. We take into account the Carmichael coal mine specifics, such as geographical location and costs. We address the uncertainty faced by the Carmichael project through the lens of three diverging scenarios for global coal demand, focusing particularly on demand in the Asian region. We distinguish a global *High demand* scenario, which depicts a continued important role for coal due to low climate policy ambitions, from a *Moderate decline* scenario in the spirit of the 2021 Glasgow COP26 climate accord. Cumulative coal consumption in these scenarios is too high to be compatible with the Paris Agreement's global warming target. We, therefore, also include a third, Paris-compatible scenario, a *1.5°C* scenario.

Beyond the Carmichael project and other greenfield coal projects in the Galilee Basin, this is relevant for all Australian steam coal production, which exports large shares of its production (IEA 2021a) and is confronted with declining domestic steam coal demand (AEMO 2020; Jotzo, Mazouz, and Wiseman 2018). Beyond Australia, it is also relevant for all other major steam coal exporting countries, such as Colombia, Indonesia, Russia, South Africa, and the USA, as their exports increasingly depend on Asian demand and domestic demand is likely to shrink as well (IEA 2021a; Yanguas Parra, Hauenstein, and Oei 2021).

Our results show that, even for very low cost assumptions, the Carmichael project is not economically viable in the long-run. Under none of the assessed scenarios, investments in coal production capacities in the Galilee Basin are made. Australian coal production decreases significantly in all scenarios due to ceasing domestic demand and shrinking export opportunities. Investments in additional coal mining capacities in other Australian basins are only viable in the most conservative demand scenario and only for replacing retiring capacities. However, already in case of moderately more ambitious climate policy in major coal consuming countries, these investments would also be dispensable. Largely the same applies to steam coal supply investments in other world regions. The risk for asset stranding is particularly high for export-oriented coal supply investments, while any coal supply expansions aggravate the competition for remaining market shares and the economically defaulting risk within the entire coal sector.

Our model results are contrasted by current real-world developments, with sales from the Carmichael mine starting in 2022. These might cover some of the sunk investment expenditures made by Adani over more than a decade of project development. This is possible in an unusually high price market, which is due to the uncertainties related to the COVID-19 recovery, the Russian war in Ukraine and flooding in some of Australia's coal regions, but not likely to perpetuate (IEA 2021a).

In the following, the core of the paper shows and discusses the results in more depth (Section 4.2). We present our model-based methodology and the scenario design in Section 4.4. More details of the parameterization of the Galilee Basin on the one hand and background information to the demand scenarios on the other hand can be found in the Supplementary Material (see Appendix C.1).

4.2 Results and discussion

In this section we present and discuss the results of our model based scenario analysis. We first give insights in consumption and production in three different global demand scenarios that we specify in Section 4.4.3. We then turn to the prospects of coal investments and asset stranding on the supply side with a particular focus on the Galilee Basin and Australia.

Figure 4.1 shows global steam coal production and consumption in all three scenarios. While global steam coal consumption remains flat until 2025 in the *High demand* scenario and then starts to decrease, it falls significantly from 2020 on in the scenarios *Moderate decline* and *1.5°C*. However, even in the most conservative scenario, the *High demand*, global steam coal consumption more than halves by 2050 compared to 2020. Only a few countries, including China, India, Indonesia, still see an increase of domestic coal demand between 2020 and 2025. From 2025 on, coal demand also declines in these countries. In the *Moderate decline* scenario, global steam coal demand reduces almost linearly to zero between 2020 and 2050. In case of stringent global climate policies (*1.5°C* scenario), an almost complete global coal phase-out is achieved already in 2040. In this case, global steam coal demand in 2030 is only a quarter of the 2020 level.

Major countries' coal consumption in the *High demand* scenario resembles the trends in the IEA (2021g) World Energy Outlook 2021 'STEPS' scenario. Only in India consumption starts to decline earlier than in 'STEPS'. By 2050, *High demand* has somewhat lower global coal demand levels than ’STEPS’ because many power plants reach their retirement age between 2045 and 2050, which leads to a sharp decline in coal demand.

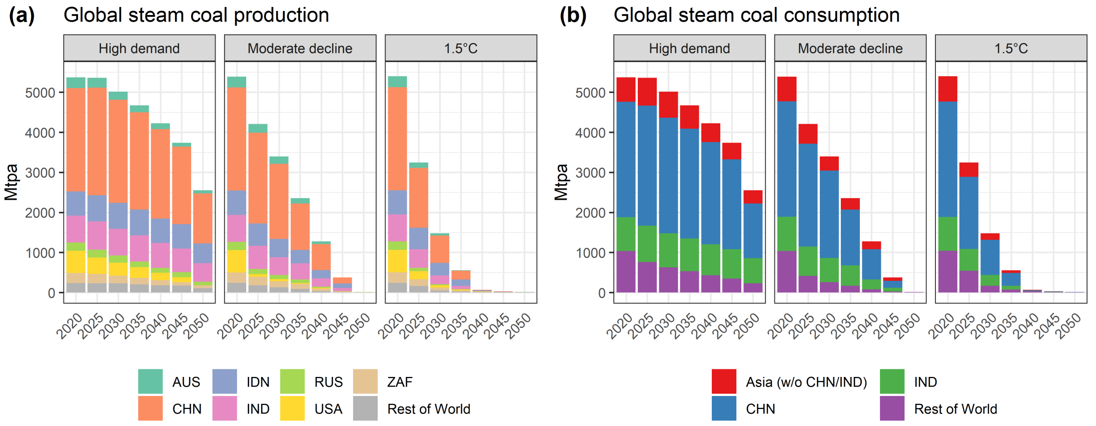


Figure 4.1: Global steam coal production (a) and consumption (b) in all scenarios in Mt per year.

Note: In (a): AUS = Australia; CHN = China; IDN = Indonesia; IND = India; RUS = Russia; USA = United States of America; ZAF = South Africa; Rest of World = Colombia, Kazakhstan, Mongolia, Mozambique, and Poland.
In (b): Asia (w/o CHN/IND) = Bangladesh, Indonesia, Japan, Malaysia, Pakistan, Philippines, South Korea, Taiwan, Thailand, and Vietnam; CHN = China; IND = India; Rest of World = Australia, Belgium, Brazil, Canada, Chile, Denmark, Finland, France, Germany, Israel, Italy, Kazakhstan, Mexico, Morocco, Netherlands, Poland, Portugal, Russia, South Africa, Spain, Turkey, United Kingdom, and United States of America.

Due to falling global demand also coal production starts to decline no later than 2025. In the *High demand* scenario this decline is felt differently among the major coal producers. While China, India, and Indonesia continue to produce at an only slightly declining level throughout 2040, production in most other major coal producing and exporting countries declines by 1/3 to 2/3 between 2020 and 2040. Yet, these are still high levels compared to the drop in the *Moderate decline* scenario, which would result in global production declining by more than 3/4 between 2020 and 2040, affecting all producers.

This ambiguity is also reflected in the investments in coal production capacities. In the *Moderate decline* scenario, only some minor investments (total: 100 Mtpa) are required in China, while existing production capacities in all other countries are sufficient to cater for the remaining demand (compare Figure 11 in the Supplementary Material (see Appendix C.1). In contrast, in the *High demand* scenario investments into new production capacities would be economic in most major producing countries (2020-2050 total: 3000 Mtpa). However, only in China, India, and Indonesia total mine capacity would be slightly expanded until 2025. Investments in all other major coal exporting countries would provide only replacement of retired capacities.

Thus, considering the high uncertainty of coal demand developments, the risk of asset stranding for new coal mine projects, greenfield and brownfield, is substantial in all countries. This finding is in line with other research that points out the increasing risk of stranding for fossil fuel supply assets (cf. Auger et al. 2021; Caldecott, Tilbury, and Ma 2013; Mercure et al. 2018; Welsby et al. 2021). In the following, we investigate in more detail to what extent the Galilee Basin projects and Australian production are subject to these uncertain global trends, and what this implies for coal supply investments and the risk of asset stranding in this sector.

4.2.1 Carmichael: Not a profitable venture

We start analyzing the economic viability of Adani's Carmichael mine using the most conservative demand scenario, the *High demand*. First we use the lower bound cost estimates of the Carmichael project to parameterize the Galilee Basin producer node, the exporter node representing the Abbot Point Terminal, and the transportation infrastructure between these two nodes (Section 4.4.1).

Despite this "pro-investment" configuration and the high-demand scenario in Asian import countries, no investments into production capacity at the Galilee Basin production node are triggered. Only if we reduced the lower bound investment cost estimates (incl. production, railway, and export harbor capacity) significantly further, would production in the Galilee Basin start (compare Figure 8 in the Supplementary Material (see Appendix C.1)). Cost reductions of up to 25% do not trigger any investment in production capacity; a reduction of 30% leads to an investment into 19 Mtpa production capacity (becoming available in 2025). But these are hypothetical cost reductions to already questionable low cost estimates.

Yet, contradicting our modeling results, production at the Carmichael mine actually started in the winter 2021/22.[3] To shed light on this new situation, we compare our results to sensitivity model runs where we assume a "sunk investment" of 10 Mtpa production capacity, i.e. 10 Mtpa production capacity are available without investment expenditures in production capacity needed (see Figure 4.2).[4] For these sensitivity runs we differentiate between the

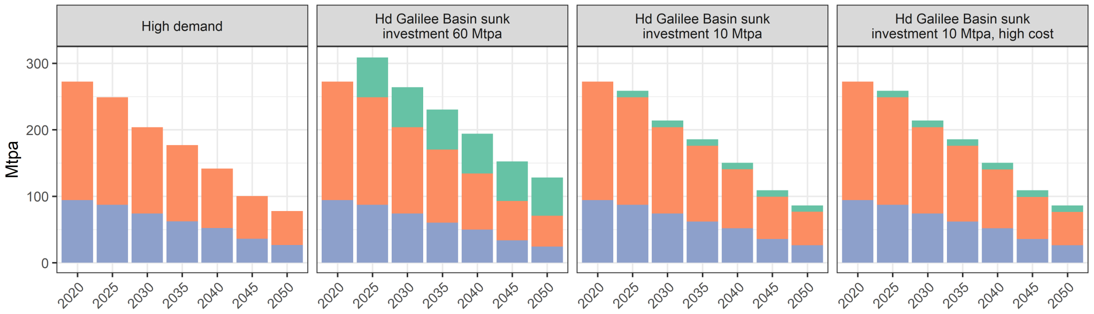
---

[3] K. Beavan. 2021. „Adani's first Carmichael Mine coal export shipment imminent after years of campaigns against it." Accessed January 5, 2022. https://www.abc.net.au/news/rural/2021-12-29/adani-ships-first-coal/100729834

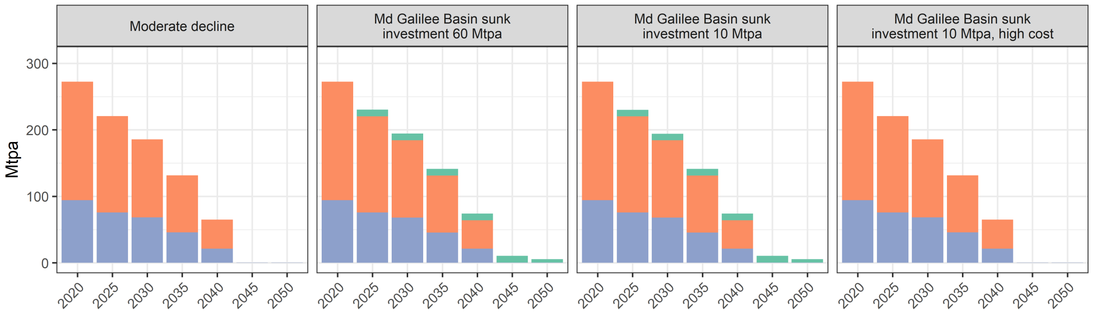
[4] The sunk investment was implemented as an existing production capacity of 10 Mtpa (and 60 Mtpa, respectively) in the Galilee Basin production node, however, requiring investments in the transportation infrastructure to the port. With additional investments only allowed from 2020 on, a complete supply chain could only be available from 2025 (the next time step in the model) on.

low and the high production cost estimates (see Table 4.1). In case of the low production cost estimate, the 10 Mtpa available mining capacity produces at full capacity in both the *High demand* and *Moderate decline* scenario. However, if production costs are high, the available capacity is producing only in the *High demand* scenario. In the other scenarios, the mine, although available, is not used.

(a) Australian steam coal production: High demand



(b) Australian steam coal production: Moderate decline



(c) Australian steam coal production: 1.5°C

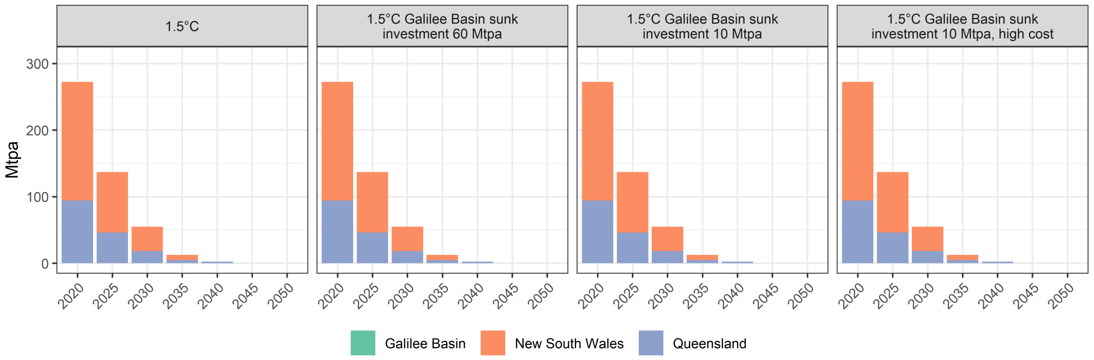


Figure 4.2: Australian steam coal production for different assumptions for the Galilee Basin under the *High demand* (Hd, panel a), *Moderate decline* (Md, panel b) and *1.5°C* scenario (panel c).

Several arguments suggest that actual costs to produce coal from the Galilee Basin are rather closer the upper end of the parameter ranges stated in Section 4.4.1 (Table 4.1). For example, the lower bound of the unit investment cost for new production capacity, as well as production cost estimates are based on the assumption that Carmichael can achieve cost advantages due to economics of scale in the very large capacity configuration (60 Mtpa) that has been abandoned in the last years. In other words, with realistic cost estimates, there is even less economic rationale for production in the Galilee Basin than in the low cost results just shown.

Figure 4.2 also shows the results for a hypothetical case of 60 Mtpa (i.e., the initially planned capacity of the Carmichael mine) available production capacity in the Galilee Basin (i.e. without investment expenditures needed). While fully used in the *High demand* scenario, less than 20 % of the capacity is used in the *Moderate decline* scenario. Interestingly, Galilee Basin coal hardly affects the global trade flows and volumes, not even in the *High demand* scenario, and does not displace other Australian exports from Queensland or New South Wales. Cumulative global consumption would increase by 0.4 percent in the *High demand* demand scenario between 2025 and 2050 in the case of 60 Mtpa available production capacity, with marginally higher consumption in Japan, South Korea, and India. However, robustness of this effect would have to be tested further, considering potential adjustments in the medium to long-term of importing countries' willingness to pay based on such a long-term change in supply.

Based on these results, it appears highly implausible that operations in the Galilee Basin can be run profitably, even if ignoring the recovery of already accrued investment costs. In other words, chances are high that even the downsized Carmichael project ends up as stranded asset. The decision to continue the development of the Carmichael mine was apparently rather a political decision (Stutzer et al. 2021; Christoff 2022), not an economically driven one.

Considering the bleak economic prospects for the Carmichael mine, it is more than doubtful if it will serve as stepping stone for the development of more coal mining projects in the Galilee Basin. However, there is also a large number of proposed new coal mine and expansion projects in other Australian coal basins (Driskell Tate, Shearer, and Matikinca 2021). These projects differ from the ones in the Galilee Basin because they are in already developed basins and require less investments into transportation infrastructure etc. In the next section, we assess the prospects of steam coal production and investments in the rest of Queensland (excluding Galilee Basin) and New South Wales, the two states which together make up for almost all steam coal production in Australia.

4.2.2 Australian supply and investments on a downward trend

Australian steam coal production has already peaked in all three scenarios and will fall significantly below the current production level by 2025 (Figure 4.3, panel (a)). In the *Moderate decline* and the *1.5°C* scenario, Australian steam coal production ends within the next two decades, namely by 2045 (*Moderate decline*) or 2040 (*1.5°C*). In the *High demand* scenario, Australian production nearly linearly declines from 2020 to about 30% of its 2020 level by 2050.

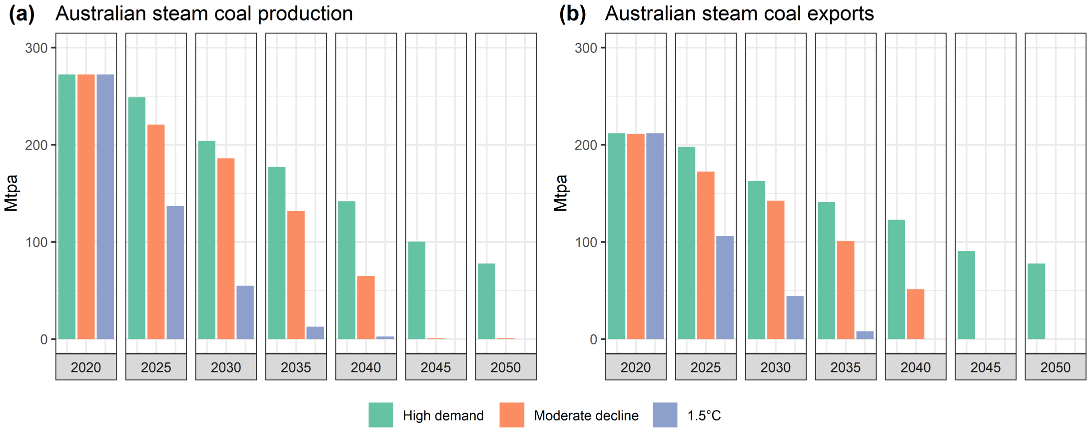


Figure 4.3: Australian steam coal production (a) and exports (b) in all scenarios in Mt per year.

Australian domestic steam coal demand declines sharply in all three scenarios, further reducing demand for Australian coal (also see Figure 9 in the Supplementary Material (Appendix C.1)). An accelerated decline in domestic coal demand can be expected since the Australian government announced in the fall of 2021 to shut down some 5 GW of coal-fired power capacity even before their originally planned shut down date (Australian Government Department of Industry, Science, Energy and Resources 2021b, 19). The draft of the latest 2022 AEMO Integrated System Plan also assumes a much faster decline in Australian coal demand than was estimated in the previous report, which forms the basis of our scenarios (see Section 4.4.3). The path considered as "most likely" by stakeholders in the new draft expects a rather fast transition from fossil fuels to renewable energies which leads to an almost complete end of steam coal-fired power generation by 2040 (AEMO 2021).

The trend in Australian production is mirrored by the trend in Australian exports (Figure 4.3, panel (b)), which is due to the coal sector's large export dependency. Currently, 75-80 % of Australian steam coal is exported, of which 90 % is shipped to Japan, China, South Korea, and Taiwan (IEA 2019a). The total export share remains at these high level throughout the entire period in all three scenarios.

The vast majority of global and Australian steam coal trade is destined for Asia (Figure 4.4). The global trend towards Asia is amplified in future years in all scenarios. Australian steam coal exports go almost completely to East Asia, including China, which does not change much over time.[5] In the basic setup of our three scenarios we have not considered a Chinese import ban for Australian coal, expecting that the import ban introduced in 2020 is of temporary nature.[6] In case these restrictions continued, we would expect a continuous rerouting of trade flows with limited influence on exporters' production volumes. To test for effects of changes in Chinese and Indian import policies, we implemented various sensitivity runs (for details see Section D in the Supplementary Material (Appendix C.1)). Besides Australia, major coal suppliers to China are Russia and the USA in the *High demand* scenario and additionally Colombia in the *Moderate decline* scenario. For more details regarding the proportion of domestic steam coal production and imports in China and other South East Asian countries see Figure 10 in the Supplementary Material (Appendix C.1).

In the *1.5°C* scenario, global seaborne coal trade is decreasing fast after 2020, ceasing at all towards 2040. Of the major exporting countries, Colombia and the USA are the first to lose their market shares in the Asian market (in 2025) due to the high distance-induced supply costs. They are followed by Russia (2030). South Africa continues to cover the remaining Indian import demand, while Indonesia (major share) and Australia (minor share) supply the remaining countries in Asia until 2035.

While investments in new production capacities in the Galilee Basin are not competitive, the model run for the *High demand* scenario yields investments in some 60 Mtpa production capacity between 2020 and 2050 in the in other Australian coal basins to replace retiring capacities (see Figure 4.5). Both in Queensland and New South Wales, retirement of mines outpaces new investments, though, and total production capacity declines continuously. In case demand declines faster, such as in the *Moderate decline* scenario, no further investments in capacities in Australia are required – or economically viable.

---

[5] With the Chinese import quota, enforced as ton constraint in CMW, Australian coal is favored over Indonesian coal due to its higher energy content. Total exports of both countries are barely affected by the Chinese import quota because Indonesian coal can potentially replace Australian coal in Asia. In reality, exports to China will likely be split mainly among Indonesia and Australia.

[6] C. Zhou and S.-L. Tan. n.d. „China-Australia relations: as demand for coal surges, how long can Beijing keep banning Australian supply?“ Accessed January 5, 2022. https://www.scmp.com/economy/china-economy/article/3147774/china-australia-relations-demand-coal-surges-how-long-can

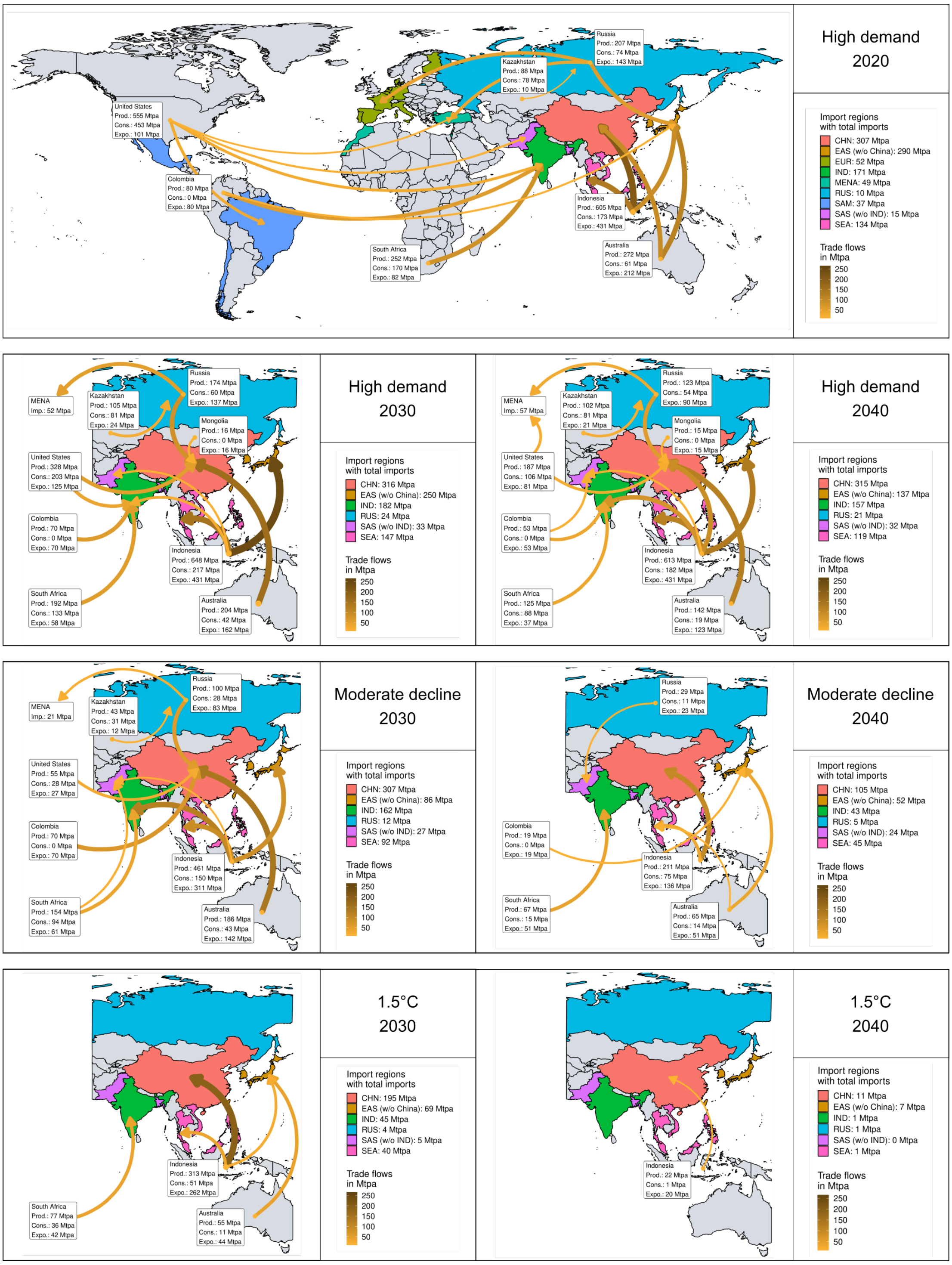


Figure 4.4: Development of major international steam coal trade flows in Asia-Pacific region 2020-2040, in all scenarios.

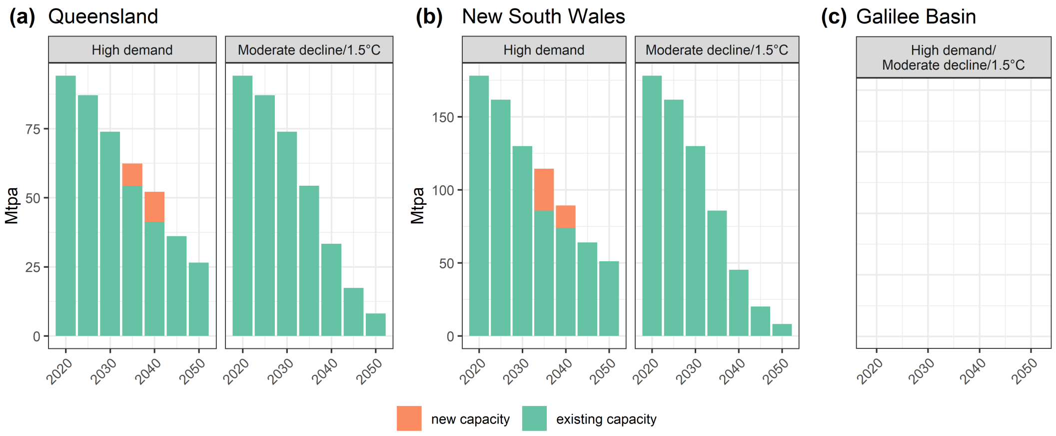


Figure 4.5: Available steam coal production capacity in Australian CMW producer nodes Queensland (a), New South Wales (b), and Galilee Basin (c), in all three scenarios in Mt per year (2020-2050). 'New capacity' denotes capacity addition (in year a) based on investment in previous model period (year $a-1$). 'Existing capacity' denotes remaining capacity from previous model periods.

This is in contrast to a large number of proposed production capacity expansions in Australia. As of October 2021, the coal project pipeline in New South Wales and Queensland (excluding Galilee Basin) contains a total of 16 Mtpa pure steam coal and 22 Mtpa steam and metallurgical brownfield projects, i.e. mine expansions. Additionally a total of 102 Mtpa pure steam coal and 157 Mtpa of steam and metallurgical greenfield projects are proposed in Queensland (excl. Galilee Basin) and New South Wales.[7] The vast majority of these proposed projects are in an early development stage (IEA 2021a, 89).

Furthermore, operating mines in the Hunter Valley - New South Wales' largest coal producing region - are currently operating at less than two thirds (62%) of their approved capacity (Campbell and Carter 2021), potentially offering some further leeway before making investments into new capacities profitable. What is more, remaining lifetime of operating coal mines in Australia as reported in Global Energy Monitor 2021a could be underestimating their potential lifetime as the data is mostly based on the duration of governmental permits for operations. In turn, required investments could be overestimated in these cases.

Obviously, any investments in new mining capacities, including brownfield expansions, further weaken the economic viability of existing operations while being strongly exposed to the risk of asset stranding. This applies to Australia, but largely also to all other world regions. Considering the potential leeway for continued and even additional coal supply

---

[7] Department of Industry, Science, Energy and Resources. 2021. *Resources and Energy Major Projects: 2021.* The Australia Institute. https://www.industry.gov.au/data-and-publications/resources-and-energy-major-projects-2021.

from existing Australian mines, investments into new coal mining capacities appear highly speculative and financially risky. Therefore, in order to avoid an ever growing share of coal capacities at risk of becoming stranded assets, current Australian expansion plans should be revised (cf. SEI et al. 2021). Based on their poor economics, the Galilee Basin projects are the most obvious candidates for early scrapping.

4.3 Conclusions and outlook

In this paper, we assess the economic viability of new coal mining capacities in the Galilee Basin, particularly of the Carmichael project, and more broadly the prospects of new investments in the steam coal sector and Australian coal production. We find that the Carmichael project in Australia's Galilee Basin is not economically viable. Even if already made investments are considered as sunk, profitable long-run operation of the available capacity is highly uncertain. We have shown that, in addition to the poor economics on the supply side, there is no long-run demand for additional coal due to ever more ambitious climate policies in Australia's traditional export markets - Japan, South Korea, and Taiwan - but also beyond, including in Adani's home market India. Also in other Australian coal basins than the Galilee Basin and in other producing countries, there is very limited room for additional investments in coal mining capacities. Ratcheting up of climate policies and regulations in line with decisions at COP26 in Glasgow in 2021 would erase the economic ground for any new coal capacities. With such tight expansion potentials, any new coal capacities will exacerbate the risk of asset stranding in the sector.

The Australian government - just as the governments of other coal exporting countries - has a lesson to learn from the case of the Carmichael project. It shows that coal export projects are everything else than a safe bet and come with a high risk of becoming stranded assets. In the wake of international climate commitments, Australia - and other coal exporters - now have a chance to reduce their fossil resource dependency early enough while they still have income from this sector to support just transition efforts. A decline in coal production will inevitably be associated with a reduction in jobs in Australia (Auger et al. 2021; Pai et al. 2021), but the right measures early on can help to smooth the transition for affected workers and communities (Jakob et al. 2020; Reitzenstein et al. 2022).

The failure of new greenfield projects shows that coal exporting countries only have a small time window left to earn revenues from coal mining. Richter, Mendelevitch, and Jotzo (2018) discussed that an export tax or a production tax in Australia and elsewhere could provide tax revenue while having some attenuating effect on global coal supply and, hence, greenhouse gas emissions. The larger the coalition of coal exporters pursuing such a policy, the more sizeable the climate effect.

There are some limitations to observe with respect to our analysis. First, we focus on the physical assets in the coal sector and we use an equilibrium model setup to assess the risk of asset stranding. However, coal supply assets can also be at risk of financial stranding due to the coal market's price volatility, as observed repeatedly in the past (for example in the USA, c.f. Mendelevitch, Hauenstein, and Holz 2019), including in 2021 in Australia.[8] Second, a major caveat of model-based analyses is the limited quality of available data. With the publication of the 'Global Coal Plant Tracker' (Global Energy Monitor 2021a), openly accessible data on coal mines has been greatly advanced. However, data on the technical lifetime of existing mines is still scarce. Thus, our results for required coal mine replacement investments have to be considered with some care (compare Hauenstein 2022c).

Lastly, the "elephant in the room" is, of course, the question why Adani has moved forward the Carmichael project despite the very high costs and lack of long-term profit prospects. The answer to this question certainly lies in the political economy and also the disconcerting inter-linkage between the coal sector and the political decision-makers in both India and Australia (e.g., Rosewarne 2016). Such political capture of coal projects must be avoided in the future if climate mitigation targets are taken seriously. Transparency on costs, stakeholders and expected externalities is what can help the public to understand the interests and stakes in such a project.

4.4 Experimental procedures

In the first part of this section, we describe the Carmichael project, which we use to characterize coal mining in the Galilee Basin and to derive parameter values for our model. We then describe the global coal sector model COALMOD-World and how the Galilee Basin and related infrastructure are represented in it (Section 4.4.2). The model code used in this analysis is available open at https://github.com/chauenstein/COALMOD-World_v2.0, as well as all data and figure code is provided in Hauenstein, Holz, Rathje, et al. (2022a). Coal production in Australia crucially depends on importing countries in Asia, so we describe coal demand developments in this region in the last part of this section (4.4.3). Based on this information we develop three demand scenarios for our model-based analysis.

---

[8] The Guardian (January 20, 2021): "BHP cuts Mount Arthur coalmine valuation by $1.5bn after thermal coal price plunges"; https://www.theguardian.com/business/2021/jan/20/bhp-cuts-mount-arthur-coalmine-valuation-by-15bn-after-thermal-coal-price-plunges, last accessed April 07, 2022.

4.4.1 The Carmichael mine in the Galilee Basin in Australia

The Galilee Basin is a steam coal basin in central Queensland in Northeastern Australia. The first significant deposits of hard coal were discovered in the 1970s. Due to the basin's relative remoteness and lack of mining infrastructure, more precise assessments of the basin's reserves were conducted only in the 2000s when global coal prices increased and greenfield exploration projects became more popular. To open up the Galilee Basin for coal production, long rail lines across floodplains and farmland have to be built, resulting in comparatively high investment and transportation costs. Additionally, the low availability of water as well as the lack of air and road transportation, power and mining infrastructure require large upfront investments.

In 2010, Adani's Carmichael mine's application process began and since then the project has gone through numerous reviews and project changes. The mine has a predicted lifetime of 60 years and is estimated to produce up to 2.3 billion tonnes of steam coal over its life cycle. It includes up to six open-cut pits, five underground mines, mine processing facilities, and a railway line from the mine to the Abbot Point coal export terminal (Cassotta, Cueva, and Raftopoulos 2021).[9]

The size of the Carmichael project was downsized several times and most drastically in 2018 after the company had failed to attract external funding. The project's investment volume was reduced from A$16.5 billion to A$2 billion (Hepburn, n.d.).[10] These savings were mostly made possible by reducing the mine's initial production capacity from 60 Mtpa to 10 Mtpa with plans to ramp up production capacity later to 27.5 Mtpa later. In addition to the A$2 billion invested by Adani itself, the Carmichael mine benefits from subsidies from the Australian and Queensland governments estimated at A$4.4 billion in total over the 30-year project life time (Buckley 2019). Most subsidies are tax breaks and reduced fees for public services, for example for water rights.

In June 2019, the Carmichael project was granted its final environmental approval. After the announced beginning of the mine's operation had been postponed several times, Adani commenced the construction of the mine in 2019 and produced first coal in early 2022.

Given the possible role model function of the Carmichael mine for other Galilee Basin projects, we base our subsequent analysis on cost estimates and other data for the Carmichael project. Also, we use the characteristics of the Abbot Point Terminal for coal export port

---

[9] Also see Queensland Gov. n.d. „Carmichael Coal Mine and Rail Project - Project overview.“ Accessed June 21, 2021. https://www.statedevelopment.qld.gov.au/coordinator-general/assessments-and-approvals/coordinated-projects/completed-projects/carmichael-coal-mine-and-rail-project

[10] For all calculations we use an exchange rate of 1 A$ = 0.7721 US$ which is a representative average exchange rate for the period 2013-2021 (https://www.macrotrends.net/2551/australian-us-dollar-exchange-rate-historical-chart). It excludes the very high exchange rate period around 2010.

Table 4.1: Characteristics of the Carmichael mine and project, including railway transport and exports.

Parameter	Lower bound	Upper bound
Reserves [Mtpa]	2300	
Energy content [kcal/kg]	4950	
Initial production capacity [Mtpa]	0	
Investment cost for new production capacity [million US$/Mtpa]	106	183
Starting value of marginal cost intercept [US$/t]	24	37
Slope of marginal cost curve [US$/t^2]	0.15	
Initial rail transport capacity [Mtpa]	0	
Investment costs for rail transport capacity [million US$/Mtpa]	31.34	40.34
Railway transport costs [US$/t]	7.87	11.36
Initial export capacity [Mtpa]	25	50
Investment costs for additional export capacity [million US$/Mtpa]	8	82
Port fee [US$/t]	4.6	5

data of the Galilee Basin. Table 4.1 provides the overview of the main parameters for the Carmichael project. We include lower bound and upper bound estimates where there is uncertainty on the parameter values. Details on parameter value derivation and on value ranges can be found in Section A in the Supplementary Material (see Appendix C.1); more background information on the Galilee Basin including Carmichael and other coal mine projects can be found in the Supplementary Material (see Appendix C.1).

Let us highlight a few data points. First, the Carmichael coal has a relatively low average energy content of 4950 kcal/kg (net as received, NAR) (Reddy and Rosencranz 2018). This is 17.5% lower than the standard Australian benchmark coal (exports via the Newcastle port) with an average energy content of 6000 kcal/kg (Australia Institute, n.d.).

Second, there is a considerable spread between the lower bound and the upper bound estimates of investment costs in production capacity (mine) and export capacity (Abbot Point port), and to a lesser extent also in railway transportation capacity. However, these spreads are not due to the potentially diverging nature of the data sources. Rather, this data was taken from different stages of the project planning. Generally, the downsizing of the project over time - only developing the easier accessible parts of the mine, the shorter railway line, the expansion of only the existing export terminal - has led to lower investment costs by Mtpa annual capacity.

Third, there is also much uncertainty on the operational costs, with upper bounds of production (mining) and railway transport costs about 50% higher than the lower bound estimates. The lower bound estimates for combined Galilee Basin operational supply costs

(FOB: production + railway transport + export port fee) are in the same range as the FOB costs of the other Australian suppliers from New South Wales and Queensland, but slightly higher than other suppliers to the Asian market. The more realistic upper bound estimates, however, are more expensive than all other major suppliers to the Asian market.

4.4.2 The COALMOD-World model

COALMOD-World (CMW) is a partial equilibrium model of the world steam coal market (see Hauenstein (2022c) for a detailed description of the model version used here and Holz et al. (2016) for further model background information). The model includes all major steam coal producers, trade routes and consumers. Producers and exporters are represented as profit maximizing players with perfect foresight under specific operational and technical constraints. Consumption nodes are represented via inverse demand functions, based on exogenously derived (scenario-specific) coal demand levels (see 4.4.3 for details). Market clearing conditions endogenously determine regional coal prices. Production and trade volumes, as well as investments in production and transport infrastructure are endogenous model decisions. Investments in additional capacities are made if profitable over the model horizon (net present value optimization). The added capacity becomes available in the subsequent period after the investment decision is made. Production capacities are retired once they reach the end of their technical lifetime, as introduced in Hauenstein (2022c). Producers face specific extraction costs, age structures of their existing mine capacities, remaining coal reserves, coal qualities, and expansion potential per period. In accordance with findings of previous studies (cf. Haftendorn and Holz 2010; Trüby and Paulus 2012) the steam coal market is modelled as perfectly competitive. The model is calibrated for its starting year 2015. The model can be accessed and downloaded via https://github.com/chauenstein/COALMOD-World_v2.0 and all input and result data files, as well as the code to reproduce the figures, are provided in Hauenstein, Holz, Rathje, et al. (2022a).

While the model formulation generally focuses on operational and technical constraints, we include one politically defined constraint on the total amount of Chinese coal imports (for details see Hauenstein (2022c)). Although not officially announced, China *de facto* restricts the amount of coal imported (IEA 2021a; Gosens, Turnbull, and Jotzo 2022). We include an import quota that restricts all international seaborne imports into China to 300 Mt per year. This value is derived from import volumes in recent years and is a rather conservative, large quota compared to results by Gosens, Turnbull, and Jotzo (2022) and recent media announcements[11] suggest even lower quotas in future years.

---

[11] See, for example, Bloomberg News, March 14, 2022: China Seeks to Cut Reliance on Coal Imports With Mining Boom. https://www.bloomberg.com/news/articles/2022-03-14/china-seeks-to-cut-coal-import-reliance-with-mining-boom (visited on 03/29/2022)

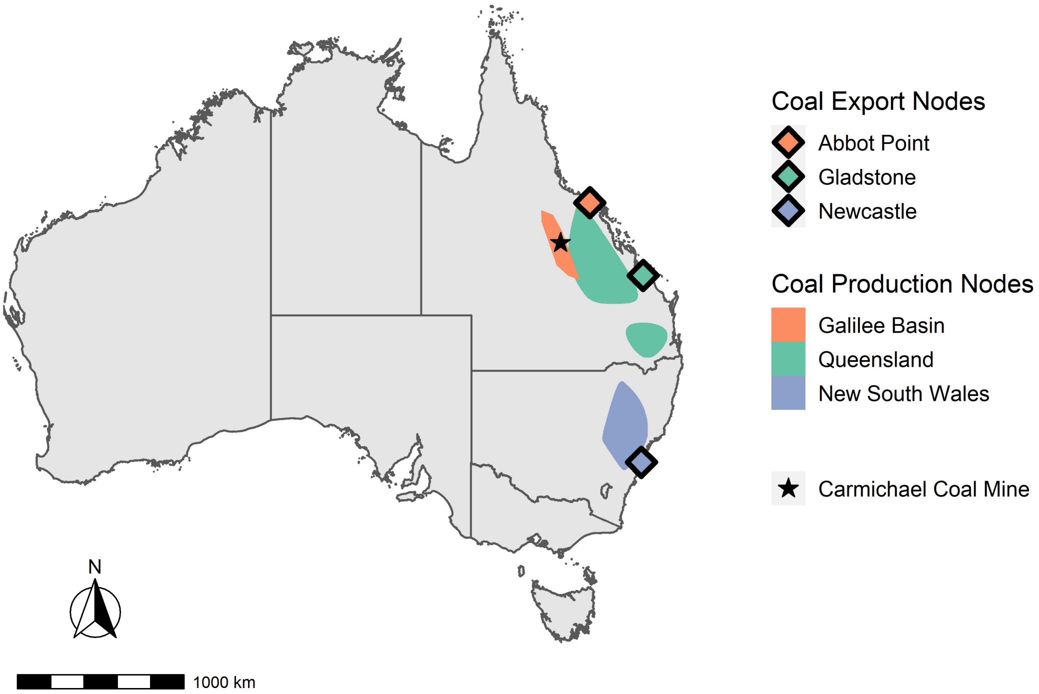


Figure 4.6: Overview of CMW coal production and export nodes in Australia.

The Galilee Basin is introduced as one additional producer node. It is the third producer node in Australia, in addition to New South Wales and (the rest of) Queensland (Figure 4.6). The dedicated export terminal of the Galilee Basin node is Abbot Point. As described in Section 4.4.1, the Galilee Basin producer node is parameterized based on Adani's Carmichael project. In order to analyse the economic viability of the construction and operation of the Galilee Basin, the initial production capacity (in 2015 and 2020) as well as the initial transport capacity are set to 0 Mtpa. This means that investments are required before starting any mining operations. Moreover, where data value ranges were assessed in Section 4.4.1, we use lower end cost estimates and higher end available capacity estimates in order to not underestimate the investment potential in the Galilee Basin.

4.4.3 Coal demand developments and scenarios with a focus on Asia

As the world's second largest steam coal exporter Australia plays a major role for the coal supply in Asia. Japan, China, South Korea, Taiwan and India (in descending order) are the main destinations of Australian coal (Office of the Chief Economist 2021). In 2019, almost 90 % of Australia's steam coal exports were shipped to these countries (IEA 2021e, 2021f).

Table 4.2 gives an overview of steam coal consumption, production and imports from Australia in 2019, as well as of coal and climate policies and targets of main consumers of Australian steam coal. China and India alone account for two thirds of global steam coal consumption, but can supply most of the coal they need through domestic production. Japan, South Korea and Taiwan, in contrast, have no domestic coal reserves and are heavily dependent on imports (IEA 2021f). Large parts of their coal imports have traditionally come from Australia.

Table 4.2: Overview of main Australian coal importing countries and Australia

	AUS	CHN	IND	JPN	KOR	TWN
Steam coal consumption 2019 (Mtpa)[a]	55	3315	866	141	102	59
Steam coal production 2019 (Mtpa)[a]	271	2970	678	1	1	0
Steam coal imports 2019 (Mtpa)[a]	0	232	183	140	102	60
Imports from Australia 2019 (%)[b]	-	38%	2%	57%	31%	40%
Coal phase out/ down schedule[c]	-	peak in 2025	-	-46% (2019-2030)	phase out by 2050	-33% (2019-2025)
Carbon-neutrality target date[d]	2050	2060	2070	2050	2050	2050

[a] IEA 2021f.

[b] Share of Australian coal in total imports of the respective country. Own calculations with data from IEA 2021e and IEA 2021f.

[c] China: Reuters 2021[12]; Japan: own calculations with data from METI 2021, 12 and Argus Media 2021[13]; South Korea: Argus Media 2021[14]; Taiwan: own calculations with data from Bureau of Energy, MOEA 2018, 10.

[d] Australia: Australian Government Department of Industry, Science, Energy and Resources 2021a, 3; China: Chinese Government 2021, 2; India: BBC 2021[15]; Japan: Japanese Government 2021, 1; South Korea: The Government of the Republic of Korea 2020, 7–8; Taiwan: Taiwan News 2021[16].

While coal continues to be a major energy source in many Asian countries, the coal sector has come under increased pressure also in these countries due to cheaper alternative power sources, as well as ratcheted up environmental and climate targets (cf. IEA 2021a; Littlecott et al. 2021; Yanguas Parra, Hauenstein, and Oei 2021). Globally, the coal plant utilization (capacity factor) has declined between 2010 and 2019 from 60 to 51 %. In China, the average capacity factor of coal plants has even fallen below 50 % since 2015. In India, it is still higher but has dropped from 76 % in 2010 to 57 % in 2019 (Jones, Graham, and Tunbridge 2020).

Since a record high number in 2015, commissioning of new coal capacity has recently dropped to a low level not seen since 2005 (Global Energy Monitor et al. 2021, 6). Global coal power capacity under development has declined by about 1,000 GW, or 66 %, between 2015 and 2020, while in the same time around 1,000 GW of planned coal capacity additions were cancelled (Global Energy Monitor et al. 2021, 7). And this trend has continued dynamically in 2021. Around COP26 in late 2021, China, the last major provider of public finance for overseas coal projects, announced an end to this funding, following earlier commitments of Japan and South Korea. This would leave only 22 GW of planned new coal capacities in Asia outside of China and India by end 2021 (not considering projects already under construction), if all formerly Chinese finance backed plans are cancelled. And of these remaining planned 22 GW only a minority has secured financing (Suarez and Gray 2021).

With a slowdown of capacity additions, the coal plant fleet is ageing in most countries. While in China and most South and South-East Asian countries, excluding India, the average age of operating coal units is only around ten to twelve years (as of January 2021), it is 16 years in India and South Korea, and 21-23 years in Japan and Taiwan. Thus, more and more units reach the average retirement age, which is now as low as 22 years in China, but 35 years in other East Asian countries, and 43 years in India (Global Energy Monitor 2021a).

Furthermore, Australia, Japan, South Korea and Taiwan have announced plans to achieve greenhouse gas neutrality by 2050, while China aims for 2060, and India for 2070. However, only South Korea has announced an explicit coal phase-out target (by 2050), while some of the other countries have only set intermediate energy sector targets. Australia and India have not announced any concrete plans to phase out coal combustion. Similarly, despite the high gains in public health, water consumption and other indicators that China could expect from a rapid coal phase-out (He et al. 2020), the largest coal consumer (and producer) so far has only seen vague announcements of peaking coal use and emissions before 2030. A more detailed description of the steam coal demand and the climate policies in these countries is provided in Section B in the Supplementary Material (see Appendix C.1)

Scenario design

Based on the above outlined developments, we design three plausible but diverging global coal demand scenarios which are the aggregate of different national and regional trends (Table 4.3). The *High demand* scenario, with a continued important role for coal in the current policy environment, is contrasted with a *1.5°C* scenario, where coal phase-out is the result of ambitious emission reduction targets. Furthermore, we define the *Moderate decline* scenario as an intermediate coal demand scenario, which is based on limited climate ambitions and an understanding to reduce the role of coal in the long-term, in the spirit of the 2021 Glasgow COP26 climate accord. All scenario input data files are available in Hauenstein, Holz, Rathje, et al. (2022a).

Table 4.3: Scenario overview

<table>
<tr><th><i>High demand</i></th><th><i>Moderate decline</i></th></tr>
<tr><td colspan="2">Asian countries</td></tr>
<tr><td>- Assumed lifetime: 40 years (South Korea: 30 years);</td><td>- Assumed lifetime: 25 years;</td></tr>
<tr><td>- Capacity factors: linear reduction to 50% by 2050 (China: 40%), thereafter constant;</td><td>- Capacity factors: linear reduction to 40% by 2030, thereafter constant;</td></tr>
<tr><td colspan="2">Australia</td></tr>
<tr><td>- Based on AEMO (2020) ISP 2020 Central Scenario;</td><td>- Based on AEMO (2020) ISP 2020 Fast Change Scenario;</td></tr>
<tr><td colspan="2">Rest of the world</td></tr>
<tr><td>- Based on IEA (2020d) WEO 2020 STEPS;</td><td>Based on IEA (2020d) WEO 2020 SDS;</td></tr>
<tr><td colspan="2"><i>1.5°C</i></td></tr>
<tr><td colspan="2">Based on IPCC (2018a) 1.5°C mitigation scenarios analyzed by Yanguas Parra et al. (2019)
- Median unabated coal consumption of 1.5°C scenarios fulfilling additional sustainability criteria (no/limited temperature overshoot; limited BECCS and carbon uptake from AFOLU);</td></tr>
</table>

We design coal demand pathways for each Asian market as part of the global coal demand scenarios (*High demand* and *Moderate decline*) based on the national coal and energy sector specifics, as well as energy and climate policies. Such “bottom-up” scenarios provide more plausible ranges of coal demand developments by considering physical infrastructure constraints and regional, sector specific developments than do aggregated energy system and general equilibrium models (Hauenstein and Holz 2021). A 1.5°C mitigation scenario requires unprecedented changes of the energy sector in many Asian countries (Vinichenko, Cherp, and Jewell 2021), we therefore rely on IPCC (2018a) data for our *1.5°C* scenario. In all scenarios, consumption levels for the year 2020 are based on extrapolated 2015-2019 regional coal demand trends.[17] We, thereby, intend to smooth the short term COVID-19 effect on coal markets in 2020 (IEA 2020c, 2021c).

In the *High demand* and *Moderate decline* scenario we calculate future steam coal generation capacity in Asian countries[18] based on unit-level coal-fired power plant data from the Global Coal Plant Tracker (Global Energy Monitor 2021a). We assume that coal-fired generation units will retire in the announced year, if a shutdown date is available in the data. For all other units that are operating or under construction we assume retirement after 40 years of operation[19] (*High demand*), the conservative benchmark used also by Clark, Zucker, and Urpelainen (2020) and Global Energy Monitor et al. (2021), or after 25 years of operation (*Moderate decline*), based on the low average retirement age of coal plants observed in recent years, in particular in China. We exclude planned power plants that are not yet under construction, assuming that the large majority of these projects will be scrapped before starting production.

For capacity factors of coal power generation, we assume a further reduction based on the falling trend of the last years and depending on climate policy ambitions. In the *High demand* scenario, we use a linear reduction of the current capacity factors to 50 % by 2050[20], remaining constant thereafter. For the *Moderate decline* scenario we assume a significantly faster decline of the capacity factory, which is linearly reduced to 40% in 2030 and then remains at this level until 2050.

Figure 4.7 shows the changes in steam coal demand until 2050 of major importers of Australian steam coal in the different scenarios. The inevitable decline is delayed in China and India due to capacities under construction coming online in the next years and a younger coal plant fleet. In comparison to our *High demand* scenario, the *Moderate decline* and *1.5°C* scenario show a much faster decline in steam coal demand.

---

[17] OECD iLibrary World Energy Statistics: https://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances_enestats-data-en (visited on 03/26/2021).

[18] Asian countries represented in CMW: Bangladesh, China, Indonesia, India, Japan, Malaysia, Pakistan, Philippines, South Korea, Taiwan, Thailand, Vietnam

[19] An exception is South Korea where an average retirement age of 30 years is assumed as this corresponds to the planned operational lifetime in the government's 'Basic Plan for Long-term Electricity Supply and Demand' Y. N. Agency. 2020. „S. Korea unveils draft plan to foster renewable energy.“ Yonhap News Agency. Accessed January 17, 2022. https://en.yna.co.kr/view/AEN20200508002200320.

[20] Except for China where the capacity factor is already below 50 % today and where we assume a linear reduction to 40 % in 2050. For those countries where no current capacity factor is available, a capacity factor of 55% was assumed based on the "Rest of the world" factor from Jones, Graham, and Tunbridge (2020, 11)

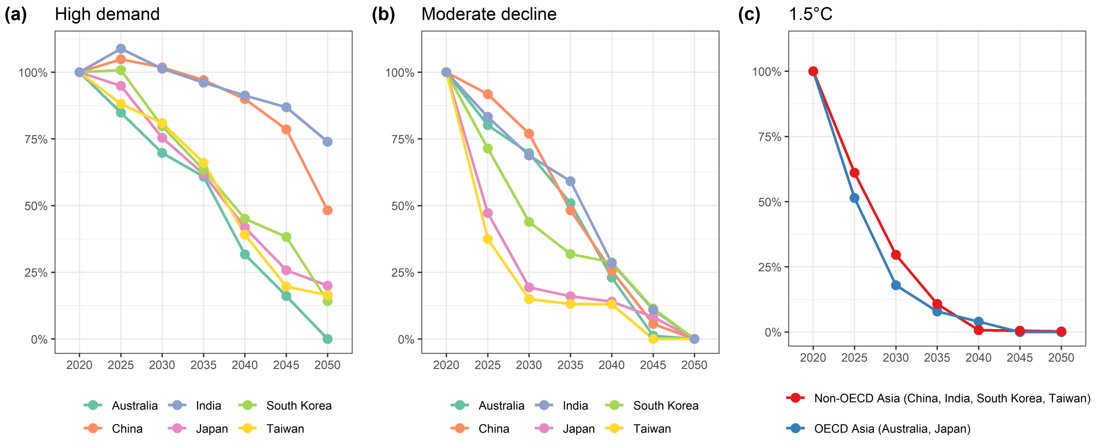


Figure 4.7: Change in steam coal demand [%] in Japan, China, South Korea, Taiwan and India in the *High demand* (a), *Moderate decline* (b) and *1.5°C* scenario (c).

For Australian domestic coal demand we apply scenario data of the 2020 Integrated System Plan (ISP) by AEMO (2020). For the *High demand* we use their "Central Scenario", which predicts a coal demand decrease determined by current policies. As the data in this scenario only go to 2042, we have continued the trend linearly to 2050, whereby Australian coal demand will fall to zero in 2050. For the *Moderate decline* scenario we use their "Fast Change Scenario" which assumes a fast energy transition and both national and international strategies to reduce future CO_2 emissions (AEMO 2020, 32). It predicts an almost linear decline of Australian steam coal demand beginning in 2020 and reaching zero by 2045.

For all other countries, we use steam coal demand trend data of the IEA (2020d) "Stated Policies Scenario" (STEPS) for our *High demand*, and of the "Sustainable Development Scenario" (SDS) for our *Moderate decline* scenario. STEPS is based on current and stated policies and does not aim at meeting climate targets. It anticipates a rapid recovery from the COVID-19 pandemic and expects GDP after 2021 to be as high as before the pandemic. The share of renewable energies is assumed to grow but coal will still account for about 30 % of global power supply in 2040 (IEA 2020d, 342). The SDS, in contrast, foresees a more sustainable recovery from the pandemic. It projects a significant increase in renewable energy investment over the next decade, with coal accounting for about 8 % of global power supply in 2040 (IEA 2020d, 343).

We also design a climate policy scenario with an effective coal exit, the *1.5°C* scenario. It is based on the IPCC (2018a) special report on 1.5°C scenarios. Yanguas Parra et al. (2019) selected those 1.5°C scenarios that also fulfil other sustainability criteria such as reasonably limited use of biomass with CCS (BECCS) and limited carbon uptake from afforestation or land use. For each model year (i.e. 2025, 2030, 2035, and so on), we take the regional growth rates of the median global coal consumption of these selected scenarios.

Chapter 5

The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?

This chapter is based on joint work with Roman Mendelevitch, and Franziska Holz published in *Climate Policy* 19 (10): 1310–24 under the title: "The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?". DOI: 10.1080/14693062.2019.1641462; published open access under CC BY NC ND 4.0.

5.1 Introduction

The U.S. under former President Obama (2008-2016) showed great ambitions to take a leading role in climate policy, in particular, through the Climate Action Plan. Things changed dramatically with the inauguration of President Trump in January 2017. He made clear that climate change would no longer be an issue of high priority for the U.S. government (The White House 2017). Trump's executive orders revoked and rescinded a number of 'Energy and Climate-Related Presidential and Regulatory Actions' and determine that 'All [Environmental Protection] Agency Actions that Potentially Burden the Safe, Efficient Development of Domestic Energy Resources [like coal]' shall be reviewed (Trump 2017). President Trump has indeed aggressively rolled back environmental regulation and commitments, with a complete re-organisation of the environmental administration and, most prominently, by announcing to leave the Paris Agreement and replacing the Clean Power Plan with the Affordable Clean Energy rule (EPA 2018). One of his declared primary goals during the election campaign, but also in his presidency, is to 'End the War on Coal!' and to revitalize the coal sector (Davenport 2016). This alludes to the strong role that the U.S. coal sector used to play in the past and its enormous and fast decline in the last decade, amounting to -35 % in only ten years between 2008 and 2018.

The Trump administration's efforts to support coal are manifold and extend to a broad range of policy areas. Under the Obama and other previous administrations, energy and environmental policy were used as intermediaries to address climate change, given the lack of consensus at a federal level on climate policy. However, Trump actually uses energy and environmental policy to address his industrial policy targets -which may have strong implications for climate policy. While supporting domestic coal-fired power generation is the most obvious form of support, and was the first to be announced after Trump's election, another focus has been on relieving pressure on mining and, more recently, on expanding access to the international market for U.S. coal. The drastic change in U.S. climate policy under President Trump has sparked research on possible global effects on emission reduction efforts. Jotzo, Depledge, and Winkler (2018) provide a first overview of the emerging literature.

According to Höhne et al. (2017) changes of environmental regulations under the Trump administration, without compensation by other actors, are likely to cause U.S. emissions to flatten instead of continuing to decline, in the short term. However, they argue that, from a 2030 perspective, the policy rollbacks are not likely to have a major impact. Similarly, Urpelainen and Van de Graaf (2018) argue that Trump's policy interventions will not reverse trends in U.S. greenhouse gas emissions. Somewhat in contrast, Erickson and Lazarus (2018) note that ending the Obama administration's moratorium on fossil fuel extraction from U.S. federal land – as done by the Trump administration – may lead to foregoing emission savings of up to 280 Mt CO_2 annually by 2030. Undertaking a rough sector-by-sector assessment, Galik, DeCarolis, and Fell (2017) conclude that the effect of Trump's policies will at most be a flattening of U.S. CO_2 emissions at 2015 levels. Depending on the number of his terms, they estimate a total increase in emissions of 12 $GtCO_2e$ to 20 $GtCO_2e$ until 2050. Taking a global perspective, Selby (2018) emphasises the negative effect on the global energy transition.

While all these studies highlight the decisive role of coal in the energy mix to assess future emission profiles, they lack a detailed analysis of the current and future drivers in the U.S. energy sector. Moreover, they fail to analyse the role of the U.S. as a major coal producer and supplier on the international steam coal market.[1] In sum, it remains unclear from the literature, if the policy rollback or newly introduced policies can slow down the decline of the U.S. coal industry or even turn the tide.

Our paper tries to fill that gap. Thus our research addressed the question of whether Trump's policies can effectively reverse the death spiral (i.e. strong decline of U.S. coal production since 2008) of the U.S. coal industry. For this, we take into account domestic and global coal sector inter-relations. We assess the role of previously tightened environmental regulation compared to cheap alternative electricity generation (gas, renewables) and the age structure of the US coal-fired generation fleet. We then detail current policy measures intended to support the U.S. coal sector. We develop several scenarios around the main policy measures in order to quantify their effects on U.S. coal production and exports using the COALMOD-World model.

5.2 Political support for the U.S. coal sector under Trump

In this section, we give an overview of recent developments in coal consumption and production in the U.S. Subsequently, we derive main domestic policy drivers that may influence future U.S. coal production. Finally, we focus on three more concrete policy measures regarding coal, which are in place or proposed by the Trump administration as a basis for our scenarios in the subsequent sections. In our scenario analysis, we aim at quantifying potential effects and interdependencies. Therefore, we deliberately abstract from the underlying

---

[1] The U.S. has been the second largest coal producer worldwide for a long time, accounting for approximately 10 % of global coal production (IEA 2018). India surpassed U.S. coal production for the first time in 2016. The U.S. is a net exporter of coal, for both steam and metallurgical coal. Due to its relatively high prices, the U.S. is considered a swing supplier for international met and steam coal markets (IEA/OECD 2017a).

policy process and possible entry points to postpone or prevent policy implementation, as this is not in the focus of the paper.

5.2.1 The Death Spiral: Development of the U.S. coal sector in the last decade

In the past decades, the coal sector has been a central element of U.S. power generation as well as of the U.S. mining sector. In this section, we want to highlight the recent developments of the sector, both in terms of coal use (consumption) and in terms of coal mining (production).

U.S. domestic coal consumption and production peaked in 2007 / 2008 at around 1.0 -1.1 billion tons.[2] Thereafter, a steep decline set in, with consumption dropping to 650 million tons per year (Mtpa) in 2017, the lowest value since 1982. Production declined to 660 Mtpa in 2016, recovering slightly in 2017 to 700 Mtpa (see Figure S1 in the Supplementary Material (AppendixD.1)).[3] U.S. coal exports during this period were between 55 and 115 million tons per year, with a relatively stable share of metallurgical coal at around 60 %.[4]

Many studies have analysed the decline of the U.S. coal sector (e.g., Coglianese, T. Gerarden, and Stock 2017; Culver and Hong 2016; Houser, Bordoff, and Marsters 2017; Kok 2017; Schlissel, Sanzillo, and Feaster 2018; Sussams and Grant 2015; DoE 2017). Overall, the explanations can be divided into two categories. The first focuses on domestic demand, especially the demand for steam coal in the electricity sector. The second looks at U.S. coal production, which largely depends on domestic demand, but is also subject to global demand and other factors such as mining regulation.

5.2.1.1 Demand side: Coal-fired power generation in the U.S.

Approximately 93 % of domestic coal consumption, relatively constant over the last ten years, goes to the U.S. electricity sector, while the remaining 7 % is used by industry, mainly as metallurgical coal. Between 2007 and 2017, U.S. electricity generation from coal declined by about 40 %.[5] Total coal-fired electric generation capacity peaked in 2011 with about 318 GW, and then declined to about 257 GW in 2017.[6]

---

[2] Figures in coal tonnage are given in metric tons. Short tons are converted using the EIA conversion factor 0.907184.

[3] EIA energy data browser: https://www.eia.gov/totalenergy/data/browser/, last accessed January 26, 2019.

[4] EIA coal data browser: https://www.eia.gov/coal/data/browser/, last accessed: July 3rd, 2018.

[5] EIA coal data browser: https://www.eia.gov/coal/data/browser/, last accessed: July 3rd, 2018.

[6] EIA electricity data: https://www.eia.gov/electricity/, last accessed January 31, 2019.

There is a broad consensus that the drop in U.S. natural gas prices is the main driver behind this decline. The so-called shale gas revolution, which started around 2007, increased U.S. natural gas production by about 45 % between 2007 and 2017 and led to a dramatic decrease in the natural gas price.[7] Thus, natural gas has outcompeted coal as a cheap fuel source for electricity generation in many regions of the U.S.,[8] with the share of electricity generation from natural gas increasing from 22 % in 2007 to 32 % in 2017 (see Figure S1 in the Supplementary Material (AppendixD.1)).

In the same period, the share of electricity generation from renewables (without hydropower) increased from 2.5 % to 10 %. Average levelized cost of electricity from (unsubsidized) wind and solar PV declined by 67 % and 86 %, respectively, between 2009 and 2017 (Lazard 2017, 10). Additionally, federal tax incentives for renewables (the Production Tax Credit) and state renewable portfolio standards supported the expansion of wind and solar power generation in addition to improved efficiencies and capacity factors of wind turbines and solar PV modules (Schlissel, Sanzillo, and Feaster 2018). At the same time, U.S. final electricity demand has stayed flat since 2007.[9] Thus, coal-fired electricity generation not only lost relative market share, but also in absolute terms.

Besides competition from cheap natural gas and renewables, environmental regulations for coal-fired power plants were tightened in the past decade (see Table S1 in the Supplementary Material (AppendixD.1) for an overview). The Obama administration promulgated nine regulations directly addressing coal-fired power generation. Opinions diverge on the actual effects of the environmental regulations on coal-fired power generation. Out of the nine Obama-era regulations, only four took effect before 2016. Coglianese, T. Gerarden, and Stock (2017, 2–3) and Houser, Bordoff, and Marsters (2017, 22) both estimate that environmental regulations (mainly the Cross-State Air Pollution Rule (CSAPR) and the new Mercury and Air Toxic Standards (MATS)) were responsible for approximately 10 % of the decline in coal mining output between 2008 and 2016. In contrast, Culver and Hong (2016) argue that the decline of U.S. coal between 2008 and 2015 had little to do with environmental regulation due to relatively low costs of compliance, but was rather caused by the fierce competition with natural gas noted above.

Another key factor for the decline is the composition of the U.S. coal-fired generation fleet. With its high share of small and very old units, it has been particularly vulnerable to price

---

[7] EIA natural gas data: https://www.eia.gov/naturalgas/data.php, last accessed: January 26, 2019.

[8] EIA monthly data on U.S. natural gas electric power price: https://www.eia.gov/dnav/ng/hist/n3045us3M.htm, last accessed July 5th, 2018. Prices of coal and gas for power plants differ by region. Coal from Appalachian mines is the most expensive, followed by coal from the Interior Basin and the Rockies. Coal from Powder River Basin has the lowest price and was competitive with natural gas most of the time between 2012 and January 2016 with gas (Culver and Hong 2016).

[9] EIA energy data browser: https://www.eia.gov/totalenergy/data/browser/, last accessed January 26, 2019.

and cost pressure (DoE 2017). As of April 2018, the capacity-weighted average age of operating coal-fired units was 39.7 years and the average capacity of the operating units was only 323 MW.[10] About 88 % of coal-fired capacity was built before 1990 and 52 % of currently operating capacity is older than 40 years, with 14 % even older than 50 years. Figure 5.1 shows the average age and size of retired coal units. Until 2017, retired units were on average significantly older and smaller than the units of the remaining fleet. Usually, they were not equipped with significant sulfur dioxide (SO_2) control installations (DoE 2017). However, since early 2018 larger and younger, more efficient and largely regulation-compliant units have also been retired.

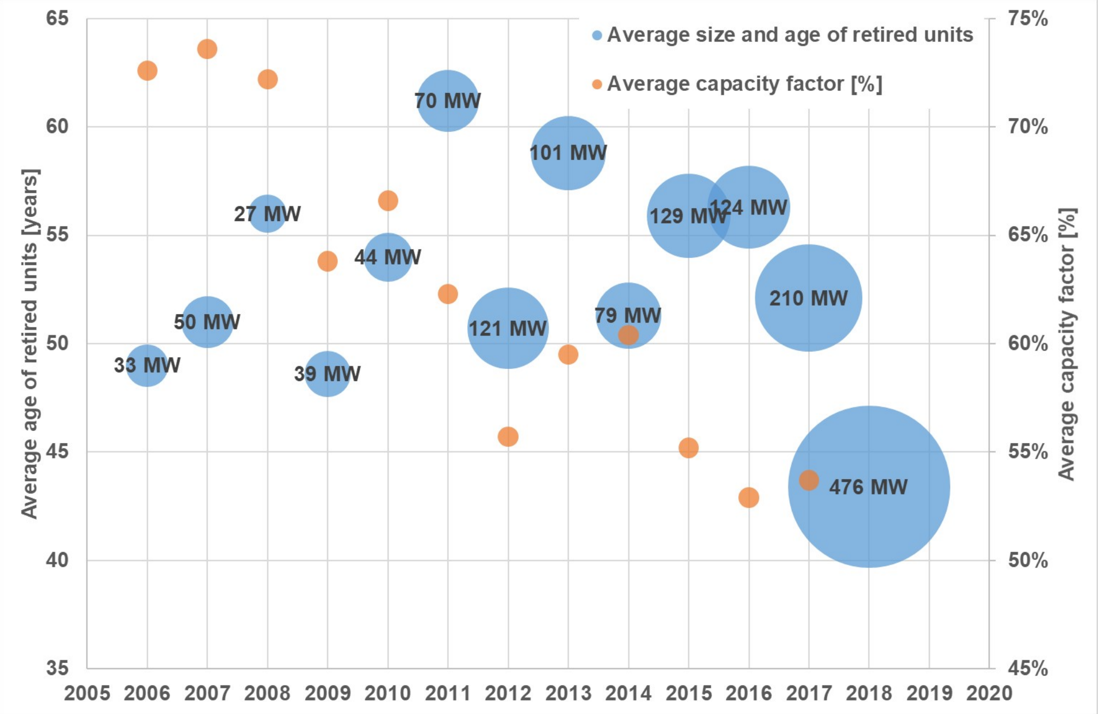


Figure 5.1: Average age and size of retired coal-fired power generation units since 2012 (net summer capacity; all sectors; utility scale); and average capacity factor of the U.S. coal-fired power generation fleet 2006-2017 (all sectors, utility scale facilities).

Source: own calculations based on EIA data (https://www.eia.gov/electricity/data/eia860M/ and https://www.eia.gov/electricity/annual/, last accessed January 15, 2019).

---

[10] Based on net summer capacity. Includes coal-fired power plants in the sectors electric utilities, independent power producers, commercial and industrial combined heat and power (CHP). Source: EIA 2018, *Preliminary Monthly Electric Generator Inventory*. https://www.eia.gov/electricity/data/eia860m/, last accessed December 20, 2018.

According to Shearer et al. (2018, 14) there are no new coal-fired power plants planned or currently under construction in the U.S., while the EIA lists two power plants that are supposed to come online in 2020 and 2022, respectively. The currently applicable 'new source performance' emission standard of no more than 1,400 lb (635 kg) CO_2/MWh would effectively require the use of carbon capture, transport, and storage (CCTS) at these units.[11] This also applies for major refurbishments or modifications of existing units that trigger New Source Review (NSR)[12], which are therefore not very likely to happen. Rather, more coal-fired power plants are expected to retire over the next years. Feaster (2018) estimates that (at least) 36.7 GW will be retired between 2018 and 2024. Rhodium Group even expects the retirement of 60 to 86 GW of net summer coal capacity by 2025 compared to 2018 (John 2018).

This data clearly shows that the current U.S. coal-fired generation fleet will not sustain electricity production at current levels in the medium-term without substantial refurbishment and investments. Tightened environmental regulation has only exacerbated a competitive situation, which was gloomy before. Therefore, one must expect a further decrease of U.S. coal consumption.

5.2.1.2 Supply side: U.S. coal production

U.S. coal is extracted primarily from three large regions: the Appalachian region near the Atlantic Coast, the Interior Region, extending from Lake Michigan to Texas, and the Western Region with the Powder River Basin (PRB) and the Rocky Mountains as main coal basins (Figure 5.2).[13] As coal extracted in the U.S. goes in large part to the domestic power sector, the decrease in domestic coal use has also led to a decline in U.S. coal production.

Some U.S. steam and metallurgical coal is exported. The size of these exports has varied in the past decades, mostly driven by global coal prices and demand. U.S. coal producers generally act as swing suppliers for the international coal market, strongly following the fluctuations in international coal prices with the size of their supplies to the market. Exports were in the range of 4 % to 13 % of U.S. coal production (54 Mt -114 Mt) in the period 2006 to 2017.[14] About 50 % to 70 % of U.S. coal exports are metallurgical coal. Due to their geographic location, the coal regions are differently connected to export ports: While

---

[11] See Supplementary Material (AppendixD.1) for more details on this and other regulations.

[12] The New Source Review (NSR) is a permitting process under the Clean Air Act. It is triggered if new polluting facilities are built or existing ones are modified in such a way that emissions increase. These facilities have to fulfill state-of-the-art emission standards, even if the pre-modification facility was exempt from those standards. See also EPA *Permitting Under the Clean Air Act*: https://www.epa.gov/caa-permitting, last accessed July 2, 2019.

[13] A large share of the coal production in the Northern Great Plains basin, is lignite (except for PRB), which is locally consumed (“mine-mouth”) and therefore not in the focus of this analysis.

[14] EIA coal data browser: https://www.eia.gov/coal/data/browser/, last accessed: July 3rd, 2018.

coal from the Appalachian region and the Interior Basin can be shipped to the export terminals on the Atlantic Coast as well as the Gulf of Mexico, these terminals are too expensive to be reached by the Western Region and PRB coal. Some PRB coal is exported via the Canadian province of British Columbia and some small quantities via terminals in California.

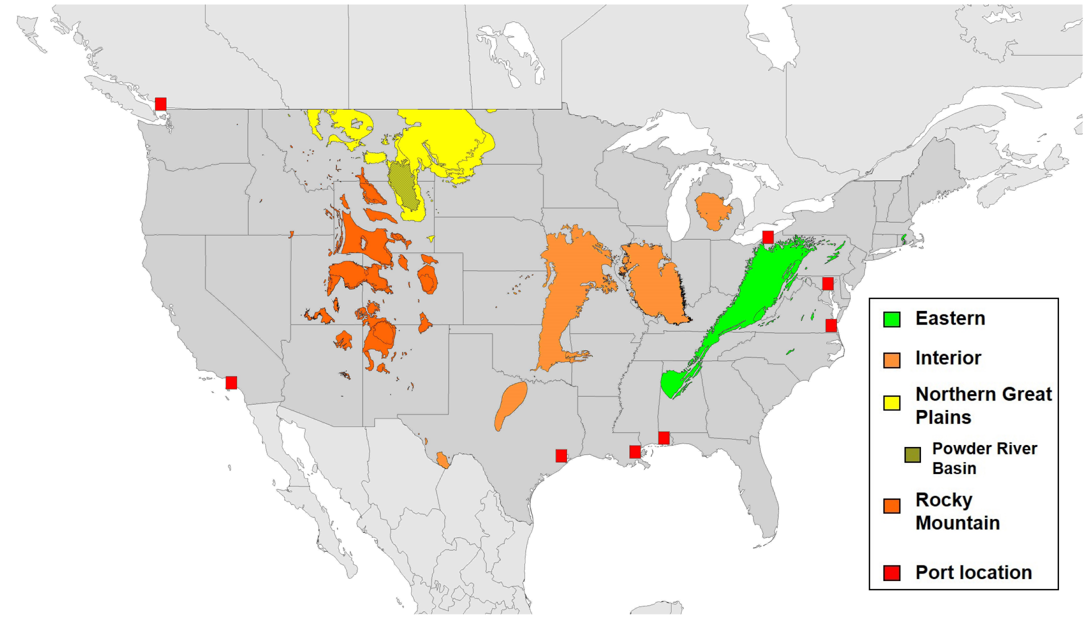


Figure 5.2: Main U.S. coal extraction regions and port locations.

Source: Own depiction based on U.S. Geological Survey data, available at https://pubs.usgs.gov/of/2012/1205/, last accessed January 18, 2019.

After 2008, global coal prices were rising and Asian demand was expected to grow continuously. Between 2008 and 2011, U.S. coal companies invested heavily in coal assets domestically and abroad to meet forecasted international coal demand. However, global demand peaked in 2013/2014 and the situation of U.S. coal producers completely turned. The combined market capitalization of the four leading coal companies in the U.S. (Alpha Natural Resources, Arch Coal, Peabody Energy, and Walter Energy) dropped from $44.6 *billion* in 2011 to just $45 *million* in 2016.[15] These companies had borrowed large sums for the acquisition of assets to meet the expected Asian demand growth. By 2015, debts exceeded their market capitalization by far. These four big -as well as many smaller -U.S. coal producers therefore had to file for bankruptcy around 2015/16. These bankruptcies and the market adjustments in the coal-mining sector of course had a sizeable impact on

---

[15] Statista (2018) Statista Dossier Coal. https://www.statista.com/study/11644/coal-statista-dossier/, p. 32, last accessed December 20, 2018.

employment. The total number of coal mine employees in the U.S. dropped from 92,000 in 2011 to 52,000 in 2016.[16] Jobs in the Appalachian region were especially affected, with about 50 % of the 60,000 jobs in 2011 vanishing by 2016. During the same period, coal mine productivity in the Appalachian region increased by on average 13 %, yet remaining at about 10 % of levels in the PRB.[17]

In 2017, after large write-offs of liabilities, Peabody Energy, Arch Coal and Alpha Natural Resources, as well as several smaller-size coal companies, emerged from bankruptcy. However, the situation for the U.S. coal sector remains difficult and expectations for a recovery of the coal sector have been low. Indeed, bankruptcies of U.S. coal companies have continued in recent years, now mostly by companies that serve the domestic market.

5.2.2 Rescinding the Obama administration's national coal policies

Promising relief, the Trump administration tries to support the U.S. coal sector both on the demand (i.e. in the electricity sector) and supply sides (i.e. coal mining). Here, we briefly discuss the individual measures. For a more detailed overview of the relevant policies and their status under the Obama and the Trump administration and associated references, see Supplementary Material (AppendixD.1).

For the U.S. electricity sector, the Environmental Protection Agency (EPA) was ordered to review the Clean Power Plan (CPP). The CPP was enacted by the Obama Administration in 2015 and was originally scheduled to come into effect in 2022. It set limits on CO_2 emissions from (existing) power plants by defining nationwide emissions performance standards. To replace the CPP, the EPA proposed the so-called Affordable Clean Energy rule (ACE) (EPA 2018). On 19 June 2019, the final ACE was issued by the EPA and thereby the CPP was finally repealed (EPA 2019a). In contrast to the CPP, the ACE only addresses coal-fired power plants and leaves it to the states to set their individual standards. Moreover, in the ACE proposal, the EPA proposed an update of the NSR, such that the requirement to apply for approval for major modifications of power plants, and hence the requirement to update emission control technologies, would be softened (EPA 2018). This reform of the NSR is not part of the issued ACE but is supposed to be implemented with a separate final action (EPA 2019b, 5).

---

[16] EIA Coal Data Browser: https://www.eia.gov/coal/data/browser/, last accessed January 31, 2019. Coal mining employment has been on the decline for decades: from a peak of more than 800,000 in the 1920s to 130,000 in 2011 (including contractors; Houser, Bordoff, and Marsters 2017, 5).

[17] EIA Coal Data Browser –Aggregate coal mine productivity: https://www.eia.gov/coal/data/browser/#/topic/37, last accessed 04/26/2019.

Moreover, conventional power generators continue to lobby for financial support from the Trump administration, which has been very responsive. For example, in 2017, the Department of Energy requested that the profits of new and existing coal-fired (and nuclear) power plants should be guaranteed by the Federal Energy Regulatory Commission (FERC). Moreover, the Trump administration is contemplating using emergency powers to subsidize coal-fired power plants. Grid operators could be ordered to buy electricity from coal and nuclear power plants to prevent these from shutting down. So far, the FERC has denied these requests.

On the supply side, the Trump administration has enacted several law changes to support coal. Most prominently, Trump lifted the moratorium on new coal mine leases on federal land, which his predecessor had introduced in 2016, and reduced the size of two national monuments in Utah. Further, the Valuation Rule (of exported coal) of the former Obama administration was rescinded by the Department of Interior in August 2017. This rule was supposed to close a loophole that allowed coal exports without paying royalties to the federal government. Additionally, the Royalty Policy Committee, an Interior Department advisory panel, proposed to reduce royalties to be paid by companies extracting coal, oil and gas from federal lands and U.S. waters. The Obama-era environmental regulations Stream Protection Rule and Resource Management Planning, both affecting mining activities, were repealed in the first months of 2017.

5.2.3 CCTS: The Silver Bullet?

carbon capture, transport, and storage (CCTS; often also carbon capture and storage, CCS) is seen by many as a necessary measure to keep global warming below 2°C (Haszeldine et al. 2018). Many also see it as an opportunity to continue the use of coal for power generation (IEA/OECD 2017a). However, the expected rate of technological and economic progress of CCTS and the implementation of large-scale CCTS projects has not, so far, been achieved, neither for coal-fired power plants with CCTS, nor for CCTS in other sectors (Hirschhausen, Herold, and Oei 2012; Mendelevitch et al. 2018; Schlissel and Wamsted 2018). Costs of new as well as retrofitted CCTS-equipped coal-fired power generation units are currently prohibitively high compared to new gas-fired power plants and renewables, and expectations for cost reductions of CCTS technology are low (Schlissel and Wamsted 2018; EIA 2018b). In the U.S., CCTS is currently largely supported by the oil industry, which participates in the CCTS value chain as CO_2 user for Enhanced Oil Recovery (Doukas, Redman, and Kretzmann 2017).

President Trump is eager to support 'clean coal'.[18] However, he has not distinguished himself as a bold CCTS supporter so far. Still, with the Bipartisan Budget Act of 2018, support for CCTS projects was increased by providing substantial tax credits for such projects.[19] This reformed tax incentive could spur further development and application of CCTS, also in the power generation sector. However, the increase of support remains low compared to current cost estimates and it is therefore questionable whether a significant number of new or retrofitted coal-fired power plants with CCTS will be in place in the near term (Bennett and Stanley 2018). Moreover, governmental funding for CCTS research and development has been significantly reduced at the same time.

5.2.4 Exports via the U.S. West Coast

In the context of declining domestic demand and rising world market prices, U.S. coal producers were eager to find new outlets on the international coal market, especially in Asia (Cornot-Gandolphe 2015; IEA 2013; Houser, Bordoff, and Marsters 2017). However, export infrastructure is key to this issue. Currently, the only way to export U.S. coal from the West Coast is via small capacities in California (total of 6 Mtpa in three ports) and Canadian ports in British Colombia. Exporting via British Columbia requires long distance rail transport which is used at full capacity (Power and Power 2013). Thus, in the wake of the strong increase in Asian and world coal demand in the 2000s, plans were made to construct export terminals along the U.S. West Coast, in California, Oregon and Washington. Table S2 in the Supplementary Material (AppendixD.1) details the existing and proposed export terminals along the U.S. American and Canadian West Coast; more recently, alternative options such as exporting via Mexico's Pacific Coast are also being discussed. The Trump administration has started to show some interest in the topic with a request for 'a white paper assessing opportunities to advance U.S. coal exports' by the Secretary of Energy (NCC 2018, IX).

There have been extensive local concerns about public health, environmental impacts and consequences for global CO2 emissions associated with new export infrastructure (Western Interstate Energy Board 2012). With lower global coal prices after 2013, exporting PRB coal via new West Coast ports somewhat lost its attractiveness. By 2017, all proposed terminals except two were shelved and did not proceed further due to denied (environmental) permits or because the proponents themselves abandoned the projects. The two remaining planned terminals are the Millenium Bulk Terminal (40 Mtpa) and the Oakland Bulk and

---

[18] Bade, Gavin (31.01.2018), *Trump touts end of 'war on beautiful, clean coal' in State of the Union.* https://www.utilitydive.com/news/trump-touts-end-of-war-on-beautiful-clean-coal-in-state-of-the-union/516000/, last accessed August 17, 2018.

[19] See Supplementary Material (AppendixD.1) for more details on this and other regulations.

Oversized Terminal (4.5 Mtpa), which are still undergoing court challenges, but are equally unlikely to be realized. Indeed, these terminal projects have not received explicit support by the Trump administration (Volcovici 2018).

Given the effective opposition to commercial ('civilian') export terminal projects, the Trump administration, in particular the Secretary of the Interior, suggests using military bases for coal exports instead, or at least consider the construction of such terminals on federal lands.[20] However, given modest global coal prices and ample supplies from other world regions, in addition to large (idle) port capacities in other U.S. regions (coal ports at the Atlantic Coast and the Gulf of Mexico were running at average utilization rates of only 24 % in 2016 (IEA/OECD 2017a, 129), it appears unlikely that these ideas will be realized.

5.3 Modelling U.S. and global coal markets with the COALMOD-World model

We use the COALMOD-World model to assess the implications of the different scenarios (detailed below) on U.S. and international steam coal markets (see Holz et al. (2016) for a detailed description of the model). COALMOD-World is a comprehensive partial equilibrium model of the world steam coal market that features profit-maximizing producers and exporters supplying to a competitive global market. It assesses effects on global steam coal trade, prices, and investments in mines and infrastructure. The model has been used to assess climate policy implications in various contexts (cf. Haftendorn, Kemfert, and Holz 2012; Holz et al. 2018; Mendelevitch 2018; Richter, Mendelevitch, and Jotzo 2018).

In the COALMOD-World model, we differentiate between different producing and consuming regions and take into account distance-related transportation costs, in addition to region-specific production and investment costs of coal mining. For the U.S., we distinguish the three main geographical mining regions as four separate model nodes (PRB, Rocky Mountains, Appalachia, and Interior Basin). On the consumption side, we differentiate between consumption nodes at the country and regional level depending on their individual levels of coal demand and their paces of coal demand adjustment. We divide the U.S. coal market into five regional nodes: USA-West, USA-North-Central, USA-South-Central, USA-Southeast, and USA-Northeast (Holz et al. 2016).

---

[20] https://apnews.com/573a19c3d43643e5b2d961b46cd99c67, last accessed August 3, 2018.

5.3.1 Policy scenarios and data

In Section 5.2 above, we detail a number of current and potential future policy measures supposedly targeted at revitalizing the U.S. coal sector. Focussing on the effects of the CPP, possible West Coast exports, and support for CCTS, we develop six policy scenarios, which we apply in either a *moderate* or an *ambitious climate policy* pathway (see Table 5.1).

The *moderate climate policy* pathway sees the global community taking some limited action against climate change at the ambition level of the current nationally determined contributions (NDCs). However, this sets the world on course for a rise in global mean temperature by some 3.2°C (2.6 -4.0°C) above pre-industrial levels by the end of this century (Fekete et al. 2017, 1). Global consumption of steam coal continues at a relatively high level and decreases only little below current consumption levels by 2050. We do not assume any large-scale application of CCTS under the *moderate climate policy* pathway, because the motivation to deploy this costly technology is insufficient if no strong, binding climate targets exist (Budinis et al. 2018; Haszeldine et al. 2018).

The *ambitious climate policy* pathway implies a drastic reduction of GHG emissions from fossil fuel consumption to limit global warming to 2°C by 2100. The U.S., possibly under a new administration, returns to an active mitigation strategy. Global steam coal consumption is reduced significantly by 2050. We derive growth rates of steam coal consumption, including in the U.S., from the 450ppm scenario of IEA's WEO 2016, which is in line with the 2°C target and includes a significant amount of coal-fired power generation capacity equipped with CCTS technology by 2040 (260 GW, see IEA/OECD 2016b, 208). We use this data to assess the effect of increased support and availability of CCTS on the coal supply.

The first three scenarios (*Rollback*, *CPP*, *Rollback_ports*) fall under the *moderate climate policy* pathway. For all scenarios in this pathway, we use U.S. coal consumption forecasts from AEO 2018 (EIA 2018a) which are rather high given the power plant fleet's vintage structure and current energy economic trends (see Section 5.2). However, they provide a good representation of the views of the Trump administration regarding future U.S. energy sector developments, which are in the focus of our analysis.

The scenario *Rollback* represents U.S. domestic coal consumption induced by new, lax environmental policy under Trump. More concretely, this scenario assumes that the CPP is cancelled, resulting in retrofitting investments and live-time extensions for existing coal power plants and consequently increasing domestic coal demand in the U.S. We contrast this situation to the scenario *CPP*, where the CPP is assumed to remain in place. The scenario *Rollback_ports* assumes that, in addition to measures from the scenario *Rollback*,

Table 5.1: Scenario overview.

Pathway (global dimension)	Scenario	Clean Power Plan	West Coast ports	CCTS	2°C target
Moderate climate policy	*Rollback**	-	-	-	-
	*CPP***	+	-	-	-
	*Rollback_ports****	-	+	-	-
Ambitious climate policy	*2°C_CCTS*****	+	-	+	+
	*2°C_no-CCTS******	+	-	-	+
	2°C_CCTS_ports	+	+	+	+

*Rollback: assumes growth rate for coal consumption based on IEA WEO 2017 NPS (IEA/OECD 2017b); for U.S.: reference consumption from AEO 2018 (EIA 2018a), this reflects the current legal situation as of 2017 without CPP measures.
**CPP: assumes growth rate for coal consumption based on IEA WEO 2017 NPS (IEA/OECD 2017b); for U.S.: CPP consumption from AEO 2018 (EIA 2018a).
***ports: assumes possibility to expand western port export capacity by 50 Mt each 5 years from 2020 onwards.
****2°C_CCTS: assumes growth rate for coal consumption based on IEA WEO 2016 450 ppm scenario (IEA/OECD 2016b).
*****2°C_no-CCTS: assumes growth rate for coal consumption based on IEA WEO 2016 450 ppm without coal consumed by coal-fired power generation capacities equipped with CCTS. (see Box 1 in the Supplementary Material (Appendix D.1) for details).

the Trump administration manages to extend support for the U.S. coal sector by pushing through West Coast coal export ports against massive opposition.

The *ambitious climate policy* pathway includes the scenarios *2°C_CCTS*, *2°C_no-CCTS*, and *2°C_CCTS_ports*. The scenario *2°C_CCTS* assumes that the increased support for CCTS under Trump and possible further support make CCTS available as a mitigation option for coal-fired power stations in the long run. Thus, steam coal consumption does not have to be phased out entirely by 2050, while the 2°C climate target is still achieved. The scenario *2°C_no-CCTS*, in contrast, assumes that CCTS will not be an economically viable option for coal-fired power plants until 2050. Hence, to achieve the 2°C target, coal consumption has to decline even further. The scenario *2°C_CCTS_ports* extends the *2°C_CCTS* scenario by allowing additional West Coast exports.

5.3.2 Results on future coal consumption

Figure 5.3 shows global and U.S. steam coal consumption, and U.S. steam coal production in all six scenarios. At the global scale, the three scenarios in the *moderate climate policy* pathway differ only slightly (at max. 170 Mtpa or 3 % in 2050). As expected, average global steam coal consumption in the *ambitious climate policy* pathway is significantly lower, no matter whether CCTS is available or not. While consumption in all three scenarios of the *moderate climate policy* pathway is around 5,600 Mtpa to 5,700 Mtpa in 2030 and around 5,300 Mtpa to 5,500 Mtpa in 2050, it drops to around 2,800 Mtpa (*CPP*) to

3,100 Mtpa (*Rollback* & *Rollback_ports*) in 2030 and 200 Mtpa (*2°C_no_CCTS*) to 800 Mtpa (*2°C_CCTS* & *2°C_CCTS_ports*) in 2050 in the *ambitious climate policy* pathway, respectively. Even if available, CCTS can only decelerate the global phase-out of coal-fired power generation, but not stop it entirely. Cumulative CO_2 emissions from coal-fired power generation between 2015 and 2050 amount to approximately 470-480 Gt (on average ca. 10 Gt per year) in all three scenarios in the *moderate climate policy* pathway (see Table S3 in the Supplementary Material (Appendix D.1)).In the *ambitious climate policy* pathway, less than half the amount of CO_2 is released into the atmosphere from coal-fired power generation (210 Gt total emissions 2015-2050).

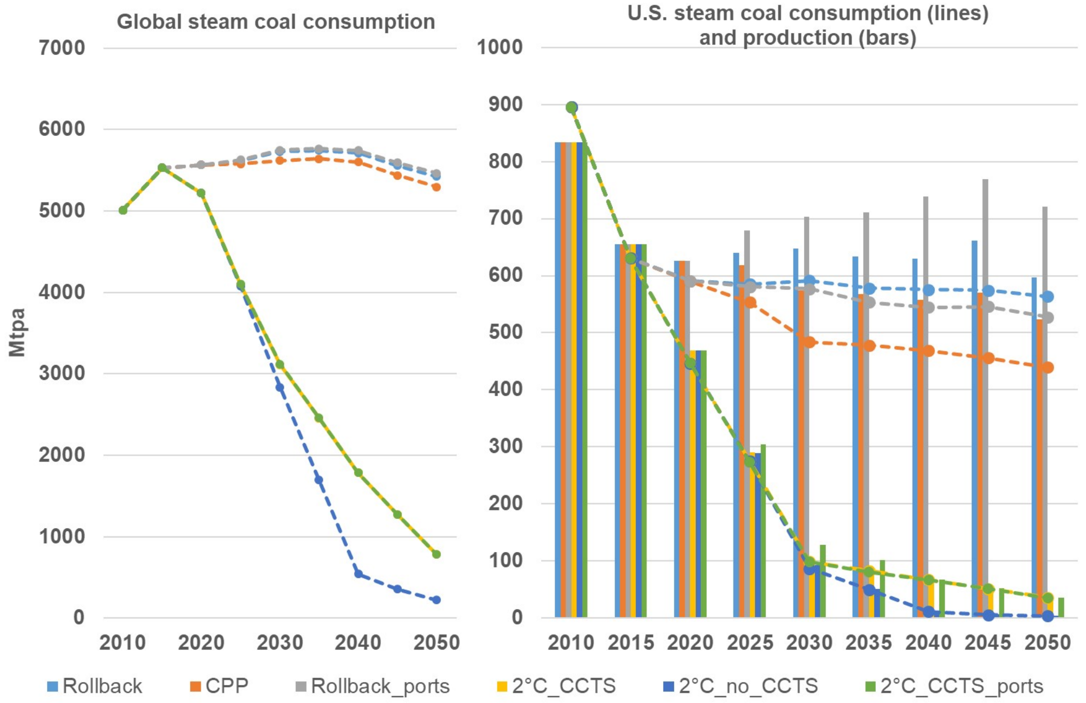


Figure 5.3: COALMOD-World results for global and U.S. steam coal consumption, and U.S. steam coal production 2010 –2050 in all scenarios.

Note: Scenarios 2°C_CCTS and 2°C_CCTS_Ports fully overlap.

U.S. steam coal consumption declines below 2015 levels in all scenarios in the following years. In scenarios with a policy rollback (*Rollback* and *Rollback_ports*), consumption declines rather slowly (-10 % and -16 %, respectively, in 2050 compared to 2015), while in the *CPP* scenario, consumption declines by around 30 %. Cumulative CO_2 emissions from U.S. coal-fired power generation between 2015 and 2050 amount to approximately 43 to 44 Gt (on average ca. 1.2 Gt per year) in the *Rollback* and *Rollback_Ports* scenarios (see

Table S3 in the Supplementary Material (AppendixD.1)). In the *CPP* scenario, cumulative emissions from U.S. coal-fired power generation are about 13 % lower (38 Gt) than in the *Rollback* scenario(s).

In the *ambitious climate policy* pathway, U.S. coal consumption drops within 15 years by more than 80 % to around 100 Mtpa in 2030. Cumulative CO_2 emissions from coal-fired power generation between 2015 and 2050 amount to approximately 13 Gt in all three scenarios of this pathway.[21] Annual emissions drop from ca. 1.3 Gt in 2015 to less than 0.6 Gt in 2025, and ca. 0.2 Gt in 2030.

5.3.3 Trump's effects on U.S. coal production in a moderate climate policy world

Policy interventions of the Trump administration in favour of coal, represented in the *Rollback* scenario, lead to a stabilization of steam coal production in the U.S. in the long-run at about the production level of 2015 (see Figure 5.3). However, replacing the CPP with a rather coal friendly rule does not lead to a return to former high, pre-2015 production levels. Revoking the CPP changes U.S. coal production only slightly in the short run because the CPP was scheduled to take effect only in 2022. Only after 2025, are production levels in the *Rollback* scenario around 11 % higher than in the *CPP* scenario. Regionally disaggregated, this additional production comes mainly from the PRB. Production in the Appalachia and Interior regions remains at 2015 levels.

The scenario *Rollback_ports* shows the effect of additional export port capacities along the U.S. West Coast. Total U.S. steam coal production rises slowly after 2020. The absolute increase in production induced by these ports (compared to the *Rollback* scenario) amounts to approximately 60 Mtpa by 2030 and 120 Mtpa by 2050. While this leads to slight production increases in all regions compared to the *Rollback* scenario, this additional demand is served mostly by an increase in production in the PRB. However, West Coast export opportunities in combination with the policy rollbacks of the Trump administration still do not lead to a return of U.S. coal production to the peak levels of the 2000s.

---

[21] For simplicity, the coal demand from CCTS-equipped coal-fired power stations is assumed not to cause CO_2 emissions. Given capture rates between 85 % and 95 %, the difference in total CO_2 emissions is small.

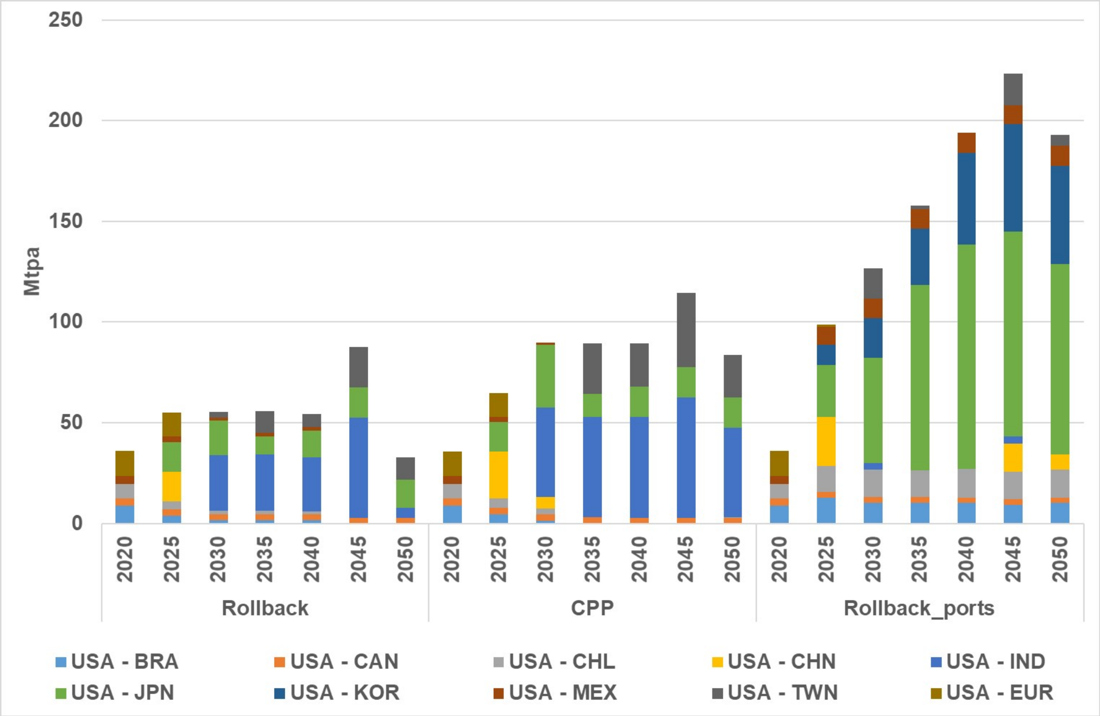


Figure 5.4: COALMOD-World results for U.S. steam coal exports 2020 -2050 in moderate climate scenarios.

Under the *moderate climate policy* pathway, exports increase in all three scenarios compared to 2015 (see Figure 5.4). Exports in the *Rollback* scenario are lower than in the CPP scenario due to the higher domestic demand in the *Rollback* scenario. In the *Rollback_ports* scenario, new West Coast export capacities facilitate additional exports of about 100 Mtpa by 2035, and 150 Mtpa by 2050. In all scenarios, U.S. export destinations shift from Europe and the Americas towards Asian countries. While in the scenarios *Rollback* and *CPP*, without new West Coast export facilities, U.S. exports from 2030 onwards go mostly to India, Japan and South Korea are the two main destinations under the scenario *Rollback_ports*.[22] Here, they replace mainly Colombia and Russia as coal suppliers.

Between 2020 and 2050, cumulative investments in the range of four billion US$ (in 2010 US$) in new U.S. transport and export infrastructure would be necessary to realize the additional exports in the scenario *Rollback_Ports*. Furthermore, cumulative investments in mining capacities between 2020 and 2050 would have to increase by about 80 % in the *Rollback_Ports* scenario compared to the *Rollback* scenario, albeit at a relatively low level

---

[22] The underlying model does not consider specific coal quality requirements of different power plants. Oei and Mendelevitch (2019) highlight this issue which hampers substitutability between different suppliers. This could possibly constrain demand for low-energy content PRB coal.

of 10.7 billion US$.[23] For comparison, in 2012 alone, capital expenditure in the sector was around 9 billion US$.[24] In the *CPP* scenario, cumulative investments in coal production capacities are halved compared to the *Rollback* scenario.

While many qualitative studies assess the possible effects of policy changes under the Trump administration on U.S. coal supply and consumption, quantitative assessment is very limited. Assuming a full regulatory rollback and arguing for coal exports to remain at current levels, Houser, Bordoff, and Marsters (2017, 38) find that total U.S. coal production, including metallurgical coal and lignite, could rise to 820 Mt in 2030 compared to 610 Mt in 2030 under Obama administration policies. They stress, however, that depending on the development of primary energy prices, U.S. coal consumption by 2022 could either further decline to 550 Mt or rise to 800 Mt (720 Mt in reference case). Similarly, the EIA projects in its reference case that U.S. coal production will remain relatively flat at around 680 Mt until 2050 (EIA 2018a, 92). With the CPP being implemented, coal production would decrease to 570 Mt by 2030 and ca. 540 Mt by 2050 (EIA 2018a, 91–92).

5.3.4 U.S. coal production in an ambitious climate policy world

If the political frame to get on track for reaching the 2°C target is reset, prospects for U.S. coal production look significantly different (see Figure 5.3). U.S. steam coal production drops under all three scenarios in the ambitious climate policy pathway by around 85 % between 2015 and 2030. Coal production vanishes in all regions between 2020 and 2030 except in the PRB.

CCTS cannot prevent this drastic decline even under optimistic assumptions regarding the availability of CCTS technology (*2°C_CCTS*). The largest part of the decline in U.S. steam coal production takes place before CCTS for coal-fired power plants is widely available. The availability of CCTS only changes prospects for U.S. steam coal production starting in 2030. Without CCTS (*2°C_No_CCTS*), U.S. steam coal production declines from around 90 Mt in 2030 to only 10 Mt in 2040. A sensitivity model run with a 1.5°C target shows an even more drastic decline, with a coal phase-out in the U.S. by 2030. With CCTS available, coal production declines more slowly after 2030 and reaches ca. 40 Mtpa in 2050. This is around 6 % of 2015 production levels.

---

[23] COALMOD-World includes a mine mortality mechanism by which production capacity depreciates over time according to extraction. Investments are necessary to replace the depreciated capacities. However, the new mines are assumed to have higher costs because typically easiest-to-access deposits are mined first. Average mine maturity differs between regions.

[24] See U.S. Census Bureau, 2012 Economic Census. Capital expenditures (except land and mineral rights) http://www2.census.gov/econ2012/EC/sector21/EC1221SG1.zip.

The possibility of exporting steam coal via the West Coast does not change prospects for U.S. steam coal production significantly in this pathway. Exports stay below 35 Mtpa in all three scenarios and by 2040 no more steam coal is exported from the U.S. (see Figure S2 in the Supplementary Material (AppendixD.1)). The U.S. retains its role as a swing supplier. In the Asian market, U.S. coal competes on the margin with, e.g., low cost Indonesian coal. U.S. coal loses its market shares rapidly towards 2035 to 2040 (depending on the scenario), while other exporting countries continue to serve the Asian market. In the Atlantic markets, U.S. coal has already disappeared by 2020. In other words, U.S. coal exports are very vulnerable to climate policy in these markets.

No investments in coal supply infrastructure are made from 2020 onwards, except in scenario *2°C_CCTS_Ports*, where some investments into additional export facilities are made (ca. 300 million US$).

5.4 Consclusions

At the latest by the time of the second presidential term of Barack Obama, prospects for the U.S. coal sector were already fading fast. Many have blamed Obama's Climate Action Plan and other climate policy measures that targeted emission reduction from coal-fired generation as a primary driver of this decline. Indeed, U.S. coal-fired power generation is the primary destination of U.S. coal production. However, in the U.S. electricity sector, coal suffers less from climate and other environmental regulation and more from lower competitiveness compared to recently built gas-fired power plants and renewables. Our literature survey shows that current and recent US environmental policies have had relatively little effect on U.S. coal production and consumption. From this perspective, revoking environmental policies will not change the fundamental economics in the energy market. Unless new regulation disproportionately favours coal-fired generation over other energy technologies, lax rules will not turn the tide for coal. Notably, market support for renewables and natural gas production is not under question by the current administration. Obama's climate policies worked to reinforce market forces and helped natural gas and renewables to outcompete coal, while Trump's policies and policy rollbacks try to pull in the opposite direction. Using a comprehensive model of the international steam coal market, we assess the effects of this policy change on U.S. steam coal production, exports, and investments.

We use rather high assumptions on U.S. coal consumption in the pro-coal scenarios provided by the EIA which neglect current structural and economic trends. Moreover, we assume prompt policy implementation, despite many potential entry points to postpone or prevent policy implementation. Nevertheless, our results with the COALMOD-World model show that in no case does coal production return to the all-time high levels of the 2000s (about 20 % higher than 2015 levels). Compared to a case with environmental regulation (CPP), U.S. coal production would increase by one-eighth in the next years but still stay far from the levels of 2010 or before. Accordingly, the policy rollback would increase CO_2 emissions from the U.S. coal sector by 13 %, stabilizing U.S. coal consumption at approximately 2015 levels. However, if the Trump administrations takes its promise of reviving coal seriously, it will need to take much bolder action. In this paper, we therefore look at two additional scenarios, which potentially bring about a change to the current trend in the coal sector: a hypothesised break of opposition against West Coast coal export ports or a widespread application of CCTS technology.

Establishing coal exports via the U.S. West Coast requires overcoming the regulatory hurdles to expand terminal capacity. Moreover, investments to expand coal transport infrastructure would become necessary, in particular to allow exports from the low-cost PRB in the Western United States These investments would be at high risk of becoming stranded, given that U.S. coal exports vanish under an *ambitious climate policy* pathway and production drops precipitously. While West Coast exports support PRB coal, there is no scenario which allows the Eastern coal basins (Appalachia and Interior) -which Trump had in mind when claiming to 'make coal great again' -to return to their pre-2015 production levels. Assuming current labour productivity levels, which differ by an order of magnitude between the PRB and Appalachian basins, a shift in production towards the PRB implies a further reduction in jobs in the coal sector.

CCTS cannot save the U.S. coal sector either. The strong financial and policy support that is required to realize private investments into this costly technology can only be justified if climate change mitigation is accepted as the ultimate underlying objective. However, this also means embarking on an ambitious climate policy pathway that leaves little space for coal-fired power generation, even with CCTS in place. The availability of the technology makes the difference between 100 Mtpa and 50 Mtpa of steam coal production by 2035, thus it only mildly decelerates the rapid coal phase-out that is required to meet the 2°C target.

In summary, new U.S. policies are not likely to turn the tide for U.S. coal. To the contrary, the coal sector is under ever-increasing risk of asset stranding, because it is uncertain which climate policy trajectory will be taken, both domestically and internationally. Coal mining assets are particularly at the risk of stranding (while domestic coal-fired power plants continue to be so, too). This is even more true from a global climate policy perspective, as much of the difference between scenarios is driven by exports, even without West Coast ports being available. Traditionally a supplier to Europe and the Americas, the U.S. will take the role of a swing supplier between the Atlantic and the Pacific coal markets. Due to its higher supply costs to the import markets compared to other exporters (e.g. Indonesia, South Africa), it can only be the marginal supplier to Asian markets such as India, Japan, and South Korea. In other words, while exports can potentially contribute to the survival of U.S. coal production for a few more years, they make the U.S. coal sector even more vulnerable to sudden climate policy shifts in other world regions.

Chapter 6

The U.S. coal sector between shale gas and renewables: Last resort coal exports?

This chapter is based on joint work with Franziska Holz published in *Energy Policy* 149 (2021) 112097 under the title: “The U.S. coal sector between shale gas and renewables: Last resort coal exports?”. DOI: 10.1016/j.enpol.2020.112097; published open access under CC BY 4.0.

6.1 Introduction

In many countries around the world, governments and utility companies have started to engage in coal-phase out processes (Jewell et al. 2019; Rentier, Lelieveldt, and Kramer 2019). Others hold out hope for more prosperous times in the coal sector (Mendelevitch, Hauenstein, and Holz 2019). This paper explores the future of the coal sector in the United States of America (U.S.), adding a detailed coal sector perspective to the Energy Modeling Forum 34 (EMF34) results. We find that while the politics are different in the U.S. and in Europe, future outcomes may be similar. However, these trends are not yet reflected in many energy scenarios such as those of the U.S. Energy Information Administration (EIA) and of the EMF34 models.

Round 34 of the Energy Modeling Forum (EMF) deals with "North American Energy Trade and Integration" (Huntington et al. 2020). Our bottom-up analysis of the coal sector is meant to complement its system-wide analyses. Coal still plays a major role in North America, and especially in the U.S. power sector, yet its future is very uncertain. For the U.S. example, our results show that numerical modeling of electricity, energy and energy-economy relationships need to take into account the vintage structure of the coal-fired power plant fleet as well as its reduced competitiveness compared to renewables and shale gas. In addition, global coal demand trends need to be considered when assessing possible futures for coal production in the USA.

Coal has long been a mainstay of U.S. baseload power generation as well as the U.S. mining sector. However, U.S. domestic coal consumption and production was about halved between 2008 and 2019, with consumption dropping to 520 million tons (Mt) in 2019, the lowest value since 1978. Production declined to 640 Mtpa in 2019.[1] Approximately 93 % of domestic coal consumption, relatively constant over the last ten years, goes to the U.S. electricity sector. U.S. coal-fired power generation are directly influencing coal production. Power generation from coal lost large market shares, reaching less than 25 % in 2019 (966 TWh). This went along with an increasing number of coal-fired power plants retiring, without new ones being constructed, leaving an aging fleet with a current average age of 41 years in 2020.

U.S. federal government support for continued use of coal remains strong, despite a global trend to "powering past coal" and more and more coal phase-out decisions in developed countries (Blondeel, Van de Graaf, and Haesebrouck 2020). In June 2019, the EPA issued the so-called Affordable Clean Energy rule (ACE), which replaced the Clean Power Plan

---

[1] EIA energy data browser: https://www.eia.gov/totalenergy/data/browser/, last accessed March 30, 2020. Figures in coal tonnage are given in metric tons. Short tons are converted using the IEA conversion factor 0.907184.

(CPP) of the previous administration (EPA 2019a), despite the negative emission and health effects that must be expected (Thomson, Huelsman, and Ong 2018). In contrast to the CPP, the ACE allows for very soft emission control regulation of coal-fired power generation by the states. On the supply side strict environmental regulations in the 'Stream Protection Rule' and the 'Resource Management Planning' have been relaxed.

However, economic drivers have led to the continuous decline of U.S. coal mining and power generation. Mendelevitch, Hauenstein, and Holz (2019), Feaster (2018), Houser, Bordoff, and Marsters (2017), Wang, Li, and Li (2019) and others have documented and analyzed the downward trend of U.S. coal production and consumption in the U.S. electricity sector. They essentially come to four main reasons for this decline: 1) the shale gas boom; 2) an increasing amount of renewable electricity generation; 3) the tightened environmental regulations of the power sector (but with less effect than the previous two reasons); and 4) the very old fleet of coal-fired power plants. And this trend continues. More coal-fired power plants are expected to retire over the next years,[2] and new builds are very unlikely in the context of low-price (shale) gas and increasingly cheap renewables.[3] Yet, these U.S. electricity and coal sector trends are not reflected in many U.S. energy forecast scenarios, such as by the EIA. Also in the results of the EMF34 group (Huntington et al. 2020) this downward trend of coal-fired electricity generation is only partially reflected. Figure 6.1 shows that many models in their reference scenarios project a stable amount of coal-fired generation after 2020 (panel b), so that coal has a significant share in the electricity mix in 2040 of 20 to 30 % (panel a).[4] Given the current average age of 41 years of coal-fired power plants, new investments in coal-fired electricity generation would be necessary to achieve this. However, such investments are very unlikely in the current economic circumstances of low-cost competing renewables and gas and, indeed, the industry has no plans for new coal power plants.[5] Notwithstanding, the EIA forecasted for the year 2040 940 TWh from coal in the Annual Energy Outlook 2019 (EIA 2019), i.e. approximately the level of 2019 (966 TWh).[6]

---

[2] EIA 860M January 20120, https://www.eia.gov/electricity/data/eia860m/, last accessed March 30, 2020.

[3] The Covid-19 crisis, starting in the first quarter of 2020, reinforces the downward trends and shows the vulnerable economic situation of the coal sector (Oei, Yanguas-Parra, and Hauenstein 2020). While power production from other sources, especially renewables, only decreased slightly or even increased, power generation from coal fell drastically (IEA 2020c), increasing the strain on coal producers worldwide markedly (Oei, Yanguas-Parra, and Hauenstein 2020).

[4] A notable exception is the MUSE model, which also finds lower total electricity generation and higher renewables share in the U.S. (Huntington et al. 2020).

[5] See, for example, the power plant tracker at https://endcoal.org/global-coal-plant-tracker/.

[6] In the 2018 edition of its Annual Energy Outlook (EIA 2018a) it was even higher, with 1,160TWh of net electricity generation from coal in 2040.

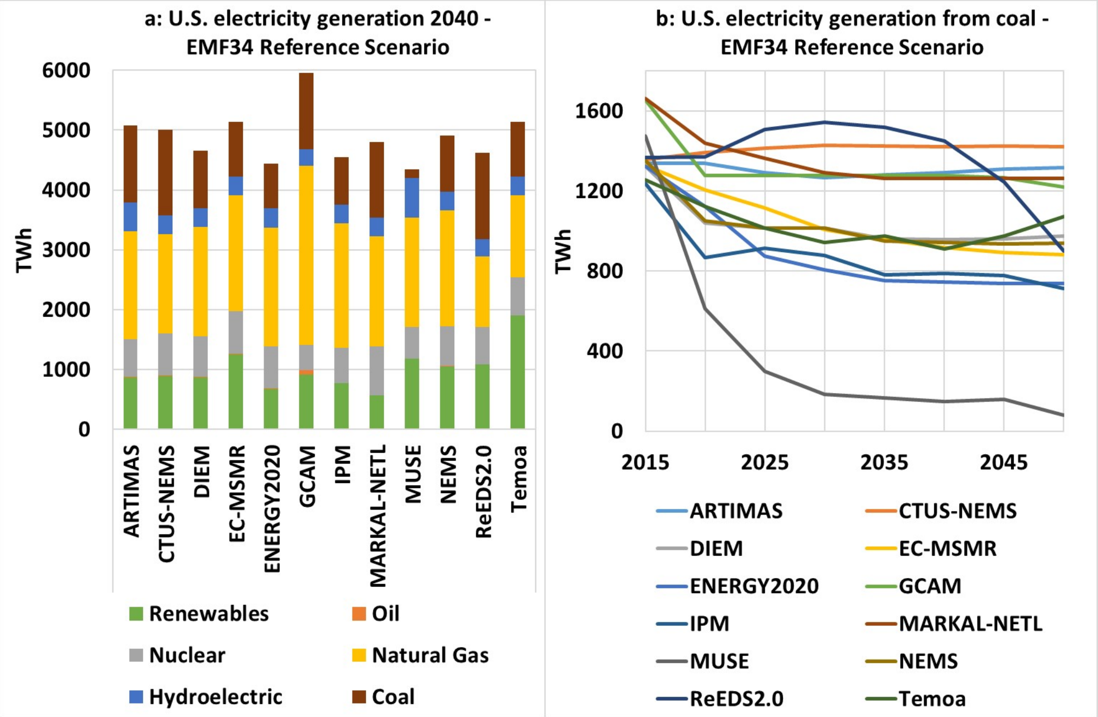


Figure 6.1: Overview of EMF34 results for a: U.S. electricity generation mix in 2040 (left), and b: U.S. electricity generation from coal (right) of various models ("EMF34 Reference Scenario" (Modelers' Choice Scenario)).

Source: (Huntington et al. 2020).

In this paper, we investigate how U.S. coal production is affected by current and possible future market and policy trends. Furthermore, we assess to what extent coal exports could compensate for declining domestic demand. Exports have repeatedly been presented by the industry as "savior" of the U.S. coal mining and mining jobs (Cornot-Gandolphe 2015; NCC 2018). We use our results to discuss the prospects of coal mining employment in the different U.S. coal basins.

Exports have been only a marginal market for U.S. coal producers of both steam (thermal) and metallurgical (coking) coal. Due to their relatively high supply costs, U.S. coal producers generally act as marginal suppliers for the international coal market, strongly following the fluctuations in international coal prices with the size of their supplies to the market. With a shrinking domestic market, the question is whether U.S. coal producers can increase their exports to secure future revenues.

However, coal production in the U.S. is far from uniform. The four coal basins in the U.S. - Appalachia in the East, the Interior region (Center), the Powder River Basin (PRB) in the (North) West and the Rocky Mountains region - have very different characteristics. Most importantly, PRB coal can be produced at much lower costs than in any other region because it comes from large opencast mines. This has led to a continuous increase of the share of PRB coal in total U.S. coal supply in the last decades.[7] When prospecting the future of the U.S. coal sector, it is a natural question whether this trend in favor of PRB coal will continue and whether there are scenarios - notably those with higher or lower exports - in which this trend is reinforced or attenuated. Due to their geographic location, the coal regions are differently connected to export ports and PRB coal, in particular, can hardly access export markets because of the de facto moratorium on West Coast export terminals (Mendelevitch, Hauenstein, and Holz 2019).

We use the COALMOD-World model (Holz et al. 2016) to quantify our arguments and provide numbers for future coal production, consumption, and exports. We draw on and complement scenarios from EMF34 on "North American Energy Trade and Integration" (Huntington et al. 2020).[8] Some of the scenarios are parameterized with results of the GCAM model's EMF 34 scenarios. In other words, we soft-link the sectoral COALMOD-World model with the Integrated Assessment Model GCAM (Calvin et al. 2019).

In the remainder of this paper, we describe our method by detailing the modelling approach as well as the scenarios in Section 6.2. In Section 6.3, we present an overview of the global and U.S. results of the scenarios. In Section 6.4, we discuss the impact of exports and include scenario runs with the option of expanding U.S. West Coast export ports. We extend the analysis to investigate the scenarios' effects on the different U.S. coal regions in the long run in Section 6.5, before concluding in Section 6.6. The Appendix E includes more details, in particular on alternative U.S. coal power pathways as well as our results.

6.2 Method

Our approach is typical for an EMF exercise: a) we use a numerical model, here the sectoral global coal market model COALMOD-World (Holz et al. 2016), and b) we run a variety of scenarios with this model. In addition, to assess implications of EMF34 scenarios, we soft-link the COALMOD-World with the Integrated Assessment Model GCAM (Global Change Assessment Model; Calvin et al. 2019) for some of the scenarios. Even though

---

[7] EIA energy data browser: https://www.eia.gov/totalenergy/data/browser/, last accessed March 30, 2020.

[8] See https://emf.stanford.edu/projects/emf-34-north-american-energy-trade-and-integration, which also provides detailed scenario results. Last accessed September 29, 2020.

both COALMOD-World and GCAM are global models, we focus on the U.S. results, both national and regional results.

6.2.1 COALMOD-World Model and Data

In the center of our quantitative analysis is a holistic model of the world steam coal market, COALMOD-World. It calculates steam coal production, trade, and prices for the world's regions. It features a detailed representation of domestic and international steam coal supply until 2050 and includes endogenous investment decisions in production, land transport, and export capacity, as well as an endogenous mechanism that updates production costs due to resource depletion (Holz et al. 2016; Holz et al. 2015). For the analysis in this paper, we have updated the model extensively, also compared to Mendelevitch, Hauenstein, and Holz (2019), to include recent data from the International Energy Agency (IEA 2019a, 2019b) and other, mostly national sources, for the U.S.A., China, India, etc. For example, the model is now calibrated for 2015 and we fix 2020 consumption levels to values extrapolated from the 2015 to 2018 trends in order to take into account the development trends of the past years.

Mathematically, COALMOD-World is a perfect foresight equilibrium model that collects the profit maximization problems of the major player types in the global steam coal market, namely producers and exporters, and balances their supply with demand in the coal consumption regions. The model specification has a focus on the supply side of coal (coal extraction, coal transport) and includes extraction costs and extraction constraints, transport costs and transport constraints, investments in mining and transport. Both the seaborne and the overland international trade as well as the national markets are included, with large countries split in regional nodes. We associate each player with one of these nodes.

The U.S. is represented with four supply nodes which represent the major steam coal basins: Appalachia in the East, Interior, Rocky Mountains (Rockies) in the Western coal region, and Powder River Basin (PRB) in the Northern Great Plains. On the demand side, we split the entire U.S. (Lower 48 plus Alaska) in five consumption nodes: North Central, North East, South Central, South East, West, see Figure 6.2).[9]

---

[9] Our definition of the U.S. nodes is based on the EIA disaggregation. The EIA electricity data disaggregates the U.S. in ten regions ('New England', 'Middle Atlantic', etc.). In most cases, we aggregate two EIA regions to obtain the COALMOD-World demand nodes shown in Figure 6.2.

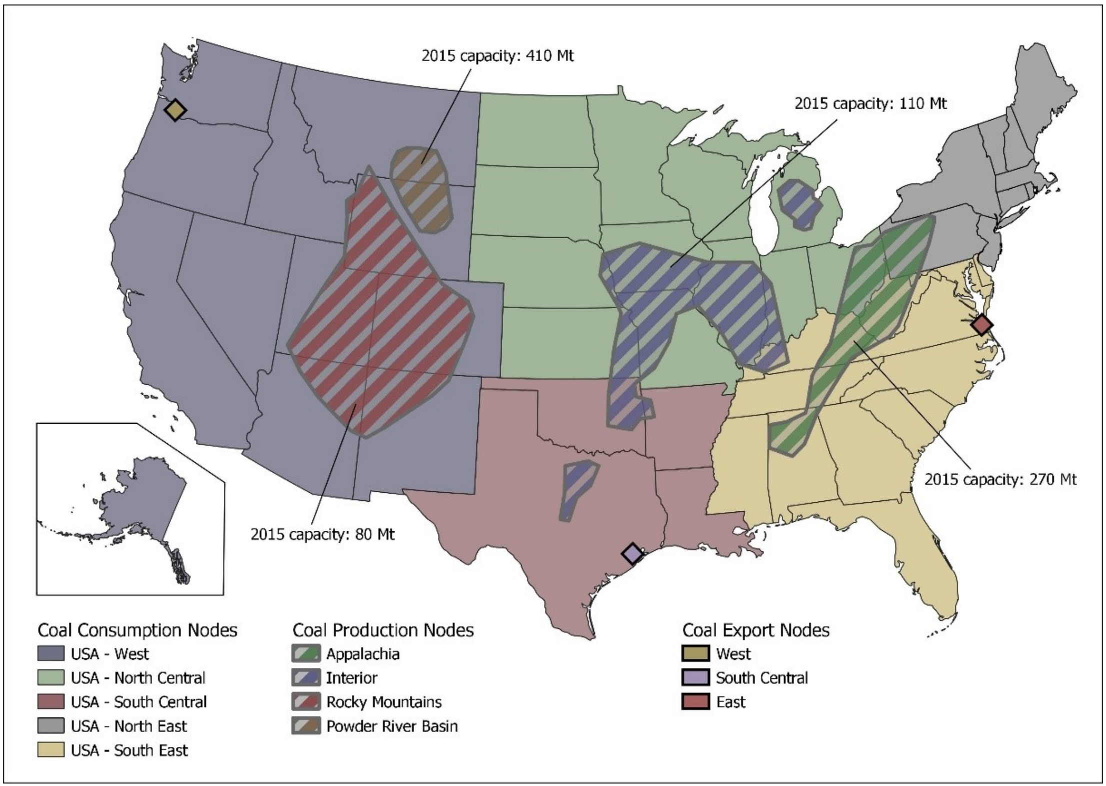


Figure 6.2: U.S. coal basins, consumption regions and reference export port locations in the COALMOD-World model.

Demand is expressed in PJ (i.e. peta joules, a unit of energy), and for each coal producing region its specific average energy content is used to convert from mass (million metric tons, Mt) to energy (PJ). We include future demand trends by applying the regional growth rates from various data sources (see Section 6.2.2) to our 2020 coal consumption values in each demand node. 2020 values are obtained by extrapolating the trend between 2015 and 2018 from IEA (2019a) to 2020.

6.2.2 Two sets of scenarios, one cross-cutting policy shock

We develop two sets of scenarios in order to, on the one hand, assess the plausibility of the EMF34 coal results shown in Figure 6.1, and on the other hand, show that alternative futures with more stringent climate policy will have an even stronger effect on the U.S. coal sector than the trends of the past decade. The first set of scenarios are “status quo” scenarios which - generally speaking - assume a sustained, high average global coal demand to 2050 and a continuation of the status quo policies in the U.S. with a substantial role for coal in the power sector. Clearly, we do not assume any climate or coal phase-out policy in any of these scenarios. Except for one, all EMF34 scenarios are status quo scenarios to a smaller or larger extent (Huntington et al. 2020).

Our second set of scenarios are climate policy scenarios which assume climate policy measures in place that effectively reduce the role of coal in the global and the U.S. energy system. Only one EMF34 scenario falls into this category, namely the "Carbon Policy" scenario (Huntington et al. 2020) which we implement using GCAM's coal results. Table 6.1 gives an overview of our five scenarios and their main assumptions.

Table 6.1: Our scenarios and their main characteristics.

Status quo **scenarios**	***Climate policy*** **scenarios**
EIA_reference - U.S. coal demand growth rate from EIA (2019) AEO *Reference Scenario* - Global coal demand growth rate from IEA (2019b) WEO *Stated Policies Scenario*	***1.5°C*** - Based on IPCC "*1.5°C*" scenarios analyzed by Yanguas Parra et al. (2019), here: median coal consumption without CCS of scenarios fulfilling sustainability criteria (limited BECCS & carbon uptake from AFOLU)
GCAM_no_policy - Coal demand growth rates in the U.S. and all other countries from GCAM EMF34 reference scenario results - "No policy" baseline scenario of GCAM	***GCAM_carbon_policy*** - Coal demand growth rates from the GCAM results of the EMF34 Carbon Policy scenario - GCAM runs with global CO_2 price of 35 USD in 2022, and then 5 % growth per year to 137 USD in 2050 (EMF34 assumption)
US_bottom_up - Future U.S. coal demand is calculated from U.S. coal-fired power generation unit data from EIA with an average life-time assumption of 60 years and a constant capacity factor of 0.5 - Global coal demand growth rate from IEA (2019b) WEO *Stated Policies Scenario*	

We distinguish three status quo scenarios, of which two can be considered EMF34 scenarios. The first one of them, the scenario EIA_reference uses coal demand growth rates for the U.S. regions from the Reference case of the EIA (2019) "Annual Energy Outlook"[10] and the coal demand growth rates from the IEA (2019b) Stated Policies Scenario (formerly called New Policies Scenario) for the other world regions. EIA (2019, 107–108) assumes a decline of coal-fired power generation by 18 % between 2018 and 2035 in the U.S. and a stable level thereafter until 2050. Given the current vintage structure of the U.S. power sector fleet, this implies investments in new coal-fired power plants (or plants of 80 years and

---

[10] For detailed data tables of the EIA (2019) Annual Energy Outlook see https://www.eia.gov/outlooks/archive/aeo19/, last accessed September 23, 2020.

more running) as well as an increasing capacity factor of these coal-fired power plants. Both assumptions seem unrealistic in the current market environment of cheap shale gas and low-cost renewables (Mendelevitch, Hauenstein, and Holz 2019), which is why we contrast the EIA_reference scenario with the US_bottom_up scenario. Both these scenarios are defined with the same international environment, IEA's Stated Policies Scenario (IEA 2019b), which is a conservative scenario assuming only the implementation of the currently committed nationally determined contributions (NDCs) and no further climate action. It, therefore, comes with stable global coal demand until 2050.

The second status quo scenario, "GCAM_no_policy", is based on the results of the GCAM model's EMF34 Reference Scenario. GCAM's Reference Scenario results are among the highest coal use results of all EMF34 models and are the highest electricity generation levels (Figure 6.1). For the "soft link" of COALMOD-World and GCAM, we take the GCAM results for coal demand as input data for COALMOD-World. GCAM is a global integrated assessment model which features a detailed multi-sector representation that explores both human and earth system dynamics (Calvin et al. 2019). In particular, it includes a detailed energy sector module which distinguishes the major fuels (including coal) and various energy transformation technologies. In its recent update for EMF34, it takes into account the vintage structure of the U.S. coal-fired power sector and restricts expansion of this (as well as the European coal power) sector.[11] The EMF34 runs go to 2050 and can therefore not report on the temperature development to 2100. In GCAM, the U.S. is one separate node, out of 32 nodes in total. To implement our GCAM scenarios, we map the GCAM nodes to the CMW nodes and apply the regional growth rates of the GCAM results (2020-2050) to our base year demand (2020). EMF34 did not prescribe assumptions for the models' "reference scenarios" but describes them as "modelers' choice". GCAM's reference scenario for EMF34 is a no-policy baseline as is usual in integrated assessment modelling exercises. It is, therefore, clearly a status quo scenario.

For the US_bottom_up scenario, we base future U.S. steam coal demand on bottom-up information on observable trends regarding retirement age and capacity factor of U.S. coal-fired power plants. We take include the geographic location, (net summer) capacity, age, and announced retirement dates of all U.S. coal-fired generation units.[12] In addition to

---

[11] There is also a U.S. version of the GCAM model (GCAM-USA). While the level of spatial disaggregation of the USA differs significantly between the two model versions, the data is similar. GCAM-USA was recently used in Feijoo et al. (2020) who also find stable U.S. coal consumption levels through to 2050 in a scenario of "National Policies Implemented" (similar assumptions than EIA_reference) and almost a doubling of coal consumption in a "NoPolicy" scenario.

[12] Based on data provided in EIA's Preliminary Monthly Electric Generator Inventory EIA860M as of August 2019 (https://www.eia.gov/electricity/data/eia860M/). We include all generator units in the sectors 'Electric Utility', 'Industrial CHP', 'Industrial Non-CHP', 'IPP CHP', and 'IPP Non-CHP', in all plant states, except Hawaii (HI), with nameplate capacities of equal to/greater than 50MW, for the technologies 'Conventional Steam Coal' and 'Coal Integrated Gasification Combined Cycle', excluding the energy source 'lignite' (LIG).

the announced retirements listed by the EIA, we include those retirement announcements reported in the weekly newsletter CoalWire, published by Global Energy Monitor, that were not listed in form EIA860M yet.[13] We assume that coal-fired generation units are retired in the announced year. To all other units we apply the conservative - or, rather, generous - assumption of a 60 years life-time.

While U.S. net electricity generation stayed rather constant around 4,100TWh between 2010 and 2019, the share covered by coal declined by about 48 % (from 45 %, 1,847TWh, in 2010 to 23 %, 966TWh, in 2019). Total coal-fired electric generation capacity peaked in 2011 with about 318 GW, and then declined to 229 GW in December 2019.[14] Initially, small and very old units retired. But in recent years, more and more plants that were larger and/or younger than the average fleet age were shut down. As of January 2020, the capacity weighted average age of the remaining fleet is 41 years. The capacity factor of coal-fired power generation units dropped from 67.1 % in 2010 to 47.5 % in 2019.[15]

As of November 2019, the retirement of about 35GW between 2020 and 2030 had been announced publicly, with a current average age of 48 years of the concerned units. Of the remaining capacity, more than 20 % are older than 50 years. In other words, they will exit the market (because they reach the assumed life-time end of 60 years) - and thereby stop using coal - in the year 2030 at the latest. By 2050, only around 70 units (27GW) of the currently existing units will be left in the market. Table 6.2 shows the regional development of coal-fired power generation capacities. Different age structures of the regional coal-fired power plant fleets lead to differing decline speeds (see Appendix E for alternative scenario assumptions). While the capacity in the South Central region remains relatively constant until 2035 due to a younger than average fleet, it is reduced by at least around 50 % in all other regions by then. For comparison, the table shows the remaining capacity according to the Reference case of the EIA (2019) “Annual Energy Outlook”, which remains relatively constant at about 150GW after 2030.

We calculate the coal demand from the power sector by assuming a constant capacity factor of 0.5 to all coal-fired power plants. This capacity factor assumption differs strongly from the EIA assumptions. The EIA assumes that in a decade or a little more, when most old power plants will have left the market, the average capacity factor will increase again - because fewer but younger power plants are supposed to deliver the same amount of electricity than today (EIA 2019). However, this assumption neglects at least that the

---

[13] Global Energy Monitor, CoalWire. https://endcoal.org/category/coalwire/, last accessed April 1, 2020.

[14] EIA electricity data: https://www.eia.gov/electricity/, last accessed March 30, 2020.

[15] EIA, Electric Power Monthly, Table 6.07.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_a, last accessed April 1, 2020.

Table 6.2: Coal-fired power generation capacities in GW in five U.S. consumption regions, 2020-2050, in *US_bottom_up* scenario.

	2020	2025	2030	2035	2040	2045	2050
Consumption Region	GW						
West	25.8	22.1	13.9	12.6	9.7	3.9	3.1
North Central	83	68.4	56.8	42.1	21.8	11.8	9
South Central	24.4	23.1	23.1	23.1	17.4	7.2	3.9
South East	74.1	63.2	56.2	35	28.2	13.9	9.9
North East	11.8	9.9	6.7	2.9	2.3	1.6	1.5
U.S. total	219.1	186.7	156.7	115.7	79.4	38.4	27.4
AEO2019 U.S. total*	227.7	176.3	161.8	151.1	150	148.2	148.2

*EIA Annual Energy Outlook (AEO) 2019 Reference case values for comparison. Source: EIA (2019).

strong rise of renewables of the past decade is likely to continue given the international efforts in further cost decrease in both renewables and flexibility options.

We chose conservative and “pro coal” assumptions for our US_bottom_up scenario consistent with the status quo category. Recent trends indicate an even lower capacity factor (47.5 % in 2019, 2015-2018 around 53-54 %)[16], and earlier shut-down of coal-fired power plants than after 60 years lifetime (average, capacity-weighted retirement age of considered U.S. coal-fired generation units in 2019: 46.3 years).[17]

We apply the resulting growth (decline) rate of power generation from coal-fired units to the 2020 base demand for steam coal to obtain each future period’s reference demand assumption which we need as model input. Figure 6.3 shows the derived future steam coal demand assumptions in all five U.S. consumption regions in our US_bottom_up scenario. Figure E.1 in the Appendix E shows steam coal demand in U.S. consumption regions based on a range of alternative retirement age and capacity factor assumptions. Even for very coal-friendly assumptions (e.g., 70 years lifetime and 70 % capacity utilization), coal demand will decline substantially and be reduced by half or more until 2050. In contrast, in the Reference case of the EIA (2019) “Annual Energy Outlook” coal-fired power generation falls only slightly below its 2020 level (1,024TWh) throughout the considered time horizon (2050: 914TWh), due to the assumed capacity factor increase and the halted coal generation

---

[16] EIA, Electric Power Monthly, Table 6.07.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_a, last accessed April 1, 2020

[17] EIA, Electricity, Preliminary Monthly Electric Generator Inventory. https://www.eia.gov/electricity/data/eia860M/, last accessed April 1, 2020.

capacity retirements. Thus, the EIA also projects steam coal demand to decrease only slightly between 2020 and 2050 (-13 %) in this scenario.[18]

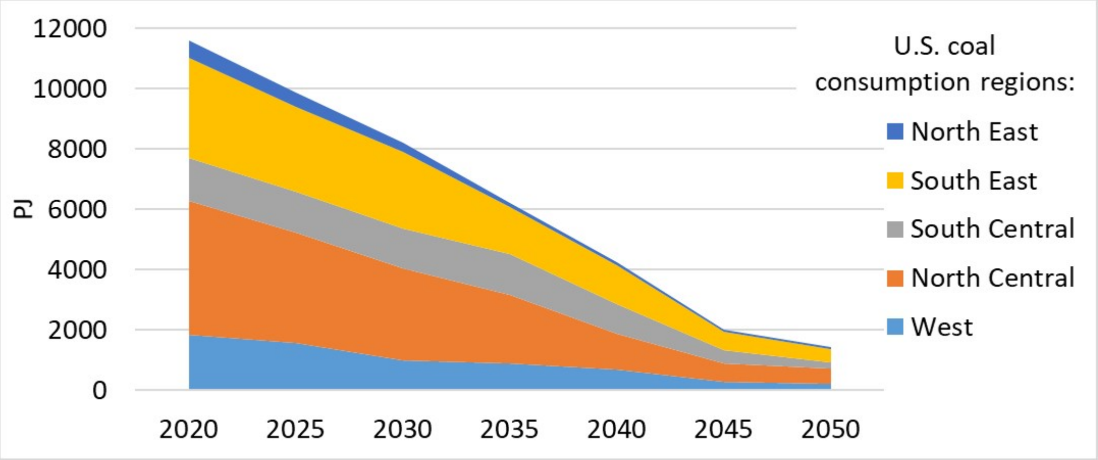


Figure 6.3: U.S. steam coal demand assumption in the *US_bottom_up* scenario in PJ (disaggregation into five consumption regions), with the life-time assumption of 60 years and constant capacity factor of 0.5.

We contrast the three status quo scenarios with two climate policy scenarios, one of them being an EMF34 scenario. The latter one, the "GCAM_carbon_policy" scenario, is based on the GCAM results for the EMF34 scenario "Carbon Policy". This scenario assumes a uniform global CO_2 price of 35 USD in 2022 which grows by 5 % growth per year until 2050.[19] Global coal demand in GCAM reduces by only 42 % between 2020 and 2050, with the strongest reduction late in the model horizon, after 2045. While U.S. electricity generation from coal between 2020 and 2050 decreases by 70 % in GCAM, the 2050 level is still five times the average of the other EMF34 models' carbon policy scenario results. In other words, GCAM_carbon_policy is a rather moderate climate policy scenario, both globally and for the U.S.

We also design a climate policy scenario with an effective coal exit, the "1.5°C scenario". It is based on the IPCC (2018a) report on 1.5°C scenarios. Yanguas Parra et al. (2019) selected those 1.5°C scenarios that also fulfil other sustainability criteria such as reasonably limited use of biomass with CCS (BECCS) and limited carbon uptake from afforestation or land use. For each model year (i.e. 2025, 2030, 2035, and so on), we take the regional growth rates of the median global coal consumption of these scenarios.

---

[18] See AEO 2019 Reference Case Projection Table 15: https://www.eia.gov/outlooks/archive/aeo19/tables_ref.php, last accessed September 23, 2020.

[19] These CO2 price assumptions are implemented by GCAM. COALMOD-World cannot implement a CO_2 price because it only includes coal and no other energy vector (emission source).

We consider the scenarios EIA_reference, GCAM_no_policy, and GCAM_carbon_policy as EMF34 scenarios which are either based on common input used by the EMF34 group or directly on results of EMF34 scenarios. In contrast, the scenarios US_bottom_up and 1.5°C are our "modelers' choice" scenarios.

In all scenarios, the baseline assumption is that U.S. exports via the West Coast are only possible via the existing - small - capacities (in total five Mtpa); no investments in U.S. West Coast export terminals are allowed. There currently is a de facto ban on creating new coal export capacity (new terminals or expansion of existing ones) in California, Oregon, and Washington. A number of new projects were introduced in the past two decades but none was granted permission, due to complex permitting and strong environmental concerns by local policy makers (Cornot-Gandolphe 2015; Mendelevitch, Hauenstein, and Holz 2019). More recently, constructing new terminals on federal land (e.g., former military ports) was suggested. However, their realization is questionable because railroad transportation to the ports is also a big issue of contention in the U.S. West Coast states. With this counterfactual policy shock we analyze whether new export capacities would make a difference to the export chances of U.S. coal suppliers, and if yes, to which extent.

We apply a policy shock that allows for endogenous investments in U.S. West Coast export capacities in the scenarios "_ports" of up to 50 Mtpa per 5-year period.[20][21]In other words, we may then see an expansion of U.S. West Coast export capacities when it is economically rational, for example because of strong demand in Asia and idle production capacities in the U.S., in particular in the Powder River Basin and the Rockies. With this, we want to analyze whether a coal phase-out by domestic power generation can be compensated by the U.S. coal producers by exporting more to the world markets.

6.3 Five scenarios for U.S. and global coal demand trends

In this section, we want to provide an overview of the global and U.S. results from the five COALMOD scenarios introduced in Section 6.2.2, and to highlight three main lessons that can be learnt from these results:

---

[20] Investments in all other export capacities, including U.S. Gulf Coast and East Coasts are equally allowed in all scenarios. Costs, capacities, and maximum expansions are not varied between scenarios.

[21] Coal terminals vary in size. For example, each of the two coal terminals in the Baltimore ports has a size of approx. 14 Mtpa. The unrealized projects Millenium Bulk Terminal (WA) and Gate Pacific Terminal (WA) were approx. 44 Mtpa each (https://www.eia.gov/todayinenergy/detail.php?id=32092, last accessed October 11, 2020). This means that 50 Mtpa can be expected to be one very large or more smaller ports.

1. There is significant uncertainty on the outlook for the U.S. coal sector, even in the absence of explicit climate policies. It depends strongly on the assumptions for the U.S. power sector development and, to a lesser extent, the access to global markets.
2. The current assumptions by the U.S. Energy Information Agency - which has been the source for most EMF34 models and scenarios - are biased towards coal given the vintage structure of the U.S. coal-fired power plant fleet and recent market trends. These assumptions have a very strong influence on the future level of U.S. coal demand and production and must be viewed critically. They can be called “pro-coal” scenarios and implicitly rely on further support mechanisms for coal power in the U.S.
3. If the global success of renewables continues in combination with effective climate policy, the U.S. loses its option to shift a share of its coal production to the world markets. This option is already limited now and in the status quo future scenarios because of the U.S. suppliers’ high relative supply costs which make them the marginal suppliers in the import markets.

In Section 6.4, we delve deeper into the topic of exports of U.S. coal. There, we also include scenarios with West coast ports. In Section 6.5 we analyze the details of these scenarios for the different U.S. coal regions.

Looking first at the global coal use trends to 2050 (Figure 6.4), we can easily discern the five scenarios. We see that GCAM_no_policy is an extreme no-policy scenario in which “status quo” leads to a strong increase of global coal demand, about 37 % above 2020 levels and well above 7000 Mtpa. This can well be interpreted as an upper bound of future coal demand. The other status quo scenarios exhibit rather constant demand over time, with a moderate increase until the 2030s when they peak below 6000 Mtpa and then a return to approximately 2020 levels around 5400 Mtpa. GCAM_carbon_policy is a “middle-of-the-road” scenario with only moderate climate policy assumed. The global demand reduction between 2020 and 2050 is only 37 %, to about 3400 Mtpa. In contrast, the 1.5°C scenario leads to a strong and early fall of global coal demand: by 2030 coal demand is already 73 % lower than in 2020, and 99 % lower by 2040

Main consumers in all scenarios are China (between 48 % and 52 % of cumulative global consumption between 2020 and 2050) and India (between 18 % and 23 %), but the US also is a major coal consumer (between 6 % and 9 % of cumulative coal consumption, with the smallest share in the US_bottom_up scenario). These countries’ shares in global coal demand stay rather constant over time in most scenarios, i.e. their demand evolves similarly to the global trend. An exception, amongst others, is the U.S. demand in the US_bottom_up scenario, which reaches a share of only 1 % of global demand in 2050.

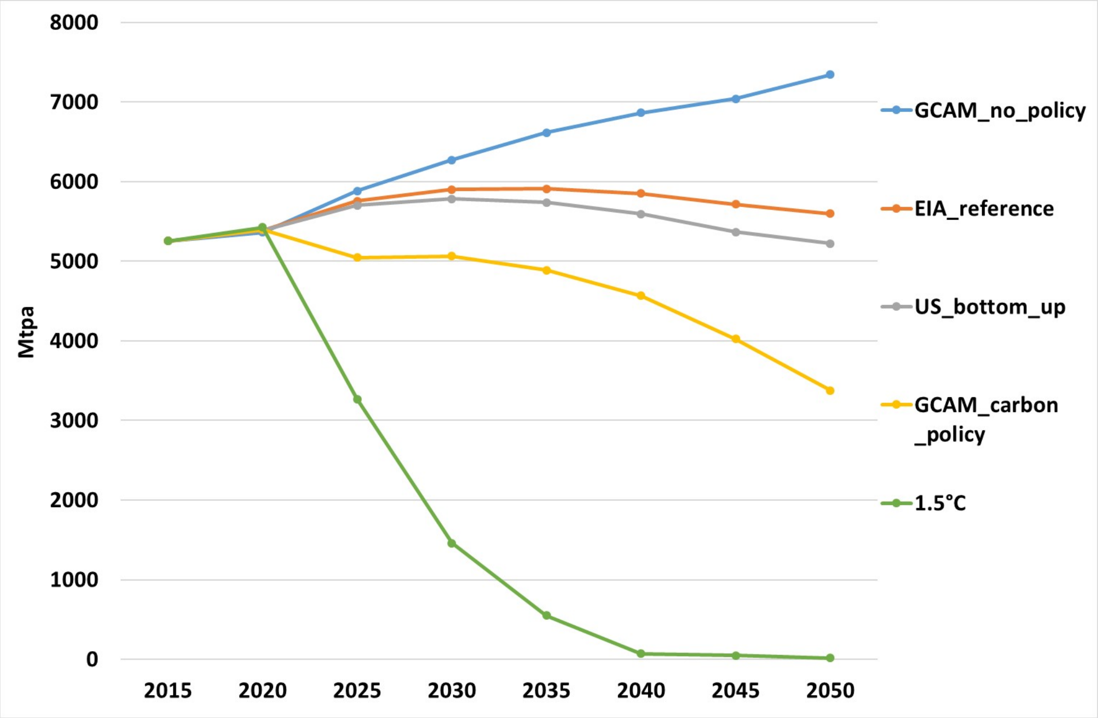


Figure 6.4: Global steam coal consumption in Mt per year in all scenarios.

India's demand generally increases to around 30 % of global demand in most scenarios by 2050.

We see already in the global numbers of the status quo scenarios that adjusting the U.S. consumption expectations has a notable effect on the total coal consumption: in our scenario US_bottom_up, global coal consumption 2050 is almost 7 % lower than in the scenario "EIA_reference". Turning to the U.S. numbers (Figure 6.5a), this result is even more obvious: while the scenario "GCAM_no_policy" contrarily forecasts an increase between 2020 and 2050 by 15 % and the scenario EIA_reference only a slight decrease by 12 %, the scenario US_bottom_up comes with a strong decrease by 87 %. We need to keep in mind that the observed decrease of U.S. coal use between 2015 and 2020 only was more than 20 %.[22] The strong decrease in the US_bottom_up scenario reflects the exit of more and more coal-fired power plants, either because of economic and other retirement decisions, or that reach 60 years of age (our assumed maximum lifetime).

---

[22] EIA Coal Data Browser: https://www.eia.gov/coal/data/browser/, last accessed June 4, 2020.

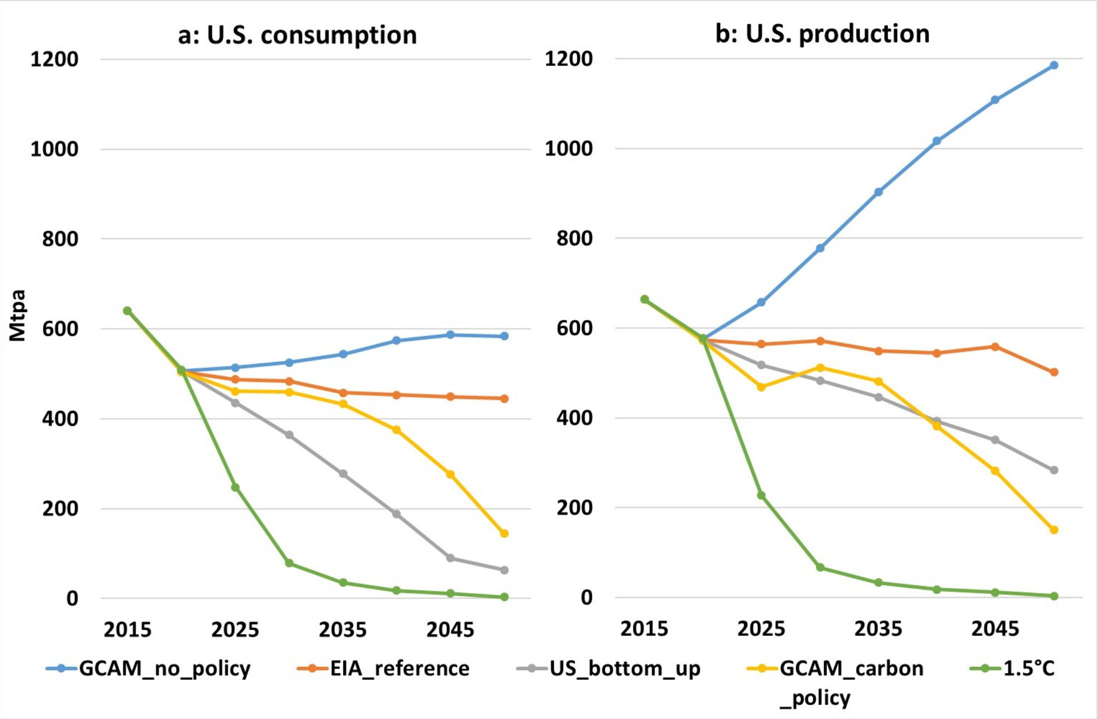


Figure 6.5: a: U.S. steam coal consumption (left), and b: production (right) 2015-2050 in Mt per year in all scenarios.

The U.S. coal supply has traditionally served primarily the domestic demand and has exported only a small share of the U.S. coal production. In other words, U.S. production levels are usually close to U.S. consumption levels. Figure 6.5b shows that the various scenarios have somewhat diverging perspectives on this. The congruence of domestic production and consumption continues to be largely the case in the EIA_reference,[23] the GCAM_carbon_policy and the 1.5°C scenarios. In contrast, the GCAM_no_policy scenario forecasts such a strong growth in production that domestic consumption cannot keep up the pace. Production levels well above 1000 Mtpa would exceed the all-time peak level of U.S. production of 2008.[24] Yet another picture is given by the US_bottom_up scenario

---

[23] Our method of applying the source data growth rate to our own base year data leads to a slight deviation of the COALMOD-World results in the EIA_reference scenario with the EIA AEO 2019 numbers. EIA AEO 2019 finds coal production in total (thermal coal + metallurgical coal) to decrease from 629 Mtpa to 537 Mtpa from 2020 to 2050. In other words, applying EIA growth rates in COALMOD-World leads to slightly slower decrease of U.S. production, of 12 % decrease between 2020 and 2050, compared to a 15 % decrease in the EIA AEO 2019 numbers. Approximately 50 Mtpa of the total U.S. coal volumes have been metallurgical coal in the last years. Subtracting 50 Mtpa from the aforementioned numbers brings us to the same range of thermal coal volumes as in the COALMOD-World results in Figure 6.5.

[24] In 2008, U.S. production of bituminous and sub-bituminous, the two coal categories included in our analysis, was 1063 million short tons, which is equivalent to 993 Mtpa (https://www.eia.gov/coal/annual/pdf/tableES1.pdf, last accessed April 26, 2020).

in which the bleak outlook for coal-fired power generation leads to the consumption fall outpacing the - slow - production decline. In both scenarios, U.S. production net of domestic consumption leaves considerable volumes of 120 Mtpa and more for exports (also see Section 6.4).

6.4 Increasing U.S. coal exports - A realistic option?

In this section, we investigate whether a coal phase-down by domestic power generation can be compensated by the U.S. coal suppliers exporting more to the world markets as suggested by Knittel, Metaxoglou, and Trindade (2016). We do this by analyzing the export volumes in the different scenarios, including the scenarios with the policy shock of West coast terminals being allowed (scenarios named "_ports"). Clearly, such a shock is very unlikely because of the strong and effective local opposition to coal ports, but it is still helpful to analyze their potential effects (see Section 6.2.2).

Exports were in the range of 4 % to 15 % of U.S. coal production (54 Mt - 114 Mt) in the period 2006 to 2018.[25] About 50 % to 70 % of U.S. coal exports are metallurgical coal. U.S. steam coal has relatively high supply costs - production and transport costs summed up - and is the marginal supplier in most international markets.[26] Therefore, the possibility for U.S. coal suppliers to deliver to other markets is very price-sensitive and varies considerably over time and between scenarios (Figure 6.6).[27] Generally, U.S. exports are higher when global demand is higher (status quo scenarios) and when domestic demand is lower, such as in the US_bottom_up scenario.[28] The 1.5°C scenario shows the fundamental importance of sufficiently high global demand for U.S. exports to realize: the generalized global coal phase-out brings the import demand down to zero despite a lot of U.S. supply capacity being idle and able to export. In contrast, in the US_bottom_up scenario, a scenario with both sustained global demand and idle U.S. coal supply capacities, exports are multiplied by more than three between 2020 and 2050.

---

[25] EIA coal data browser: https://www.eia.gov/coal/data/browser/, last accessed March 26, 2020.

[26] In the COALMOD-World model structure, we assume a different demand (function) in each model node (country). Hence, an exporter addresses different nodal demands for (imported and/or domestically produced) coal. In other words, there is not a single "world market" and prices differ between demand nodes.

[27] In some years in the past, the U.S. even were net importer of coal. In some of the future scenarios, too, we see some imports, mostly small volumes from Columbia.

[28] Also see Table E.1 in the Appendix E for the share of exports of U.S. production in each scenario.

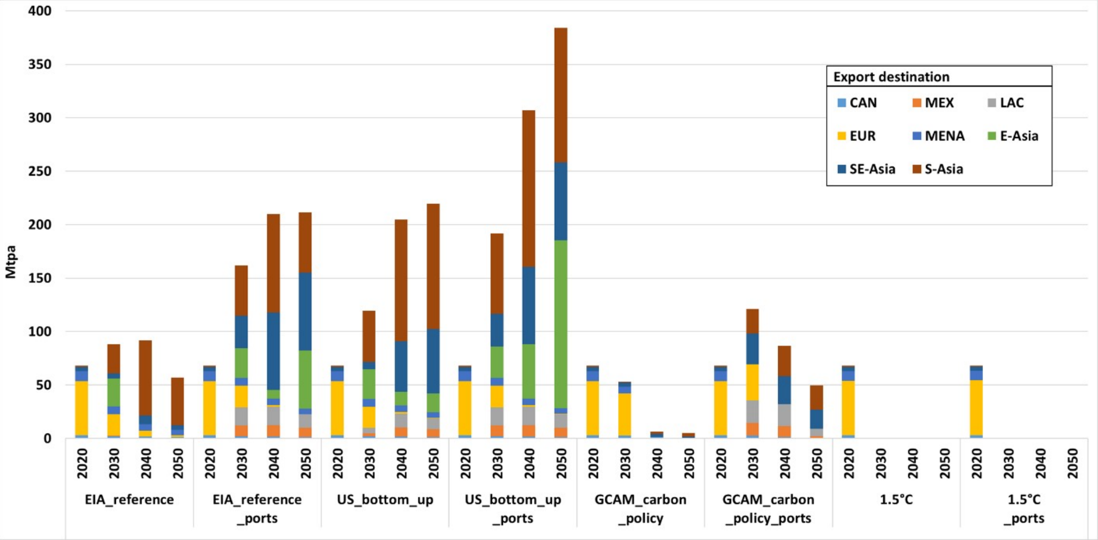


Figure 6.6: U.S. coal exports 2020-2050 and their destination in Mt per year.

Note: Countries represented in importing regions: CAN = Canada; MEX = Mexico; LAC = Brazil, Chile; EUR = Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Portugal, Spain, United Kingdom; MENA = Israel, Morocco, Turkey; E-Asia = China, Japan, South Korea, Taiwan; SE-Asia = Malaysia, Philippines, Thailand, Vietnam; S-Asia = Bangladesh, India, Pakistan.

The role of the U.S. as marginal supplier to the world's import markets is also reflected in its diversified importer portfolio (Figure 6.6). At first, the large number of importers may be puzzling given the (perfectly) competitive nature of the global steam coal market. However, it is due to the marginal position of the U.S. in the importers' supply curve,[29] and to the fact that the graphs show an aggregation of several U.S. exporters. While Europe has traditionally been a major market for U.S. coal, the importance shifts to the Asian-Pacific market (even in scenarios without West Coast ports, assuming Panama Canal utilization), reflecting the general strong demand push in Asia and the shrinking coal demand in Europe. U.S. exports will benefit from limited Indonesian reserves and can increase the volumes sent to South Asia and Eastern Asia over time. These demand regions are in the Pacific basin, so opening new terminals on the Pacific Coast of the U.S. would potentially have a further increasing effect.

We indeed observe a - relatively strong - effect of increasing exports when U.S. West Coast ports are allowed (Figure 6.6). The effect is almost the same in the US_bottom_up and EIA_reference scenarios, with exports more than 150 Mtpa higher in the ports scenarios than in the baseline scenarios. This is the effect of the global demand assumptions, which

---

[29] In other words, as formulated by an analyst, the U.S. "come in when there are problems in the market" (https://foreignpolicy.com/2018/04/04/trump-makes-american-coal-great-again-overseas/, last accessed April 28, 2020).

in these two scenarios are based on the "Stated Policies Scenario" (IEA 2019b) coal demand trends - which include a stable coal demand over time. In contrast, even a moderate global climate policy scenario such as the GCAM_carbon_policy scenario forecasts only a low level of U.S. exports, even when West Coast ports are allowed (about 50 Mtpa in 2050). In the ambitious climate policy scenario 1.5°C, the U.S. also cease exporting after 2020 when West Coast terminal investments are allowed.

For a marginal supplier as the U.S., prudence on investments in the coal value chain is a good idea in times of high uncertainty. The breadth of our scenarios - which are all more or less realistic and plausible (except probably for the "no-policy" scenarios GCAM_no_policy and GCAM_no_policy_ports) - gives an indication of the wide range of possible outcomes for the U.S. coal sector. Between an extensive phase-out of coal in the 1.5°C scenario which complies with the commitments in the Paris Agreement and a stability of U.S. coal production at 2018 levels above 600 Mtpa with high domestic consumption and exports in the EIA_reference_ports scenario, there is a spread of more than 300 Mtpa in exports and 600 Mtpa in production. However, the strong spread in outcomes between the different scenarios shows that assets in the U.S. coal value chain continue to be at risk of becoming stranded if a lower demand scenario realizes than envisaged at the moment of the investment decision.

Export dependency on world regions with uncertain demand development is only reinforcing the uncertainty on domestic demand (Shearer et al. 2020). As marginal suppliers, the U.S. exporters do not have much of a choice where to export to. However, markets such as India, Vietnam, or Pakistan that only recently still counted an impressive pipeline of coal power plant projects have recently considerably reduced their project numbers, mostly under the influence of lower renewable costs.[30] Moreover, the Corona pandemic - and the accompanying energy demand reduction - is likely to reinforce the trends of increasing renewable use and phase-down of coal use (Oei, Yanguas-Parra, and Hauenstein 2020). This means that coal import requirements may well be considerably lower than the status quo demand that we model, and closer to demand in the climate policy scenarios, which eventually come with a phase-out of coal before 2050.

6.5 Competition between U.S. coal regions?

In the last two decades, the U.S. coal sector has seen a shift of importance away from Appalachian coal to a dominance of PRB coal. While both regions had an equal share of U.S. coal production in 2002 (36 %), the Powder River Basin now supplies almost half

---

[30] Also see a recent short analysis by Feaster and Cates in https://ieefa.org/ieefa-u-s-why-exports-wont-save-american-coal/, last accessed October 11, 2020, and Wamsted, Feaster, and Cates (2020).

of the U.S. coal (43 % in 2018) and Appalachia only a quarter (26 %). Appalachia has also suffered from the rise of coal from the Interior region (from 13 % in 2002 to 20 % in 2016 and 18 % in 2018). The shift was due to a multitude of factors such as the location of demand, the low sulfur content of PRB and Interior (Illinois) coal, but importantly also the low costs of production in very large opencast mines in the PRB compared to smaller mines and many (inherently expensive) underground mines in the Appalachia region. This long-run trend was reinforced by a pronounced relative production cost increase in Appalachia which was mainly due to declining labor productivity (Jordan, Lange, and Linn 2018).

However, there starts to be an understanding that PRB will not be safe from the mine closure trend that started in Appalachia - which comes hand in hand with job losses, which mean not only wage losses but also health and pension benefit losses.[31]

Total U.S. coal production varies over different scenarios as shown above. However, the scenarios' trends do not unfold evenly in all four U.S. steam coal production regions. Figure 6.7 shows exemplarily the production in the four production regions for the EIA_reference, the US_bottom_up, and the 1.5°C scenarios. Furthermore, it shows where the produced coal goes to, i.e. the five U.S. consumption regions and exports.

In the EIA_reference scenario, coal production in the Interior and the Rockies remains relatively constant between 2020 and 2050, while it declines steadily in Appalachia and PRB. PRB coal goes mainly to the North and South Central demand regions where demand declines somewhat over time. However, PRB still produces as much as all the other regions together by 2050. Appalachia loses more and more of its domestic customers and depends largely on coal exports to the international market.

The US_bottom_up scenario shows a drastically different picture, especially for PRB. Production declines in all basins due to significant domestic demand reductions, but PRB cannot compensate the immense decline of demand in North and South Central by similar amounts of exports due to its landlocked location. For Appalachia, the Rockies, and the Interior exports play a significant role to prevent larger production cuts. Already by 2030, Appalachia produces almost solely for the international market. This shows the importance of taking the vintage structure of the power plants into account, as in the US_bottom_up scenario. Figure E.3 in the Appendix E shows the differences in regional U.S. coal consumption for the years 2020-2050 between the scenarios.

In the US_bottom_up_ports scenario with West Coast export expansion possibilities, additional U.S. production comes from PRB (compared to scenario US_bottom_up). Production levels in Appalachia, Interior and the Rockies are similar to the baseline scenario.

---

[31] See, for example, https://www.vox.com/energy-and-environment/2019/7/9/20684815/coal-wyoming-bankruptcy-blackjewel-appalachia, last accessed October 11, 2020.

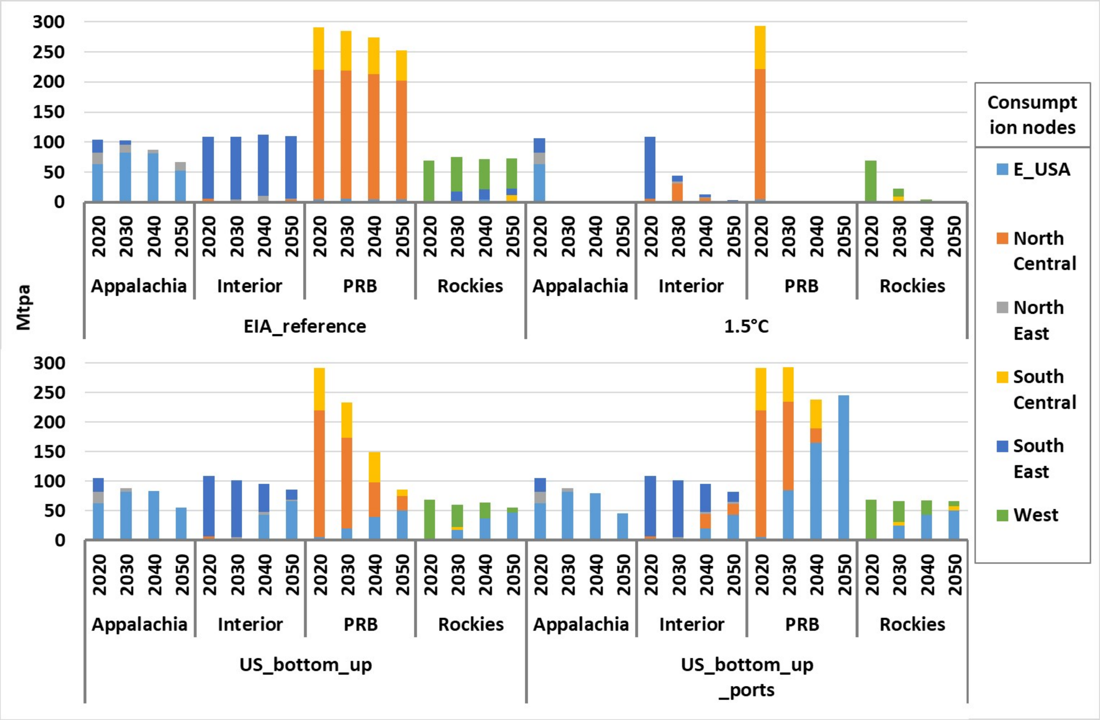


Figure 6.7: Disaggregation of supplies by U.S. coal regions (x-axis) to domestic consumption regions and exports (E_USA) 2020-2050 in Mtpa (in scenarios *EIA_reference*, *1.5°C*, *US_bottom_up*, and *US_bottom_up_ports*).

PRB even reduces its domestic sales (to North Central) to export more, while Interior and Rockies shift some of their domestic sales to North Central and South Central.

In case of stringent global climate policies (1.5°C scenario), reducing coal demand in the U.S. and globally, coal production ceases in Appalachia and PRB as early as 2030. International demand will not compensate for domestic decline in this case. Thus, betting on increasing exports in the future might be a risky game for U.S. coal producers, in particular in the Appalachia region which is highly export-dependent.

Altogether, we find three drivers of regional production trends:

1. Differences in regional U.S. demand (due to differing assumptions on coal power plant fleet development) lead to substantially different regional supply mixes.
2. Allowing for new West Coast ports leads to a different regional allocation of supplies and, generally, comes with a higher production by PRB.

3. The development of demand in the export destinations, determined i.a. by climate policy, leads to a different regional supply structure in the U.S. because the regions do not have equal access to export capacities (different costs and capacities).

Overall, we see a continued decline of production in Appalachia across the different scenarios. The future of PRB production could be bleak if domestic demand continues to decline, especially in U.S. North Central and South Central consumption regions. Additional export terminals along the U.S. West Coast could ease production cuts in PRB, provided global demand is sustained. However, they are very unlikely in the regional context of strong opposition by the population, the regulators, and policy makers (Mendelevitch, Hauenstein, and Holz 2019).

This will also affect further development of employment in the coal sector. According to the EIA, around 50,000 direct employees worked in coal mining in the years 2016-2018, down from 92,000 in 2011.[32] Large regional differences exist in numbers of jobs per region, as well as the productivity (output of coal per working hour). More than 50 % of the U.S. coal mining jobs are in Appalachia, around 20 % in Interior, and around 10 % each in the Rockies and PRB. Labor productivity in Appalachia, where coal is mostly produced in underground mines, is only about half of the value in the Interior basin and the Rockies. It is only 10 % of the productivity in PRB where very large opencast mines operate (see Table E.1 in the Appendix E for details).[33] Thus, comparatively small reductions of Appalachian coal production could lead to a larger decrease of overall coal mining employment than major production cuts in PRB. On the other hand, increased PRB production in case of improved access to Asian markets might only slightly alleviate U.S. coal mining employment issues.

Considering our results for future U.S. coal production, coal mining employment is likely to decrease in all U.S. coal regions. However, this does not necessarily have to induce negative long-run consequences for these regions. Much in contrast, other authors found that U.S. coal regions, in particular but not exclusively Appalachia, have suffered from a resource curse with lower education levels and lower long-run economic growth than comparable regions without coal (Douglas and Walker 2017).[34] In any case, the prospect of job losses

---

[32] EIA coal data browser, „Aggregate coal mine average employees"; https://www.eia.gov/coal/data/browser/, last accessed May 10, 2020. This includes jobs in lignite and coking coal mining, which we estimate to account for about 10-15 % of all coal mining jobs, based on shares of production and productivity in different mine types. There is no data on subcontractor employment from this source, and data from other sources is incomplete.

[33] However, labor productivity in PRB was 64 % higher in 2001 than 2014-2018. A generalized labor productivity decrease was observed in all U.S. coal mining basins in that period: by 49 % in Appalachia, 17 % in Interior, and 35 % in the Rockies. This is somewhat surprising given the global trend to improvements in labor productivity due to increased automation.

[34] Betz et al. (2015) do not find a negative effect on per capita income of coal mining regions, but a significant negative on entrepreneurship which is a factor of long-term economic growth.

in the next decades could be mitigated if economic policies helped mine workers compensate for losses of income, and health and pension benefits on the one hand, and convert to other jobs on the other hand. The experience in Appalachia has shown that without compensation policies, income losses and political radicalization may be lasting (Weber 2020).

6.6 Conclusion and Policy Implications

While in many countries around the world, governments and utility companies have started to engage in coal-phase out processes, the U.S. still mourn the heydays of its coal sector. In this paper, we take a closer look at the U.S. coal sector and put into perspective the coal sector numbers of EMF34 and the U.S. Energy Information Administration. We use a coal-sector model to show the implications of various EMF34 scenarios and contrast them with our own scenarios that take into account the current downward trend of coal. We argue that the “downward spiral” of U.S. coal is triggered by drivers that lie outside the coal sector - mostly competition from cheap shale gas and renewables - and will, therefore, not be stopped. Our scenario results show that it can, at most, be delayed. Moreover, the coronavirus pandemic may well lead to speeding up the downward trend in the U.S., too.

We show that a status quo scenario that takes realistic - and even conservative - assumptions on lifetime and capacity factor, as well as investments of U.S. coal power plants, leads to a considerably lower U.S. coal production and consumption than a scenario based on EIA assumptions. Moreover, scenarios with U.S. and global climate policy efforts, lead to even lower U.S. coal production and consumption. However, there is a noticeable difference in the exact levels depending on the climate policy stringency. Among our scenarios, only the ambitious 1.5°C climate policy scenario would lead to a phase-out of U.S. coal by 2050. A moderate climate policy, such as the one suggested by GCAM in EMF34, could still see around 300 Mtpa coal production in the U.S. by 2050.

We soft-link with the GCAM model as the one example of the EMF34 model suite with relatively high coal consumption levels in its reference and carbon policy scenario. Yet, also most other models project relatively high coal shares in 2040 in their reference cases (Figure 6.1). We argue that a more detailed consideration of the coal sector could enhance robustness of model results. Our detailed coal-sector model results for the U.S. suggest that the EMF34 results for U.S. coal are rather high-end estimates while current markets trends push coal’s share in the U.S. energy mix most likely significantly lower.

The decline of U.S. coal production can be delayed by increasing exports, and most prominently if exports to the energy-hungry Asian economies via the U.S. West Coast were possible. In the - unlikely - case of U.S. exports via the West Coast, U.S. coal production can increase in the long run by up to 150 Mt per year. However, betting on exports is a risky strategy for U.S. producers because they are the marginal suppliers to the world's import markets due to their comparatively high costs. Asian coal expansion plans are becoming more and more uncertain because these countries can benefit from cheap renewables, too. "The myth of export-market expansion" (Wamsted, Feaster, and Cates 2020) has given hope and artificial respiration to parts of the U.S. coal sector for more than a decade but it is becoming ever more unlikely.

Yet, the breadth of our scenarios gives an indication of the wide range of possible outcomes for the U.S. coal sector. Between a Paris-compatible 1.5°C scenario and a scenario with stable U.S. coal production at 2018 levels with high domestic consumption and exports in the EIA_reference_ports scenario, there is a spread of more than 300 Mtpa in exports and 600 Mtpa in production. However, the strong spread in outcomes between the different scenarios shows that assets in the U.S. coal value chain are at a substantial risk of becoming stranded if a lower demand scenario realizes than envisaged at the moment of the investment decision. In fact, such stranding - and subsequently mothballing - of mines has been seen across the USA in the past decade, as the upstream effect of shutting down more and more domestic coal-fired power plants. The loss of value of previously high priced assets such as coal mines has caused multiple bankruptcies in the U.S. coal sector - and our results, in addition to the increasing funding problems, suggest that the series of bankruptcies may well continue.

Recent political attention focused on the Appalachian coal region. This region lost most coal jobs, both in relative and in absolute numbers in the last decades due to the hard mining conditions in small and underground mines. Our numerical results show that the Powder River Basin region - where large opencast mines allow for much higher productivity - similarly will be strongly affected by the decline of U.S. coal consumption in the next decades. This is due to the regional supply structure within the country: PRB delivers to regions where coal power plants are nearing the end of the lifetime. The two other basins, Interior and Rockies, are more resilient because they supply regions with a younger coal power plant fleet.

Our results are a warning for policy makers in the U.S. to start action. The decline of U.S. coal is inevitable and actions must be taken to guarantee a fair and just transition out of coal to the mining communities. The experience of the last decades was that coal mine bankruptcies led to income and pension losses for miners, while company owners could escape from their entrepreneurial responsibilities.

The Energy Modeling Forum and the U.S. Energy Information Agency provide important input to U.S. energy policy-making. Credible and realistic scenarios are necessary to guide policy decisions that can be sustaining in the long-run. The EIA therefore needs to put an increased effort in updating its own scenario assumptions to the reality of the U.S. power sector. It is not helpful for the affected communities to provide the illusion of hope for a recovery of the U.S. coal sector when adaptation to the new reality is needed instead. The EIA has made small steps in adjusting its AEO scenario assumptions in the last few years, however, it now needs to be more ambitious.

Chapter 7

Overcoming political stalemates: The collaborative governance experience of the German Coal Commission

---

This chapter is based on joint work with Isabell Braunger, Alexandra Krumm, Hanna Brauers and Pao-Yu Oei currently under review in *Climate Policy*.

7.1 Introduction

To meet the international 1.5°C (or well-below 2°C) climate target, a substantial decline in global coal consumption is needed by 2030 (IPCC 2018a, 2022). However, despite the reduction of coal consumption in some countries, global consumption has remained relatively flat over the last decade (IEA 2020a). At the UN Climate Change Conference in Glasgow (2021) the international community has agreed to phase down global coal (UNFCCC 2021), renewing impetus to address a timely transition away from coal. In individual countries, societal and political pressure to deliver on climate mitigation and to phase out coal is growing (Blondeel, Van de Graaf, and Haesebrouck 2020; Rinscheid and Wüstenhagen 2019). However, in other countries, the future of coal remains highly contested, due to economic dependencies on coal, fear of job losses, and incumbent actors profiting from the status quo (Diluiso et al. 2021; Jakob et al. 2020; Newell 2018; Jewell et al. 2019). This can lead to stalemate situations between opposing stakeholders, with the incumbent system increasingly becoming under pressure, however, still able to prevent or delay a transition away from fossil fuels, such as coal (Brisbois and Loë 2016; Leach, Scoones, and Stirling 2010; Sabatier and Weible 2007; Seto et al. 2016). A few countries, such as Canada, Chile, and several European countries, have announced a coal phase-out in recent years (Europe Beyond Coal; Ritchie 2021). However, in most of these countries, coal only played a subordinate role in the energy system and in terms of employment at the time of the decision (Blondeel, Van de Graaf, and Haesebrouck 2020; Jewell et al. 2019; IEA 2019a).

A notable difference is Germany, the world's largest lignite producer and consumer, with high economic and social dependence on coal in some of its coal mining regions (Jewell et al. 2019; Oei, Brauers, and Herpich 2020). Based on the recommendations of a stakeholder commission, the "Commission on Growth, Structural Change and Employment", hereinafter referred to as the (Coal) Commission, Germany determined to phase out coal consumption and production the latest by 2038, and to implement structural change measures for affected regions (Gürtler, Löw Beer, and Herberg 2021). The agreement of the Coal Commission received wide attention and was celebrated by many as a milestone to phase out coal, after several political attempts to reduce Germany's use of coal in previous years had failed due to overwhelming resistance by supporters of a continued use of coal, within and outside of governing parties (Furnaro 2022; Hermwille and Kiyar 2022). Particularly, the coal industry and related unions, energy-intensive industries, as well as politicians in coal mining regions tried to stall any policy to reduce coal use in Germany (Hermwille and Kiyar 2022; Kalt 2021; Leipprand and Flachsland 2018).

Collaborative (or participatory) governance CG approaches, such as the Coal Commission, are considered to offer possibilities to overcome stalemate situations and promote consensus-oriented decisions that exceed lowest common denominator compromises in previously highly contested issues (e.g., Emerson and Nabatchi 2015; Sabatier and Weible 2007). However, lack of win-win scenarios, strong belief heterogeneity, or power imbalances among participants can limit the success of CG (Brisbois and Loë 2016; Dutterer and Margerum 2015). Considering conflicts over the future of coal, scholars argue that just transition objectives and stakeholder involvement could contribute to achieve timely and equitable coal phase-outs (Diluiso et al. 2021; Jakob et al. 2020; Muttitt and Kartha 2020).

In the Coal Commission, representatives of different interest groups were supposed to develop recommendations for a phase-out pathway and closing date for coal, and measures to support structural change in affected regions (BMWi 2019). Due to a history of intensive conflicts and highly diverging objectives among stakeholders, many questioned beforehand if the Coal Commission could resolve the issues at hand, while others criticized it for being not ambitious enough in its climate objectives (Grothus and Setton 2020; Gürtler, Löw Beer, and Herberg 2021; Hermwille and Kiyar 2022). However, in the end the Commission achieved to develop and pass recommendations supported by all influential actors in the related German context, achieving a high level of legitimacy for these recommendations and overcoming the previous stalemate situation (Gürtler, Löw Beer, and Herberg 2021; Praetorius et al. 2019).

In this paper, we assess how the stalemate situation in the German conflict over the future of coal was overcome, enabling the agreement on a coal phase-out in Germany. We focus on the process of the "Commission on Growth, Structural Change and Employment" and the question, how this Commission achieved to breach the previous stalemate situation and how the final recommendations were formed.

To assess this stakeholder commission process and the formation of its final recommendations, we apply the integrative framework for collaborative governance (IFCG), introduced by Emerson, Nabatchi, and Balogh (2012). This framework enables the systematic and empirical assessment of CG processes. For the empirical analysis, we use semi-structured interviews conducted with 18 participants of the Coal Commission and qualitative content analysis (Gläser and Laudel 2010). Our findings may help to further the debate on politics of phasing out coal and achieving just transitions, and contested sustainability transitions in general. In particular, our findings may inform similar stakeholder commission processes in other countries or of other unresolved issues, such as the future of fossil fuel consuming industries.

This paper is structured as follows: Section 7.2 presents the IFCG and methods applied. Section 7.3 presents the analysis of the Commission's system context, drivers, and regime formation. In Section 7.4, we present the findings on the dynamics of the Commission. We discuss our findings in Section 7.5 and in Section 7.6 follows our conclusion.

7.2 Theoretical approach and methodology

In Germany, so-called *expert commissions*[1] have a long tradition in the political system, providing advice on a specific topic on an ad hoc basis, or as institutionalized permanent councils (Krick 2013; Siefken 2016). The German Coal Commission is a typical example of such an expert commission with its mandate for policy formulation and its participants fulfilling the dual role of representatives or stakeholders, and at the same time of experts to their specific fields (cf., Krick 2015). In the literature on CG this corresponds to an externally directed collaborative governance regime (CGR) (cf., Emerson and Nabatchi 2015, Chapter 8).

The integrative framework for collaborative governance by Emerson, Nabatchi, and Balogh (2012) builds on a wide range of literature for the analysis of different forms of collaboration and collaborative processes (e.g., Ansell and Gash 2007; Innes and Booher 1999), and has been widely used to assess collaborative (governance) processes (Emerson and Nabatchi 2015). We use the IFCG to structure our analysis of the Coal Commission and the decision-making process of its members.

7.2.1 Integrative framework for collaborative governance

Figure 7.1 depicts the IFCG as three nested layers comprising the outer system context and the collaborative governance regime (CGR), which contains the collaboration dynamics and actions.

The system context includes the “political, legal, socioeconomic, environmental and other influences that affect and are affected by the CGR” (Emerson, Nabatchi, and Balogh 2012, 5). *Drivers* from the system context form and influence the direction of a CGR. This can include, in the case of externally directed CGRs (cf., Emerson and Nabatchi 2015, Chapter 8), the formulation of a mandate and the selection of participants. Emerson and Nabatchi (2015, 44) posit that the following four drivers are necessary to initiate a CGR and motivate relevant stakeholders to engage: “(1) uncertainty, (2) interdependence, (3) consequential

---

[1] Siefken (2016, 3) defines expert commissions in the German political system as „temporary appointed bodies (···) [whose members] for the most part come from the science community and interest groups -but not predominantly come from the parliament, government, and administration. They are tasked with providing subject-specific sound advice for policy plans, programs and measures” (own translation). Krick (2015) speaks of hybrid advisory committees, yet addressing the same bodies.

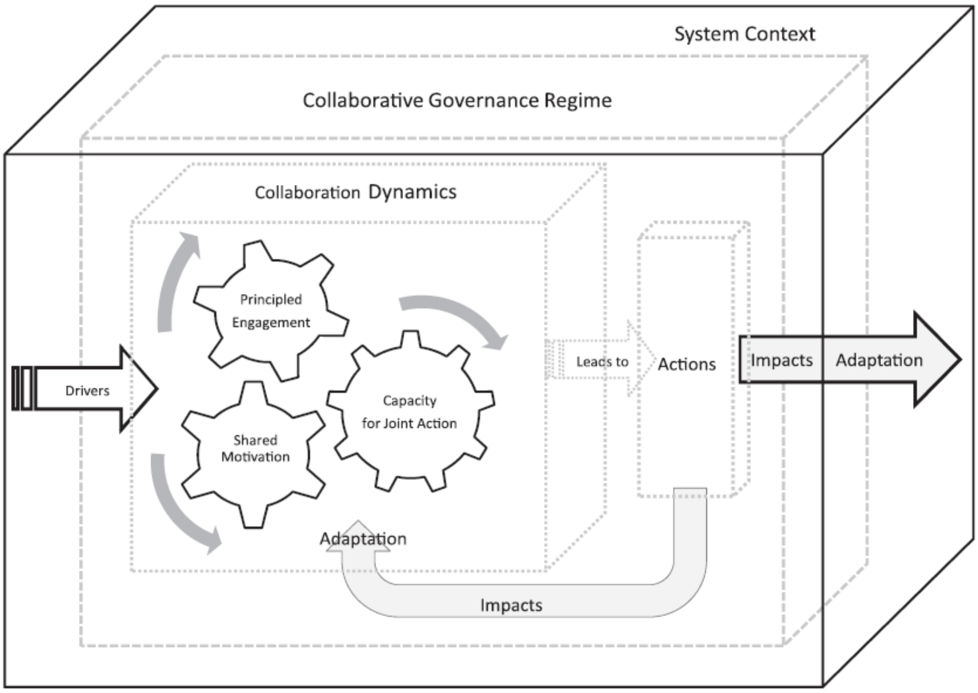


Figure 7.1: The integrative framework for collaborative governance. Reproduced with permission from Emerson, Nabatchi, and Balogh (2012).

Source: Emerson, Nabatchi, and Balogh (2012, 6).

incentives, and (4) initiating leadership". We lay out the system context, drivers, and regime formation of the Coal Commission in Section 7.3.

The CGR encompasses the process of collaboration among the participants, as well as possible actions resulting from this collaboration, which can influence both, the ongoing collaboration, or the outer system. At the heart of the CGR are the collaboration dynamics, which can lead to collaborative actions or outputs, such as a piece of policy advice. They consist of ***principled engagement, shared motivation,*** and ***capacity for joint action***, which are in iterative interaction with each other (as depicted in Figure 7.1). Each collaboration dynamic comprises further elements (see Section F.1 in the Appendix F for details):

- *Principled engagement* relates to an effective engagement of all participants, enabling fair and inclusive discussions and decision-making among participants, which seeks "to solve problems, resolve conflicts, or create value together" (Emerson and Nabatchi

2015, 58–59). It comprises the four elements *discovery, definition, deliberation*, and *determination.*

- *Shared motivation*, with the four elements *trust, mutual understanding, internal legitimacy*, and *commitment*, fosters the participants' engagement with each other and in the CG process.
- *Capacity for joint action* "is the functional dimension of collaboration dynamics that enables participants to accomplish their collective purpose ⋯[and] is conceptualized as the combination of four elements: *procedural and institutional arrangements, leadership, knowledge*, and *resources*" (Emerson and Nabatchi 2015, 68–69).

7.2.2 Data collection and analysis

We conducted 18 semi-structured expert interviews with members of the Coal Commission or their personal assistants, and the administrative office between November 2020 and March 2021 (chairs and administrative office (4); affected regions and communities (3); environmental associations (4); science (1); trade unions (2); business/industry (3); other (1)). Interviews with participants of the Commission process served to provide information on the inner working procedures, events, and interactions among participants. The interviews lasted between approx. 60 and 90 minutes and were conducted in German. Due to the COVID-19 pandemic, only one interview was conducted in person, all others via the video-conference tool Zoom.[2] The interviews were recorded and transcribed, resulting in 469 pages of interview data.

We used a qualitative content analysis approach (Gläser and Laudel 2010) to process the interview data. We coded for 18 categories using the coding tool provided by Gläser and Laudel (2010). Twelve categories were deducted from the twelve elements of collaboration dynamics of the IFCG (see Section 7.2.1). We added inductively six categories on: 1) stakeholder networks within the Commission; 2) external influences on the Commission's work; 3) represented interests; 4) covered topics; 5) suggestions for improvements of Commission work; 6) other.

Additional information which we use in particular to describe the system context, the drivers and the formation of the Coal Commission is knowledge that was acquired during a research project from 2017-2022 on the German coal phase-out process, including numerous visits to all coal regions and regular meetings with all involved stakeholders, as well as through the insights of published reports, research articles, and documents from the Commission process.

---

[2] To ensure data protection, a university version of the software was used.

7.3 The Coal Commission: System context, drivers, and regime formation

As the IFCG describes, processes and developments within the studied CGR need to be seen in the historical and surrounding system context, and depend on drivers enabling and forming the CGR. In this section, we commence with the historical developments and situation in Germany that led to the initiation of the Coal Commission and composes the system context in which the Commission was situated. This is followed by the drivers and incentives for participation, and the initial formation of the Commission.

Germany began to manage the reduction of hard coal (Oei, Brauers, and Herpich 2020) and lignite mining (Stognief et al. 2019) back in the 1960s. Reasons for the decline in mining were globalization (as imported coal was cheaper) and the later unification of Germany (since industries in the East were less cost effective than those in the West). Overall employment in the coal sector decreased from approximately 600,000 in the 1950s to less than 20,000 direct jobs in 2020. About 40% of German power production in 2017 was based on coal, down from more than 50% up to 2002.[3] In the late 2000s, however, incumbent utilities were still planning to expand coal-fired power generation capacities, and expecting only a slow growth of renewables (Kungl and Geels 2018). Even in the early 2010s, a phase-out of coal power in Germany, parallel to the phase-out of nuclear power, was barely considered in the political debate (Furnaro 2022).

Towards the mid-2010s, pressure on the coal sector increased. Germany was expected to fall short of its 2020 climate targets, and, furthermore, the Paris Agreement made it seem inevitable that coal use would have to be reduced (Leipprand and Flachsland 2018). Several attempts to regulate the phase-out of coal failed due to resistance by the utilities and mining companies, which saw their business model threatened, and industry actors, which were worried about rising energy prices (Furnaro 2022). In 2016 the so-called ‘safety standby’ was implemented, which compensates a few selected lignite power plants for shutting down, but failed to initiate the complete phase-out of coal (DIW Berlin, Wuppertal Institut, and Ecologic Institut 2019). Decisions on the future of coal by the governing coalition of CDU/CSU and SPD was further complicated because “(⋯) the conflict lines did not seem to fall between but within the major political parties, at least the SPD and CDU” (Hermwille and Kiyar 2022, 29). Within the Federal Government, the Ministry for Economic Affairs had tended to argue in favor of the continued use of coal prior to the establishment of the Coal Commission, while the Ministry for the Environment had continuously argued in favor of a phase-out (Markard, Rinscheid, and Widdel 2021). In general, however, the

---

[3] Energy-Charts: Annual net electricity generation in Germany. Available online: https://www.energy-charts.info, accessed on November 19, 2021.

government had been in favor of moderate rather than radical change (Leipprand and Flachsland 2018).

After being strictly against any measures for an early phase-out, a number of unions including Verdi started to consider options for a policy-induced coal phase-out. However, other trade unions, such as the IGBCE,[4] continued to lobby for continued coal mining (Kalt 2021). Mining regions feared that they would face negative economic and social consequences due to job and tax revenue losses, and demanded financial support to manage the upcoming transition (Oei, Hermann, et al. 2020). On the other hand, local residents feared losing their homes due to the destruction of villages in the event of continued coal mining, and environmental NGOs called for a coal phase-out between 2025 and 2035 (Löw Beer et al. 2021).

Overall, this created a situation of high uncertainty over the future of coal in Germany, with none of the interest groups powerful enough to enforce a decision (Hermwille and Kiyar 2022; Leipprand and Flachsland 2018). The positions around the debate of coal were so divergent that a top-down decision from the government would have been very vulnerable to criticism from all sides, offering little to gain for political parties (Löw Beer et al. 2021). As early as 2016, the Federal Government announced the establishment of some kind of commission in their Climate Protection Plan 2050.

In 2018, the then newly appointed Federal Government implemented the Coal Commission (Grothus and Setton 2020). The appointment resolution, or mandate, of the Commission set out the task to develop an “action program” by the end of 2018 (BMWi 2019, 109). This action program was to ensure the achievement of the Climate Action Plan 2030 target for the energy sector (-61 to -62 % emission reduction compared with 1990 levels), while supporting structural change and economic development in affected regions, including the establishment of a fund from primarily federal resources for structural change. Furthermore, it was to include a pathway and a final date for the phase-out of coal-fired power generation. All these aspects were to be combined in a manner to achieve social acceptability and social cohesion (BMWi 2019, 109).

The literature highlights the importance of incentives for cooperation and as a starting point for participation, which played a crucial role in relation to the Commission (Emerson and Nabatchi 2015). Considering the stalemate situation, highly contentious environment, and uncertainty in the debate about the coal-phase out over the years (Hermwille and Kiyar 2022; Leipprand and Flachsland 2018), the Commission presented the opportunity to get negotiating power and influence over the future of coal in Germany, as well as the distribution of funds for structural change. Furthermore, the Commission provided

---

[4] Industriegewerkschaft Bergbau, Chemie, Energie –Trade union for mining, chemicals and energy industries.

a starting point to collaborate across boundaries (Gürtler, Löw Beer, and Herberg 2021; Hermwille and Kiyar 2022).

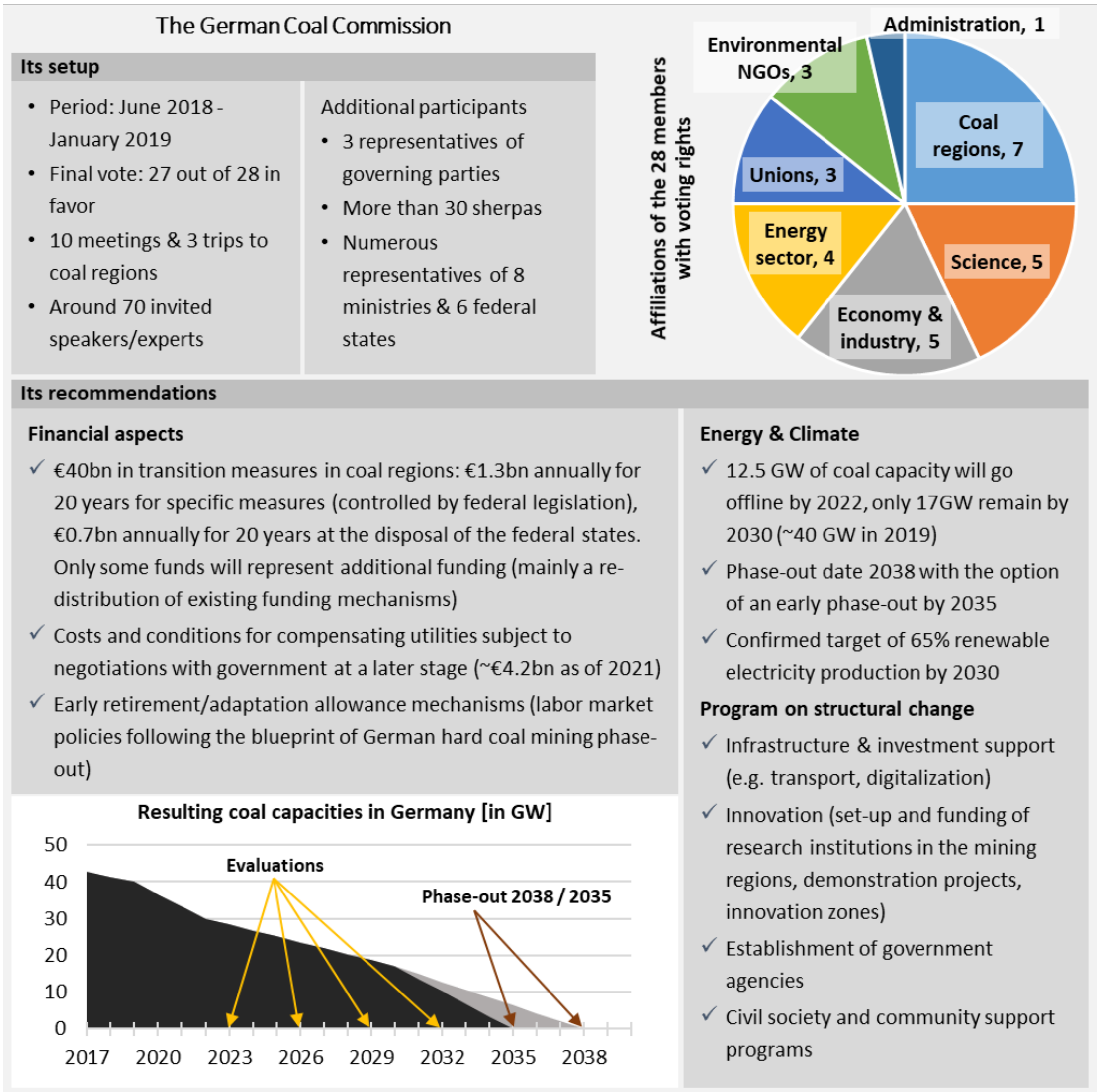
The selection of members and the initial formation of the Commission also played a role in stakeholders deciding to join the Commission (Emerson and Nabatchi 2015; Gürtler, Löw Beer, and Herberg 2021). The Commission comprised four chairs and 24 stakeholder representatives with voting rights (hereinafter referred to as (Commission) members). In the run-up to the Commission, established actors were asked for advice, as well as lobbied for the inclusion of certain stakeholder groups (Grothus and Setton 2020). In the end, the Commission represented the major interest groups involved in discourse on coal in Germany at that time (cf., Leipprand and Flachsland 2018; Markard, Rinscheid, and Widdel 2021).[5] Figure 7.2 shows the different general stakeholder groups represented by the Commission members. However, interests within those stakeholder groups were anything but homogeneous. For example, out of the seven regional representatives, two were against continued mining, representing communities at risk of destruction, while four were in favor of continued mining, for example, due to the impact on jobs. Considering the members' general positions regarding an early coal phase-out, around one third each of the 28 members were considered as being inclined towards an early coal phase-out, against it, or undecided, based on their institutional affiliations. All 28 members were allowed to bring along with them personal assistants without voting rights, who were referred to as 'sherpas'. In addition, three members of the German parliament (from all governing parties), 8 representatives from related ministries and 6 members from federal states were appointed as participants without voting right -resulting in plenary sessions being held with around 100 participants. An administrative office was formed to support the Commission's work.

7.4 Coal Commission CGR: Developing joint recommendations for the German coal phase-out

In this section, we present our findings for the collaborative governance regime of the German Coal Commission. Based on the information collected in the interviews and documents, we assess how the Commission's members managed to find and agree on joint recommendations for a coal phase-out in Germany. In Table F.2 and Section F.2 in the Appendix F we present the results for the full list of elements of the CGR.

---

[5] Some people, however, criticized that no young persons and limited female representation was present in the commission (Gürtler, Löw Beer, and Herberg 2021).



The German Coal Commission

Its setup

- Period: June 2018 - January 2019
- Final vote: 27 out of 28 in favor
- 10 meetings & 3 trips to coal regions
- Around 70 invited speakers/experts

Additional participants

- 3 representatives of governing parties
- More than 30 sherpas
- Numerous representatives of 8 ministries & 6 federal states

Its recommendations

Financial aspects

- ✓ €40bn in transition measures in coal regions: €1.3bn annually for 20 years for specific measures (controlled by federal legislation), €0.7bn annually for 20 years at the disposal of the federal states. Only some funds will represent additional funding (mainly a re-distribution of existing funding mechanisms)
- ✓ Costs and conditions for compensating utilities subject to negotiations with government at a later stage (~€4.2bn as of 2021)
- ✓ Early retirement/adaptation allowance mechanisms (labor market policies following the blueprint of German hard coal mining phase-out)

Resulting coal capacities in Germany [in GW]

Energy & Climate

- ✓ 12.5 GW of coal capacity will go offline by 2022, only 17GW remain by 2030 (~40 GW in 2019)
- ✓ Phase-out date 2038 with the option of an early phase-out by 2035
- ✓ Confirmed target of 65% renewable electricity production by 2030

Program on structural change

- ✓ Infrastructure & investment support (e.g. transport, digitalization)
- ✓ Innovation (set-up and funding of research institutions in the mining regions, demonstration projects, innovation zones)
- ✓ Establishment of government agencies
- ✓ Civil society and community support programs

Figure 7.2: The German Coal Commission: set-up and results.

Authors' depiction based on BMWi (2019).

The Commission convened for the first time on June 26, 2018. Nine further plenary meetings and visits to the three lignite regions of Germany were held over the next few months, culminating in a final report agreed upon by 27 (out of 28) members on January 25, 2019.[6] During its process, 67 additional external experts were invited to provide input so as to pave the way for a sufficiently fact-based decision-making process. Figure 7.2 shows the

---

[6] One person representing the Lusatian coal region voted against the outcome as her demands to guarantee the safeguarding of villages in Lusatia from potential destruction was not included in the final report.

Commission's central recommendations, which include a phase-out pathway for German coal-fired power generation, measures to support structural change in the affected regions, and financial support and compensation.

Establishing basics for collaboration and working structures

The challenge of the Coal Commission was to find compromises among the in part each other opposing objectives of the high number of involved stakeholders. Furthermore, many of the Commission's members and participants had been involved personally in the long lasting conflict over the future of coal production and power generation in Germany, and animosities among different members existed at the start [int_5; int_11]. However, as detailed in Section 7.3 above, the mandate offered a strong incentive for stakeholders to engage in the process of the Commission and thereby potentially be able to influence German energy and structural change policies.

The expert hearings during the first meetings in the Coal Commission, the site visits, and one joint dinner offered the opportunity to get to know the other participants without having to engage in (public) fierce discussions and bargaining [int_1; int_5; int_6; int_11; int_13]. Furthermore, these exchanges, as well as the later work in small and confidential rounds, contributed to improve the mutual understanding of positions and objectives, and to build up trust between members [int_1; int_5; int_8; int_10; int_13; int_16]. Confidence in the process and its effectiveness to find common solutions and recommendations was high among most members [int_1; int_8; int_10; int_16]. Over time, the majority of members became seriously engaged and were motivated to contribute to a successful outcome of the Commission [int_1; int_8; int_10; int_15]. Several interviewees pointed out that this built up mutual trust and understanding among members across divides of interest groups, and their shared commitment to the process were key enabling factors for constructive and enduring negotiations [int_5; int_11; int_16].

> "*[⋯] it was also a very important point in this Commission's work that Commission members from different camps trusted each other, trusted each other's professionalism, trusted each other's values, trusted each other to get through things.*" Interview_11.

Several interviewees mentioned that arranging more meetings of an informal nature, such as the one joint dinner, and earlier during the Commission's working period, would have been means of increasing trust and understanding among members even further [int_1; int_3; int_5; int_11]. In contrast, leaks of information from plenary assembly meetings to the press challenged the trust in others and the process itself [int_2; int_5; int_7; int_8;

int_17], yet, other experienced negotiators were not surprised by leaks in such a political process [int_6; int_9].

The leaks, and the large size of the plenary assembly meetings, often with 100 or more participants, did not allow for a constructive working atmosphere in these meetings [int_10]. Members therefore rarely departed from their initial positions and little progress was made in these meetings, and the large size made it impracticable for drafting texts [int_5; int_12; int_14; int_16].

> "*[···]it became clear that a lot of time could pass in such a large group, but in the end there would be no coal compromise. And then there were considerations to convene a group of people who had been in the Coal Commission, who more or less represented all groups and were accepted by all. The group was then supposed to try to discuss and negotiate all the central issues in some form in as protected a space as possible.*" Interview_9.

Topical split: energy vs. structural change

The commission in one of their first meetings decided to split the group in two working groups, one for "Energy Industry and Climate Targets", and one for "Economic Development and Jobs in the Regions" (BMWi 2019, 111) to separate and ease the discussions and deliberations [int_8]. However, commission members did not want to be absent in either of the groups as the topics were closely linked and interest groups needed cohesion funds as well as phase-out dates as bargaining power. Besides agreeing on such funds, the environmental interest group had little to bargain within the discussions, except the threat of leaving the Commission [int_3; int_8]. Thus, after having met in these subgroups only once, it was decided to convene instead in the plenary assembly only [int_7].

The writing of the draft for a first report of the Commission in October 2018 was delegated to the administrative office. However, several members perceived this draft as politically influenced[7] and requested changes in the organizational and working structures of the Commission [int_5; int_11; int_14]. As a result, one of the chairs set up the first so-called *Friends of Chair* (FoC) group and selected six Commission members for it [int_11]

---

[7] The administrative office of the Coal Commission, tasked with providing administrative assistance in the form of organizing expert hearings and site visits, or drafting texts, was criticized for not working transparently, as well as for reaching politically influenced decisions [int_5; int_8; int_10; int_12]. This criticism was nourished by the staffing of the administrative office, which was thought to be politically motivated. For example, some staff had been posted from administrations of affected federal states [int_5; int_8].

The Friends of Chair groups

In this first FoC group on "energy and climate", two out of six members represented environmental interests, while the others represented the energy sector, industry, and unions.[8] Members representing locally affected people were not part of this FoC [int_5; int_6; int_9]. The second FoC group on "structural development and employment" was only implemented in November, after several federal state prime ministers had intervened and demanded greater support for affected coal regions. This second FoC group mainly included members that represented local and regional economic interests, as well as employees' and employers' interests. Several interviewees stressed that the adequate choice of their members, which needed to represent sufficiently all interest groups, be accepted by their constituency to negotiate in their name, and be willing to engage in finding compromises, was an important factor for the successful work of the FoC groups was [int_5; int_9; int_11; int_13].

These FoC groups, although not provided with an official mandate by the Commission's plenary assembly, became central institutions of the further deliberation process on the way to the joint recommendations. In these groups, the critical details were discussed and texts for the interim and final reports prepared [int_5; int_6; int_8; int_9]. Their intimate and high-level character contributed to foster trust and shared commitment among the involved members, and a goal-oriented working atmosphere [int_5; int_9; int_11; int_13]. The confidential nature of the FoC groups allowed their members to depart from their public demands, or temporarily surpass their constituency's "red lines" (which would not have been possible in public or in the plenary), to explore possible compromises [int_5; int_9]. From their initiation on until mid of December, the FoC groups convened very frequently, often multiple times per week [int_5]. In this process, the sherpas of the FoC members played an important role, meeting in FoC sherpa rounds, and preparing text drafts that then were further discussed and refined by the FoC members to be then introduced in the plenary assembly [int_5; int_10; int_11]. The plenary assembly remained the institution, where decisions had to be passed by a two-thirds majority to be included in the Commission's recommendations.[9]

---

[8] Members of the FoC energy & climate: Stefan Kapferer (BDEW), Stefan Körzell (DGB), Holger Lösch (BDI, Dieter Kempf' s sherpas), Felix Matthes (Öko-Institut), Kai Niebert (DNR), and Katharina Reiche (VKU). Members of the FoC structural development & employment: Christine Herntier (Mayor of Spremberg), Steffen Kampeter (BDA), Michael Kreuzberg (Head of the District Authority of Rhein-Erft-Kreis), Matthias Platzeck (Commission Chair), Reiner Priggen (Landesverband Erneuerbare Energien NRW), Gunda Röstel (Stadtentwässerung Dresden), Christiane Schönefeld (Federal Employment Agency), Stanislaw Tillich (Commission Chair), and Michael Vassiliadis (IGBCE). Source Löw Beer et al. (2021).

[9] While the mandate for the Coal Commission included the objectives and the list of appointed chairs and members, it did not specify the working procedures of the Commission. Thus, one of the first tasks of the Commission was to agree on and pass procedural rules for its work, which happened during the first plenary assembly meeting of the Commission [int_3; int_10]. It was determined that decisions would

The night of the final negotiations

The general parts of the final report were prepared by the FoC groups and the administrative office, and decided upon in the plenary assembly. However, key issues, like the concrete phase-out pathway and end date, and the size of the structural change fond, remained open questions and were not talked about in the plenary until the last day of the Commission [int_5; int_7; int_10]. After convening in the plenary assembly during the last day without resolving these issues, members of the FoC and the chairpersons met separately to negotiate compromises for these points [int_5; int_11].

First, a decision on the part on structural change was made, before starting the final negotiations on the coal phase-out pathway and date. Thus, compromises concerning the latter issues had to be reached within this same field, excluding compromises including structural change questions [int_3]. Furthermore, members of the environmental group generally supported demands for a just transition for workers and structural change in the affected regions, which members of the unions did not rejoin by an equivalent support vice versa. This eventually weakened the negotiating position of the environmental side towards the unions regarding an early phase-out [int_1].

These negotiations were led rigorously among the participants, including the utilization of the short-term absence of individual members to change previously reached formulation decisions with these members [int_11]. The members participating in these discussions then met during several pauses with the other members of their interest groups to consider possible compromises and red lines, and continue the negotiations based on these interest group positions [int_5; int_11]. Despite continuously large conflicts of interest and the tough style of the negotiations, members finally reached compromises for all remaining issues [int_11]. This was also driven by the fear of an overall failure of the Commission, if no solution would have been found during that night; the continuation of talks on the next day was no option due to the risk of leaks and resulting external pressure in case of any interruption of the negotiation talks [int_6; int_11].

The Commission's chairs

The role of the chairpersons was described as very ambiguously. Many of the interviewees perceived the chairs as advocates for certain interests,[10] and counterpart for the associated

---

have to be passed by the members with a two-thirds majority in the plenary assembly, which should guarantee that no decision could be passed without the consent of one of the major interest groups [int_3].

[10] Two chairs were associated with the structural and economic interests of coal regions, one was perceived as also representing Federal Government interests and one was associated with environmental interests.

interest groups only, rather than as neutral moderators [int_3; int_9, int_12]. Several interviewees also criticized missing concepts and moderation by the chairs to facilitate more inclusive exchange and communication within the Commission, and effective problem-solving approaches [int_5; int_11; int_13]. In the beginning, it remained unclear how the Commission would arrive at joint decisions or who would write the Commission's reports [int_3; int_7].

> "*[⋯] I don't think anyone [of the chairpersons] really had a concept of how a Commission has to go through different phases and then also come to results, which to some extent sees the different interests and then creates a balance of interests instead of the smallest common compromise.*" Interview_3.

On the other hand, several interviewees mentioned that the leadership by the chairs, and particularly by one of the chairs, who was perceived by many as the unofficial leader of the Commission (due to being most partisan and well connected to the government), was very important for the successful deliberations and decision-making in difficult situations [int_6; int_7; int_13; int_15; int_16]. It was also this chair who had chosen the members of the first FoC group, which was perceived as an important decision for the successful deliberations in this group [int_5; int_9; int_11; int_13].

Role of federal state representatives and national government

The federal states had representatives in the Commission in the form of two former federal states prime ministers, serving as chairs. In addition, each affected federal state could appoint an additional representative, sometimes being the active federal (prime) ministers having no voting rights but still very active participation during all sessions [int_3; int_5; int_11].

> "*[⋯] the prime ministers [⋯] not unskillfully maneuvered in such a way that the federal states had the right to intervene and speak in the Commission at any time. They made extensive use of this [⋯] so that the federal states were very, very strongly represented in the Commission with their statements.*" Interview_16.

It was considered important to address the interests of the federal states, as it was clear to the Commission members that they could potentially block the implementation of measures at a later stage [int_5; int_8; int_11]. The federal state governments involved had been strong supporters of continued coal mining in the past (cf., Hermwille and Kiyar 2022). Furthermore, the (former) prime ministers of Eastern federal states continuously expressed the fear of an early coal phase-out driving voters into the arms of the party of the extreme right, the *Alternative für Deutschland* (AfD), at the then upcoming federal elections [int_1;

int_7]. In November 2018, the Commission was about to agree on the first part of the final report on measures for structural change. However, the prime ministers considered the foreseen funds for affected regions as too low. Subsequently, Chancellor Merkel ordered the Commission to resume its work and revise its recommendations, effectively delaying the Commission and potentially increasing total funds for the coal regions [int_5; int_6; int_14].

The possibility to make relatively unrestricted recommendations for the size of the fund for structural change, the establishment of which was provided for in the mandate, comprising primarily federal resources (BMWi 2019), provided an important leverage for compromises. Federal state governments were willing to give up their opposition to the coal phase-out to some extent in turn for financial compensation [int_5; int_6; int_12; int_15].

> "*[...] because whether they get another billion or not for structural measures - that's decisive for a prime minister when he says I'm also getting the railway line. For the environmental side, which is fighting for the climate, it doesn't matter.*" Interview_16.

The Federal Government was furthermore indirectly involved in the Commission's work through its close contact to one of the chairs [int_9; int_14]. The ministries' representatives were not publicly active within the plenary sessions, but in the background, had continuous close consultations to check whether the discussed proposals could actually be implemented [int_11; int_16].

Members' participation possibilities and influence

Most interviewees stressed the different roles and participation possibilities of the individual Commission members. Depending on their negotiation experience, connectedness, expertise, and available resources (e.g., time, staff), members had higher or lower chances to influence the Commission's work [int_7; int_9; int_11] (also see Table F.2 in Appendix F). As described above, key deliberation processes took place outside of the plenary assembly, for example, in the FoC groups or bilateral talks in between sessions. Even though several interviewees stated that, the composition of FoC groups represented all interest groups [int_5; int_6; int_9; int_13], access to these groups remained exclusive [int_11]. This limited the possibility for many members to participate in deliberating the core contents, because they were constrained to introduce their opinion into these groups via other members of their interest groups [int_3; int_4; int_13; int_15]. For the coordination and consultation within interest groups, these met separately from the other Commission meetings throughout the process of the Commission [int_5; int_11]. Many decisions, like who would belong to the FoC groups, were not discussed nor decided by the plenary assembly, but by the chairs after consulting with individual members [int_3; int_5; int_11; int_12]. Members without experience in such processes found it hard to know how to introduce and enforce their demands in the right way, at the right place and the right time [int_4; int_12]. For example, while all members were able to make demands and suggest topics for debate in the plenary assembly, topics usually had to be supported by other influential members or FoC groups to be considered for debate within the FoC groups where the first drafts of documents were written [int_16].

7.5 Discussion

In the above analysis, we show how the German Coal Commission reached an agreement on the future of coal supported by all major interest groups (Hermwille and Kiyar 2022). Stakeholder commissions as such provide opportunities to resolve stalemate situations and to trigger off a ratcheting up of climate ambitions in the aftermath. Yet, it was also criticized for delivering a late and expensive coal phase-out within their recommendations. In the following, we discuss our findings on how the Commission achieved to breach the stalemate situation and how its final recommendations were formed.

The Commission created and fostered a collaborative environment, enabling the cooperative work on finding joint solutions. It provided a space for individuals representing the various interest groups to get to know each other on a personal level and engage in a direct exchange. This contributed to increase the level of mutual understanding and trust, and the willingness to find an agreement. This can be considered a major achievement of the Commission compared to the previous situation, in which pro- and contra-coal interest groups formed "enemy camps" (Grothus and Setton 2020, 283). Despite some drawbacks (e.g., limited opportunities for informal exchange among participants; insufficient confidentiality of Commission meetings), the Commission's members developed a shared commitment to engage intensively to achieve the Commission's objectives, a precondition for successful collaborative policy formulation processes (Ansell and Gash 2007; Emerson, Nabatchi, and Balogh 2012).

However, the willingness of the different interest groups to participate and engage in such a collaborative approach, working on compromise-based policy recommendations, depends on the lack of alternatives to enforce a unilateral policy formulation (Emerson and Nabatchi 2015; Sabatier and Weible 2007). The context of the German Coal Commission was characterized by the highly contested and uncertain future of coal, the lack of sufficient power for one interest group or coalition to enforce their interests (cf., Hermwille and Kiyar 2022), and political parties with more to lose than to gain from taking the responsibility for a decision (Löw Beer et al. 2021). In this situation, leaving the decision to a stakeholder commission offered policymakers the possibility to dilute responsibility and gain legitimacy for a derived policy (Gürtler, Löw Beer, and Herberg 2021), and interest groups the possibility to actively shape a possible policy formulation. On the other hand, the participants knew that it would be very difficult to enforce their interests outside of the Commission, and leaving the Commission would have born the risk of leaving the decision up to others.

Yet, aligning the objective of an early coal phase-out with (local) economic and political interests remained challenging. In the Coal Commission, this dilemma was eased by public funds at hand of the Commission to distribute among affected stakeholders -substantially burdening the taxpayers, without having them explicitly represented. This was possible to do so in Germany, given the economic capacities of Germany, and may not be possible in countries with less economic capacities or in times of crisis. In historic comparison, costs implied by these recommendations amount to only about one-fifth to one-third of the sum of subsidies paid to hard coal production in Germany between 1950 and 2008 (Hermwille and Kiyar 2022). Nevertheless, high costs and payments to individual stakeholders, if perceived as not serving the common good, bear the risk of reducing an agreement's legitimacy (Gürtler, Löw Beer, and Herberg 2021). Regarding gender aspects the Commission was less balanced: Although jobs in the affected regions are likely to be created in the service sector, in which women make up the majority of employees (Walk et al. 2021), discussions focused heavily on male dominated industrial jobs.

Gürtler, Löw Beer, and Herberg (2021) find that the German Coal Commission partly derived its legitimacy from its bottom-up rhetoric of including regional stakeholders' interests, yet ultimately led to recommendations for top-down policies. One reason for the limited bottom-up character of the recommendations might have been, apart from the comprehensive mandate (cf., Gürtler, Löw Beer, and Herberg 2021), the difficulties of stakeholders representing local interests to participate effectively in the Commission process, due to limited negotiation experience and other resources. Few influential members of the Commission drafted and decided largely upon key contents of the final recommendations, a regular issue of such participatory processes (cf., Brisbois and Loë 2016). A leadership more sensitive to such power imbalances as well as additional resources to level the playing field might be able to remove some of these barriers (Newig et al. 2018). In addition, younger generations and perspectives from countries most affected by the climate crisis were barely represented.

Overall, the Commission facilitated the members to decide on joint recommendations and with this overcoming the stalemate in the contentious environment. While the collaborative setting contributed to reconciling previously heated and emotional debates, it was also the very specific contextual situation at that moment in time in Germany that all veto players considered participating in the Commission and passing a joint agreement as best option to pursue their political interests.[11] Furthermore, the relatively costly approach with large public funds for structural change and other measures raises the question to what extent the German Coal Commission case could be an example for other phase-out decisions (cf., Hermwille and Kiyar 2022). Considering economic possibilities and functioning of government, similar processes to promote a just and timely coal phase-out might also be an option for some other major coal producing and consuming countries like Australia or the USA (cf., Jewell et al. 2019).

Limits to our study include, that it cannot be determined for sure whether a counterfactual policy formulation process, for example, a citizen forum, or simply a decision by the Federal Government would also have achieved a coal phase-out agreed upon by the diverse interest groups. Furthermore, our study is based on a single case in a wealthy country. Another advantage for the German coal commission was the existence of numerous studies that had investigated potential techno- and socio-economic effects of different coal phase-out scenarios in Germany. Since energy transitions in general are very context-specific processes, it is rather difficult to generalize our results. A comparative study, possibly including other forms of collaborative institutions such as citizen assemblies, could nevertheless help to improve our understanding of the possibilities of collaborative governance approaches to manage phase-out processes in line with ambitious climate targets.

7.6 Conclusions

The recommendations of the German “Commission on Growth, Structural Change and Employment” on a coal phase-out pathway and structural change measures were a major step to ending the use of coal in one of the world’s major coal consuming countries, easing the following decision by Europe to target climate neutrality by 2050. Prior to the Commission, the situation was “highly contentious” with counteracting objectives and heated debates between different interest groups leading to a stalemate situation in the debate about the necessary coal phase-out.

This paper explores the role of the Coal Commission to reach joint recommendations in the debate on the coal phase-out in Germany and how they were formed. We find that

---

[11] Not considered here due to the scope of the study, but relevant for further considerations are the later differences in the two laws that were passed to implement the coal phase-out and structural change processes compared to the Commission’ s recommendations. Therefore, key members of the Coal Commission publicly withdrew their support (https://www.dnr.de/presse/pressemitteilungen/mitglieder-der-kohlekommission-zur-aufkuendigung-des-kohle-kompromisses?L=928, last accessed March 31, 2022).

the Commission helped to find joint recommendations and overcome long standing stalemate situation by providing a safe space to build up trust and understanding which was important considering the highly contentious situation. The broadly defined mandate and the provision of public funds by the Federal Government largely defined the possible solution space for the Commission. It provided the mandate and significantly influenced the willingness of incumbent actors to participate and agree on a phase-out by offering high compensation payments to affected regions and companies. The political and economic pressure and absence of other alternatives contributed to actors willingness to engage in the Commission and find joint recommendations. Having shifted discussions in Germany from if to how to do a coal phase-out, enabled the next government to move the agreed-on phase-out date from 2038 to 2030.

Critical aspects concerning the work within the Commission are the fact that existing power imbalances influenced the way members could participate resulting in a domination of the decision-making process by certain members. Nevertheless, the Commission managed to overcome a decade-long stalemate that several other attempts by the government had failed to resolve. Its findings, are highly context specific, but provides valuable insights for other coal phase-out debated and participatory governance approaches. Further research can examine similar processes in other countries to draw overarching conclusions.

Appendix A

Appendix to Chapter 2: Stranded assets and early closures in global coal mining under 1.5°C

A.1 COALMOD-World version 2.0

CMW covers about 90 % of global steam coal production and consumption, represented by 22 coal producing nodes (geographically distinguishing the major coal producing regions), and 45 coal consuming nodes (major consuming countries and regions) (Holz et al. 2016). It is a dynamic partial equilibrium model formulated as mixed complementarity problem. The model features two stylized types of players, namely producers and exporters, which are represented by profit maximizing behavior under specific operational and technical constraints (compare Figure A.1). Players have perfect foresight and optimize profits over the entire model horizon. In line with empirical findings the steam coal market is modeled as being perfectly competitive (cf. Haftendorn and Holz 2010; Trüby and Paulus 2012; IEA 2013). Consumers are represented by inverse demand functions. Regional prices are endogenously determined in accordance with market clearing conditions. Hence, the decision to rely on imports or on domestic production of steam coal is an endogenous outcome of the model. Quality differences of steam coal across production regions are taken into account.

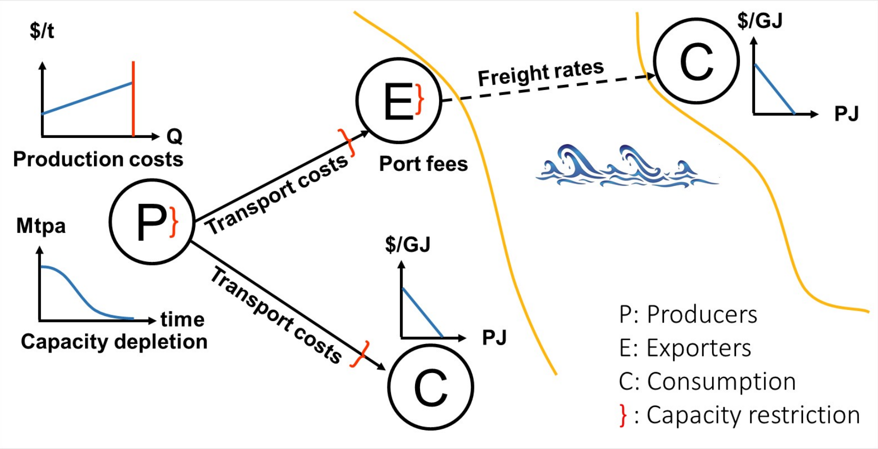


Figure A.1: Basic features of COALMOD-World v2.0 model structure. Reproduced with permission from Haftendorn, Holz, and Hirschhausen (2010).

Source: Adapted from Haftendorn, Holz, and Hirschhausen (2010).

Furthermore, the model features endogenous investment into production, transportation, and export capacities.[1] Once an expansion is profitable over the model horizon, an investment decision is made. The new capacity becomes operational in the subsequent period. Marginal production costs are assumed to increase with cumulative extraction. The model is calibrated for the year 2015, and 2020 consumption levels are fixed to values extrapolated from the 2015 to 2019 trends (IEA, n.d.) in order to take into account the market development trends of the past years instead of the COVID-19 induced short term effect on coal markets (IEA 2020c, 2021c).

The newly added retirement mechanism is explained in detail in the following sections. An additional new feature of the new model is a Chinese coal import quota that restricts the amount of annual imports into China, which is explained in section A.1.3. The complete mathematical description of the here introduced model version is provided in the Appendix A.4. For the model code see Hauenstein (2022b).

A.1.1 Retirement mechanism in CMW v2.0

CMW production nodes represent coal mining regions or countries, which in turn generally depict numerous coal mines. To approximate the retirement of individual mines the model is adjusted to take into account node-specific average remaining lifetime of existing production capacities, as well as an average lifetime for new mines. The time-dependent physical retirement of mining capacities is integrated in the production capacity constraint of the producer's profit optimization problem (see Eq. A.7 in the Suppl. Material A.4.2.1). Eq. A.1 shows the new production capacity constraint.

$$\begin{aligned}
&cap_f^P \cdot RE_{af}^P \\
&+ \sum_{a'<a} \left(inv_{a'f}^P \cdot RN_{af}^P \right) \\
&- \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \geq 0, \quad \left(\alpha_{af}^P \right)
\end{aligned} \tag{A.1}$$

Line one in Eq. A.1 defines the remaining capacity in time period a as the product of the initial capacity of producer f (cap_f^P) and the retirement factor for existing mines RE_{af}^P. The second line defines the remaining capacity in time period a of all investments (inv_{af}^P)

---

[1] Maintenance investments, which are necessary to keep mines and other infrastructure functioning at their initial production capacity (for example, investments in equipment maintenance and replacement), are not considered separately in the model; rather, they are included in production and transportation costs.

made in previous periods and the respective retirement factor for new capacities RN^P_{af}. The sum of lines one and two need to be greater or equal to the total production of producer f in the period a (total production of producer f is the sum of coal delivered to domestic consumers c (x_{afc}) and to exporters e (y_{afe}); κ_f is the producer dependent energy-content factor converting from energy to mass units). α^P_{af} is the dual variable (shadow price) of the production capacity constraint.[2]

In order to implement the time dependent retirement, existing capacity and new investments are multiplied with inverse logistic functions (retirement factors) which determine the time specific remaining share of the these capacities, respectively. RE^P_{af} and RN^P_{af} represent the retirement factors for existing and new capacities, respectively:

$$RE^P_{af} = \frac{1}{1 + (depe^P_f)^{-(ord(a)-(mlexist^P_f/5+1))}} \tag{A.2}$$

$$RN^P_{af} = \frac{1}{1 + (depn^P_f)^{-(ord(a)-(mlnew^P_f/5+1)-ord(a'))}} \tag{A.3}$$

The newly introduced parameters $mlexist^P_f$ and $mlnew^P_f$ are the average (remaining) lifetime of a producer's initial capacity and of new capacities, respectively, both with the unit 'years' (not model periods).[3] The parameter $depe^P_f$ is the base in the retirement factor for existing mines (Eq. A.2). It is defined for each producer, depending on the remaining lifetime of its initial production capacities.[4] In case $mlexist^P_f$ is small, a rather steep retirement curve is assumed, thus a small $depe^P_f$. In case $mlexist^P_f$ is larger, $depe^P_f$ is increased, which translates into a flatter retirement curve with increasing tails around the average lifetime (partial retirement of the node's mining capacity starts earlier and continues further into the future relative to *mlexist*, respectively, than in the case of a smaller *mlexist*). $ord(a)$ returns the relative position of a in the set of model years (e.g., $ord(2015)$ would return 1).

---

[2] For a full list of sets, parameters and variables used in CMW v2.0, see Tables A.7 to A.9 in the Suppl. Material A.4.1.

[3] Mine lifetimes (given in years in the input file) need to be transformed to model time periods and increased by one for the retirement functions (e.g, 10 years need to enter as 3 etc.): $mlexist^P_f/5 + 1$

[4] $depe^P_f$ is set to the following values:

$$depe^P_f = 0.2 \quad \forall mlexist^P_f < 10$$
$$depe^P_f = 0.2 + (mlexist^P_f - 10)/5 \cdot 0.1 \quad \forall 10 \leq mlexist^P_f \leq 25$$
$$depe^P_f = 0.5 \quad \forall mlexist^P_f > 25$$

For new mines the base in the retirement factor (Eq. A.3) is denoted by the parameter $depn_f^P$. For new mines an average lifetime ($mlnew$) of 25 years is assumed (see Section A.1.2 below), with a $depn_f^P$ of 0.2. This rather small value for $depn_f^P$ is chosen based on the assumption that new mines will be able to produce in the first periods almost at their full initial capacity, with few mines producing much shorter or longer, respectively, than the average lifetime $mlnew$.

The new formulation of the capacity constraint (Eq. A.1) does not include the mine mortality term of previous model versions anymore,[5] assuming that also idle production capacities will need new investments if idle for some time. Retirement of capacities therefore is implemented as independent of production in previous years.[6] CMW includes also a constraint on maximum production capacity additions per period a, which is adjusted to allow for additional investments to replace capacities retired in previous periods (see Eq. A.8 in the Suppl. Material A.4.2.1).

A.1.2 Estimating coal mines' lifetimes based on GCMT data

The newly added retirement mechanism is based on the mines' age. It differentiates between newly added capacities (endogenous investment decisions by model) and in the model's base-year (2015) existing capacities. For the former, a global applicable average lifetime is assumed, while for the latter coal basin specific remaining average lifetimes are applied. The lifetimes are based on the 'Global Coal Mine Tracker' (GCMT; version of June 2021), an open access database on coal mines (Global Energy Monitor 2021b).

Approximating the remaining average lifetime of existing capacities in each represented production node is more difficult. Information on remaining lifetimes is available only for a minority of the reported operating mines in the GCMT. More generally available is the reserve to production ratio (R/P) of mines, which represents the possible remaining years of production at full capacity if all reserves are exploited. However, while R/P values

---

[5] In previous model versions, the mine mortality mechanism represented the process of how fast the cheapest mines in a coal basin are mined out (Holz et al. 2016). The induced loss of production capacity was implemented as a function of cumulative extraction. The average mine mortality rate amounted to about 1 % p.a. (Holz et al. 2016, 52). Hence, for a node producing at full capacity and with continuous capacity replacement investments, the full initial capacity would have to be replaced only every 100 years.

The removal of the mine mortality term from the capacity constraint is considered to be acceptable, as the reduction of mining capacity due to mine mortality is only a minor share of removal compared to the new retirement mechanism. Furthermore, considering remaining mine lifetime and reserve/production ratios in the retirement of existing mines also considers the basin specifics to some degree.

[6] The model is run in 5-year time steps, thus, it seems reasonable, that mines also "degrade" even if not producing.

Personal communication with coal industry experts: Idle mines are very expensive to keep in operational conditions (more so for underground mines). In case of an expected return to production idle mines are kept in operational conditions for possibly one to one and a half years.

provide information on available physical resources, the technical lifetime of a mine also depends, i.a., on available infrastructure, physical accessibility of reserves, governmental permits, etc. To approximate the remaining lifetime of mines with R/P reported only, the relationship of remaining mine lifetime to R/P for operational steam coal mines with both values reported is estimated here with a logarithmic regression function (see Figure A.2). For this regression analysis, data for mines from the GCMT data is filtered to include only steam coal mines (excl. lignite and pure met coal mines)[7] with both, remaining lifetime and R/P, included. From this set, all Chinese mines are excluded (see Section 2.1 in the parent article). Additionally, mines with an R/P of less than ten or more than 45 years, respectively, are excluded due to the limited number of data points for those categories. Furthermore, mines with reported remaining lifetime larger than their reported R/P were excluded, as the R/P ratio implies a physical limit to the maximum lifetime (considering production at full capacity).

From this regression analysis, the following relationship of remaining lifetime of existing mines ($mlexist$) to R/P is derived for all mines with $10 \leq R/P \leq 45$. For mines with $0 \leq R/P < 10$ a simple linear correlation is considered, and for all mines with $45 < R/P$ the lifetime is set to the lifetime of new mines of 25 years:

$$\begin{aligned} mlexist &= 0.7 \cdot R/P \quad \forall R/P < 10 \\ mlexist &= 12.297 \cdot \ln(R/P) - 21.522 \quad \forall 10 \leq R/P \leq 45 \\ mlexist &= 25 \quad \forall R/P > 45 \end{aligned} \tag{A.4}$$

These approximations are then applied to the reported R/P of mines in order to obtain remaining lifetime estimates for a larger number of mines. Then, for each node the weighted average of the respective approximated remaining lifetimes is taken, weighted by each mine's share of the total represented nodal capacity. In order to account for the difference in the model's starting year (2015) and the data in the GCMT, representing the year 2020, resulting remaining lifetimes for all nodes are extended by five years.

The results of the regression analysis were then verified by triangulation with literature information and expert judgements. For the following nodes, *mlexist* was adjusted thereupon to better represent local conditions: P_KAZ reduced by ten years (relatively old mines with limited remaining lifetime according to coal sector experts); P_IND_Orissa reduced by eight years (very limited coverage of mines in GCMT; similar mine structure as in P_IND_North); all Chinese production nodes minus ten years, except P_CHN_SIS, for which it is reduced by eight years (according to industry experts, reserve data for Chi-

---

[7] Applying the following filters to the GCMT database categories: 'Status' = 'Operating', AND 'Coal Type' = 'Anthracite' & 'Bituminous' & 'Subbituminous', AND 'Coal Grade' = 'Thermal' & 'Thermal & Met' & '(Blanks)'.

nese coal mines should be considered only as rough estimates, and not as actually explored reserves, which leads to overestimation of remaining mineable reserves (Personal communication with coal industry experts, March to May 2021); according to Auger et al. (2021, 13) most existing Chinese coal mines will reach their end-of-life within the next 20 years). Table A.1 shows the resulting remaining lifetime values for all CMW v2.0 producer nodes.

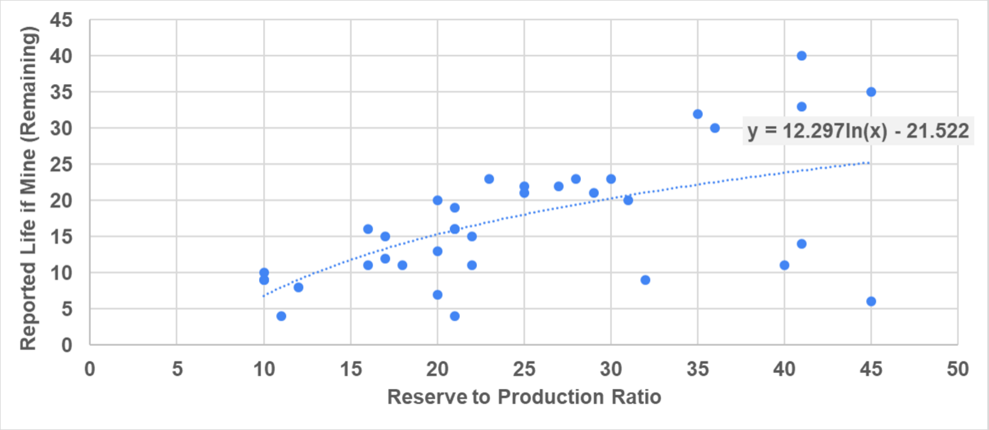


Figure A.2: Relationship of remaining mine lifetime to R/P ratio of thermal coal mines (excl. Chinese mines). Source: Own calculation based on data from (Global Energy Monitor 2021b).

The implemented retirement for nodal coal production capacities is illustrated in Figure A.3. It shows the decline of the cumulative global steam coal production capacity available in 2015 (excluding capacity additions). Nodal production capacities are retired following an inverse logistic curve, with 50 % of the capacities retired when the node-specific average retirement age is reached. About half of the operating coal production capacities operating in 2015 will be retired by 2035, and by 2050 almost all capacities will be out of service.

Table A.1: Average remaining lifetimes of coal production capacities for all CMW producer nodes in years (for start year 2015).

CMW producer node	Average remaining lifetime (mlexist)
P_USA_PRB	21
P_USA_Rocky	20
P_USA_ILL	23
P_USA_APP	17
P_COL	23
P_POL	17
P_KAZ	15
P_RUS	24
P_ZAF	19
P_IND_North	22
P_IND_Orissa	22
P_IND_West	13
P_IND_Soutth	19
P_IDN	18
P_CHN_SIS	20
P_CHN_Northeast	18
P_CHN_HSA	15
P_CHN_YG	10
P_AUS_QLD	21
P_AUS_NSW	19
P_MNG	30
P_MOZ	30

Source: Own approximations, based on (Global Energy Monitor 2021b).

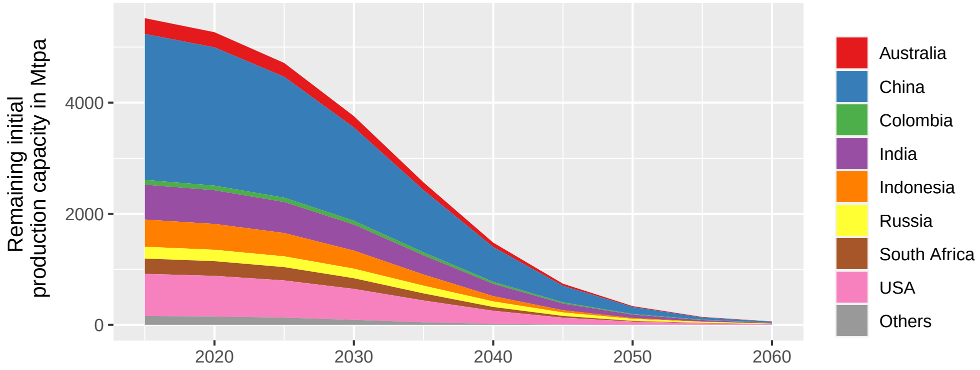


Figure A.3: Retirement of initial (2015) coal mine capacities in COALMOD-World v2.0: decline of cumulative production capacity (grouped by countries) in case of zero new capacities from 2015 on.

Assumptions on lifetimes are a critical factor for the assessment of investments in new production capacities. Particularly, as there is only limited data available and generalization for coal mine lifetimes is difficult. Therefore, effects of lifetime assumption variations on investment results were assessed. Results of this sensitivity analysis are presented in Figure A.4. Results for investments react as expected to an increase/decrease of the lifetime of existing and new mines. Shorter lifetimes require significant additional capacity additions in the considered period in a high demand scenario, while longer lifetimes significantly decrease capacity additions. In contrast, results for (regional) production volumes are relatively robust.

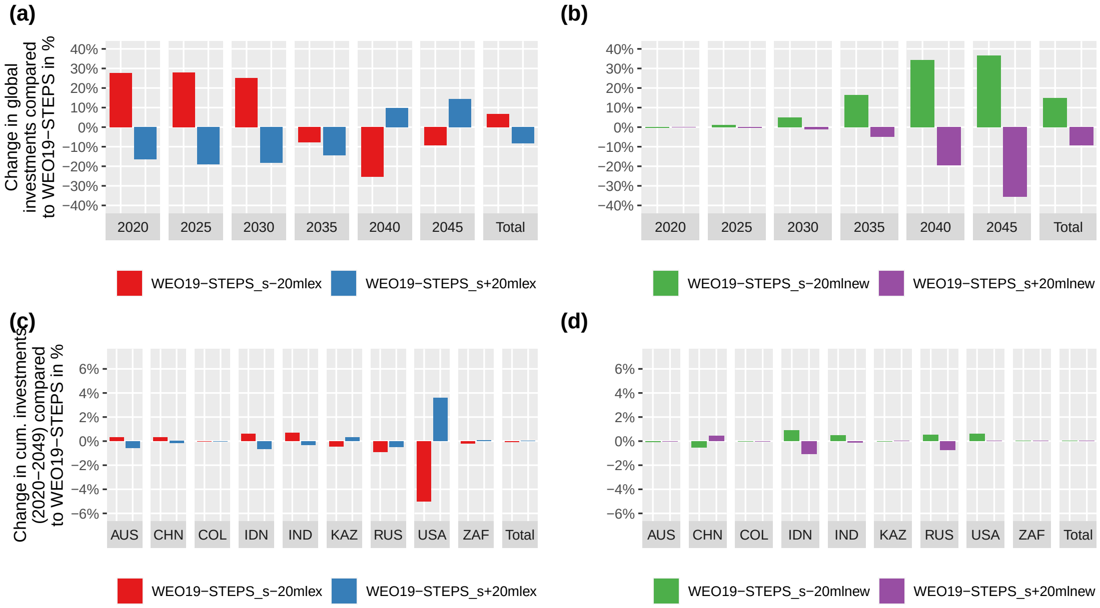


Figure A.4: Sensitivity of CMW results (*WEO19-STEPS* scenario) to changes in coal mine-lifetime assumptions.
(a) and (b) show the sensitivity of global 5-year and cumulative (2020-2049) coal mine capacity investments to an increased/decreased remaining lifetime of existing production capacities (*mlexist*) by +/- 20 % (a), as well as increased/decreased lifetime of new capacities (*mlnew*) by +/- 20 % (b), respectively. Reducing *mlexist* leads to preponed investments in the first periods. Vice versa, increasing *mlexist* leads to a slightly less pronounced postponement of investments. Decreasing *mlnew* increases required investments from 2030 on, and vice versa, required investments decrease from 2030 on for increased *mlnew*, respectively.
(c) and (d) show the sensitivity of selected countries' and global cumulative production (2020-2049) results to changes in *mlexist* ((c), +/- 20 %) and *mlnew* ((d), +/- 20 %). Cumulative global production is not significantly influenced by changes in *mlexist* and *mlnew*, respectively. Regional production, however, can be affected significantly. In case of increased (decreased) *mlexist*, for example, the USA produce more (less). The USA have a large fleet of existing mines, but only few new investments are made in the USA in a *WEO19-STEPS* scenario. Additional (reduced) U.S. production is compensated by slightly reduced (increased) production in other countries in this scenario. Sensitivity of regional production volumes to changes in *mlnew* is less pronounced.

Note: In (a) and (b) investments in model years represent total investments per period, e.g., 2020-2024.

A.1.3 China's import quota

An additional new feature of the new model is a Chinese coal import quota that restricts the amount of annual imports into China. Although the model generally focuses on operational and technical constraints, this politically defined restriction of the largest global coal consumer is included because of its potentially significant impact on the international coal market. China officially has no import quota, but *de facto* annual coal imports are restricted (IEA 2021a; Gosens, Turnbull, and Jotzo 2022). Here, the annual quota for all international seaborne imports into China is set to 300 million tons (Mt) from 2020 on, representing the maximum imports in the past few years (IEA 2021a). This is a rather conservative estimate given that China might further restrict imports in the future, as a recent study on current developments in the Chinese coal sector (Gosens, Turnbull, and Jotzo 2022) has shown.

To include the *de facto* Chinese import restriction, equation A.5 is added as constraint for all non-Chinese exporters in CMW v2.0 and imposes a limit on the sum of annual seaborn coal imports to China.[8] The sum of all coal shipped from non-Chinese exporters to Chinese sea ports in period a need to be less or equal to the annual import quota $China\_IQ_a$ (in million tons per year). ρ_a^{CHN} is the dual variable of the constraint.

$$China\_IQ_a - \sum_{NoChina\_exp(e)} \sum_{China\_sea(c)} z_{aec} \cdot \kappa_e \geq 0 \quad \left(\rho_a^{CHN}\right) \tag{A.5}$$

A.2 Coal demand scenarios

CMW runs are based on exogenous coal demand scenarios. Coal demand growth data is derived from the applicable sources, such as IPCC (2022), and these growth rates are applied to CMW demand node specific historic steam coal demand data. Real-world coal demand in 2020 was influenced significantly by the COVID-19 pandemic (-4.5 % compared to 2019 (IEA 2021g, 322)), yet long-term effects of the pandemic on coal demand are less clear (IEA 2021c; Yanguas Parra, Hauenstein, and Oei 2021). Thus, CMW node-specific coal demand for the model year 2020 is based on an extrapolation of 2015-2019 nodal trends, in order to avoid an overestimation of the pandemic induced demand reduction.

Table A.2 summarizes the scenarios included in this study and their data sources. Only 1.5°C coal demand scenarios are considered that do not imply high temperature overshoots.

---

[8] Chinese steam coal imports via land make up a very small share of its total imports only and are not considered here.

Temperature overshoot pathways, as well as BECCS and other land-use based approaches to withdraw carbon dioxide from the atmosphere are debated intensively regarding their potentials and risks (cf. Braunger and Hauenstein 2020; Creutzig et al. 2021; Minx et al. 2018; Rogelj et al. 2019). Regarding CCS, many have argued that its adoption could enable an extended use of coal (cf. Budinis et al. 2018). However, so far CCS is not deployed on large-scale and it is highly questionable if CCS-(retro)fitted coal-fired power plants will play a significant role in the future power sector (cf. Martin-Roberts et al. 2021; Grant et al. 2021; Yanguas Parra et al. 2019). Thus, 1.5°C coal demand scenarios are considered once without CCS, and once with CCS (for results see Section A.3)

Table A.2: Summary of scenarios and underlying data.

Name	Description
1.5°C (*lower bound*, *central*, *upper bound*)	Set of three coal phase-out scenarios based on the growth rates of results for “Secondary Energy|Electricity|Coal|w/o CCS” (regionally disaggregated; region category R5) of IPCC (2022) scenarios that limit warming to 1.5°C (>50 %) with no or limited overshoot (n=80)(data available in Byers et al. (AR6 Scenarios Database). Out of these 80 scenarios, annual 0.25-0.75 percentile values for coal consumption are used to build the *1.5°C* scenario set. Growth rates of 0.25, 0.75, and 0.5 (median) percentile values were taken for the *lower bound*, *upper bound*, and *central 1.5°C* scenarios, respectively.
WEO19-STEPS	Coal demand growth rates are derived from IEA’s ’World Energy Outlook 2019’ ’Stated Policies Scenario’ data for ’Coal’ in ’Power sector’ in ’Energy demand’ (IEA 2019b, 682–742).

[9]ote: For *1.5°C w/ CCS* (*lower bound*, *central*, *upper bound*) growth rates of the sum of the results for “Secondary Energy|Electricity|Coal|w/o CCS” AND “Secondary Energy|Electricity|Coal|w/ CCS” of IPCC (2022) scenarios that limit warming to 1.5°C (>50 %) with no or limited overshoot are used (n=80) (data available in Byers et al. (AR6 Scenarios Database).

The three *1.5°C* scenarios represent the annual 0.25-0.75 percentile range for coal consumption in the power sector of IPCC (2022) 1.5°C scenarios with no or limited overshoot. The power sector accounts for about 70 % of total steam coal demand (IEA 2019a, II.17). Other major steam coal users include the iron and steel (besides metallurgical coal), cement, and chemical industry. With the switch to less fossil fuel dependent production processes (IEA 2020e, cf.), coal demand in these sectors is considered to develop similarly to the power sector. Values of “Secondary Energy|Electricity|Coal|w/o CCS (|w/ CCS)” are most widely available in the IPCC (2022) scenarios for five world regions, Asian countries except Japan (R5ASIA), Countries from the Reforming Ecomonies of the Former Soviet Union (R5REF), Countries of the Middle East and Africa (R5MAF), Latin American countries (R5LAM), and OECD90 and EU (and EU candidate) countries (R5OECD90+EU), to which CMW demand nodes are mapped to according to the respective country (Byers et al., AR6 Scenarios Database). The regional growth rates are then applied to the respective nodal 2020 steam coal demand values.

Some IPCC (2022) scenarios do not provide results in five-year steps (Byers et al., AR6 Scenarios Database). In case of missing five-year results, ten-year results are interpolated linearly, if ten-year values of adjacent time steps are > 0.

IEA (2019b) provides projections only until 2040. For 2045-2060 values are forecasted linearly based on the values for 2030-2040. For regions with positive 2030-2040 growth, demand is kept flat at 2040 demand.

A.3 Additional results

A.3.1 Annual steam coal exports

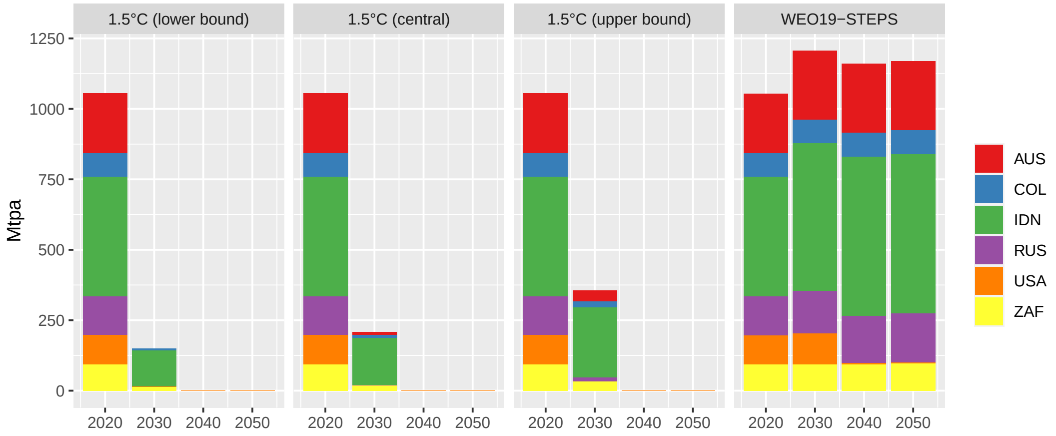


Figure A.5: Results for annual steam coal exports (Mtpa) of major exporting countries in all scenarios.

Table A.3: Nodal annual steam coal production (selected years) in *1.5°C*, *WEO19-STEPS*, and *1.5°C w/ CCS* scenarios in Mtpa.

	1.5°C (lower bound)			1.5°C (central)			1.5°C (upper bound)			WEO19-STEPS			1.5°C /w CCS (low. b.)			1.5°C /w CCS (cent.)			1.5°C /w CCS (up. b.)		
Node\Year	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
P_AUS_NSW	178	1	0	178	9	0	178	30	0	178	190	194	178	5	0	178	13	0	178	42	1
P_AUS_QLD	94	1	0	94	4	0	94	15	0	94	104	104	94	2	0	94	6	0	94	21	3
P_CHN_HSA	248	0	0	248	32	0	248	135	0	248	200	355	248	9	0	248	49	0	248	135	0
P_CHN_Northeast	103	4	0	103	8	0	103	28	0	103	71	54	103	7	0	103	11	0	103	38	0
P_CHN_SIS	1962	118	0	1962	198	0	1962	415	0	1962	2203	1773	1962	156	0	1962	234	3	1962	534	34
P_CHN_YG	258	17	0	258	37	0	258	52	0	258	243	274	258	28	0	258	45	0	258	52	0
P_COL	84	6	0	84	12	0	84	22	0	84	84	84	84	8	0	84	16	1	84	28	7
P_IDN	597	143	0	597	189	0	597	295	0	597	796	915	597	169	0	597	204	5	597	352	37
P_IND_North	406	44	0	406	65	0	406	125	0	406	508	567	406	54	0	406	73	1	406	150	12
P_IND_Orissa	150	14	0	150	34	0	150	81	0	150	178	248	150	24	0	150	41	0	150	98	0
P_IND_South	66	0	0	66	0	0	66	0	0	66	75	91	66	0	0	66	0	0	66	0	0
P_IND_West	59	0	0	59	0	0	59	0	0	59	89	149	59	0	0	59	0	0	59	0	0
P_KAZ	83	0	0	83	9	0	83	10	0	83	108	88	83	3	0	83	10	0	83	10	4
P_MNG	7	0	0	7	0	0	7	0	0	7	17	19	7	0	0	7	0	0	7	0	0
P_MOZ	2	0	0	2	0	0	2	0	0	2	6	10	2	0	0	2	0	0	2	0	0
P_POL	65	1	0	65	3	0	65	5	0	56	42	2	65	2	0	65	5	0	65	9	3
P_RUS	207	0	0	207	6	0	207	19	0	207	187	200	207	2	0	207	11	0	207	22	9
P_USA_APP	112	0	0	112	1	0	111	2	0	106	67	8	112	1	0	112	2	0	112	5	1
P_USA_ILL	103	5	0	103	7	0	104	15	0	106	78	40	102	6	0	102	15	1	103	23	9
P_USA_PRB	263	0	0	265	3	0	266	6	0	269	228	171	264	0	0	265	6	0	266	10	4
P_USA_Rocky	69	1	0	69	3	0	68	6	0	64	44	6	69	2	0	68	6	0	67	10	4
P_ZAF	263	14	0	263	37	0	263	66	0	263	218	156	263	19	0	263	42	2	263	84	10

Note: Geographical representation of production nodes (P_ ...): AUS_NSW = New South Wales, Australia; AUS_QLD = Queensland, AUS; CHN_HSA = Henan & Shandong & Anhui & Jiangxi & Jiangsu, China; CHN_Northeast = Liaoning & Heilongjiang & Jilin, China; CHN_SIS = Shanxi & Inner Mongolia & Shaanxi & Hebei & Ningxia & Gansu, China; CHN_YG = Yunnan & Guizhou & Sichuan & Hunan & Chongqing & Hubei, China; COL = Colombia; IDN = Indonesia; IND_North = Arunachal & Assam & Chhattisgarh & Jammu Kashmir & Jharkhand & Madhya Pradesh & Meghalaya & Uttar Pradesh & West Bengal, India; IND_Orissa = Odisha; IND_South = Telangana; IND_West = Maharashtra; KAZ = Kazakhstan; MNG = Mongolia; MOZ = Mozambique; POL = Poland; RUS = Russia; USA_APP = Alabama & Kentucky (East) & Maryland & Ohio & Pennsylvania & Tennessee & Virginia & West Virginia, USA; USA_ILL = Arkansas & Illinois & Indiana & Kansas & Kentucky (West) & Louisiana & Mississippi & Missouri & Oklahoma & Texas, USA; USA_PRB = Wyoming; USA_Rocky = Alaska & Arizona & Colorado & Montana & New Mexico & North Dakota & Utah & Washington, USA; ZAF = South Africa.

Table A.4: Cumulative nodal excess capacities (2020-2050) in *1.5°C*, *WEO19-STEPS*, and *1.5°C w/ CCS* scenarios in Mtpa and %.

	1.5°C (lower bound)		1.5°C (central)		1.5°C upper bound)		WEO19-STEPS		1.5°C /w CCS (low. b.)		1.5°C w/ CCS (cent.)		1.5°C /w CCS (up. b.)	
Node	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%
P_AUS_NSW	1940	72	1790	67	1607	60	0	0	1909	71	1768	66	1506	56
P_AUS_QLD	1196	75	1120	71	1021	64	0	0	1184	75	1090	69	939	59
P_CHN_HSA	1139	41	981	35	466	17	0	0	1093	39	895	32	464	17
P_CHN_Northeast	891	61	696	48	597	41	0	0	865	60	679	47	543	37
P_CHN_SIS	23220	73	20790	65	18428	58	0	0	22865	71	20324	64	17237	54
P_CHN_YG	298	17	148	8	28	2	0	0	225	13	110	6	15	1
P_COL	1079	69	976	62	861	55	1	0	1058	67	897	57	683	44
P_IDN	5366	55	4597	47	3495	36	0	0	5109	52	4062	42	2504	26
P_IND_North	5395	72	4870	65	4297	57	0	0	5304	71	4698	63	3984	53
P_IND_Orissa	1609	59	1467	54	1191	44	0	0	1545	57	1430	53	1073	40
P_IND_South	816	83	762	77	720	73	0	0	811	82	760	77	717	73
P_IND_West	538	65	433	52	433	52	0	0	519	63	433	52	433	52
P_KAZ	558	60	380	41	367	39	0	0	543	58	377	40	284	30
P_MNG	150	90	131	78	125	75	0	0	150	90	131	78	124	74
P_MOZ	40	90	40	90	30	67	0	0	40	90	40	90	30	67
P_POL	629	73	587	68	530	62	36	4	626	73	553	64	446	51
P_RUS	3318	83	3133	78	2905	73	0	0	3307	83	3088	77	2669	67
P_USA_APP	1728	83	1659	80	1602	77	593	28	1722	83	1646	79	1557	75
P_USA_ILL	1824	80	1716	76	1662	73	291	12	1813	80	1634	72	1429	63
P_USA_PRB	5300	88	5240	87	4974	83	1009	14	5298	88	5194	86	4852	81
P_USA_Rocky	1255	84	1212	81	1157	77	398	27	1251	83	1179	79	1063	71
P_ZAF	2644	67	2364	60	2030	51	0	0	2597	66	2289	58	1752	44

Table A.5: Premature coal mine capacity retirements in 2030 in *1.5°C* and *1.5°C w/ CCS* scenarios in Mtpa and %.

	1.5°C (lower bound)		1.5°C (central)		1.5°C (upper bound)		1.5°C /w CCS (low. b.)		1.5°C /w CCS (cent.)		1.5°C /w CCS (up. b.)	
Node	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%	Mtpa	%
P_AUS_NSW	129	99	121	93	100	77	125	96	117	90	88	68
P_AUS_QLD	73	98	70	94	59	80	72	97	68	92	53	72
P_CHN_HSA	135	100	103	77	0	0	126	93	86	64	0	0
P_CHN_Northeast	68	95	64	89	44	61	65	90	60	85	33	46
P_CHN_SIS	1392	92	1312	87	1095	73	1354	90	1275	84	975	65
P_CHN_YG	35	67	15	28	0	0	24	46	7	14	0	0
P_COL	64	92	58	83	47	68	62	88	54	77	42	60
P_IDN	310	68	265	58	158	35	284	63	249	55	101	22
P_IND_North	292	87	271	81	211	63	281	84	263	78	186	55
P_IND_Orissa	109	89	89	73	42	34	99	81	82	67	25	20
P_IND_South	48	100	48	100	48	100	48	100	48	100	48	100
P_IND_West	35	100	35	100	35	100	35	100	35	100	35	100
P_KAZ	45	99	36	79	35	78	42	94	35	78	35	78
P_MNG	7	100	7	100	7	100	7	100	7	100	7	100
P_MOZ	2	100	2	100	2	100	2	100	2	100	2	100
P_POL	41	97	40	94	37	87	41	96	37	87	34	79
P_RUS	174	100	168	97	155	89	172	99	163	94	152	87
P_USA_APP	103	100	102	99	101	98	102	99	101	98	98	95
P_USA_ILL	96	95	94	93	86	85	95	94	86	85	78	77
P_USA_PRB	281	100	278	99	275	98	281	100	275	98	271	96
P_USA_Rocky	70	98	69	96	66	92	70	98	66	92	62	87
P_ZAF	178	93	155	81	125	65	172	90	149	78	108	56

Table A.6: Nodal coal mine stranded assets (2020-2050) in *1.5°C* and *1.5°C w/ CCS* scenarios in billion USD_{2015}.

Node	1.5°C (lower bound)	1.5°C (central)	1.5°C (upper bound)	1.5°C /w CCS (low. b.)	1.5°C /w CCS (cent.)	1.5°C w/ CCS (up. b.)
P_AUS_NSW	5	5	4	5	5	4
P_AUS_QLD	3	3	3	3	3	3
P_CHN_HSA	4	5	2	4	5	2
P_CHN_Northeast	3	4	2	3	3	2
P_CHN_SIS	53	60	47	52	59	44
P_CHN_YG	0	1	0	0	1	0
P_COL	3	3	2	2	3	2
P_IDN	9	10	7	8	10	5
P_IND_North	8	9	7	8	9	7
P_IND_Orissa	3	3	3	3	3	2
P_IND_South	1	2	1	1	2	1
P_IND_West	1	1	1	1	1	1
P_KAZ	1	1	1	1	1	1
P_MNG	1	1	0	1	1	0
P_MOZ	0	0	0	0	0	0
P_POL	2	3	2	2	3	2
P_RUS	8	8	7	7	8	6
P_USA_APP	6	6	6	6	6	6
P_USA_ILL	5	5	5	5	5	4
P_USA_PRB	11	11	11	11	11	10
P_USA_Rocky	4	4	4	4	4	3
P_ZAF	6	7	5	6	7	5

A.3.2 Nodal results and results for 1.5°C scenarios with CCS

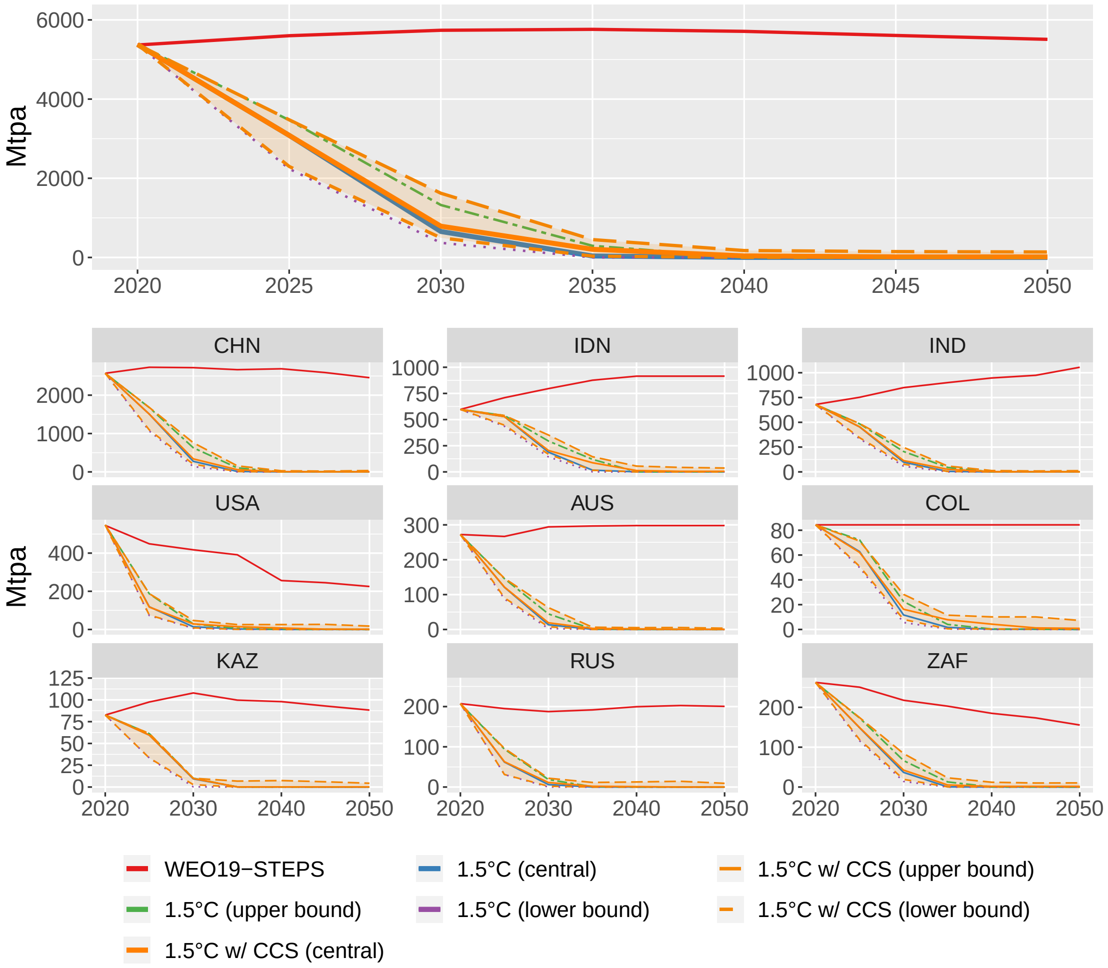


Figure A.6: Global annual steam coal consumption (Mtpa) in all scenarios (*1.5°C* scenarios with and without CCS) (top panel) and annual steam coal production (Mtpa) in major producing countries.

Note: Shaded orange area shows range of *1.5°C w/ CCS* scenarios.

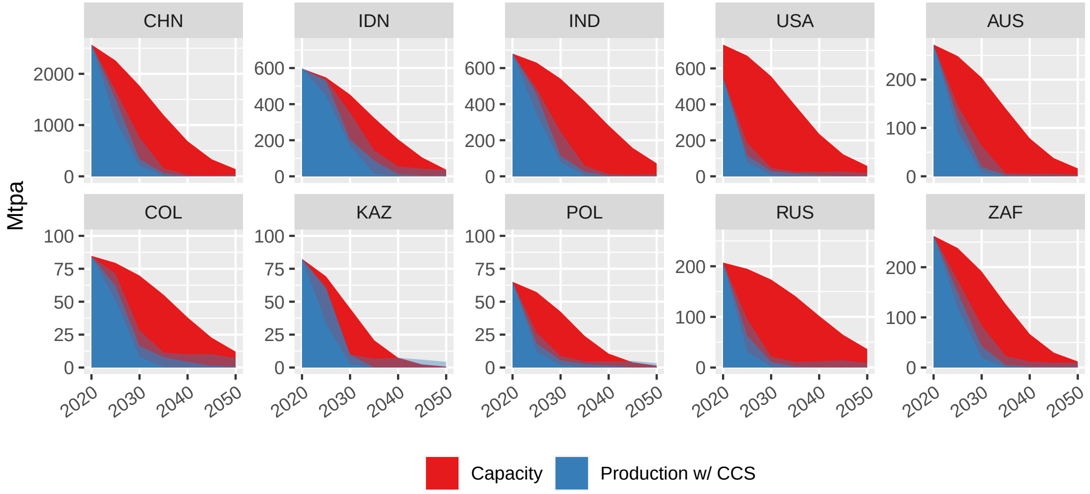


Figure A.7: Stranded coal capacity: Countries' annual steam coal production capacity (red) vs. production in *1.5°C w/ CCS* scenarios (blue, with shaded area representing the range of the *1.5°C w/ CCS* scenarios).

A.3.3 Sensitivity analysis

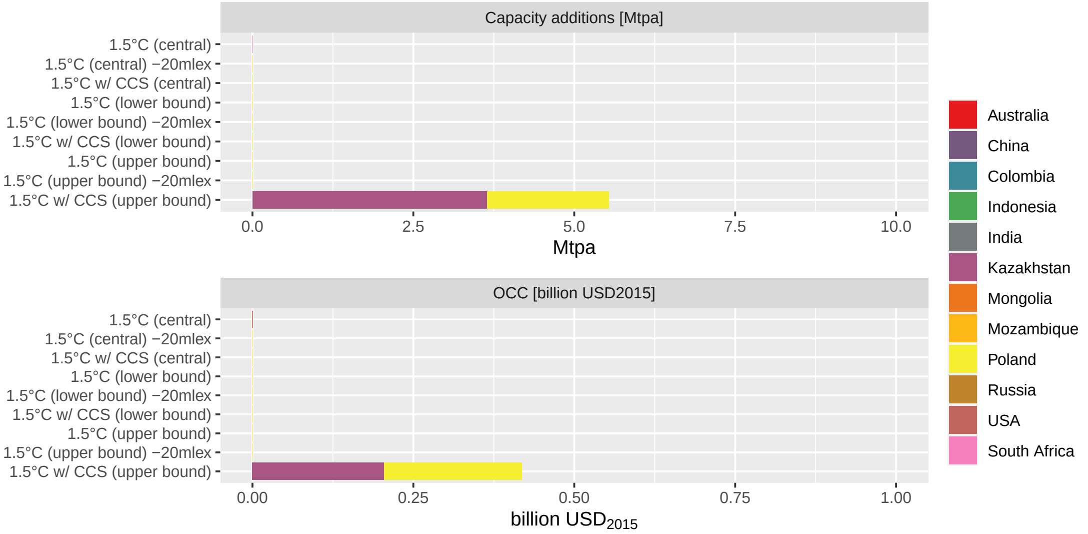


Figure A.8: Sensitivity of cumulative investments (2020-2049) in new coal mine capacities in *1.5°C* scenarios to changes in lifetime of existing mines (*mlexist*). *mlexist* increased (+20mlex)/decreased (-20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. Capacity additions in Mtpa, as well as related overnight capital costs (OCC) in billion USD_{2015}.

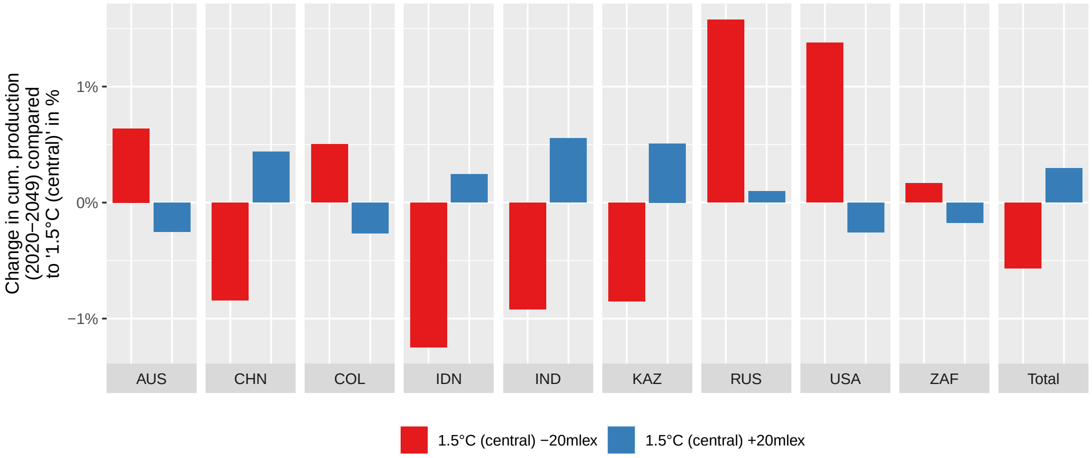


Figure A.9: Sensitivity of selected countries' and global cumulative production (2020-2049) in central *1.5°C* scenario to changes in lifetime of existing mines (*mlexist*). *mlexist* decreased (-20mlex)/increased (+20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. Relative change of resulting cumulative production compared to base case of central *1.5°C* scenario. Generally increasing/decreasing *mlexist* leads to marginal changes in results for countries' and global cumulative production only.

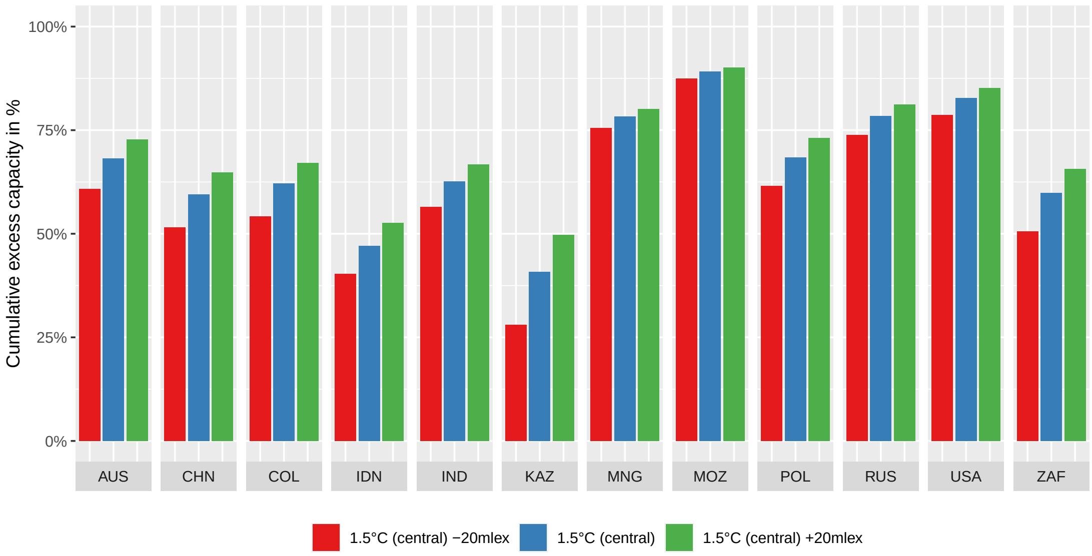


Figure A.10: Sensitivity of countries' cumulative excess capacity (2020-2049) in central *1.5°C* scenario to changes in lifetime of existing mines (*mlexist*). *mlexist* decreased (-20mlex)/increased (+20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. Shorter remaining lifetimes for existing mines lead as expected to reduced cumulative excess capacities. The order of magnitude remains the same for a country's excess capacity. However, the effect of changes in *mlexist* to excess capacity results differ among countries.

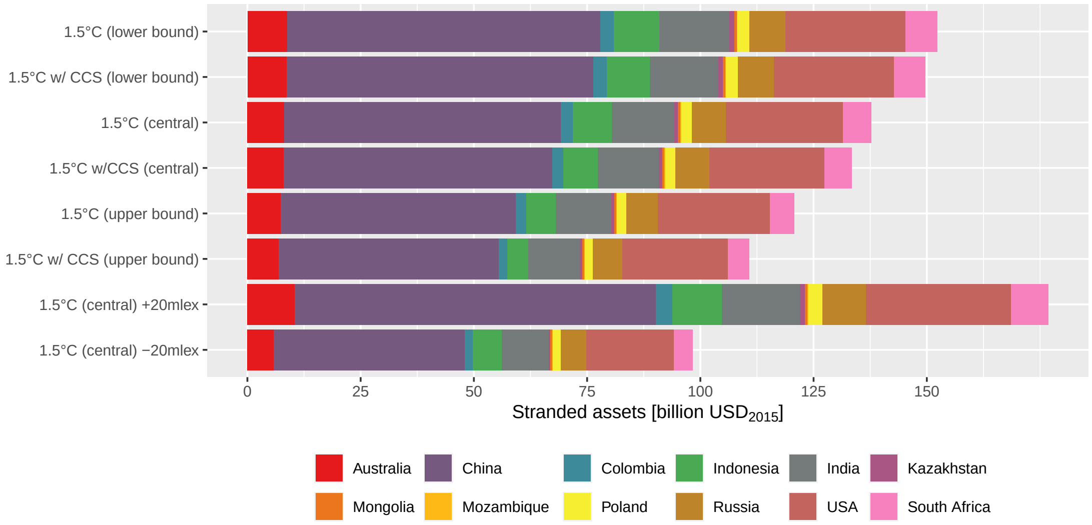


Figure A.11: Sensitivity of stranded assets' volume (2020-2049) in central *1.5°C* scenario to changes in lifetime of existing mines (*mlexist*). *mlexist* decreased (-20mlex)/increased (+20mlex) by 20 % compared to applied *mlexist* values in CMW v2.0. The volume of stranded assets is highly dependent on assumptions regarding the remaining lifetime, and thus the already recovered share of overnight capital cost, of existing mines.

A.4 Mathematical formulation of CMW v2.0, its sets, parameters, and variables

A.4.1 CMW v2.0: Sets, parameters, variables

Table A.8: List of parameters in the COALMOD-World model version 2.0.

Parameter name	Description	Unit
b_{ac}	demand curve slope of demand node c in period a	[USD/GJ^2]
cap^{E}_{e}	initial export capacity of exporter e	[Mt/a]
cap^{P}_{f}	initial production capacity of producer f	[Mt/a]
cap^{TC}_{fc}	initial transport capacity from producer f to consumer c	[Mt/a]

Continued on next page

Table A.8: *(continued)* List of parameters in the COALMOD-World model version 2.0.

Parameter name	Description	Unit
cap^{TE}_{fe}	initial transport capacity from producer f to exporter e	[Mt/a]
$China\_IQ_a$	import quota for maximum annual imports via sea into China in period a	[Mt/a]
$China\_lic_a$	Chinese export licence restricting maximum annual Chinese exports in period a	[Mt/a]
$Cinv^E_e$	investment cost for export capacity expansion for exporter e	[USD/t]
$Cinv^P_f$	investment cost for producer capacity expansion for producer f	[USD/t]
$Cinv^{TC}_{fc}$	investment cost for transport capacity expansion from producer f to consumer c	[USD/t]
$Cinv^{TE}_{fe}$	investment cost for transport capacity expansion from producer f to exporter e	[USD/t]
$DemInter_{ac}$	demand curve intercept of demand node c in period a	[USD/GJ]
$depe^P_f$	base of inverse logistic function determining retirement of cap^P_f	[ ]
$depn^P_f$	base of inverse logistic function determining retirement of inv^P_{af}	[ ]
$epsi_{ac}$	price elasticity of demand node c in period a	[ ]
fee_e	port handling fee for exporter e	[USD/t]
$\overline{inv}^E_e$	maximum export capacity expansion of exporter e	[Mt/a per 5 year period]
$\overline{inv}^P_f$	maximum production capacity expansion of producer f	[Mt/a per 5 year period]
ι_{ec}	binary parameter for Chinese import quota; 0 for all e and c, except for $e = NoChina\_exp_e$ and $c = China\_sea_c$	[ ]
κ_e	energy content of coal shipped by exporter e	[t/GJ]
κ_f	energy content of coal produced by producer f	[t/GJ]
$mc\_int\_start_f$	starting value of intercept of marginal cost curve for producer f	[USD/t]
$mc\_int\_var_f$	intercept variation factor	[ ]

Continued on next page

Table A.8: *(continued)* List of parameters in the COALMOD-World model version 2.0.

Parameter name	Description	Unit
mc_slp_f	slope of marginal cost curve for producer f	[USD/t^2]
$mlexist_f^P$	average remaining lifetime of cap_f^P	[years]
$mlnew_f^P$	average lifetime of new capacity investments inv_{af}^P	[years]
p_{ac}^{ref}	reference steam coal price in demand node c in period a	[USD/GJ]
$plength$	period length	(5) years
r_e	discount factor applied by exporter e	[ ]
r_f	discount factor applied by producer f	[ ]
res_f	resource endowment (coal reserve) of producer f	[Mt]
$searate_{ec}$	freight rate for transport from exporter e to consumer c	[USD/t]
$t\_i_{ae\,sea}$	Import tax for import from port e to port sea in period a	[USD/t]
θ_{ec}	binary parameter for Chinese export restriction; 0 for all e and c, except for $e = CHN_E$ and $c = NoChina\_sea_c$	[ ]
$trans_{fc}^C$	transportation cost from producer f to consumer c	[USD/t]
$trans_{fe}^E$	transportation cost from producer f to exporter e	[USD/t]
y_{ac}^{ref}	reference steam coal consumption of demand node c in period a	[PJ]

A.4.2 Mathematical formulation of CMW v2.0

A.4.2.1 CMW v2.0: producer's problem

The producers maximize their profit $\Pi_f^P(x_{afc};\ y_{afe};\ inv_{af}^P;\ inv_{afc}^{TC};\ inv_{afe}^{TE})$ over the total model horizon A for all model years $a \in A$. The producers extract and treat (produce) the coal and can sell it either to local demand nodes (x_{afc}) or to the exporters (y_{afe}). They bear the production (C_{af}^P) and the inland transport costs ($trans^C fc$, $trans_{fe}^E$). Further, they can invest in additional production capacities (inv_{af}^P) and in transport capacities to local demand (inv_{afc}^{TC}) or to the exporter (inv_{afe}^{TE}). These investments are subject to constraints.

Table A.7: List of sets in the COALMOD-World model version 2.0.

Set name	Description	Range
a	model year	[2015, 2020, 2025, 2030, 2035, 2040, 2050, 2055, 2060]
c	consumer nodes	see Holz et al. (2016); node removed for Ukraine; nodes added for Bangladesh, Pakistan, and Vietnam
$China\_sea_c$	subset of c, all Chinese consumers with port	
e	exporter nodes	see Holz et al. (2016); nodes removed for Ukraine and Venezuela; node added for Russia West
f	producer nodes	see Holz et al. (2016), nodes removed for Canada, Ukraine, Venezuela, and Vietnam
$land_c$	subset of c, all consumers only reachable by land	
$NoChina\_exp_e$	subset of e, all exporters except Chinese exporters	
$NoChina\_sea_c$	subset of c, all consumers with port except Chinese consumers	
sea_c	subset of c, all consumers with port	

Table A.9: List of variables in the COALMOD-World model version 2.0.

Variable name	Description	Unit
$\alpha_{afc}^{cap^{TC}}$	shadow price of transport capacity constraint from producer f to consumer c in period a	[USD/t]
$\alpha_{afe}^{cap^{TE}}$	shadow price of transport capacity constraint from producer f to exporter e in period a	[USD/t]
$\alpha_{af}^{inv^{P}}$	shadow price for maximal production capacity expansion constraint for producer f in period a	[USD/t]
α_{af}^{P}	shadow price of production capacity constraint for producer f in period a	[USD/t]
α_{f}^{res}	shadow price of resource constraint for producer f over entire model time horizon	[USD/t]
inv_{ae}^{E}	investment in export capacity by exporter e in period a	[Mt/a]
inv_{af}^{P}	investment in production capacity by producer f in period a	[Mt/a]
inv_{afc}^{TC}	investment in transport capacity from producer f to consumer c in period a	[Mt/a]
inv_{afe}^{TE}	investment in transport capacity from producer f to exporter e in period a	[Mt/a]
μ_{ae}^{E}	shadow price of exporter capacity constraint for exporter e in period a	[USD/t]
$\mu_{ae}^{inv^{E}}$	shadow price of maximal exporter capacity expansion constraint for exporter e in period a	[USD/t]
p_{ac}^{C}	price paid by consumer to exporter or producer in period a	[USD/GJ]
p_{ae}^{E}	price paid by exporter or producer in period a	[USD/GJ]
π_{a}^{CHN}	shadow price of Chinese export restriction constraint in period a	[USD/t]
ρ_{a}^{CHN}	shadow price of Chinese import quota constraint in period a	[USD/t]
x_{afc}	sales from producer f to consumer c in period a	[PJ]
y_{afe}	sales from producer f to exporter e in period a	[PJ]
z_{aec}	sales from exporter e to consumer c in period a	[PJ]

$$\begin{aligned}
&\max_{x_{afc};\, y_{afe};\, inv^{P}_{af};\, inv^{TC}_{afc};\, inv^{TE}_{afe}} \quad \Pi^{P}_{f}(x_{afc};\, y_{afe};\, inv^{P}_{af};\, inv^{TC}_{afc};\, inv^{TE}_{afe})\\
&= \sum_{a\in A} \left(\frac{1}{1+r_f}\right)^{a} \cdot \Big[\sum_{c} p^{C}_{ac} \cdot x_{afc} + \sum_{e} p^{E}_{ae} \cdot y_{afe}\\
&- C^{P}_{af}[x_{afc},\, y_{afe}]\\
&- \sum_{c} trans^{C}_{fc} \cdot x_{afc} \cdot \kappa_f - \sum_{e} trans^{E}_{fe} \cdot y_{afe} \cdot \kappa_f\\
&- inv^{P}_{af} \cdot Cinv^{P}_{f}\\
&- \sum_{c} inv^{TC}_{afc} \cdot Cinv^{TC}_{fc} - \sum_{e} inv^{TE}_{afe} \cdot Cinv^{TE}_{fe}\Big]
\end{aligned} \tag{A.6}$$

s.t.

Production capacity constraint:

$$\begin{aligned}
&cap^{P}_{f} \cdot RE^{P}_{af} + \sum_{a'<a} \left(inv^{P}_{a'f} \cdot RN^{P}_{af}\right)\\
&- \left(\sum_{c} \kappa_f \cdot x_{afc} + \sum_{e} \kappa_f \cdot y_{afe}\right) \geq 0, \quad (\alpha^{P}_{af})
\end{aligned} \tag{A.7}$$

Maximum production capacity additions constraint:

$$\begin{aligned}
&\overline{inv\_start}^{P}_{f} + (RE^{P}_{af} - RE^{P'}_{af}) \cdot cap^{P}_{f} + \sum_{a'<a} \left(inv^{P}_{a'f} \cdot (RN^{P}_{af} - RN^{P'}_{af})\right)\\
&- inv^{P}_{af} \geq 0 \qquad \left(\alpha^{inv^{P}}_{af}\right)
\end{aligned} \tag{A.8}$$

Resource endowment (reserve) constraint:[10]

$$res_f - \sum_{a\in A} \left(\sum_{c} x_{afc} \cdot \kappa_f + \sum_{e} y_{afe} \cdot \kappa_f\right) \cdot plength \geq 0 \qquad (\alpha^{res}_{f}) \tag{A.9}$$

Transport capacity from producer f to consumer c constraint:

$$cap^{TC}_{fc} + \sum_{a'<a} inv^{TC}_{afc} - x_{afc} \cdot \kappa_f \geq 0 \qquad \left(\alpha^{cap^{TC}}_{afc}\right) \tag{A.10}$$

---

[10] This constraint was slightly updated compared to previous model versions. So far, the last period a (2050) was considered to be only a period of one year, yet there is no reason why $plength = 5$ should not apply to $a\$ord(a) = card(a)$ (the last period). Thanks to Ruud Egging for pointing that out!

Transport capacity from producer f to exporter e constraint:

$$cap^{TE}_{fe} + \sum_{a'<a} inv^{TE}_{efc} - y_{afe} \cdot \kappa_f \geq 0 \qquad \left(\alpha^{cap^{TE}}_{afe}\right) \tag{A.11}$$

Non-negativity constraints:

$$x_{afc} \geq 0;\ y_{afe} \geq 0;\ inv^{P}_{af} \geq 0;\ inv^{TC}_{afc} \geq 0;\ inv^{TE}_{afe} \geq 0 \tag{A.12}$$

Production cost function:

$$\begin{aligned} C^{P}_{af} = &\left(mc\_int_{af} + \frac{1}{2} \cdot mc\_slp_f \cdot \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f\right)\right) \\ &\cdot \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f\right) \end{aligned} \tag{A.13}$$

Endogenous cost mechanism:

$$\begin{aligned} mc\_int_{af} &= mc\_int\_start_f \\ &\quad + mc\_slp_f \cdot mc\_int\_var_f \cdot \sum_{a'<a} \left(\sum_c x_{a'fc} \cdot \kappa_f + \sum_e y_{a'fe} \cdot \kappa_f\right), \\ &\quad mc\_int_{af} \text{ (free)} \end{aligned} \tag{A.14}$$

Retirement factors for existing RE^{P}_{af} and new mines RN^{P}_{af}, as well as the respective factors ($RE^{P'}_{af}$ and $RN^{P'}_{af}$) with a shift by one unit in the exponent of the inverse logistic function (used in Eq. A.8 to depict the difference between model periods of available capacity cap^{P}_{f} and cumulative investments $inv^{P}_{a'f}$, respectively):

$$RE^{P}_{af} = \frac{1}{1 + (depe^{P}_{f})^{-(ord(a)-(mlexist^{P}_{f}/5+1))}} \tag{A.15}$$

$$RE^{P'}_{af} = \frac{1}{1 + (depe^{P}_{f})^{-(ord(a)-(mlexist^{P}_{f}/5+1-1))}} \tag{A.16}$$

$$RN^{P}_{af} = \frac{1}{1 + (depn^{P}_{f})^{-(ord(a)-(mlnew^{P}_{f}/5+1)-ord(a'))}} \tag{A.17}$$

$$RN^{P'}_{af} = \frac{1}{1 + (depn^{P}_{f})^{-(ord(a)-(mlnew^{P}_{f}/5+1-1)-ord(a'))}} \tag{A.18}$$

A.4.2.2 CMW v2.0: exporter's problem

The exporters maximize their profit $\Pi_e^E(z_{aec};\, inv_{ae}^E)$ over the total model horizon A for all model years $a \in A$. The exporters buy the coal from the producers for the price p_{ae}^E and sell it to the consumers at price p_{ac}^C. They bear the harbor fee (fee_e), the sea transport costs ($searate_{ec}$), as well as potential import taxes (t_i_{ec}). They can invest in additional harbor capacities (inv_{ae}^E). These investments are subject to constraints.

$$\begin{aligned}
&\max_{z_{aec};\, inv_{ae}^E} \quad \Pi_e^E(z_{aec};\, inv_{ae}^E) \\
&= \sum_{a \in A} \left(\frac{1}{1+r_e}\right)^a \cdot \Big[\sum_c p_{ac}^C \cdot z_{aec} \\
&- \sum_c p_{ae}^E \cdot z_{aec} \\
&- \sum_c z_{aec} \cdot fee_e \cdot \kappa_e \\
&- \sum_c z_{aec} \cdot searate_{ec} \cdot \kappa_e \\
&- \sum_c z_{aec} \cdot t\_i_{ec} \cdot \kappa_e \\
&- inv_{ae}^E \cdot Cinv_{ae}^E\Big]
\end{aligned} \tag{A.19}$$

s.t.

$$cap_e^E + \sum_{a'<a} inv_{ae}^E - \sum_c z_{aec} \cdot \kappa_e \geq 0 \quad \left(\mu_{ae}^E\right) \tag{A.20}$$

$$\overline{inv}_{ae}^E - inv_{ae}^E \geq 0 \quad \left(\mu_{ae}^{inv^E}\right) \tag{A.21}$$

$$z_{ec} \geq 0;\; inv_{ae}^E \geq 0 \tag{A.22}$$

Furthermore, Chinese imports and exports are restricted. Equation A.23 imposes a limit on the sum of annual seaborn coal imports to China.

$$China\_IQ_a - \sum_{NoChina\_exp(e)} \sum_{China\_sea(c)} z_{aec} \cdot \kappa_e \geq 0 \quad \left(\rho_a^{CHN}\right) \tag{A.23}$$

The model includes also the option to restrict Chinese coal exports, which has been a political intervention in the past. This constraint, if enabled, is applied on the one Chinese exporter E_CHN and its exports to all consumption nodes with a non-Chinese import port (i.e., countries $NoChina(c)$) using equation (A.24). $China\_lic_a$ represents the level of Chinese export licenses for a given year in million tons.

$$China\_lic_a - \sum_{NoChina(c)} z_{a\,CHN\_E\,c} \cdot \kappa_e \geq 0 \quad \left(\pi_a^{CHN}\right) \tag{A.24}$$

A.4.2.3 Final demand and market clearing

Demand is defined via a linear inverse demand function of the type $p_{ac} = DemInter_{ac} + b_{ac} \cdot y_{ac}$ with $b_{ac} = \frac{p_{ac}^{ref}}{y_{ac}^{ref}} \cdot \frac{1}{\varepsilon_{ac}}$ and $DemInter_{ac} = p_{ac}^{ref} - b_{ac} \cdot y_{ac}^{ref}$, following the demand elasticity definition $\varepsilon_{ac} = \frac{y_{ac} - y_{ac}^{ref}}{p_{ac} - p_{ac}^{ref}} \cdot \frac{p_{ac}}{y_{ac}}$. This gives the following inverse demand function depending on the consumed quantity $y_{ac} = \sum\limits_{f} x_{afc} + \sum\limits_{e} z_{aec}$:

$$p_{ac} = p_{ac}^{ref} + \frac{1}{\varepsilon_{ac}} p_{ac}^{ref} \left(\frac{y_{ac}}{y_{ac}^{ref}} - 1 \right) \tag{A.25}$$

The following market clearing condition determines the price given the demand function $p_{ac}\left(x_{afc}, z_{aec}\right)$ at the demand node c:

$$p_{ac}^{C} - p_{ac} \left(\sum_{f} x_{afc}, \sum_{e} z_{aec} \right) = 0 \quad , p_{ac}^{C} \text{ (free)} \tag{A.26}$$

A second market clearing condition determines the the price p_{ae}^{E} at the exporting node e:

$$0 = y_{afe} - \sum_{c} z_{aec} \quad , p_{ae}^{E} \text{ (free)} \tag{A.27}$$

A.4.2.4 CMW v2.0: KKTs

- **Karush-Kuhn-Tucker conditions (KKTs) of producer's problem**

Need to consider "endogenous cost mechanism" (Eq. A.14) when taking derivative - substitute A.14 in A.6 before taking derivative.

$$
\begin{aligned}
0 \leq & \left(\frac{1}{1+r_f}\right)^a \cdot \Big[- p^C_{ac} \\
& + mc\_int\_start_f \cdot \kappa_f + mc\_slp_f \cdot \kappa_f \cdot \left(\sum_c x_{afc} \cdot \kappa_f + \sum_e y_{afe} \cdot \kappa_f \right) \\
& + mc\_slp_f \cdot mc\_int\_var_f \cdot \kappa_f \cdot \sum_{a'<a} \left(\sum_c x_{a'fc} \cdot \kappa_f + \sum_e y_{a'fe} \cdot \kappa_f \right) \\
& + trans^C_{fc} \cdot \kappa_f \Big] \\
& + mc\_slp_f \cdot mc\_int\_var_f \cdot \kappa_f \cdot \sum_{a'>a} \left(\frac{1}{1+r_f}\right)^{a'} \cdot \left(\sum_c x_{a'fc} \cdot \kappa_f + \sum_e y_{a'fe} \cdot \kappa_f \right) \\
& + \alpha^P_{af} \cdot \kappa_f \\
& + plength \cdot \alpha^{res}_f \cdot \kappa_f \\
& + \alpha^{cap^{TC}}_{afc} \cdot \kappa_f \\
& \perp x_{afc} \geq 0
\end{aligned}
\tag{A.28}
$$

KKT for y_{afe}, accordingly to x_{afc}:

$$
\begin{aligned}
0 \leq & \left(\frac{1}{1+r_f}\right)^a \cdot \Big[- p^E_{ae} \\
& ... \\
& + trans^E_{fe} \cdot \kappa_f \Big] \\
& ... \perp y_{afe} \geq 0
\end{aligned}
\tag{A.29}
$$

$$\begin{aligned} 0 \leq & \left(\frac{1}{1+r_f}\right)^a \cdot Cinv_{af}^{P} - \sum_{a'>a} \left(\alpha_{a'f}^{P} \cdot RNR_{af}^{P}\right) \\ & - \sum_{a'>a} \left(\alpha_{a'f}^{inv^P} \cdot (RNR_{af}^{P} - RNR_{af}^{P'})\right) \\ & + \alpha_{af}^{inv^P} \perp inv_{af}^{P} \geq 0 \end{aligned} \tag{A.30}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot Cinv_{fc}^{TC} - \sum_{a'>a} \alpha_{afc}^{cap^{TC}} \perp inv_{afc}^{TC} \geq 0 \tag{A.31}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot Cinv_{fe}^{TE} - \sum_{a'>a} \alpha_{afe}^{cap^{TE}} + \alpha_{afe}^{inv^{TE}} \perp inv_{afe}^{TE} \geq 0 \tag{A.32}$$

$$\begin{aligned} 0 \leq & \; cap_f^{P} \cdot RE_{af}^{P} + \sum_{a'<a} \left(inv_{a'f}^{P} \cdot RN_{af}^{P}\right) \\ & - \left(\sum_{c} \kappa_f \cdot x_{afc} + \sum_{e} \kappa_f \cdot y_{afe}\right) \perp \alpha_{af}^{P} \geq 0 \end{aligned} \tag{A.33}$$

$$\begin{aligned} 0 \leq & \; \overline{inv}_f^{P} + (RE_{af}^{P} - RE_{af}^{P'}) \cdot cap_f^{P} + \sum_{a'<a} \left(inv_{a'f}^{P} \cdot (RN_{af}^{P} - RN_{af}^{P'})\right) \\ & - inv_{af}^{P} \perp \alpha_{af}^{inv^P} \geq 0 \end{aligned} \tag{A.34}$$

$$0 \leq res_f - \sum_{a \in A} \left(\sum_{c} x_{afc} \cdot \kappa_f + \sum_{e} y_{afe} \cdot \kappa_f\right) \cdot plength \perp \alpha_f^{res} \geq 0 \tag{A.35}$$

$$0 \leq cap_{fc}^{TC} + \sum_{a'<a} inv_{afc}^{TC} - x_{afc} \cdot \kappa_f \perp \alpha_{afc}^{cap^{TC}} \geq 0 \tag{A.36}$$

$$0 \leq cap^{TE}_{fe} + \sum_{a'<a} inv^{TE}_{afe} - y_{afe} \cdot \kappa_f \perp \alpha^{cap^{TE}}_{afe} \geq 0 \tag{A.37}$$

Retirement factor for new mines with reversed order of a and $a^{'}$ in exponent RNR^P_{af} (needed in Eq. A.30), as well as the respective factor $RNR^{P^{'}}_{af}$ with a shift by one unit in the exponent of the inverse logistic function:

$$RNR^P_{af} = \frac{1}{1 + (depn^P_f)^{-(ord(a') - (mlnew^P_f/5+1) - ord(a))}} \tag{A.38}$$

$$RNR^{P^{'}}_{af} = \frac{1}{1 + (depn^P_f)^{-(ord(a') - (mlnew^P_f/5+1-1) - ord(a))}} \tag{A.39}$$

- **KKTs of exporter's problem**

$$\begin{aligned} 0 \leq & \left(\frac{1}{1+r_e}\right)^a \cdot \Big[- p^C_{a\,sea} \\ & + p^E_{ae} + fee_e \cdot \kappa_e + searate_{e\,sea} \cdot \kappa_e + t\_i_{ae\,sea} \cdot \kappa_e \Big] \\ & + \mu^E_{ae} \cdot \kappa_e + \theta_{e\,sea} \cdot \pi^{CHN}_a \cdot \kappa_e + \iota_{e\,sea} \cdot \rho^{CHN}_a \cdot \kappa_e \perp z_{aec} \geq 0 \end{aligned} \tag{A.40}$$

$$0 \leq \left(\frac{1}{1+r_e}\right)^a \cdot Cinv^E_{ae} - \sum_{a'>a} \mu^E_{ae} + \mu^{inv^E}_{ae} \perp inv^E_{ae} \geq 0 \tag{A.41}$$

$$0 \leq cap^E_e + \sum_{a'<a} inv^E_{ae} - \sum_c z_{aec} \cdot \kappa_e \perp \mu^E_{ae} \geq 0 \tag{A.42}$$

$$0 \leq \overline{inv}^E_{ae} - inv^E_{ae} \perp \mu^{inv^E}_{ae} \geq 0 \tag{A.43}$$

China's import restriction:

$$0 \leq China\_IQ_a - \sum_{NoChina\_exp(e)} \sum_{China\_sea(c)} z_{aec} \cdot \kappa_e \perp \rho_a^{CHN} \geq 0 \tag{A.44}$$

China's export restriction:

$$0 \leq China\_lic_a - \sum_{NoChina(c)} z_{a\,E\_CHN\,c} \cdot \kappa_e \perp \pi_a^{CHN} \geq 0 \tag{A.45}$$

- **Final demand and market clearing**

$$p_{ac}^{C} - p_{ac}\left(\sum_{f} x_{afc}, \sum_{e} z_{aec}\right) = 0 \quad , p_{ac} \text{ (free)} \tag{A.46}$$

$$0 = y_{afe} - \sum_{c} z_{aec} \quad , p_{ae}^{E} \text{ (free)} \tag{A.47}$$

A.4.2.5 Previous CMW capacity and maximum investment constraint

The production capacity constraint in its previous form (Eq. A.48) as represented in Holz et al. (2016) and used in recent applications of the model (i.a., Mendelevitch, Hauenstein, and Holz 2019; Hauenstein and Holz 2021; Yanguas Parra, Hauenstein, and Oei 2021)], including the mine mortality mechanism (second line):

$$\begin{aligned} & cap_f^P + \sum_{a'<a} inv_{af}^P - \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \\ & - \sum_{a'<a} \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \cdot mc\_int\_var_f \geq 0 \end{aligned} \tag{A.48}$$

As well as the previous formulation of the maximum investment constraint A.49:

$$\overline{inv}_f^P - inv_{af}^P \geq 0 \qquad \left(\alpha_{af}^{inv^P} \right) \tag{A.49}$$

Appendix B

Appendix to Chapter 3: The Death Valley of coal - Modelling COVID-19 recovery scenarios for steam coal markets

B.1 Mapping the Impact of COVID-19 on the steam coal market

The following figure maps various (in-)direct impacts of COVID-19 on the international steam coal market which are the basis for the developed scenarios.

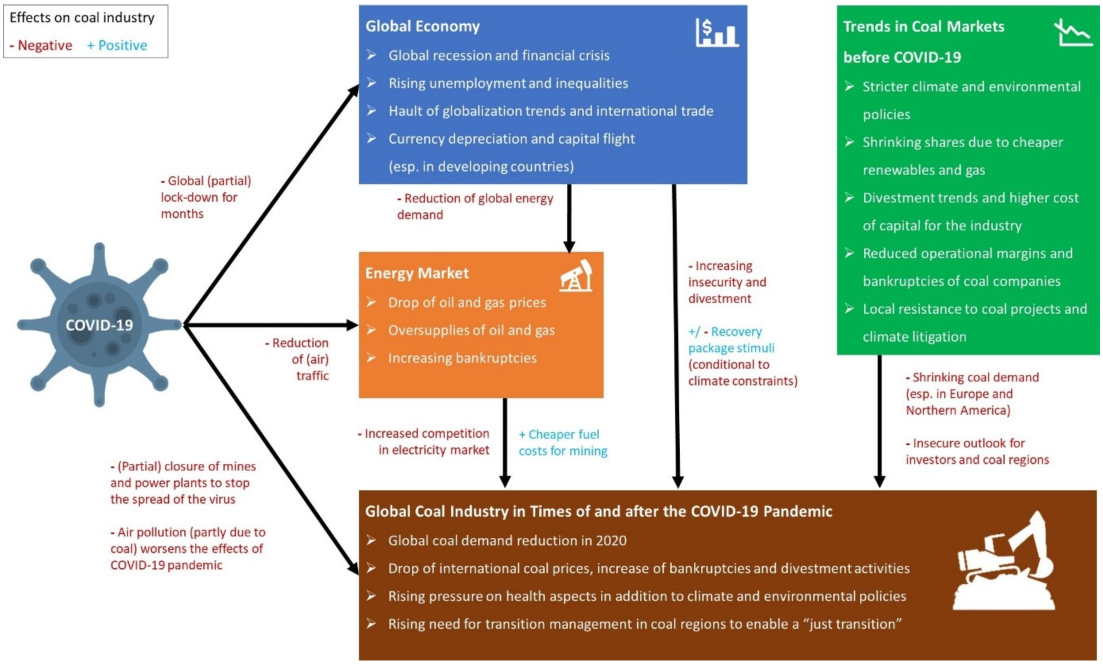


Figure B.1: Summary of impacts of COVID-19 on steam coal markets.

Source: Own depiction.

B.2 Disaggregation of sources for scenario building and possible shortcomings

Table B.1: Overview relevant consulted sources per region/country.

Region/Country	Number of relevant news articles	Articles with mentions green recovery measures	Articles with mentions brown recovery measures	Articles with mentions neutral/not relevant recovery measures
United States of America	17	2	6	9
Mexico	5	0	3	2
Canada	7	2	2	3
Brazil	6	0	3	3
Other Central and South America	19	4	1	14
European Union - general	15	14	0	1
UK	16	9	1	6
EU –Individual Member States	67	38	8	21
South Africa	6	3	1	2
Other Africa	25	5	1	19
Russia	5	1	1	3
Other Eurasia	5	1	1	3
China	16	5	4	7
India	13	4	2	7
Japan	11	2	0	9
South East Asia	22	5	7	10
South Korea	7	5	1	1
Other Asia Pacific	6	2	0	4
Australia	9	3	6	0

Note: individual references for reviewed news articles can be provided upon request

The shortcomings of this methodology include potential biases towards OECD countries; considering the level of detail and amount of information available is bigger than for non-OECD countries; potential omission of important information in local languages given that the team only reviewed materials in English, Spanish, Portuguese, and German; the lack of academic literature on the topic available at the moment of information collection; and a quantitative bias towards the International Energy Agency demand outlooks given that at the moment of the study, no other relevant global energy outlook had provided COVID-19-adjusted projections. We have tried to mitigate these shortcomings by 1) including the largest number of possible sources with relevant information (e.g. news articles and

Table B.2: Summary results sources triangulation for short and medium-term coal demand scenarios per region.

Coal electricity generation (TWh)	2020 shock		Compounded green recovery factor 1= STEPS / 0=SDS		Other climate policy environment	References to Green Recovery
Region	small	big	Min	Max		
USA	-25%	-50%	0	0.5	low	low
Other North America	-15%	-30%	0.2	0.6	medium	low
Brazil	-15%	-30%	0.3	0.8	low	low
Other Central and South America	-15%	-30%	0.2	0.6	medium	medium
Europe	-20%	-40%	0	0.5	high	high
South Africa	-15%	-30%	0.2	0.7	medium	medium
Other Africa	-15%	-30%	0.2	0.5	medium	medium
Middle East	-10%	-20%	0.1	0.9	low	low
Russia	-10%	-20%	0.5	1	low	low
Other Eurasia	-10%	-20%	0.4	0.9	low	low
China	-4%	-8%	0.2	0.8	high	medium
India	-5%	-10%	0.1	0.6	high	medium
Japan	-5%	-10%	0.4	0.9	low	low
South East Asia	-5%	-10%	0.3	0.8	medium	medium
Other Asia Pacific	-5%	-10%	0.3	0.6	medium	low

grey literature); 2) actively searching for opposing narratives on the future developments of individual countries (e.g. environmental groups vs coal industry); 3) contrasting the underlying assumptions of the IEA projections at the country level with i) the judgment of the national expert consulted, and ii) bottom-up estimates of current and planned coal power generation capacity, based on global database of coal power plant fleet.

B.3 Comparison of WEO 2019 and WEO 2020

At the moment of the analysis, the latest version of the IEA World Energy Outlook (WEO) available was the WEO 2019. During the process of peer-review and publication of this paper, the WEO 2020 became available. This version is supposed to have corrected for the COVID-19 shock in their energy sector projections, and reduced both short-term and long-term projections for coal generation. Table B.3 shows a comparison of total coal power generation, as well as cumulative coal generation capacity net additions between the two STEPS scenarios.

The WEO 2020 has –as in all previous years –reduced its coal projection in its annual outlook, showcasing the need for more accurate forecasts. As a general trend, the IEA projects a lower coal pipeline in its updated 2020 STEPS scenario showing for the first

Table B.3: Comparison coal power generation and coal power generation capacity for STEPS scenario in WEO 2019-2020.

	WEO 2019 cumulative net additions (GW), 2019-2040	WEO 2020 cumulative net additions (GW), 2020-2040	Diff between WEO 2020-WEO 2019
North America	-121.9	-209.5	-87.6
Central and South America	-0.8	-3.6	-2.8
Europe	-137.2	-141.2	-4
Africa	0.2	-9.3	-9.5
Middle East	6.2	5.2	-1
Eurasia	-22.2	-21.2	1
Asia Pacific	368.7	174.9	-193.8
China	71.9	59.1	-12.8
India	187	24.7	-162.3
World	92.8	-204.9	-297.7

Global coal power generation WEO 2019 vs WEO 2020 STEPS scenario (TWh)

	WEO 2019	WEO 2020	Diff
2030	10408	9294	-0.11
2040	10431	8984	-0.14

time a net global reduction in coal generation capacity until 2040 (more retirements than additions). However, detailed explanations on the assumptions changes that explain the differences between cumulative power generation capacity retirements and additions in the individual regions/countries are missing, leaving important questions unanswered.

This lack of detail makes it difficult to compare the updated STEPS scenario with our post-COVID scenarios in detail. However, in general terms, we can observe that the STEPS scenario of the WEO 2020 represents only a modest change in the pre-COVID trends for the coal power generation sector. This is illustrated by the fact that projected long-term coal demand is still higher than even the highest of our post-COVID scenarios, as illustrated in Figure B.2. Moreover, the slopes of the two scenarios for coal demand have a very similar long-term slope, showing that structural changes in coal markets that could follow the COVID-crisis (e.g. strong green recovery policies) have not been taken into account in the revised long-term projections, and the short-term shock is just seen as temporary, which strands in strong contrast with the scenarios we have developed in this paper.

Therefore, our criticism of the WEO results not sufficiently representing the upcoming downturn of coal is still valid also for the WEO 2020.

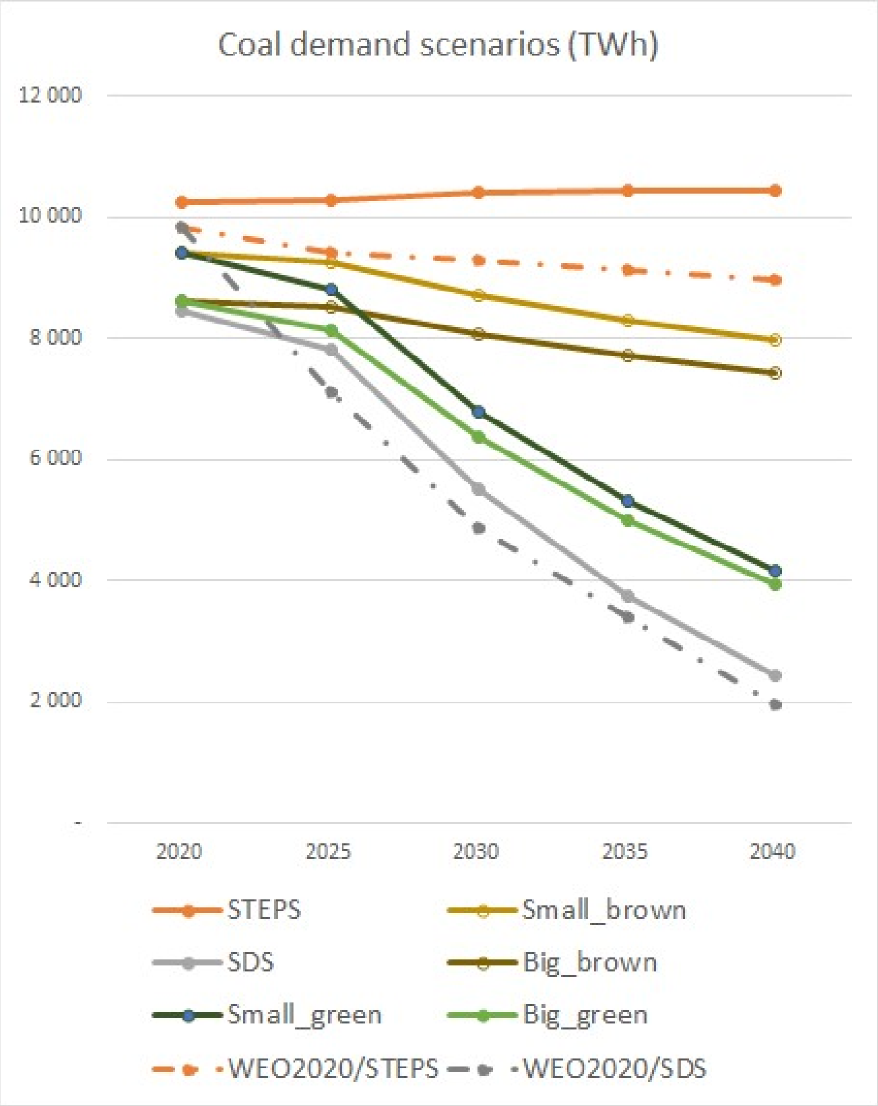


Figure B.2: Comparing coal demand scenarios with the WEO 2020.

B.4 More detailed results of the scenario runs

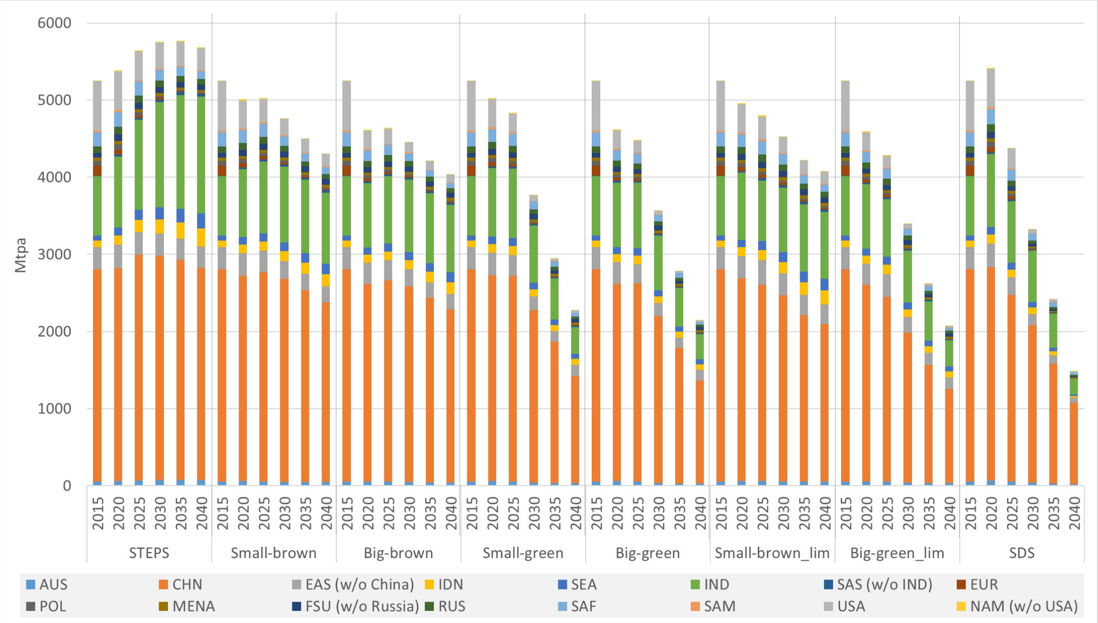


Figure B.3: Steam coal consumption in major consumption countries and regions in all scenarios, 2020-2040.

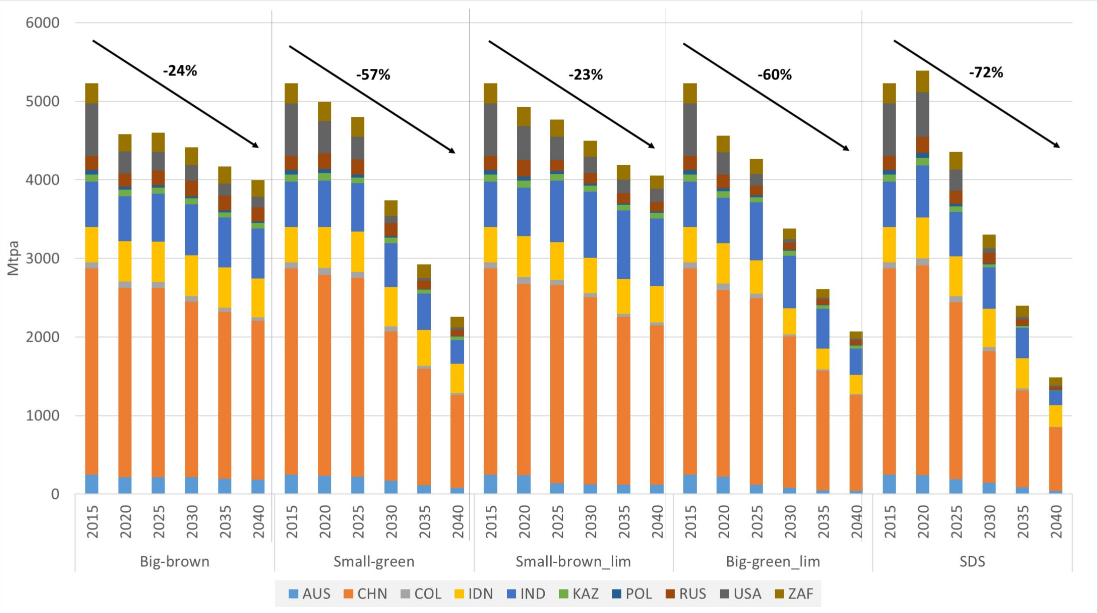


Figure B.4: Steam coal production by major steam coal producing countries 2015-2040 in additional scenarios.

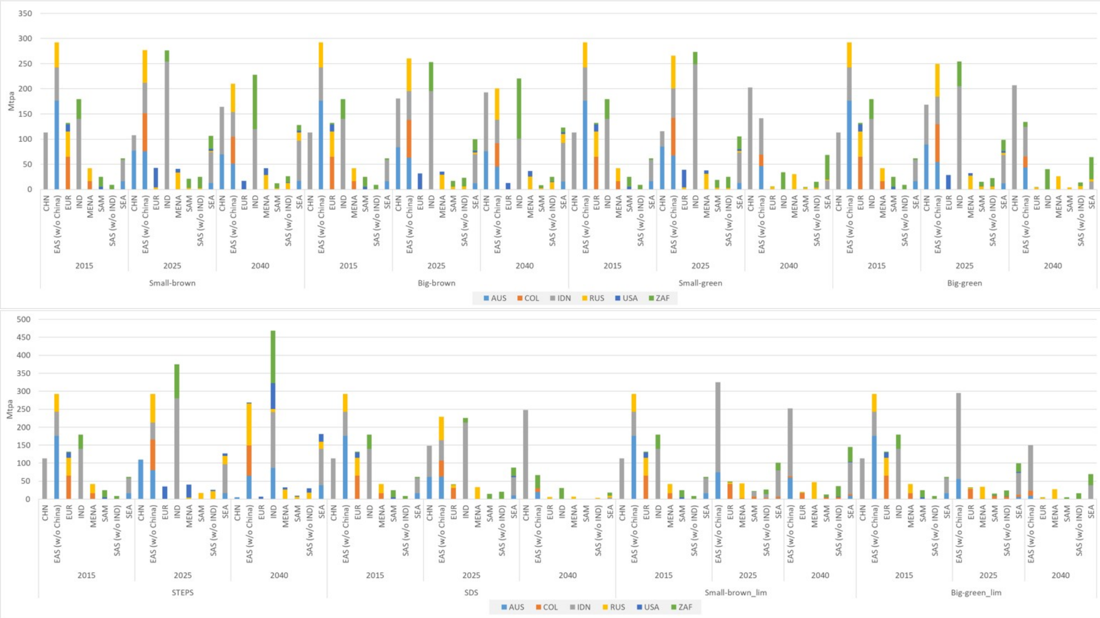


Figure B.5: Steam coal imports by major steam coal import regions (x-axis) in 2015, 2025, and 2040 from major steam coal exporters (y-axis).

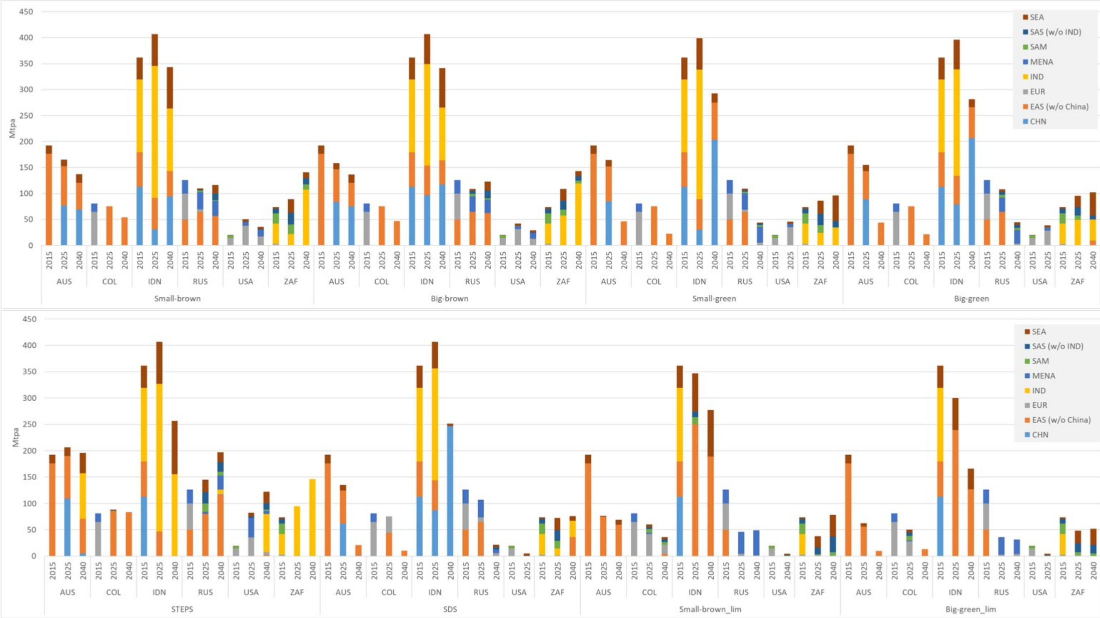


Figure B.6: Steam coal exports by major steam coal exporters (x-axis) in 2015, 2025, and 2040 to major steam coal import regions (y-axis).

Appendix C

Appendix to Chapter 4: Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin

C.1 Supplemental Information

Supplementary data associated with this article can be found, in the online version (pp. 29-45; section title “Appendix”), at
https://www.diw.de/documents/publikationen/73/diw_01.c.840655.de/dp2003.pdf (Hauenstein, Holz, Rathje, et al. 2022b).

Appendix D

Appendix to Chapter 5: The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?

D.1 Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1080/14693062.2019.1641462 (Mendelevitch, Hauenstein, and Holz 2019).

Appendix E

Appendix to Chapter 6: The U.S. coal sector between shale gas and renewables: Last resort coal exports?

E.1 Sensitivities of U.S. coal demand: retirement age & capacity factor

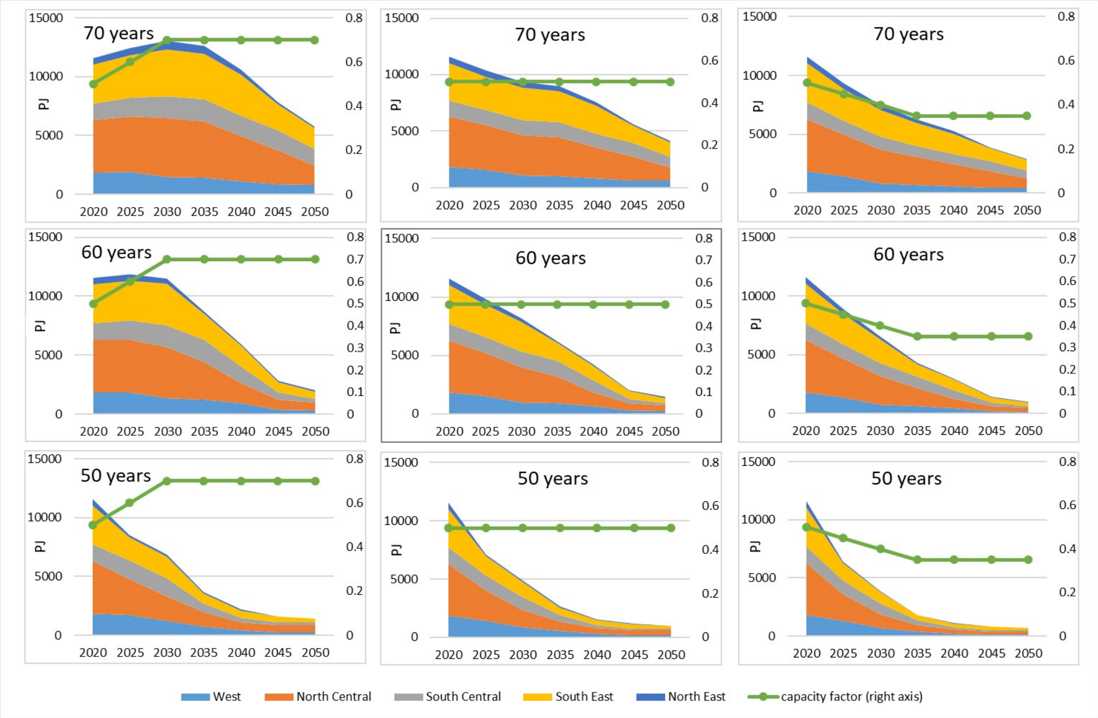


Figure E.1: U.S. coal power plant fleet [coal demand in PJ] development for alternative assumptions on retirement age and capacity factor (green line, right scale) by region between 2020 and 2050.

E.2 Effect of West coast ports on U.S. coal production

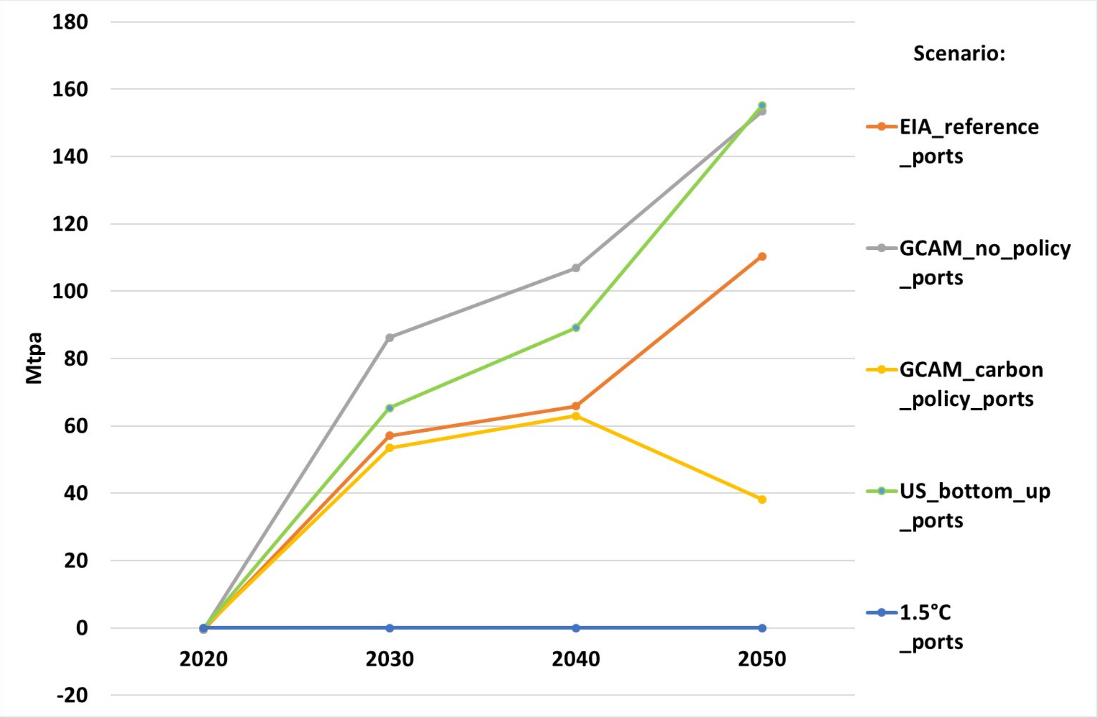


Figure E.2: Difference in U.S. coal production 2020-2050 in Mtpa per year between scenarios without and with new coal ports allowed on the U.S. West Coast.

Table E.1: Share of exports in U.S. steam coal production in various scenarios.

	EIA_reference	EIA_reference_ports	US_bottom_up	US_bottom_up_ports	1.5°C	1.5°C_ports
2020	12 %	12 %	12 %	12 %	12 %	12 %
2025	14 %	20 %	16 %	23 %	-9 %	-9 %
2030	15 %	26 %	25 %	35 %	-19 %	-19 %
2035	17 %	31 %	38 %	48 %	-5 %	-5 %
2040	17 %	34 %	52 %	64 %	1 %	1 %
2045	20 %	41 %	74 %	83 %	1 %	1 %
2050	11 %	35 %	78 %	88 %	1 %	1 %

E.3 Varying speed of regional coal demand decline

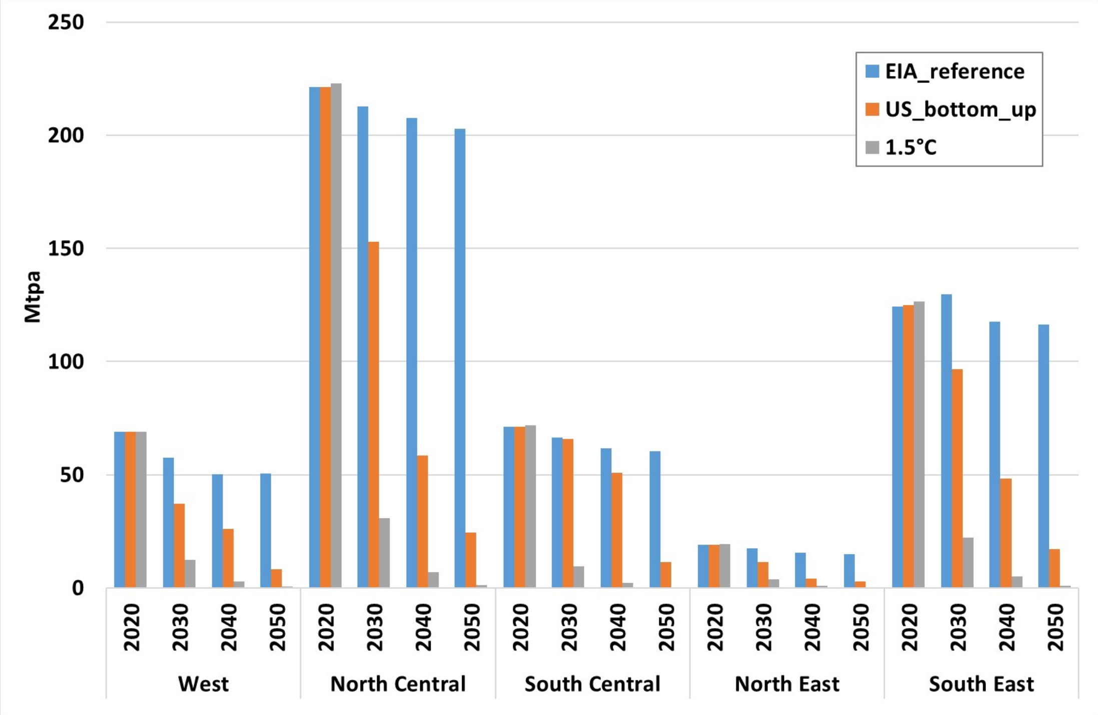


Figure E.3: Regional U.S. coal consumption 2020-2050 in Mt per year in various scenarios.

E.4 Regional coal mining employment characteristics

Table E.2: Average (2014-2018) productivity, annual working hours per employee, and jobs per Mtpa coal produced in the four U.S. coal regions.

Average data for 2014-2018	Appalachia	Interior	Rockies	PRB
Productivity [Mtpa/hour]	2.59	4.74	6.61	26.05
Annual working hours per employee	2219	2319	1832	2049
Jobs per Mtpa	174.04	90.93	82.56	18.74

Source: Own calculations based on data from EIA coal data browser: https://www.eia.gov/coal/data/browser/, last accessed May 05, 2020.

Appendix F

Appendix to Chapter 7: Overcoming political stalemates: The collaborative governance experience of the German Coal Commission

F.1 Theoretical framework: Elements of the three collaborative dynamics

Principled engagement comprises the elements **discovery**, **definition**, **deliberation**, and **determination**. The process of discovery aims to exchange information among participants, to gather new information, and to understand other participants' interests better. Definition is about aspects such as agreeing on the boundaries of the problem at hand. The deliberation process focuses on the problem-solving-oriented engagement of participants, and exchange among them, in contrast to a "mere bargaining or negotiation" situation (Newig et al. 2018, 283). Finally, many determinations are needed to structure the actual collaborative process and to agree on joint outputs (Emerson and Nabatchi 2015).

Shared motivation comprises the elements **trust**, **mutual understanding**, **internal legitimacy**, and **commitment**. The development of trust among participants is essential, enabling open exchange and providing the basis for mutual understanding, which "refers to the ability to comprehend and respect others' positions and interests, even when one might not agree with them" (Emerson and Nabatchi 2015, 66). Both of these elements are necessary to achieve internal legitimacy, which results in participants trusting in the process and its efficacy. Based on these elements, bonds evolve between the participants of shared commitment, "which enable participants to cross the organizational, sectoral, and/or jurisdictional boundaries that previously separated them and commit to a shared path" (Emerson, Nabatchi, and Balogh 2012, 14).

Capacity for joint action comprises the elements **procedural and institutional arrangements**, **leadership**, **knowledge**, and **resources**. Procedural and institutional arrangements comprise "formal and informal rules and protocols, institutional design, and other structural dimensions ⋯[that] manage the repeated interactions of multiple participants over time" (Emerson and Nabatchi 2015, 69). Leadership can be essential in multiple forms, such as to facilitate the deliberation process, to resolve conflicts, or to reach joint decisions. Chairs should therefore be "neutral and skilled mediators" whose main tasks are to implement professional and working norms, to settle disputes between members, and to facilitate an equal say in discussions and decisions for all stakeholders (Sabatier and Weible 2007, 206). Shared knowledge about the issues at hand is one of the bases for collaboration. In this context, it can be understood as "social capital of shared information that has been weighed, processed, and integrated with the values and judgments of CGR participants" (Emerson and Nabatchi 2015, 72). Resources, such as time, institutional support, or personal connections, are rarely distributed equally among participants. To enable the fair and equal participation of all participants, it is necessary to address differences in resource endowments (Emerson and Nabatchi 2015; Newig et al. 2018).

F.2 Collaborative Governance elements in the Coal Commission

Table F.1: Elements of collaboration dynamics in the Coal Commission.

Principled Engagement		Description	Importance for process
Discovery	Expert hearings and site visits in coal mining regions	67 external experts were heard in the first Commission meetings; Field trips to three lignite regions of Germany	Opportunity for participants to highlight their positions (by inviting specific experts) and to get to know other participants and their positions outside of bargaining situation [int_1; int_5; int_6; int_13]; Varying perception of added informational value depending on participants' previous knowledge levels [int_5; int_10; int_13]
Definition	Mandate	Mandate provided definition of tasks and goals	Discussion of interpretation of mandate in Commission meetings, but as each interest group persisted on the most favorable interpretation in their sense the initial mandate remained the point of reference [int_1; int_5; int_13; int_16]
	Content related definitions		No joint synthesis or definitions of common knowledge made [int_3; int_13];

Continued on next page

Table F.1: *(continued)* Elements of collaboration dynamics in the Coal Commission.

Deliberation	Plenary assembly	Often more than 100 participants; public character [int_10]	Members rarely departed from their initial positions, leaving little room for constructive compromise [int_12]; E.g., ultimate phase-out date was not seriously discussed in the plenary session until the last night [int_11]
	Deliberation of core contents	Took place mostly outside of the Coal Commission's plenary assembly, e.g., in FoC groups	Members without access to the other formats – such as FoC groups – where controversial topics were discussed, were largely excluded from the direct process of deliberating the core content [int_13; int_15; int_4]; Confidential nature of the FoC groups allowed their members to depart from their public demands, or temporarily surpass their constituency's "red lines" (which would not have been possible in public), to explore possible compromises [int_9; int_5].
	Agenda setting		All members were able to make demands and suggest topics for debate in the plenary session, such topics only had little chance of being discussed in further depth unless they were supported by other influential members or FoC groups [int_16]
Determination	Procedural rules	No preset procedural rules but had to be decided upon by the members in first meetings	Procedural rules passed at the start of the Commission; Some procedural arrangements changed in the course of the process, such as the creation of FoC groups. Individual or group influence on these arrangements varied [int_3; int_10; int_11; int_12]

Continued on next page

Table F.1: *(continued)* Elements of collaboration dynamics in the Coal Commission.

	Official decision process	Final decisions required voting in plenary assembly	Drafts for key elements, such as the procedural rules, meeting agendas, and the interim and final reports, were prepared by the administrative office, the chairs, and the FoC groups [int_10; int_11; int_14; int_18]
	Unofficial decision processes	Many decisions based on informal talks and meetings; decisions taken by the chairs [int_3; int_5; int_11; int_12]	Decisions on additional arrangements (e.g., FoC); Selection of possibilities to be available for final vote
Shared Motivation		Description	Importance for process
Trust	Historic relations of participants	Personal relationships from interactions prior to Commission's work	Relatively strong distrust between some individual members [int_2; int_5; int_8]
	Site visits and joint dinner	Field trips to coal regions with all Commission members; one joint dinner	Informal atmosphere allowed sharing positions more freely, and building personal relationships [int_5; int_11]
	Information leaks	Information from Commission meetings and discussions was forwarded unofficially to the press	Leaks were perceived as a standard procedure by those with more experience in political negotiation processes, while members with less experience perceived them as a breach of trust and disappointment in the group. In general, the high media attention made work in the Commission difficult [int_2; int_5; int_8; int_17].

Continued on next page

Table F.1: *(continued)* Elements of collaboration dynamics in the Coal Commission.

	Personal ties	Large size of commission (number of members); limited number of informal meetings	It was not possible to build a personal bond with all members due to the size of the Commission and the lack of informal meetings [int_2; int_5; int_8].
Mutual Understanding	Site visits		Site visits and exchange fostered understanding of actors' objectives and constraints [int_1; int_10]
	Joint work in Commission		The atmosphere improved over time and it was possible to establish respectful interaction "at a distance" throughout the Commission [int_5; int_13]. Some members were able to find "a common language" across interest group borders, while others struggled, depending on their personality and their experience with negotiation processes [int_11]
	Attendance of individual members during assembly meetings	A few members were repeatedly absent	Difficult to establish personal relationships or trustful collaboration with them [int_2; int_5]
Internal Legitimacy			High confidence in the process and its effectiveness among most members [int_1; int_8; int_10; int_16];
Commitment	Joint work in Commission		Rapprochement among Commission members, and a common desire to reach a compromise [int_15; int_16]
Capacity for Joint Action		Description	Importance for process

Continued on next page

Table F.1: *(continued)* Elements of collaboration dynamics in the Coal Commission.

Procedural and Institutional Arrangements	Plenary assembly	Members (voting right) + sherpas + non-member participants ; Right to speak for federal state representatives	Federal state representatives very actively involved as speakers [int_16]
	Sherpas	Members' assistants (no voting right)	Important role, engaged in exchange, discussion, and coordination outside the limited meeting times [int_10; int_11]
	Friends of Chair (FoC) groups	1) "energy and climate" (from August on, six members) 2) "structural development and employment" (from November on; seven members)	Critical details were mainly discussed in these small circles involving only a few members [int_5; int_6; int_9]
	Interest groups	Members with similar interests formed interest groups to discuss possible negotiation strategies, red lines for compromises, and demands	Deliberation space within interest groups and possibility for members without seat in FoC to introduce and discuss negotiation points for FoC meetings [int_12; int_13; int_16

Continued on next page

Table F.1: *(continued)* Elements of collaboration dynamics in the Coal Commission.

Leadership	Chairs (four)	Selected and appointed by government; Task to lead Commission's work and meetings	Very different roles taken by the four chairs; Large discrepancies in political experience and personal networks, resulting in different levels of power and influence; Perceived as advocates for certain interest groups instead of neutral moderators [int_3; int_9; int_12]; Important role in moderation of negotiations [int_15]; No concept/strategy to balance stakeholders' interests and achieve compromise [int_3]
	Administrative office	Organizational work of Commission (e.g., site visits, plenary meetings), provision of text drafts, meeting agendas	Non-transparent working procedures and politically influenced [int_5; int_8; int_10; int_12]; Staff from ministries and administrations of affected federal states not perceived as neutral [int_5; int_8]
Knowledge	Expert hearings		No joint synthesis or definitions of common knowledge made [int_3; int_13]; Debates were generally based on scientifically sound and by experts supported arguments [int_17]
Resources	See Table F.2		

F.2.1 Capacity for joint action

The element of **procedural and institutional arrangements** encompasses all formal and informal structures of the Coal Commission to enable discussions and to reach a compromise. The institutions included a plenary assembly involving all members, the inclusion of at least one assistant per member, referred to as sherpas, and a division between Coal Commission members with voting rights and non-member participants without voting rights who were able to participate in the general exchange and discussion. The sherpas played an important role because they also engaged in exchange, discussion, and coordination outside the limited meeting times [int_10; int_11].

One important arrangement that emerged during the work of the Coal Commission were the so-called Friends of Chair (FoC) groups. Critical details were mainly discussed in these small circles involving only a few members [int_5; int_6; int_9]. The ability to work and meet in smaller groups was an important aspect on the path to a compromise, given that they offered the opportunity for more concrete and confidential discussions. Furthermore, since the size of the plenary assembly made it an inappropriate instrument for writing texts for the interim and final reports, the FoC groups provided the opportunity to draft such texts. Even though several interviewees stated that the composition of FoC groups represented all interest groups [int_5; int_6; int_9; int_13], the meetings remained exclusive and non-transparent [int_3; int_11; int_15]. The first FoC group on “energy and climate” was set up in August after several members approached the chairs requesting changes in the Commission’s working structures because little progress had been made in the general sessions [int_5; int_14]. Two out of six of the first FoC’s members represented environmental interests, while the others represented the energy sector, industry, and unions.[1] The second FoC group on “structural development and employment” was only implemented in November, after several federal state prime ministers had intervened and demanded greater support for affected coal regions. This group mainly included members that represented local and regional economic interests, as well as employees’ and employers’ interests. Furthermore, members from environmental associations, for instance, were generally also in support of the demands for just transition and structural change processes [int_1], ultimately leaving them with little to offer the unions in return for their support for an earlier phase-out. Furthermore, this split into these two FoC groups also separated the deliberations on energy and climate issues on the one hand, and structural development and employment issues on the other.

In addition to establishing FoC groups, members with similar interests formed interest groups to discuss possible negotiation strategies, red lines for compromises, and demands. Another arrangement concerned the participatory possibilities of federal state representatives. The members decided that federal state representatives should have the right to

---

[1] Members of the FoC energy & climate: Stefan Kapferer (BDEW), Stefan Körzell (DGB), Holger Lösch (BDI, Dieter Kempf’s sherpas), Felix Matthes (Öko-Institut), Kai Niebert (DNR), and Katharina Reiche (VKU). Members of the FoC structural development & employment: Christine Herntier (Mayor of Spremberg), Steffen Kampeter (BDA), Michael Kreuzberg (Head of the District Authority of Rhein-Erft-Kreis), Matthias Platzeck (Commission Chair), Reiner Priggen (Landesverband Erneuerbare Energien NRW), Gunda Röstel (Stadtentwässerung Dresden), Christiane Schönefeld (Federal Employment Agency), Stanislaw Tillich (Commission Chair), and Michael Vassiliadis (IGBCE). Source Löw Beer et al. (2021).

speak during the Commission's meetings [int_10], which they proceeded to make extensive use of [int_16].

The chairs had different roles in the **leadership** of the Coal Commission, mainly due to their diverse political experience and personal networks, resulting in different levels of power and influence. Two chairs, former prime ministers of federal states with coal mining regions, were associated with the structural and economic interests of coal regions. Another chair, a former federal minister, was perceived as also representing Federal Government interests, due to his being in constant exchange and contact with the government. The fourth, a university professor, was associated with environmental interests. The chairs were perceived by many of the interviewees as advocates for certain interests, rather than as neutral moderators [int_3; int_12, int_9]. One interviewee noted that the chairs often only saw themselves as responsible for a certain group [int_12], which reinforced the power imbalance and unequal treatment of members. Interviewees generally described interaction with the four very different chairs as being challenging [int_3; int_6; int_11; int_9]. However, one interviewee pointed out that the different positions were brought together by the chairs, and especially by one chair due to his political experience [int_15].

Overall, cooperation among chairs and the administrative office, as well as with governmental institutions, was considered rather weak [int_5; int_8]. In particular, it was criticized that there was no concept of how the Coal Commission was to reach a compromise that actually balanced the stakeholders' interests, rather than simply achieving the lowest common denominator [int_3]. The administrative office, tasked with providing administrative assistance to the Coal Commission in the form of organizing expert hearings and site visits, or drafting texts, was also criticized for not working transparently, as well as for reaching politically influenced decisions [int_5; int_8; int_10; int_12]. This criticism was nourished by the staffing of the administrative office, which was thought to be politically motivated. For example, some staff had been posted from administrations of affected federal states [int_5; int_8].

A large number of experts were invited to speak on different topics. However, several interviewees mentioned limited efforts to create a shared **knowledge** base [int_3; int_11; int_15]. Especially established and well-informed members had a limited interest in reducing knowledge deficits of other members or in revisiting their own positions and creating a common knowledge base [int_1; int_5; int_9]. Although specific information was requested from external experts, no joint synthesis of the presented expert input or definitions of common knowledge was prepared [int_3; int_13]. However, debates were generally based on scientifically sound and by experts supported arguments [int_17].

Collaborative **resources** may take different forms, such as time, funding, technical and logistical support, power, and expertise (Emerson, Nabatchi, and Balogh 2012). Resource disparities and mismanagement can affect the outcome and the “perceived and real fairness, legitimacy, and efficacy of CGRs” (Emerson, Nabatchi, and Balogh 2012, 16). Table F.2 describes the identified differences in resource endowment, grouped into five resource types. Overall, the differences in expertise, capacity, and financial resources led to the actors’ different starting conditions and the differences in the opportunities to engage in the process [int_11; int_9; int_7]. It was mentioned that although it was difficult to fully erase the initial resource disparities, it was possible to compensate for some of them [int_11].

F.2.2 Principled engagement

For successful principled engagement, it is important that participants **discover** the interests and positions of others, enabling them to acquire expert knowledge in the broad field of topics addressed. During the first few months of the Coal Commission, information and insights were provided by 67 expert hearings, as well as field trips to coal mining regions. Interestingly, participants assessed this input very differently. Some stated that they acquired a lot of new information thanks to this input [int_10], while others gained little from these processes [int_13; int_5]. However, some of the particularly well established and informed actors emphasized that these processes gave them the opportunity to highlight their own positions, and to get to know the other participants without having to engage in fierce discussions and bargaining [int_6; int_13; int_5; int_1].

The **deliberation** on the main decisions largely took place outside of the Coal Commission’s plenary assembly. In the plenary discussions, members rarely departed from their initial positions, leaving little room for constructive compromise [int_12]. This was due at least in part to the ultimately public nature of the plenary meetings, caused by constant leaks to the public, as well as the size of the meetings, often with 100 or more participants [int_10]. As an example, the debate on the ultimate phase-out date was not seriously discussed in the plenary session until the last night [int_11]. Members without access to the other formats -such as FoC groups -where controversial topics were discussed, were largely excluded from the direct process of deliberating the core content [int_13; int_15; int_4]. Although all members were able to make demands and suggest topics for debate in the plenary session, such topics only had little chance of being discussed in further depth unless they were supported by other influential members or FoC groups [int_16]. The confidential nature of the FoC groups allowed their members to depart from their public demands, or temporarily surpass their constituency’s “red lines” (which would not have been possible in public), to explore possible compromises [int_9; int_5].

The element of **definition** was rather implicit in many instances and is intertwined with **determination**. For example, the understanding of the tasks and expectations of the Coal

Commission according to the political mandate introducing the Commission was discussed among the members [int_13; int_5; int_16], yet no side was willing to accept a more favorable interpretation for their opponents [int_1; int_5]. Similarly, the interpretation of expert information, as stated above, was subject to each participant's own judgement, since no joint synthesis of the presented expert input was prepared [int_13; int_11]. The procedural rules were discussed and passed at the start of the Coal Commission. However, some procedural arrangements changed in the course of the process, such as the creation of FoC groups or the right of federal state government representatives to speak. Individual or group influence on these arrangements varied [int_12; int_10; int_3; int_11].

As with the deliberation of core elements, determination was also linked to the work of FoCs and other small groups. However, final decisions had to be reached in the plenary assembly. Drafts for key elements, such as the procedural rules, meeting agendas, and the interim and final reports, were prepared by the administrative office, the chairs, and the FoC groups [int_18; int_10; int_11; int_14]. However, many of the underlying decisions on content, or who would belong to the FoC groups, were not discussed or decided in the plenary session, but were based on informal talks and meetings, and decisions were taken by the chairs [int_12; int_3; int_5; int_11]. Another prominent example of this non-transparency was the gathering of a small number of members on the very last night of the Commission to bargain over the remaining unresolved questions, such as the phase-out date. The members who were not party to this special meeting simply noticed at some point that all of the chairs and some of the members were no longer present in the Coal Commission meeting room [int_11]. Members without experience of such bargaining processes found it hard to know how to introduce and enforce their demands at the right place and the right time.

Decisions on the mandate and Commission members during the pre-Commission phase were not part of the Coal Commission's internal processes, but may well have largely determined its course: Some established members were also involved in the development phase of the Commission. For example, government officials asked them to comment on the selection of invited stakeholders or they themselves attempted to influence the wording of the mandate. Some were completely surprised by the call asking them to participate, while others were closely involved in discussions about the Coal Commission before it was officially launched [int_5; int_11; int_12; int_4].

F.2.3 Shared motivation

Trust and **mutual understanding** build the basis for collaboration among participants. In the Coal Commission, events that were frequently referred to in this regard were the field trips to coal regions and a joint dinner. For example, one interviewee mentioned that he became aware during these trips that trade unions are membership organizations, which helped him to understand those actors' constraints [int_1]. Others stated that they gained a better insight into the local situation in the coal regions [int_10]. Several members emphasized their appreciation of the joint dinner organized on one of the trips. This dinner was one of the rare occasions when members were able to meet in an informal atmosphere. This enabled them to share their positions more freely, and to build more personal relationships. Several interviewees mentioned that arranging more meetings of such nature would have been a means of increasing trust and understanding among members [int_5; int_11].

Generally, the atmosphere improved over time and it was possible to establish respectful interaction "at a distance" throughout the Commission [int_5; int_13]. Some members were able to find "a common language" across interest group borders, while others struggled, depending on their personality and their experience with negotiation processes [int_11]. There was rapprochement not only among individuals, but also in the whole group, and a common desire to reach a compromise [int_15; int_16], leading to a shared **commitment**.

However, a latent sense of mistrust shaped the work of the Coal Commission because several aspects limited the trust-building process:

- Leaks: Information was constantly leaked to the press, which made trusting cooperation more difficult. However, this was perceived differently by different actors. Leaks were perceived as a standard part of the process by those with more experience in political negotiation processes, while members with less experience perceived them as a breach of trust and disappointment in the group. In general, the high media attention made work in the Commission difficult [int_2; int_5; int_8; int_17].
- Attendance: Presence at meetings is particularly important for shared motivation. Only a few members were repeatedly absent, making it difficult to establish personal relationships or trustful collaboration with them [int_2; int_5].
- Personal ties: It was not possible to build a personal bond with all members due to the size of the Commission and the lack of informal meetings. Interviewees referred to a relatively strong distrust between some individual members [int_2; int_5; int_8].
- Administrative office: Since the administrative office was perceived as being biased, some members found it difficult to work with it.

The federal state prime ministers played a special role. Several interviewees considered their behavior to be negative for the process [int_16]. The prime ministers were described as dominant in the plenary sessions, although they only had the right to speak, and not to vote. Furthermore, their major influence became apparent from their interactions with the Federal Government in general, and in particular from the decision on funds for affected regions in November 2018. These funds led to an intervention by Chancellor Merkel, effectively delaying the Coal Commission and potentially increasing total funds for the coal regions, although all Commission members had already agreed on a compromise.

Internal legitimacy refers to individual members' confidence in the process and the effectiveness of the Coal Commission. Confidence in the process and its effectiveness was high among most members [int_1; int_8; int_10; int_16], although there was some disillusionment about the possibilities to have their own positions included in the final report [int_12]. However, most members had serious intentions to find a solution, and were committed to the process, even though it was not clear at the beginning what the final outcome would be, and how the agreements would be incorporated into the political process.

Table F.2: Identified differences in resource endowment.

Type of resource	Resource disparity	Perception and influence on the process
Time / financial / organizational	Voluntary members of organizations vs. boards of large industry associations	No level playing field regarding organizational support [int_9]; Results in power disparities and fewer time resources for the Coal Commission [int_12].
	Majority of formal and informal meetings held in Berlin	Difficult for members who do not live or work in Berlin [int_7; int_11].
	Time	Need to prioritize which (informal) meetings to attend [int_7].
Human resources	Differences in staffing	Differences in staff support and organization of support [int_15; int_12; int_13; int_7] - power imbalance [int_12; int_2].
Network	Different network with chairs	Differences lead to different treatment of members [int_12].
	Links between some members (before the Coal Commission)	Agreements in informal meetings: difficult for members outside Berlin to comprehend processes and decisions [int_11]; People with a stronger existing network who knew each other had more opportunities to influence the outcome; However, few new connections between interest groups were formed [int_11].
Negotiating and political experience	Understanding the way things work	More work for people without experience (reading “all” the papers) [int_4]; At the beginning especially, it remained unclear, particularly for inexperienced members, how decisions were to be reached, and who would decide on the agenda or write the reports [int_12; int_5; int_11].
	Negotiation experience	Correlation of level of experience and influence on outcomes [int_8; int_3; int_2]. Several personalities are said to have had a larger influence on the Coal Commission, especially due to their goal orientation, capacity in building compromises, and in-depth knowledge [int_5; int_9; int_10; int_13; int_16]; Negotiating and strategic experience helped to steer decisions.
Expertise (knowledge)	Access and capacity to gain sector-specific knowledge	No level playing field due to disparities in knowledge and access to information [int_9].

Appendix G

Erklärung Ko-Autor*innenschaften der Publikationen

Auszug aus “Kriterienliste für kumulative Dissertationen im Bereich Energiewissenschaften” zu “5. Ko-Autor*innenschaften” (Stand 11. Mai 2022):

> “Mindestens ein Artikel muss in Alleinautor*Innenschaft oder zwei Artikel in Erstautor*innenschaft geschrieben werden. Publikationen dürfen auch Gegenstand anderer (abgeschlossener oder laufender) Dissertationen der Ko-Autor*Innen sein. Die Beiträge aller Ko-Autor*in-nen an der jeweiligen Publikation sind in einer Erklärung anzugeben, die der Dissertation (z.B. im An-hang) beizufügen ist.”

Tabelle G.1 listet die Publikationen aus welchen diese kumulative Dissertation besteht, sowie die Beiträge aller Ko-Autor*innen zu diesen Publikationen auf. Dies ist mit allen Ko-Autor*innen und Betreuer*innen abgesprochen.

Christian Hauenstein
Flensburg, 30.09.2022

Table G.1: Erklärung Ko-Autor*innenschaften der Publikationen

Kapitel	**(Pre-) Publikation und Beiträge Ko-Autor*innen**
2	**Stranded assets and early closures in global coal mining under 1.5°C**
	Im Reviewverfahren in *Environmental Research Letters* unter dem selben Titel. Pre-print publiziert als: Hauenstein, Christian. (2022). 'Stranded assets and early closures in global coal mining under 1.5°C' (Version v1). Zenodo. https://doi.org/10.5281/zenodo.6473733
	Artikel in Alleinautorenschaft.
3	**The Death Valley of coal - Modelling COVID-19 recovery scenarios for steam coal markets**
	Publiziert als: Yanguas Parra, Paola, Christian Hauenstein, and Pao-Yu Oei. 2021. 'The Death Valley of Coal –Modelling COVID-19 Recovery Scenarios for Steam Coal Markets'. *Applied Energy* 288 (April): 116564. https://doi.org/10.1016/j.apenergy.2021.116564
	Gemeinsame Publikation mit Paola Yanguas Parra und Pao-Yu Oei. C. H., P. Y. P., und P.-Y. O.: Konzeptualisierung, Szenarienentwicklung, Untersuchung, Visualisierungen, Schreiben - Manuskript, Schreiben - Review & Editieren. P. Y. P. und P.-Y. O.: Expert*innenumfrage. C. H.: Modellanpassungen und Modellläufe. P. Y. P.: Projekt Administration.
4	**Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin**
	Im Reviewverfahren in *One Earth* unter dem selben Titel. Pre-print publiziert als: Hauenstein, Christian, Franziska Holz, Lennart Rathje and Thomas Mitterecker. 2022. 'Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin' *DIW Berlin Discussion Paper* 2003, Berlin: German Institute for Economic Research (DIW Berlin).
	Gemeinsame Arbeit mit Franziska Holz, Lennart Rathje und Thomas Mitterecker. C. H., F. H., L. R., und T. M.: Schreiben - Manuskript. C. H. und F. H.: Konzeptualisierung und Methodologie. C. H., L. R. und T.M.: formale Analyse und Daten Aufbereitung. C. H. und T. M.: Visualisierungen. C. H.: Projekt Administration.
5	**The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?**
	Publiziert als: Mendelevitch, Roman, Christian Hauenstein, and Franziska Holz. 2019. 'The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?' *Climate Policy* 19 (10): 1310–24. https://doi.org/10.1080/14693062.2019.1641462
	Gemeinsame Publikation mit Roman Mendelevitch und Franziska Holz. C. H., F. H., und R. M.: Konzeptualisierung, Methodologie, Untersuchung, Schreiben - Manuskript, Schreiben - Review & Editieren. C. H.: Literaturanalyse und Daten Aufbereitung. C. H. und R. M. Modellläufe und Visualisierungen. R. M.: Projekt Administration.
6	**The U.S. coal sector between shale gas and renewables: Last resort coal exports?**
	Publiziert als: Hauenstein, Christian, and Franziska Holz. 2021. 'The U.S. Coal Sector between Shale Gas and Renewables: Last Resort Coal Exports?' *Energy Policy* 149 (February): 112097. https://doi.org/10.1016/j.enpol.2020.112097
	Gemeinsame Publikation mit Franziska Holz. C. H. und F. H.: Konzeptualisierung, Methodologie, Datenerhebung, Untersuchung, Schreiben - Manuskript, Schreiben - Review & Editieren. C. H.: Daten Aufbereitung, Modellläufe, Validierung, Ergebnisvisualisierungen und Projekt Administration.
7	**Overcoming political stalemates: The collaborative governance experience of the German Coal Commission**
	Im Reviewverfahren in *Climate Policy* unter dem selben Titel.
	Gemeinsame Arbeit mit Isabell Braunger, Alexandra Krumm, Hanna Brauers und Pao-Yu Oei. C. H., I. B., A. K., H. B. und P.-Y. O.: Konzeptualisierung, Methodologie, Validierung, Untersuchung, Daten Aufbereitung, Schreiben - Manuskript. C. H., A. K. und P.-Y. O.: Schreiben - Review. C. H.: Projekt Administration.

References

ABS. 2016. *Australian Statistical Geography Standard (ASGS) Volume 1 - Main Structure and Greater Capital City Statistical Areas.* https://www.abs.gov.au/.

AEMO: Australian Energy Market Operator. 2020. *2020 Integrated System Plan. For the National Electricity Market.* https://www.aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp.

———. 2021. *Draft 2022 Integrated System Plan. For the National Electricity Market.* https://www.aemo.com.au/-/media/files/major-publications/isp/2022/draft-2022-integrated-system-plan.pdf?la=en.

Amer, M., T. U. Daim, and A. Jetter. 2013. „A review of scenario planning.“ *Futures* 46:23–40. https://doi.org/10.1016/j.futures.2012.10.003.

Ansari, D., and F. Holz. 2020. „Between stranded assets and green transformation: Fossil-fuel-producing developing countries towards 2055.“ *World Development* 130:104947. https://doi.org/10.1016/j.worlddev.2020.104947.

Ansari, D., F. Holz, and H. al-Kuhlani. 2020. „Energy outlooks compared: Different methods, different futures.“ *Economics of Energy & Environmental Policy* 9 (1).

Ansell, C., and A. Gash. 2007. „Collaborative Governance in Theory and Practice.“ *Journal of Public Administration Research and Theory* 18 (4): 543–571. https://doi.org/10.1093/jopart/mum032.

Argus. 2020a. *Argus Seaborne Coal Outlook 2020.* Technical report. https://www.argusmedia.com/en/coal/argus-seaborne-coal-outlook.

———. 2020b. *Seaborne thermal coal market faces 2020 supply adjustment.* Technical report, Argus White Paper. https://thecoalhub.com/wp-content/uploads/2020/06/SeaborneCoalWP.pdf.

Asheim, G. B., T. Fæhn, K. Nyborg, M. Greaker, C. Hagem, B. Harstad, M. O. Hoel, D. Lund, and K. E. Rosendahl. 2019. „The case for a supply-side climate treaty.“ *Science* 365 (6451): 325–327. https://doi.org/10.1126/science.aax5011.

Atteridge, A., and C. Strambo. 2020. *Seven principles to realize a just transition to a low-carbon economy.* Stockholm Environment Institute.

Audoly, R., A. Vogt-Schilb, C. Guivarch, and A. Pfeiffer. 2018. „Pathways toward zero-carbon electricity required for climate stabilization.“ *Applied Energy* 225:884–901. https://doi.org/10.1016/j.apenergy.2018.05.026.

Auer, H., P. Crespo del Granado, P.-Y. Oei, K. Hainsch, K. Löffler, T. Burandt, D. Huppmann, and I. Grabaak. 2020. „Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5°C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE.“ *e & i Elektrotechnik und Informationstechnik* 2020 (7). https://doi.org/https://doi.org/10.1007/s00502-020-00832-7.

Auger, T., J. Trüby, P. Balcombe, and I. Staffell. 2021. „The future of coal investment, trade, and stranded assets.“ *Joule* 5 (6): 1462–1484. https://doi.org/10.1016/j.joule.2021.05.008.

Australian Government Department of Industry, Science, Energy and Resources. 2021a. *Australia's Nationally Determined Contribution. Communication 2021.* https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Australia%20First/Australia%20Nationally%20Determined%20Contribution%20Update%20October%202021%20WEB.pdf.

———. 2021b. *Australia' s emissions projections 2021.* https://www.industry.gov.au/sites/default/files/October%5C%202021/document/australias_emissions_projections_2021_0.pdf.

Baer, H. A. 2016. „The nexus of the coal industry and the state in Australia: Historical dimensions and contemporary challenges.“ *Energy Policy* 99:194–202.

Baker, S. R., N. Bloom, S. J. Davis, and S. J. Terry. 2020. *COVID-Induced Economic Uncertainty.* Technical report. http://www.nber.org/papers/w26983.

Barbier, E. B. 2010. „Green Stimulus, Green Recovery and Global Imbalances.“ *World Economics* 11 (2): 149–177.

BARCLAYS. 2020. *Post-COVID Economy.* https://www.investmentbank.barclays.com/content/dam/barclaysmicrosites/ibpublic/documents/our-insights/The-post-COVID-economy/post_covid_economy.pdf.

Baruya, P. 2018. *Production and supply chain costs of coal.* Technical report CCC/280. London: Clean Coal Centre / IEA. https://www.iea-coal.org/report/production-and-supply-chain-costs-of-coal/.

Becker, R. A., A. R. Wilks, R. Brownrigg, T. P. Minka, and A. Deckmyn. 2021. *maps: Draw Geographical Maps.* https://CRAN.R-project.org/package=maps.

Bednar, J., M. Obersteiner, and F. Wagner. 2019. „On the financial viability of negative emissions.“ *Nature Communications* 10 (1): 1783. https://doi.org/10.1038/s41467-019-09782-x.

Bennett, S., and T. Stanley. 2018. *Commentary: US budget bill may help carbon capture get back on track.* https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html.

Best, R., P. J. Burke, and F. Jotzo. 2020. „Carbon Pricing Efficacy: Cross-Country Evidence.“ *Environmental and Resource Economics* 77 (1): 69–94. https://doi.org/10.1007/s10640-020-00436-x.

Betz, M. R., M. D. Partridge, M. Farren, and L. Lobao. 2015. „Coal mining, economic development, and the natural resources curse.“ *Energy Economics* 50:105–116. https://doi.org/10.1016/j.eneco.2015.04.005.

BGR. 2019. *Energy Study 2019: Data and Developments Concerning German and Global Energy Supplies.* Technical report. Hannover, Germany. https://www.bgr.bund.de/EN/Themen/Energie/Downloads/energiestudie_2019_en.pdf?___blob=publicationFile&v=6.

Blondeel, M., and T. Van de Graaf. 2018. „Toward a global coal mining moratorium? A comparative analysis of coal mining policies in the USA, China, India and Australia.“ *Climatic Change,* https://doi.org/10.1007/s10584-017-2135-5.

Blondeel, M., T. Van de Graaf, and T. Haesebrouck. 2020. „Moving beyond coal: Exploring and explaining the Powering Past Coal Alliance.“ *Energy Research & Social Science* 59:101304. https://doi.org/10.1016/j.erss.2019.101304.

Bloomberg. 2019. *China’ s Energy Game Plan Features a Giant Coal-Hauling Rail Line.* https://www.bnnbloomberg.ca/china-s-energy-game-plan-features-a-giant-coal-hauling-rail-line-1.1319050.

———. 2020a. „Banks Shunning Coal Financing Bodes Badly for New Plants in Asia.“ *Bloomberg.com.*

———. 2020b. *BlackRock Warns Korean Utility on Overseas Coal Plant Push.* https://www.bloombergquint.com/business/blackrock-warns-korea-s-power-giant-on-overseas-coal-plant-push.

BMWi. 2019. *Commission on Growth, Structural Change and Employment - Final Report.* Technical report. Berlin, Germany. https://www.bmwi.de/Redaktion/EN/Publikationen/commission-on-growth-structural-change-and-employment.pdf?___blob=publicationFile&v=3.

Bond, K., E. Vaughan, and H. Benham. 2020. *Decline and Fall: The Size & Vulnerability of the Fossil Fuel System.* Technical report. https://carbontracker.org/reports/decline-and-fall/.

Bos, K., and J. Gupta. 2019. „Stranded assets and stranded resources: Implications for climate change mitigation and global sustainable development.“ *Energy Research & Social Science* 56:101215. https://doi.org/10.1016/j.erss.2019.05.025.

BP. 2022. *Statistical Review of World Energy 2022.* Technical report. London. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

Brauers, H., P. Herpich, C. Von Hirschhausen, I. Jürgens, K. Neuhoff, P.-Y. Oei, and J. Richstein. 2018. „Coal transition in Germany Learning from past transitions to build phase-out pathways.“

Brauers, H. 2022. „Natural gas as a barrier to sustainability transitions? A systematic mapping of the risks and challenges.“ *Energy Research & Social Science* 89:102538. https://doi.org/10.1016/j.erss.2022.102538.

Brauers, H., C. Hauenstein, I. Braunger, A. Krumm, and P.-Y. Oei. 2022. *Comparing Coal Commissions: What to learn for future fossil phase-outs?* Technical report, CINTRAN. https://vpro0190.proserver.punkt.de/s/fDDJBJ2QCS3g8rg.

Brauers, H., and P.-Y. Oei. 2020. „The political economy of coal in Poland: Drivers and barriers for a shift away from fossil fuels.“ *Energy Policy* 144:111621. https://doi.org/10.1016/j.enpol.2020.111621.

Brauers, H., P.-Y. Oei, and P. Walk. 2020. „Comparing coal phase-out pathways: The United Kingdom’ s and Germany’ s diverging transitions.“ *Environmental Innovation and Societal Transitions* 37:238–253. https://doi.org/10.1016/j.eist.2020.09.001.

Braungardt, S., J. van den Bergh, and T. Dunlop. 2019. „Fossil fuel divestment and climate change: Reviewing contested arguments.“ *Energy Research & Social Science* 50:191–200. https://doi.org/10.1016/j.erss.2018.12.004.

Braunger, I., and C. Hauenstein. 2020. „How incumbent cultural and cognitive path dependencies constrain the ‘scenario cone’ : Reliance on Carbon Dioxide Removal due to techno-bias.“ *Economics of Energy & Environmental Policy* 9 (1): 137–154. https://doi.org/10.5547/2160-5890.9.1.ibra.

Breetz, H., M. Mildenberger, and L. Stokes. 2018. „The political logics of clean energy transitions.“ *Business and Politics* 20 (4): 492–522. https://doi.org/10.1017/bap.2018.14.

Brief, C. 2020a. *Analysis: China’ s Covid stimulus plans for fossil fuels three times larger than low-carbon.* https://www.carbonbrief.org/analysis-chinas-covid-stimulus-plans-for-fossil-fuels-three-times-larger-than-low-carbon.

———. 2020b. *Coronavirus: Tracking how the world' s 'green recovery' plans aim to cut emissions.* https://www.carbonbrief.org/coronavirus-tracking-how-the-worlds-green-recovery-plans-aim-to-cut-emissions.

Brisbois, M. C., and d. R. C. Loë. 2016. „Power in Collaborative Approaches to Governance for Water: A Systematic Review." *Society & Natural Resources* 29 (7): 775–790. https://doi.org/10.1080/08941920.2015.1080339.

———. 2017. „Natural resource industry involvement in collaboration for water governance: influence on processes and outcomes in Canada." *Journal of Environmental Planning and Management* 60 (5): 883–900. https://doi.org/10.1080/09640568.2016.1182899.

Brown, T., T. Bischof-Niemz, K. Blok, C. Breyer, H. Lund, and B. Mathiesen. 2018. „Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'." *Renewable and Sustainable Energy Reviews* 92:834–847. https://doi.org/10.1016/j.rser.2018.04.113.

Buckley, T. 2019. *Billionaire Adani Being Subsidised for Carmichael Thermal Coal Mine.* The Institute for Energy Economics and Financial Analysis (IEEFA). https://ieefa.org/wp-content/uploads/2019/08/IEEFA-Note_Billionaire-Adani-Being-Subsidised-for-Carmichael-Thermal-Coal-Mine_29-August-2019.pdf.

Buckley, T., and S. Nicholas. 2017. *Adani: Remote Prospects - Carmichael Status Update 2017.* The Institute for Energy Economics and Financial Analysis (IEEFA). https://ieefa.org/wp-content/uploads/2017/04/Adani-Remote-Prospects-Carmichael-Status-Update-2017_April-2017_SN.pdf.

Buckley, T., and T. Sanzillo. 2013. *Remote Prospects - A financial analysis of Adani' s coal gamble in Australia' s Galilee Basin.* The Institute for Energy Economics and Financial Analysis (IEEFA).

Budinis, S., S. Krevor, N. M. Dowell, N. Brandon, and A. Hawkes. 2018. „An assessment of CCS costs, barriers and potential." *Energy Strategy Reviews* 22:61–81. https://doi.org/10.1016/j.esr.2018.08.003.

Bui, M., C. S. Adjiman, A. Bardow, E. J. Anthony, A. Boston, S. Brown, P. S. Fennell, et al. 2018. „Carbon capture and storage (CCS): the way forward." *Energy & Environmental Science* 11 (5): 1062–1176. https://doi.org/10.1039/C7EE02342A.

Burandt, T., B. Xiong, K. Löffler, and P.-Y. Oei. 2019. „Decarbonizing China' s energy system -Modeling the transformation of the electricity, transportation, heat, and industrial sectors." *Applied Energy* 255:113820. https://doi.org/10.1016/j.apenergy.2019.113820.

Bureau of Energy, MOEA. 2018. *The Electric Power Supply and Demand Report of Taiwan.* https://www.moeaboe.gov.tw/ECW/english/content/wHandMenuFile.ashx?menu_id=8679&file_id=7047.

Byers, E., V. Krey, E. Kriegler, K. Riahi, R. Schaeffer, J. Kikstra, R. Lamboll, et al. 2022. (AR6 Scenarios Database. V. 1.0). https://doi.org/10.5281/zenodo.5886912.

Caldecott, B. 2017. „Introduction to special issue: stranded assets and the environment.“ *Journal of Sustainable Finance & Investment* 7 (1): 1–13. https://doi.org/10.1080/20430795.2016.1266748.

Caldecott, B., G. Dericks, D. J. Tulloch, L. Kruitwagen, and I. Kok. 2016. *Stranded Assets and Thermal Coal in Japan: An analysis of environment-related risk exposure.* Technical report, Sustainable Finance Programme. Oxford, UK.

Caldecott, B., O. Sartor, and T. Spencer. 2017. *Lessons from previous 'Coal Transitions' High-level Summary for Decision-makers.* Technical report. www.coaltransitions.org.

Caldecott, B., J. Tilbury, and Y. Ma. 2013. *Stranded Down Under? Environment-related factors changing China' s demand for coal and what this means for Australian coal assets.* University of Oxford, Smith School of Enterprise and the Environment, Stranded Assets Programme. https://www.inet.ox.ac.uk/files/Pfeiffer_et_al___20172C_INET_WP-Dead_on_arrival_v3_7_clean.pdf.

Calvin, K., P. Patel, L. Clarke, G. Asrar, B. Bond-Lamberty, R. Y. Cui, A. Di Vittorio, et al. 2019. „GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems.“ *Geoscientific Model Development* 12 (2): 677–698. https://doi.org/10.5194/gmd-12-677-2019.

Campbell, R., and L. Carter. 2021. *Mind the gaps.* The Australia Institute. https://australiainstitute.org.au/report/mind-the-gaps/.

Campbell, S., and L. Coenen. 2017. *Transitioning beyond coal: Lessons from the structural renewal of Europe' s old industrial regions.* Technical report, CCEP Working Paper 1709. Melbourne, Australia. https://coaltransitions.files.wordpress.com/2017/11/australian-coal-transition-industrialization-final.pdf.

Carbon Pricing Leadership Coalition. 2017. *Report of the high-level commission on carbon prices.* Technical report. Washington DC, USA. https://www.carbonpricingleadership.org.

Cardoso, A. 2015. „Behind the life cycle of coal: Socio-environmental liabilities of coal mining in Cesar, Colombia.“ *Ecological Economics* 120:71–82. https://doi.org/10.1016/j.ecolecon.2015.10.004.

Cardoso, A., and E. Turhan. 2018. „Examining new geographies of coal: Dissenting energyscapes in Colombia and Turkey.“ *Applied Energy* 224:398–408. https://doi.org/10.1016/j.apenergy.2018.04.096.

Cassotta, S., V. P. Cueva, and M. Raftopoulos. 2021. „A Case Study of the Carmichael Coal Mine from the Perspectives of Climate Change Litigation and Socio-Economic Factors.“ *Law, Environment and Development* 17 (1): 55–71.

Census. 2019. *MAF/TIGER geographic database.* https://www2.census.gov/geo/tiger/GENZ2018/shp/.

Chaturvedi, S. 2020. *India plans coal transportation infrastructure boost.* https://www.argusmedia.com/en/news/2106096-india-plans-coal-transportation-infrastructure-boost.

Chen, H. 2018. *The Questionable Future of Overseas Coal Investments.* https://www.nrdc.org/experts/han-chen/questionable-future-overseas-coal-investments.

Chen, X., and D. L. Mauzerall. 2021. „The Expanding Coal Power Fleet in Southeast Asia: Implications for Future CO $_2$ Emissions and Electricity Generation.“ *Earth's Future* 9 (12). https://doi.org/10.1029/2021EF002257.

Cherp, A., and J. Jewell. 2020. „COVID-19 weakens both sides in the battle between coal and renewables.“ *Behavioural and Social Sciences at Nature Research.*

Cherp, A., V. Vinichenko, J. Jewell, E. Brutschin, and B. Sovacool. 2018. „Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework.“ *Energy Research & Social Science* 37:175–190. https://doi.org/10.1016/j.erss.2017.09.015.

Chief Economist, A. O. of the. 2020. *Resources and Energy Quarterly - June 2020.* Technical report. https://publications.industry.gov.au/publications/resourcesandenergyquarterlyjune2020/index.html.

Chief Economist, O. of the. 2020. *Australian Resources and Energy Quarterly.* https://publications.industry.gov.au/publications/resourcesandenergyquarterlyseptember2020/index.html.

Chinese Government. 2021. *China' s Achievements, New Goals and New Measures for Nationally Determined Contributions.* https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%20Achievements,%20New%20Goals%20and%20New%20Measures%20for%20Nationally%20Determined%20Contributions.pdf.

Christoff, P. 2022. „Mining a fractured landscape: The political economy of coal in Australia.“ In *The Political Economy of Coal,* edited by Jakob, Michael and Steckel, Jan, 233–257. Routledge. https://doi.org/10.4324/9781003044543-17.

CIB, B. P. 2020. *Asia spies green recovery from Covid-19.* https://cib.bnpparibas.com/sustain/asia-spies-green-recovery-from-covid-19_a-3-3488.html.

CIEL. 2019. *Fuel to the Fire: How Geoengineering Threatens to Entrench Fossil Fuels and Accelerate the Climate Crisis.* Technical report. Washington D.C.

Clark, R., N. Zucker, and J. Urpelainen. 2020. „The future of coal-fired power generation in Southeast Asia.“ *Renewable and Sustainable Energy Reviews* 121:109650. https://doi.org/10.1016/j.rser.2019.109650.

Clarke, B., F. Otto, R. Stuart-Smith, and L. Harrington. 2022. „Extreme weather impacts of climate change: an attribution perspective.“ *Environmental Research: Climate* 1 (1): 012001. https://doi.org/10.1088/2752-5295/ac6e7d.

Clarke, L., Y.-M. Wei, A. De La Vega Navarro, A. Garg, A. N. Hahmann, S. Khennas, I. M. L. Azevedo, et al. 2022. „Energy Systems.“ In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge (UK) and New York, NY, (USA): Cambridge University Pres.

Climate Action Tracker. *Global update: Pandemic recovery with just a hint of green.* https://climateactiontracker.org/publications/global-update-pandemic-recovery-with-just-a-hint-of-green/.

Climate Analytics. 2016. *Implications of the Paris Agreement for coal use in the power sector.* Technical report. Berlin. https://climateanalytics.org/media/climateanalytics-coalreport_nov2016_1.pdf.

Coady, D., I. Parry, L. Sears, and B. Shang. 2017. „How Large Are Global Fossil Fuel Subsidies?“ *World Development* 91:11–27. https://doi.org/10.1016/j.worlddev.2016.10.004.

Coglianese, J., T. Gerarden, and J. H. Stock. 2017. *The Effects of Fuel Prices, Regulations, and Other Factors on U.S. Coal Production, 2008-2016.* Technical report. https://scholar.harvard.edu/files/coglianese/files/cgs_us_coal_production.pdf.

Coglianese, J., T. D. Gerarden, and J. H. Stock. 2020. „The Effects of Fuel Prices, Environmental Regulations, and Other Factors on U.S. Coal Production, 2008-2016.“ *The Energy Journal* 41 (1). https://doi.org/10.5547/01956574.41.1.jcog.

Collier, P., and A. J. Venables. 2014. „Closing Coal: Economic and Moral Incentives.“ *Centre for Climate Change Economics and Policy Working Paper No. 176 and Grantham Research Institute on Climate Change and the Environment Working Paper No. 157.*

Cornot-Gandolphe, S. 2014. *China' s Coal Market: Can Beijing Tame 'King Coal' ?* Technical report. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2014/12/CL-1.pdf.

———. 2015. *US Coal Exports: The Long Road to Asian Markets.* Technical report, OIES Paper CL2. Oxford, UK. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2015/03/CL-21.pdf.

Creutzig, F., K.-H. Erb, H. Haberl, C. Hof, C. Hunsberger, and S. Roe. 2021. „Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments.“ *GCB Bioenergy,* gcbb.12798. https://doi.org/10.1111/gcbb.12798.

CTI. 2011. *Unburnable Carbon: Are the World' s Financial Markets Carrying a Carbon Bubble?* Technical report. London. https://carbontracker.org/reports/carbon-bubble.

———. 2015. *The $2 trillion stranded assets danger zone: How fossil fuel firms risk destroying investor returns.* Technical report. Carbon Tracker Initiative. https://carbontracker.org/reports/stranded-assets-danger-zone/.

CTI and GRI. 2013. *Unburnable Carbon 2013: Wasted Capital and Stranded Assets.* Technical report. London, UK. http://www.carbontracker.org/wp-content/uploads/2014/09/Unburnable-Carbon-2-Web-Version.pdf.

Culver, W. J., and M. Hong. 2016. „Coal' s decline: Driven by policy or technology?“ *The Electricity Journal* 29 (7): 50–61. https://doi.org/10.1016/j.tej.2016.08.008.

Curran, G. 2021. „Coal, climate and change: The narrative drivers of Australia' s coal economy.“ *Energy Research & Social Science* 74:101955. https://doi.org/10.1016/j.erss.2021.101955.

Curtin, J., C. McInerney, B. Ó Gallachóir, C. Hickey, P. Deane, and P. Deeney. 2019. „Quantifying stranding risk for fossil fuel assets and implications for renewable energy investment: A review of the literature.“ *Renewable and Sustainable Energy Reviews* 116:109402. https://doi.org/10.1016/j.rser.2019.109402.

Davenport, C. 2016. *Donald Trump, in Pittsburgh, Pledges to Boost Both Coal and Gas.* https://www.nytimes.com/2016/09/23/us/politics/donald-trump-fracking.html.

David, M. 2017. „Moving beyond the heuristic of creative destruction: Targeting exnovation with policy mixes for energy transitions.“ *Energy Research & Social Science,* Policy mixes for energy transitions, 33:138–146. https://doi.org/10.1016/j.erss.2017.09.023.

Department of Agriculture, Water and the Environment. 2018. *Coal and coal seam gas resource assessment for the Galilee subregion.* https://www.bioregionalassessments.gov.au/assessments/12-resource-assessment-galilee-subregion/121-available-coal-and-coal-seam-gas-resources.

Department of Industry, Science, Energy and Resources. 2021. *Resources and Energy Major Projects: 2021.* The Australia Institute. https://www.industry.gov.au/data-and-publications/resources-and-energy-major-projects-2021.

Diluiso, F., P. Walk, N. Manych, N. Cerutti, V. Chipiga, A. Workman, C. Ayas, et al. 2021. „Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences.“ *Environmental Research Letters* 16 (11): 113003. https://doi.org/10.1088/1748-9326/ac1b58.

DIW Berlin, Wuppertal Institut, and Ecologic Institut. 2019. *Phasing out Coal in the German Energy Sector. Interdependencies, Challenges and Potential Solutions.* Technical report. Berlin, Wuppertal. https://www.ecologic.eu/sites/files/publication/2019/3537-kohlereader_englisch-final.pdf.

DoE, U. 2017. *Staff Report on Electricity Markets and Reliability.* Technical report. Washington DC, USA. https://energy.gov/sites/prod/files/2017/08/f36/Staff%5C%20Report%5C%20on%5C%20Electricity%5C%20Markets%5C%20and%5C%20Reliability_0.pdf.

Dong, C., Y. Qi, and G. Nemet. 2021. „A government approach to address coal overcapacity in China.“ *Journal of Cleaner Production* 278:123417. https://doi.org/10.1016/j.jclepro.2020.123417.

Douglas, S., and A. Walker. 2017. „Coal Mining and the Resource Curse in the Eastern United States.“ *Journal of Regional Science* 57 (4): 568–590. https://doi.org/10.1111/jors.12310.

Doukas, A., J. Redman, and S. Kretzmann. 2017. *Expanding Subsidies for CO2-enhanced Oil Recovery: A Net Loss for Communities, Taxpayers, and the Climate.* Technical report. Washington DC; Cleveland, USA. http://priceofoil.org/content/uploads/2017/10/45q-analysis-oct-2017-final.pdf.

Driskell Tate, R., C. Shearer, and A. Matikinca. 2021. *Deep Trouble - Tracking Global Coal Mine Proposals.* Technical report. Global Energy Monitor / Oxpeckers. https://globalenergymonitor.org/report/deep-trouble-tracking-global-coal-mine-proposals/.

Dutterer, A. D., and R. D. Margerum. 2015. „The Limitations of Policy-Level Collaboration: A Meta-Analysis of CALFED.“ *Society & Natural Resources* 28 (1): 21–37. https://doi.org/10.1080/08941920.2014.945054.

Economics, V. *Greenness of Stimulus Index.* https://www.vivideconomics.com/casestudy/greenness-for-stimulus-index/.

Economist, T. 2020. „The epidemic provides a chance to do good by the climate.“ *The Economist.*

Edenhofer, O., J. C. Steckel, M. Jakob, and C. Bertram. 2018. „Reports of coal' s terminal decline may be exaggerated.“ *Environmental Research Letters* 13 (2): 024019. https://doi.org/10.1088/1748-9326/aaa3a2.

Edmonds, J., and J. M. Reilly. 1985. *Global Energy: Assessing the Future.* New York, USA: Oxford University Press.

Edwards, M. R., R. Cui, M. Bindl, N. Hultman, K. Mathur, H. McJeon, G. Iyer, J. Song, and A. Zhao. 2022. „Quantifying the regional stranded asset risks from new coal plants under 1.5 °C.“ *Environmental Research Letters* 17 (2): 024029. https://doi.org/10.1088/1748-9326/ac4ec2.

Egging, R., F. Holz, and S. A. Gabriel. 2010. „The World Gas Model: A multi-period mixed complementarity model for the global natural gas market.“ *Energy* 35 (10): 4016–4029. https://doi.org/10.1016/j.energy.2010.03.053.

EIA. 2018a. *Annual Energy Outlook 2018.* Technical report. Washington, DC. https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf.

———. 2018b. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2018.* Technical report. Washington, DC. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

———. 2019. *Annual Energy Outlook 2019.* Technical report. Washington, DC.

———. 2020. *Annual Energy Outlook 2020.* Technical report. Washington, DC: Department of Energy, U.S. Energy Information Administration. https://www.eia.gov/outlooks/archive/aeo20/.

———. 2022a. *Annual Energy Outlook 2022.* Technical report. Washington, DC. https://www.eia.gov/outlooks/aeo/.

———. 2022b. *Coal Market Module of the National Energy Modeling System: Model Documentation 2022.* Technical report. Washington DC, USA: Energy Information Administration (EIA). https://www.eia.gov/outlooks/aeo/nems/documentation/coal/pdf/CMM_2022.pdf.

Emerson, K., and T. Nabatchi. 2015. *Collaborative governance regimes.* Georgetown University Press. https://experts.syr.edu/en/publications/collaborative-governance-regimes.

Emerson, K., T. Nabatchi, and S. Balogh. 2012. „An Integrative Framework for Collaborative Governance.“ *Journal of Public Administration Research and Theory* 22 (1): 1–29. https://doi.org/10.1093/jopart/mur011.

End Coal. 2020. *Global Coal Finance Tracker.* https://endcoal.org/finance-tracker/.

EPA. 2018. *FACT SHEET - Proposed Affordable Clean Energy Rule - Overview.* Technical report. Washington DC, USA. https://www.epa.gov/sites/production/files/2018-08/documents/ace_overview_0.pdf.

———. 2019a. *FACT SHEET - The Affordable Clean Energy Rule (ACE).* Technical report. Washington DC, USA. https://www.epa.gov/sites/production/files/2019-06/documents/bser_and_eg_fact_sheet_6.18.19_final.pdf.

———. 2019b. *Repeal of the Clean Power Plan; Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units; Revisions to Emission Guidelines Implementing Regulations.* Technical report, Federal Register. Washington DC, USA. https://www.epa.gov/sites/production/files/2019-06/documents/frn_ace_2060-at67_final_rule_20190618disc.pdf.

Erickson, P., S. Kartha, M. Lazarus, and K. Tempest. 2015. „Assessing carbon lock-in.“ *Environmental Research Letters* 10 (8): 084023. https://doi.org/10.1088/1748-9326/10/8/084023.

Erickson, P., and M. Lazarus. 2018. „Would constraining US fossil fuel production affect global CO2 emissions? A case study of US leasing policy.“ *Climatic Change,* Fossil Fuel Supply and Climate Policy, 150 (1-2): 29–42. https://doi.org/10.1007/s10584-018-2152-z.

Erickson, P., M. Lazarus, and G. Piggot. 2018. „Limiting fossil fuel production as the next big step in climate policy.“ *Nature Climate Change* 8 (12): 1037. https://doi.org/10.1038/s41558-018-0337-0.

Europe Beyond Coal. *Europe's coal exit - overview of national coal phase out commitments.* https://beyond-coal.eu/europes-coal-exit/.

Faehn, T., C. Hagem, L. Lindholt, S. Maeland, and K. E. Rosendahl. 2017. „Climate policies in a fossil fuel producing country: demand versus supply side policies.“ *The Energy Journal* 38 (1). https://doi.org/10.5547/01956574.38.1.tfae.

Fan, J.-L., M. Xu, F. Li, L. Yang, and X. Zhang. 2018. „Carbon capture and storage (CCS) retrofit potential of coal-fired power plants in China: The technology lock-in and cost optimization perspective.“ *Applied Energy* 229:326–334. https://doi.org/10.1016/j.apenergy.2018.07.117.

Fattouh, B., R. Poudineh, and R. West. 2019. *Energy Transition, Uncertainty, and the Implications of Change in the Risk Preferences of Fossil Fuels Investors.* Technical report, Oxford Energy Insight. https://www.jstor.org/stable/resrep33910.

Feaster, S. 2018. *Record Drop in U.S. Coal-Fired Capacity Likely in 2018.* Technical report. Cleveland, Ohio, USA. http://ieefa.org/wp-content/uploads/2018/10/Record-Drop-in-U.S.-Coal-Fired-Capacity-in-2018_October2018.pdf.

Feijoo, F., G. Iyer, M. Binsted, and J. Edmonds. 2020. „US energy system transitions under cumulative emissions budgets.“ *Climatic Change,* https://doi.org/10.1007/s10584-020-02670-0.

Fekete, H., L. Luna, S. Sterl, F. Hans, S. Gonzales, N. Höhne, L. Wong, et al. 2017. *Climate Action Tracker - Improvement in warming outlook as India and China move ahead, but Paris Agreement gap still looms large.* Technical report. https://climateactiontracker.org/documents/61/CAT_2017-11-15_ImprovementInWarmingOutlook_BriefingPaper.pdf.

Fisch-Romito, V., C. Guivarch, F. Creutzig, J. C. Minx, and M. W. Callaghan. 2021. „Systematic map of the literature on carbon lock-in induced by long-lived capital.“ *Environmental Research Letters,* https://doi.org/10.1088/1748-9326/aba660.

Forster, P. M., H. I. Forster, M. J. Evans, M. J. Gidden, C. D. Jones, C. A. Keller, R. D. Lamboll, et al. 2020. „Current and future global climate impacts resulting from COVID-19.“ *Nature Climate Change,* https://doi.org/10.1038/s41558-020-0883-0.

Fortescue, S. 2021. „Future of Russian Coal Exports in the Asia-Pacific.“ In *Russian Energy Strategy in the Asia-Pacific: Implications for Australia,* edited by E. Buchanan, 155–180. Canberra, Australia: ANU Press, The Australian National University.

Foxwell-Norton, K., and L. Lester. 2017. „Saving the Great Barrier Reef from disaster, media then and now.“ *Media, Culture & Society* 39:568–581. https://doi.org/https://doi.org/10.1177/0163443717692738.

Friedlingstein, P., M. W. Jones, M. O’Sullivan, R. M. Andrew, D. C. E. Bakker, J. Hauck, C. Le Quéré, et al. 2022. „Global Carbon Budget 2021.“ *Earth System Science Data* 14 (4): 1917–2005. https://doi.org/10.5194/essd-14-1917-2022.

Furnaro, A. 2022. „The last subsidy: regulating devaluation in the German coal phase-out.“ *New Political Economy* 0 (0): 1–16. https://doi.org/https://doi.org/10.1080/13563467.2022.2084523.

Furnaro, A., P. Herpich, H. Brauers, P.-Y. Oei, C. Kemfert, and W. Look. 2021. *German Just Transition: A Review of Public Policies to Assist German Coal Communities in Transition.* Technical report. Washington D.C., USA & Berlin, Germany. https://media.rff.org/documents/21-13-Nov-22.pdf.

Fuss, S., W. F. Lamb, M. W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, et al. 2018. „Negative emissions—Part 2: Costs, potentials and side effects.“ *Environmental Research Letters* 13 (6): 063002. https://doi.org/10.1088/1748-9326/aabf9f.

G7. 2022. *G7 Chair' s Summary: Joining Forces to Accelerate Clean and Just Transition towards Climate Neutrality.* Technical report. https://www.g7germany.de/resource/blob/974430/2057418/9a1d62b3c5710b4c1989f95b38dc172c/2022-06-27-chairs-summary-climate-neutrality-data.pdf.

Gabriel, S. A., A. J. Conejo, J. D. Fuller, B. F. Hobbs, and C. Ruiz. 2012. *Complementarity Modeling in Energy Markets.* 2012th ed. New-York, USA: Springer. http://dx.doi.org/10.1007/978-1-4419-6123-5.

Galik, C. S., J. F. DeCarolis, and H. Fell. 2017. „Evaluating the US Mid-Century Strategy for Deep Decarbonization amidst early century uncertainty.“ *Climate Policy* 17 (8): 1046–1056. https://doi.org/10.1080/14693062.2017.1340257.

GCCSI. 2020. *Global Status of CCS: 2020.* Technical report. Melbourne, Australia. https://www.globalccsinstitute.com/wp-content/uploads/2020/11/Global-Status-of-CCS-Report-2020_FINAL.pdf.

Geels, F. W. 2011. „The multi-level perspective on sustainability transitions: Responses to seven criticisms.“ *Environmental Innovation and Societal Transitions* 1 (1): 24–40. https://doi.org/10.1016/j.eist.2011.02.002.

———. 2013. „The impact of the financial‑economic crisis on sustainability transitions: Financial investment, governance and public discourse.“ *Environmental Innovation and Societal Transitions,* Economic-financial crisis and sustainability transition, 6:67–95. https://doi.org/10.1016/j.eist.2012.11.004.

———. 2014. „Reconceptualising the co-evolution of firms-in-industries and their environments: Developing an inter-disciplinary Triple Embeddedness Framework.“ *Research Policy* 43 (2): 261–277. https://doi.org/10.1016/j.respol.2013.10.006.

GEM and CREA. 2020. *A New Coal Boom in China.* Technical report. https://globalenergymonitor.org/wp-content/uploads/2020/06/China-coal-plant-brief-June-2020v2.pdf.

Gençsü, I., S. Whitley, M. Trilling, L. van der Burg, M. McLynn, and L. Worrall. 2020. „Phasing out public financial flows to fossil fuel production in Europe.“ *Climate Policy,* 1–14. https://doi.org/10.1080/14693062.2020.1736978.

Geoscience Australia. 2021. *Australia' s Energy Commodity Resources, 2021 Edition.* https://www.ga.gov.au/digital-publication/aecr2021/coal.

Gläser, J., and G. Laudel. 2010. *Experteninterviews und qualitative Inhaltsanalyse: als Instrumente rekonstruierender Untersuchungen.* 4th ed. VS Verlag für Sozialwissenschaften. https://www.springer.com/de/book/9783531172385.

Global Energy Monitor. 2021a. *"Global Coal Plant Tracker".* https://globalenergymonitor.org/projects/global-coal-plant-tracker/summary-tables/.

———. 2021b. *Global Coal Mine Tracker.* Technical report. https://globalenergymonitor.org/projects/global-coal-mine-tracker/.

Global Energy Monitor, CREA, E3G, Sierra Club, SFOC, Kiko Network, CAN Europe, LIFE, and Bangladesh Groups. 2022. *Boom and Bust 2022: Tracking the global coal plant pipeline.* Technical report. https://globalenergymonitor.org/wp-content/uploads/2022/04/BoomAndBustCoalPlants_2022_English.pdf.

Global Energy Monitor, Sierra Club, CREA, Climate Risk Horizons, GreenID, and Ekosfer. 2021. *Boom and Bust 2021: Tracking the global coal plant pipeline.* Technical report. https://globalenergymonitor.org/report/boom-and-bust-2021-tracking-the-global-coal-plant-pipeline-2/.

Gosens, J., A. B. H. Turnbull, and F. Jotzo. 2022. „China' s decarbonization and energy security plans will reduce seaborne coal imports: Results from an installation-level model." *Joule* 6 (4): 782–815. https://doi.org/10.1016/j.joule.2022.03.008.

Grant, N., A. Hawkes, T. Napp, and A. Gambhir. 2021. „Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways." *One Earth* 4 (11): 1588–1601. https://doi.org/10.1016/j.oneear.2021.10.024.

Green, F., and R. Denniss. 2018. „Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies." *Climatic Change,* https://doi.org/10.1007/s10584-018-2162-x.

Green, F., and A. Gambhir. 2019. „Transitional assistance policies for just, equitable and smooth low-carbon transitions: who, what and how?" *Climate Policy* 20 (8): 902–921. https://doi.org/10.1080/14693062.2019.1657379.

Green, J. F. 2021. „Does carbon pricing reduce emissions? A review of ex-post analyses." *Environmental Research Letters* 16 (4): 043004. https://doi.org/10.1088/1748-9326/abdae9.

Grothus, A., and D. Setton. 2020. „Die „Kohlekommission "aus zivilgesellschaftlicher Perspektive: Chancen und Herausforderungen bei der Partizipation in Expertengremien." *Forschungsjournal Soziale Bewegungen* 33 (1): 282–304. https://doi.org/10.1515/fjsb-2020-0023.

Gürtler, K., D. Löw Beer, and J. Herberg. 2021. „Scaling just transitions: Legitimation strategies in coal phase-out commissions in Canada and Germany." *Political Geography* 88:102406. https://doi.org/10.1016/j.polgeo.2021.102406.

Haftendorn, C., and F. Holz. 2010. „Modeling and Analysis of the International Steam Coal Trade." *The Energy Journal* 31 (4): 205–230.

Haftendorn, C., F. Holz, and C. v. Hirschhausen. 2010. *COALMOD-World: A Model to Assess International Coal Markets until 2030.* DIW Berlin Discussion Paper 1067. Berlin, Germany: German Institute for Economic Research (DIW Berlin). http://hdl.handle.net/10419/49429.

———. 2012. „The end of cheap coal? A techno-economic analysis until 2030 using the COALMOD-World model." *Fuel* 102:305–325. https://doi.org/10.1016/j.fuel.2012.04.044.

Haftendorn, C., C. Kemfert, and F. Holz. 2012. „What about coal? Interactions between climate policies and the global steam coal market until 2030." *Energy Policy* 48:274–283. https://doi.org/10.1016/j.enpol.2012.05.032.

Hainsch, K., H. Brauers, T. Burandt, L. Goeke, v. C. Hirschhausen, C. Kemfert, M. Kendziorski, et al. 2020. *Make the European Green Deal Real - Combining Climate Neutrality and Economic Recovery.* Technical report, Politikberatung kompakt. Berlin. https://www.diw.de/documents/publikationen/73/diw_01.c.791736.de/diwkompakt_2020-153.pdf.

Hanna, R., Y. Xu, and D. G. Victor. 2020. „After COVID-19, green investment must deliver jobs to get political traction." *Nature* 582 (7811): 178–180. https://doi.org/10.1038/d41586-020-01682-1.

Hanto, J., L. Krawielicki, A. Krumm, N. Moskalenko, K. Löffler, C. Hauenstein, and P.-Y. Oei. 2021. „Effects of decarbonization on the energy system and related employment effects in South Africa." *Environmental Science & Policy* 124:73–84. https://doi.org/10.1016/j.envsci.2021.06.001.

Hanto, J., A. Schroth, L. Krawielicki, P.-Y. Oei, and J. Burton. 2022. „The political economy of energy and climate policy in South Africa." In *The Political Economy of Coal,* 1st ed., 300–319. London: Routledge.

Harfst, J. 2015. „Utilizing the past: Valorizing post-mining potential in Central Europe.“ *The Extractive Industries and Society* 2 (2): 217–224. https://doi.org/10.1016/j.exis.2015.01.003.

Harstad, B. 2012. „Buy Coal! A Case for Supply-Side Environmental Policy.“ *Journal of Political Economy* 120 (1): 77–115. https://doi.org/10.1086/665405.

Haszeldine, R. S., S. Flude, G. Johnson, and V. Scott. 2018. „Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments.“ *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376 (2119): 20160447. https://doi.org/10.1098/rsta.2016.0447.

Hauenstein, C. 2022a. (COALMOD-World 2.0 data, results, figures for: Stranded assets and early closures in global coal mining under 1.5°C. V. 0.3.0). https://doi.org/10.5281/zenodo.7086153.

———. 2022b. *COALMOD-World_v2.0.* V. v2.0.0. https://doi.org/10.5281/zenodo.7077678.

———. 2022c. *Investments and stranded capacities in the global coal sector under 1.5°C.* https://doi.org/10.5281/zenodo.6473733.

Hauenstein, C., K. Hainsch, P. Herpich, v. C. R. Hirschhausen, F. Holz, C. Kemfert, M. Kendziorski, P. Y. Oei, and C. Rieve. 2022. *Electricity Supply in Germany Can Be Secured without Russian Supplies and Nuclear Energy; The 2030 Coal-Phase out Remains Possible.* Technical report, DIW focus. Berlin. https://www.diw.de/de/diw_01.c.844463.de/publikationen/diw_focus/2022_0008/electricity_supply_in_germany_can_be_secured_without_russian____and_nuclear_energy___the_2030_coal-phase_out_remains_possible.html.

Hauenstein, C., and F. Holz. 2020. *The U.S. Coal Sector between Shale Gas and Renewables: Last Resort Coal Exports?* Technical report, DIW Berlin Discussion Paper. Berlin. https://www.diw.de/de/diw_01.c.793549.de/publikationen/diskussionspapiere/2020_1880/the_u.s._coal_sector_between_shale_gas_and_renewables___last_resort_coal_exports.html.

———. 2021. „The U.S. coal sector between shale gas and renewables: Last resort coal exports?“ *Energy Policy* 149:112097. https://doi.org/10.1016/j.enpol.2020.112097.

Hauenstein, C., F. Holz, L. Rathje, and T. Mitterecker. 2022a. *COALMOD-World 2.0 input data - Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin.* https://doi.org/10.5281/ZENODO.6473606.

Hauenstein, C., F. Holz, L. Rathje, and T. Mitterecker. 2022b. *Stranded Assets in the Coal Export Industry? The Case of the Australian Galilee Basin.* Technical report 2003. Berlin: German Institute for Economic Research (DIW Berlin). https://www.diw.de/documents/publikationen/73/diw_01.c.840655.de/dp2003.pdf.

Hauser, P., B. Görlach, K. Umpfenbach, R. Perez, and R. Gaete. 2021. *Phasing Out Coal in Chile and Germany.* Technical report. Berlin and Santiago de Chile. https://static.agora-energiewende.de/fileadmin/Partnerpublikationen/2021/Energy_Partnership_Chile-Alemania_Phase-Out-Coal-Chile-Germany/20210614_CHL_Comparative_Study_Coal_Exit_CHL_GER_web.pdf.

Hausmann, R., A. Łoskot-Strachota, A. Ockenfels, U. Schetter, S. Tagliapietra, G. Wolff, and G. Zachmann. 2022. „How to weaken Russian oil and gas strength.“ *Science* 376 (6592): 469–469. https://doi.org/10.1126/science.abq4436.

He, G., J. Lin, Y. Zhang, W. Zhang, G. Larangeira, C. Zhang, W. Peng, M. Liu, and F. Yang. 2020. „Enabling a Rapid and Just Transition away from Coal in China.“ *One Earth* 3 (2): 187–194. https://doi.org/10.1016/j.oneear.2020.07.012.

Heck, V., D. Gerten, W. Lucht, and A. Popp. 2018. „Biomass-based negative emissions difficult to reconcile with planetary boundaries.“ *Nature Climate Change* 8 (2): 151. https://doi.org/10.1038/s41558-017-0064-y.

Heede, R., and N. Oreskes. 2016. „Potential emissions of CO2 and methane from proved reserves of fossil fuels: An alternative analysis.“ *Global Environmental Change* 36:12–20. https://doi.org/10.1016/j.gloenvcha.2015.10.005.

Hepburn, C., B. O'Callaghan, N. Stern, J. Stiglitz, and D. Zenghelis. 2020. „Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change?“ *Smith School Working Paper No. 20-02.*

Hepburn, C., B. O' Callaghan, N. Stern, J. Stiglitz, and D. Zenghelis. 2020. *Building back better: Green COVID-19 recovery packages will boost economic growth and stop climate change.* https://www.ox.ac.uk/news/2020-05-05-building-back-better-green-covid-19-recovery-packages-will-boost-economic-growth-and.

Hermwille, L., and D. Kiyar. 2022. „Late and expensive: The political economy of coal phase-out in Germany.“ In *The Political Economy of Coal.* Routledge.

Herpich, P., H. Brauers, and P.-Y. Oei. 2018. *An historical case study on previous coal transitions in Germany.* Technical report. Berlin, Germany. https://coaltransitions.files.wordpress.com/2018/07/2018-historical-coal-transitions-in-germany-report2.pdf.

Hirschhausen, v. C. 2022. „Die weltpolitische Lage als Beschleuniger des Klimaschutzes: Kommentar.“ *DIW Wochenbericht,* no. 27, 384. https://doi.org/10.18723/diw_wb:2022-27-3.

Hirschhausen, v. C., C. Gerbaulet, C. Kemfert, C. Lorenz, and P.-Y. Oei, eds. 2018. *Energiewende “Made in Germany”: Low Carbon Electricity Sector Reform in the European Context.* Springer International Publishing. //www.springer.com/de/book/9783319951256.

Hirschhausen, v. C., J. Herold, and P.-Y. Oei. 2012. „How a “Low Carbon” Innovation Can Fail -Tales from a “Lost Decade” for Carbon Capture, Transport, and Sequestration (CCTS).“ *Economics of Energy & Environmental Policy* 1 (2): 115–123. https://doi.org/10.5547/2160-5890.1.2.8.

Hirth, L., and J. C. Steckel. 2016. „The role of capital costs in decarbonizing the electricity sector.“ *Environmental Research Letters* 11 (11): 114010. https://doi.org/10.1088/1748-9326/11/11/114010.

Höhne, N., L. Luna, H. Fekete, S. Sterl, B. Hare, J. Cantzler, P. Parra, et al. 2017. *Action by China and India slows emissions growth, President Trump’ s policies likely to cause US emissions to flatten.* Technical report, Climata Achtion Tracker Update. https://climateactiontracker.org/documents/51/CAT_2017-05-15_UpdateChinaIndiaUS_CATUpdate.pdf.

Holz, F. 2015. „Modeling Coal and Natural Gas Markets.“ In *Emerging Trends in the Social and Behavioral Sciences.* John Wiley & Sons, Inc.

Holz, F., C. Haftendorn, R. Mendelevitch, and C. von Hirschhausen. 2016. *A Model of the International Steam Coal Market (COALMOD-World).* Technical report 85. Berlin, Germany: DIW Berlin, German Institute for Economic Research.

Holz, F., C. Haftendorn, R. Mendelevitch, and v. C. Hirschhausen. 2015. „The COALMOD-World Model: Coal Markets until 2030.“ In *The Global Coal Market - Supplying the Major Fuel for Emerging Economies,* edited by R. K. Morse and M. C. Thurber, 411–472. Cambridge, UK: Cambridge University Press.

Holz, F., I. V. Kafemann, O. Sartor, T. Scherwath, and T. Spencer. 2018. *What does “peak coal” mean for international coal exporters? A global modelling analysis on the future of the international steam coal market.* Technical report. Berlin. https://coaltransitions.files.wordpress.com/2018/09/coaltransitions_finalreport_coal-global-trade_20182.pdf.

Houser, T., J. Bordoff, and P. Marsters. 2017. *Can Coal Make a Comeback?* Technical report. New York, USA. http://energypolicy.columbia.edu/sites/default/files/energy/Center_on_Global_Energy_Policy_Can_Coal_Make_Comeback_April_2017.pdf.

Hume, N., and J. Smyth. 2020. *China expected to impose coal import restrictions.* https://www.ft.com/content/6142f1b9-58cc-47e4-b2fb-8212ad792b2d.

Huntington, H. G., J. P. Weyant, and J. L. Sweeney. 1982. „Modeling for insights, not numbers: the experiences of the energy modeling forum.“ *Omega* 10 (5): 449–462. https://doi.org/10.1016/0305-0483(82)90002-0.

Huntington, H. G., A. Bhargava, D. Daniels, J. P. Weyant, C. Avraam, J. Bistline, J. A. Edmonds, et al. 2020. „Key findings from the core North American scenarios in the EMF34 intermodel comparison.“ *Energy Policy* 144:111599. https://doi.org/10.1016/j.enpol.2020.111599.

Huppmann, D., and F. Holz. 2012. „Crude Oil Market Power–A Shift in Recent Years?“ *Energy Journal* 33 (4): 1–22.

IEA. 2013. *Coal Information.* Technical report. Paris, France: International Energy Agency. https://doi.org/10.1787/coal-2013-en.

———. 2018. *Coal Information 2018.* Technical report. Paris, France: International Energy Agency. https://doi.org/10.1787/coal-2018-en.

———. 2019a. *Coal Information 2019.* Technical report. Paris, France: International Energy Agency. https://doi.org/10.1787/4a69d8c8-en.

———. 2019b. *World Energy Outlook 2019.* Paris, France: International Energy Agency. https://doi.org/10.1787/caf32f3b-en.

———. 2020a. *Coal 2020 - Analysis and Forecast to 2025.* Technical report. Paris, France: International Energy Agency. https://www.iea.org/reports/coal-2020.

———. 2020b. *Data & Statistics.* https://www.iea.org/data-and-statistics.

———. 2020c. *Global Energy Review 2020 - The impacts of the Covid-19 crisis on global energy demand and CO2 emissions.* Technical report. Paris, France: International Energy Agency. https://www.iea.org/reports/global-energy-review-2020.

———. 2020d. *World Energy Investment 2020.* Technical report. Paris, France: International Energy Agency. https://doi.org/10.1787/6f552938-en.

———. 2020e. *World Energy Outlook 2020.* Paris, France: International Energy Agency. https://doi.org/10.1787/weo-2018-en.

———. 2021a. *Coal 2021 - Analysis and Forcast to 2024.* Technical report. Paris, France: International Energy Agency. https://www.iea.org/reports/coal-2021.

———. 2021b. *Electricity Information.* Technical report. Paris. https://www.iea.org/data-and-statistics/data-product/electricity-information.

———. 2021c. *Global Energy Review 2021.* Technical report. Paris, France: International Energy Agency. https://www.iea.org/reports/global-energy-review-2021.

———. 2021d. *Net Zero by 2050: A Roadmap for the Global Energy Sector.* Technical report. Paris, France: International Energy Agency. https://www.iea.org/reports/net-zero-by-2050.

———. 2021e. „OECD -Coal exports by destination,“ https://doi.org/10.1787/data-00463-en.

———. 2021f. „World -Coal supply,“ https://doi.org/10.1787/data-00465-en.

———. 2021g. *World Energy Outlook 2021.* Paris, France: International Energy Agency.

———. 2022a. *Coal Market Update -July 2022.* Technical report. Paris. https://www.iea.org/reports/coal-market-update-july-2022.

———. 2022b. *World - Coal supply.* Technical report, IEA Coal Information Statistics (database). https://doi.org/10.1787/data-00465-en.

———. n.d. *IEA World Energy Statistics and Balances.* Technical report. Paris, France: International Energy Agency. https://doi.org/10.1787/enestats-data-en.

IEA/OECD. 2016a. *Medium-Term Coal Market Report 2016.* Technical report. Paris, France. http://www.oecd-ilibrary.org/content/book/mtrcoal-2016-en.

———. 2016b. *World Energy Outlook 2016.* World Energy Outlook. Paris, France: International Energy Agency, OECD Publishing. https://doi.org/10.1787/weo-2016-en.

———. 2017a. *Coal 2017 - Analysis and Forecasts to 2022.* Technical report. Paris, France. http://dx.doi.org/10.1787/coal_mar-2017-en.

———. 2017b. *World Energy Outlook 2017.* World Energy Outlook. Paris, France: International Energy Agency, OECD Publishing. https://doi.org/10.1787/weo-2017-en.

IEEFA. 2019. *China: Lender of last resort for coal plants.* https://ieefa.org/ieefa-china-lender-of-last-resort-for-coal-plants/.

———. 2020a. *Japan Bank for International Cooperation takes first steps away from coal-plant financing.* https://ieefa.org/japan-bank-for-international-cooperation-takes-first-steps-away-from-coal-plant-financing/.

IEEFA. 2020b. *Southeast Asian power companies are shifting towards renewables.* https://ieefa.org/ieefa-update-southeast-asian-power-companies-are-shifting-towards-renewables/.

ILO. 2011. *GREEN STIMULUS MEASURES.* https://www.ilo.org/wcmsp5/groups/public/---dgreports/---inst/documents/publication/wcms_194185.pdf.

———. 2015. *Guidelines for a just transition towards environmentally sustainable economies and societies for all.* Technical report. Geneva, Switzerland. http://www.ilo.org/global/topics/green-jobs/publications/WCMS_432859/lang--en/index.htm.

———. 2020. *COVID-19 and the world of work: Jump-starting a green recovery with more and better jobs, healthy and resilient societies.* Technical report. http://www.ilo.org/global/topics/green-jobs/publications/WCMS_751217/lang--en/index.htm.

IMF. 2020. *World Economic Outlook, April 2020: The Great Lockdown.* Technical report, World Economic Outlook Reports. https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020.

———. *Climate Change and COVID-19.* https://www.imf.org/external/pubs/ft/fandd/2020/09/investing-in-a-green-recovery-volz.htm.

Innes, J. E., and D. E. Booher. 1999. „Consensus Building and Complex Adaptive Systems.“ *Journal of the American Planning Association* 65 (4): 412–423. https://doi.org/10.1080/01944369908976071.

IPCC. 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf.

———. 2018a. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Technical report. New York, NY, USA: IPCC. https://www.ipcc.ch/sr15/download/.

———. 2018b. „Summary for Policymakers.“ In *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, et al., 32pp. Geneva, Switzerland: World Meteorological Organization.

———. 2022. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by P. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, et al. Cambridge (UK) and New York, NY, (USA): Cambridge University Press. https://doi.org/10.1017/9781009157926.

IRENA. 2017. *Stranded Assets and Renewables: How the energy transition affects the value of energy reserves , buildings and capital stock.* Technical report. Abu Dhabi: IRENA. www.irena.org/remap.

———. 2021. *Renewable Power Generation Costs in 2020.* Technical report. Abu Dhabi.

Isoaho, K., and J. Markard. 2020. „The Politics of Technology Decline: Discursive Struggles over Coal Phase-Out in the UK.“ *Review of Policy Research,* ropr.12370. https://doi.org/10.1111/ropr.12370.

Jacobson, M. Z., M. A. Delucchi, Z. A. F. Bauer, S. C. Goodman, W. E. Chapman, M. A. Cameron, C. Bozonnat, et al. 2017. „100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World.“ *Joule* 1 (1): 108–121. https://doi.org/10.1016/j.joule.2017.07.005.

Jakob, M., and J. C. Steckel. 2022. „The political economy of coal: Lessons learnt from 15 country cases.“ In *The Political Economy of Coal.* Routledge.

Jakob, M., J. C. Steckel, F. Jotzo, B. K. Sovacool, L. Cornelsen, R. Chandra, O. Edenhofer, et al. 2020. „The future of coal in a carbon-constrained climate.“ *Nature Climate Change,* 1–3. https://doi.org/10.1038/s41558-020-0866-1.

Japan, R. E. I. of. 2020. *Four Reasons Japan Needs to Cease Coal-Fired Power Exports and Shift to Supporting Renewable Energy.* https://www.renewable-ei.org/en/activities/reports/20180626_01.html.

Japanese Government. 2021. *Japan' s Nationally Determined Contribution (NDC).* https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Japan%20First/JAPAN_FIRST%20NDC%20(UPDATED%20SUBMISSION).pdf.

Jenkins, K. E. H., B. K. Sovacool, A. Błachowicz, and A. Lauer. 2020. „Politicising the Just Transition: Linking global climate policy, Nationally Determined Contributions and targeted research agendas.“ *Geoforum* 115:138–142. https://doi.org/10.1016/j.geoforum.2020.05.012.

Jewell, J., and A. Cherp. 2019. „On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5°C?“ *Wiley Interdisciplinary Reviews: Climate Change,* https://doi.org/10.1002/wcc.621.

Jewell, J., V. Vinichenko, L. Nacke, and A. Cherp. 2019. „Prospects for powering past coal.“ *Nature Climate Change* 9 (8): 592–597. https://doi.org/10.1038/s41558-019-0509-6.

John, J. S. 2018. *Report: Cheap Natural Gas and Renewables Could Close Half of US Coal Fleet by 2030.* https://www.greentechmedia.com/articles/read/report-nearly-half-of-u-s-coal-plants-could-close-by-2030.

Johnstone, P., A. Stirling, and B. Sovacool. 2017. „Policy mixes for incumbency: Exploring the destructive recreation of renewable energy, shale gas ‘fracking,’ and nuclear power in the United Kingdom.“ *Energy Research & Social Science,* Policy mixes for energy transitions, 33:147–162. https://doi.org/10.1016/j.erss.2017.09.005.

Jones, D., E. Graham, and P. Tunbridge. 2020. *Global Electricity Analysis H1-2020.* EMBER. https://ember-climate.org/wp-content/uploads/2020/08/Report-Ember-Global-Electricity-Review-H1-2020.pdf.

Jordan, B., I. Lange, and J. Linn. 2018. *Coal Demand, Market Forces, and US Coal Mine Closures.* Technical report. Munich, Germany.

Jotzo, F., J. Depledge, and H. Winkler. 2018. „US and international climate policy under President Trump.“ *Climate Policy* 18 (7): 813–817. https://doi.org/10.1080/14693062.2018.1490051.

Jotzo, F., S. Mazouz, and J. Wiseman. 2018. *Coal transitions in Australia. Preparing for the looming domestic coal phase-out and falling export demand.* https://apo.org.au/node/190906.

Kalkuhl, M., J. C. Steckel, L. Montrone, M. Jakob, J. Peters, and O. Edenhofer. 2019. „Successful coal phase-out requires new models of development.“ *Nature Energy* 4 (11): 897–900. https://doi.org/10.1038/s41560-019-0500-5.

Kallis, G., M. Kiparsky, and R. Norgaard. 2009. „Collaborative governance and adaptive management: Lessons from California’s CALFED Water Program.“ *Environmental Science & Policy* 12 (6): 631–643. https://doi.org/10.1016/j.envsci.2009.07.002.

Kalt, T. 2021. „Jobs vs. climate justice? Contentious narratives of labor and climate movements in the coal transition in Germany.“ *Environmental Politics,* 1–20. https://doi.org/10.1080/09644016.2021.1892979.

Karlsson, M., E. Alfredsson, and N. Westling. 2020. „Climate policy co-benefits: a review.“ *Climate Policy* 20 (3): 292–316. https://doi.org/10.1080/14693062.2020.1724070.

Kartha, S., S. Caney, N. K. Dubash, and G. Muttitt. 2018. „Whose carbon is burnable? Equity considerations in the allocation of a “right to extract”.“ *Climatic Change* 150 (1-2): 117–129. https://doi.org/10.1007/s10584-018-2209-z.

Kemfert, C., F. Präger, I. Braunger, F. M. Hoffart, and H. Brauers. 2022. „The expansion of natural gas infrastructure puts energy transitions at risk.“ *Nature Energy,* https://doi.org/10.1038/s41560-022-01060-3.

Kern, F., and K. S. Rogge. 2018. „Harnessing theories of the policy process for analysing the politics of sustainability transitions: A critical survey.“ *Environmental Innovation and Societal Transitions* 27:102–117. https://doi.org/10.1016/j.eist.2017.11.001.

Koebele, E. A. 2019. „Integrating collaborative governance theory with the Advocacy Coalition Framework.“ *Journal of Public Policy* 39 (1): 35–64. https://doi.org/10.1017/S0143814X18000041.

Köhler, J., F. W. Geels, F. Kern, J. Markard, E. Onsongo, A. Wieczorek, F. Alkemade, et al. 2019. „An agenda for sustainability transitions research: State of the art and future directions.“ *Environmental Innovation and Societal Transitions* 31:1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Kok, I. 2017. *Coal Transition in the United States.* Technical report. https://coaltransitions.files.wordpress.com/2016/09/coal_us_v04.pdf.

Krick, E. 2013. *Verhandlungen im Konsensverfahren.* Wiesbaden: Springer Fachmedien Wiesbaden. http://link.springer.com/10.1007/978-3-658-00356-2.

———. 2015. „Negotiated expertise in policy-making: How governments use hybrid advisory committees.“ *Science and Public Policy* 42 (4): 487–500. https://doi.org/10.1093/scipol/scu069.

Kriegler, E., C. Bertram, T. Kuramochi, M. Jakob, M. Pehl, M. Stevanović, N. Höhne, et al. 2018. „Short term policies to keep the door open for Paris climate goals.“ *Environmental Research Letters* 13 (7): 074022. https://doi.org/10.1088/1748-9326/aac4f1.

Krumm, A., D. Süsser, and P. Blechinger. 2022. „Modelling social aspects of the energy transition: What is the current representation of social factors in energy models?“ *Energy* 239:121706. https://doi.org/10.1016/j.energy.2021.121706.

Kungl, G., and F. W. Geels. 2018. „Sequence and alignment of external pressures in industry destabilisation: Understanding the downfall of incumbent utilities in the German energy transition (1998 - 2015).“ *Environmental Innovation and Societal Transitions* 26:78–100. https://doi.org/10.1016/j.eist.2017.05.003.

Lahcen, B., J. Brusselaers, K. Vrancken, Y. Dams, C. Da Silva Paes, J. Eyckmans, and S. Rousseau. 2020. „Green Recovery Policies for the COVID-19 Crisis: Modelling the Impact on the Economy and Greenhouse Gas Emissions.“ *Environmental and Resource Economics* 76 (4): 731–750. https://doi.org/10.1007/s10640-020-00454-9.

Lazard. 2017. *Lazard's Levelized Cost of Energy Analysis - Version 11.0.* Technical report. https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf.

———. 2021. *Lazard's Levelized Cost of Energy Analysis - Version 15.0.* Technical report, LAZARD' S Levelized Costs of Energy Analysis. New York. https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf.

Lazarus, M., and H. van Asselt. 2018. „Fossil fuel supply and climate policy: exploring the road less taken.“ *Climatic Change* 150 (1): 1–13. https://doi.org/10.1007/s10584-018-2266-3.

Le Billon, P., and B. Kristoffersen. 2019. „Just cuts for fossil fuels? Supply-side carbon constraints and energy transition.“ *Environment and Planning A: Economy and Space,* 0308518X1881670. https://doi.org/10.1177/0308518X18816702.

Le Quéré, C., R. B. Jackson, M. W. Jones, A. J. P. Smith, S. Abernethy, R. M. Andrew, A. J. De-Gol, et al. 2020. „Temporary reduction in daily global CO 2 emissions during the COVID-19 forced confinement.“ *Nature Climate Change* 10 (7): 647–653. https://doi.org/10.1038/s41558-020-0797-x.

Leach, M., I. Scoones, and A. Stirling. 2010. *Dynamic sustainabilities: technology, environment, social justice.* Pathways to sustainability. London ; Washington, DC: Earthscan.

Leipprand, A., and C. Flachsland. 2018. „Regime destabilization in energy transitions: The German debate on the future of coal.“ *Energy Research & Social Science* 40:190–204. https://doi.org/10.1016/j.erss.2018.02.004.

Littlecott, C., L. Roberts, Ö. Şenlen, J. Burton, M. Joshi, C. Shearer, and M. Ewen. 2021. *No New Coal by 2021.* Berlin: E3G. https://www.e3g.org/publications/no-new-coal/.

Löffler, K., T. Burandt, K. Hainsch, and P.-Y. Oei. 2019. „Modeling the Low-Carbon Transition of the European Energy System - A Quantitative Assessment of the Stranded Assets Problem.“ *Energy Strategy Reviews* 26. https://doi.org/https://doi.org/10.1016/j.esr.2019.100422.

Löffler, K., K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert, and C. von Hirschhausen. 2017. „Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS).“ *Energies* 10 (10): 1468. https://doi.org/10.3390/en10101468.

Löw Beer, D., K. Gürtler, J. Herberg, and T. Haas. 2021. „Wie legitim ist der Kohlekompromiss? Spannungsfelder und Verhandlungsdynamiken im Prozess der Kohlekommission.“ *Zeitschrift für Politikwissenschaft,* https://doi.org/10.1007/s41358-021-00261-8.

Markard, J., R. Raven, and B. Truffer. 2012. „Sustainability transitions: An emerging field of research and its prospects.“ *Research Policy,* Special Section on Sustainability Transitions, 41 (6): 955–967. https://doi.org/10.1016/j.respol.2012.02.013.

Markard, J., A. Rinscheid, and L. Widdel. 2021. „Analyzing transitions through the lens of discourse networks: Coal phase-out in Germany.“ *Environmental Innovation and Societal Transitions* 40:315–331. https://doi.org/10.1016/j.eist.2021.08.001.

Markard, J., M. Suter, and K. Ingold. 2016. „Socio-technical transitions and policy change -Advocacy coalitions in Swiss energy policy.“ *Environmental Innovation and Societal Transitions* 18:215–237. https://doi.org/10.1016/j.eist.2015.05.003.

Marshall, J. P. 2016. „Disordering fantasies of coal and technology: Carbon capture and storage in Australia.“ *Energy Policy* 99:288–298. https://doi.org/10.1016/j.enpol.2016.05.044.

Martin-Roberts, E., V. Scott, S. Flude, G. Johnson, R. S. Haszeldine, and S. Gilfillan. 2021. „Carbon capture and storage at the end of a lost decade.“ *One Earth* 4 (11): 1569–1584. https://doi.org/10.1016/j.oneear.2021.10.002.

McCauley, D., V. Ramasar, R. J. Heffron, B. K. Sovacool, D. Mebratu, and L. Mundaca. 2019. „Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research.“ *Applied Energy* 233-234:916–921. https://doi.org/10.1016/j.apenergy.2018.10.005.

McGlade, C., and P. Ekins. 2015. „The geographical distribution of fossil fuels unused when limiting global warming to 2 °C.“ *Nature* 517:187–190. https://doi.org/https://doi.org/10.1038/nature14016.

McJeon, H., B. K. Mignone, P. O’Rourke, R. Horowitz, H. S. Kheshgi, L. Clarke, P. Kyle, P. Patel, and J. Edmonds. 2021. „Fossil energy deployment through midcentury consistent with 2°C climate stabilization.“ *Energy and Climate Change* 2:100034. https://doi.org/10.1016/j.egycc.2021.100034.

McKibbin, W. J., and R. Fernando. 2020. *The Global Macroeconomic Impacts of COVID-19: Seven Scenarios.* Technical report. Rochester, NY. https://papers.ssrn.com/abstract=3547729.

Meidan, M. n.d. *COVID-19 and the electrification of the Chinese economy.* Technical report. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/06/COVID-19-and-the-electrification-of-the-Chinese-economy.pdf.

Meinshausen, M. 2015. *Individual Report to the Land Court of Queensland on “Climate Change -Emissions”.* http://envlaw.com.au/wp-content/uploads/carmichael16.pdf.

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen. 2009. „Greenhouse-gas emission targets for limiting global warming to 2 °C.“ *Nature* 458 (7242): 1158–1162. https://doi.org/10.1038/nature08017.

Mendelevitch, R. 2018. „Testing supply-side climate policies for the global steam coal market—can they curb coal consumption?“ *Climatic Change* 150 (1): 57–72. https://doi.org/10.1007/s10584-018-2169-3.

Mendelevitch, R., C. Hauenstein, and F. Holz. 2019. „The death spiral of coal in the U.S.: will changes in U.S. Policy turn the tide?“ *Climate Policy* 19 (10): 1310–1324. https://doi.org/10.1080/14693062.2019.1641462.

Mendelevitch, R., C. Kemfert, P.-Y. Oei, and C. v. Hirschhausen. 2018. „The Electricity Mix in the European Low-carbon Transformation: Coal, Nuclear, and Renewables.“ In *Energiewende “Made in Germany”: Low Carbon Electricity Sector Reform in the European Context,* edited by C. v. Hirschhausen, C. Gerbaulet, C. Kemfert, C. Lorenz, and P.-Y. Oei. Cham, Switzerland: Springer Nature Switzerland AG.

Mendelevitch, R., and P.-Y. Oei. 2018. „The impact of policy measures on future power generation portfolio and infrastructure: a combined electricity and CCTS investment and dispatch model (ELCO).“ *Energy Systems* 9 (4): 1025–1054. https://doi.org/10.1007/s12667-017-0242-z.

Mercure, J.-F., H. Pollitt, J. Vinuales, N. Edwards, P. Holden, U. Chewpreecha, P. Salas, I. Sognnaes, A. Lam, and F. Knobloch. 2018. „Macroeconomic impact of stranded fossil fuel assets.“ *Nature Climate Change* 8:588–593. https://doi.org/https://doi.org/10.1038/s41558-018-0182-1.

Metayer, M., C. Breyer, and H.-J. Fell. 2015. „The projections for the future and quality in the past of the World Energy Outlook for solar PV and other renewable energy technologies.“ Hamburg, Germany. https://www.researchgate.net/profile/Christian_Breyer/publication/281939932_The_projections_for_the_future_and_quality_in_the_past_of_the_World_Energy_Outlook_for_solar_PV_and_other_renewable_energy_technologies/links/55ff47d308aeafc8ac8b9a4c.pdf.

METI: Ministry of Economy, Trade and Industry. 2021. *Outline of Strategic Energy Plan.* https://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/6th_outline.pdf.

Mietzner, D., and G. Reger. 2005. *Advantages and Disadvantages of Scenario Approaches for Strategic Foresight.* Technical report. Rochester, NY. https://papers.ssrn.com/abstract=1736110.

Minx, J. C., W. F. Lamb, M. W. Callaghan, S. Fuss, J. Hilaire, F. Creutzig, T. Amann, et al. 2018. „Negative emissions—Part 1: Research landscape and synthesis.“ *Environmental Research Letters* 13 (6): 063001. https://doi.org/10.1088/1748-9326/aabf9b.

Modi, A. 2020a. *India steps up initiatives to cut coal imports.* https://www.argusmedia.com/en/news/2102087-india-steps-up-initiatives-to-cut-coal-imports.

———. 2020b. *Indonesian producer body seeks deep coal output cuts.* https://www.argusmedia.com/en/news/2117714-indonesian-producer-body-seeks-deep-coal-output-cuts.

Mohn, K. 2020. „The Gavity of Status Quo: A Review of IEA’ s World Energy Outlook.“ *Economics of Energy & Environmental Policy* 9 (1). https://doi.org/10.5547/2160-5890.8.2.kmoh.

Montrone, L., J. C. Steckel, and M. Kalkuhl. 2022. „The type of power capacity matters for economic development ‑Evidence from a global panel.“ *Resource and Energy Economics* 69:101313. https://doi.org/10.1016/j.reseneeco.2022.101313.

Moody’s. 2020. *Research Announcement: Moody’s - Coal outlook stays negative amiddeclining earnings, investors’ intensifying ESG concerns.* https://www.moodys.com/research/Moodys-Coal-outlook-stays-negative-amid-declining-earnings-investors-intensifying--PBC_1211465?showPdf=true.

Mosley, L., ed. 2013. *Interview research in political science.* Ithaca: Cornell University Press.

Mukanjari, S., and T. Sterner. 2020. „Charting a “Green Path” for Recovery from COVID-19.“ *Environmental and Resource Economics* 76 (4): 825–853. https://doi.org/10.1007/s10640-020-00479-0.

Muller, N. Z., R. Mendelsohn, and W. Nordhaus. 2011. „Environmental Accounting for Pollution in the United States Economy.“ *American Economic Review* 101 (5): 1649–1675. https://doi.org/10.1257/aer.101.5.1649.

Muttitt, G., and S. Kartha. 2020. „Equity, climate justice and fossil fuel extraction: principles for a managed phase out.“ *Climate Policy,* 1–19. https://doi.org/10.1080/14693062.2020.1763900.

Muttitt, G., A. Scott, and T. Buckley. 2018. *Off Track.* Technical report, The Sky’s Limit. Washington DC; Cleveland, USA. http://priceofoil.org/content/uploads/2018/04/Off-Track-IEA-climate-change1.pdf.

Myllyvirta, L. 2020. *China’s 2060 climate pledge: long-awaited breakthrough or sugar-coating another decade of rising emissions?* https://energyandcleanair.org/china-2060-carbon-neutrality/.

Myllyvirta, L., S. Zhang, and X. Shen. 2020. *Analysis: Will China build hundreds of new coal plants in the 2020s?* https://www.carbonbrief.org/analysis-will-china-build-hundreds-of-new-coal-plants-in-the-2020s.

Nascimento, L., T. Kuramochi, G. Iacobuta, M. den Elzen, H. Fekete, M. Weishaupt, H. L. van Soest, et al. 2022. „Twenty years of climate policy: G20 coverage and gaps." *Climate Policy* 22 (2): 158–174. https://doi.org/10.1080/14693062.2021.1993776.

NCC. 2018. *Advancing U.S. Coal Exports: An Assessment of Opportunities to Enhance Exports of U.S. Coal.* Technical report. Washington DC, USA. http://www.nationalcoalcouncil.org/studies/2018/NCC-US-Coal-Exports-2018.pdf.

Nel, E. L., T. R. Hill, K. C. Aitchison, and S. Buthelezi. 2003. „The closure of coal mines and local development responses in Coal-Rim Cluster, northern KwaZulu-Natal, South Africa." *Development Southern Africa* 20 (3): 369–385. https://doi.org/10.1080/0376835032000108185.

New Economic Thinking, I. of. 2020. *4 Ways to Eradicate the Corporate Disease That is Worsening the Covid-19 Pandemic.* https://www.ineteconomics.org/perspectives/blog/4-ways-to-eradicate-the-corporate-disease-that-is-worsening-the-covid-19-pandemic.

Newell, P. 2018. „*Trasformismo* or transformation? The global political economy of energy transitions." *Review of International Political Economy* 26 (1): 25–48. https://doi.org/10.1080/09692290.2018.1511448.

Newig, J., E. Challies, N. W. Jager, E. Kochskaemper, and A. Adzersen. 2018. „The Environmental Performance of Participatory and Collaborative Governance: A Framework of Causal Mechanisms." *Policy Studies Journal* 46 (2): 269–297. https://doi.org/10.1111/psj.12209.

Nordhaus, W. D. 2013. „Chapter 16 - Integrated Economic and Climate Modeling." In *Handbook of Computable General Equilibrium Modeling,* edited by P. Jorgenson, B. Dixon, and W. Dale, 1:1069–1131. Handbook of Computable General Equilibrium Modeling SET, Vols. 1A and 1B. Elsevier.

Notten, P. van. 2005. *Writing on the Wall; Scenario Development in Times of Discontinuity.* http://www.universal-publishers.com/book.php?method=ISBN&book=1581122659.

Ocelík, P., T. Diviák, L. Lehotský, K. Svobodová, and M. Hendrychová. 2022. „Facilitating the Czech Coal Phase-Out: What Drives Inter-Organizational Collaboration?" *Society & Natural Resources* 35 (7): 705–724. https://doi.org/10.1080/08941920.2022.2065394.

Ocelík, P., K. Svobodová, M. Hendrychová, L. Lehotský, J.-A. Everingham, S. Ali, J. Badera, and A. Lechner. 2019. „A contested transition toward a coal-free future: Advocacy coalitions and coal policy in the Czech Republic.“ *Energy Research & Social Science* 58:101283. https://doi.org/10.1016/j.erss.2019.101283.

OCHA-ROAP. 2020. *China - Subnational Administrative Boundaries.* https://data.humdata.org/dataset/cod-ab-chn.

OECD. 2020a. *COVID-19 and the low-carbon transition: Impacts and possible policy responses.* http://www.oecd.org/coronavirus/policy-responses/covid-19-and-the-low-carbon-transition-impacts-and-possible-policy-responses-749738fc/.

———. 2020b. *Support for fossil fuel production rising again.* http://www.oecd.org/coronavirus/en/data-insights/support-for-fossil-fuel-production-rising-again.

Oei, P.-Y., H. Brauers, and P. Herpich. 2020. „Lessons from Germany’ s hard coal mining phase-out: policies and transition from 1950 to 2018.“ *Climate Policy* 20 (8): 963–979. https://doi.org/10.1080/14693062.2019.1688636.

Oei, P.-Y., T. Burandt, K. Hainsch, K. Löffler, and C. Kemfert. 2020. „Lessons from modeling 100% renewable scenarios using GENeSYS-MOD.“ *Economics of Energy & Environmental Policy* 9 (1).

Oei, P.-Y., C. Gerbaulet, C. Kemfert, F. Kunz, F. Reitz, and v. C. Hirschhausen. 2015. *Effektive CO -Minderung im Stromsektor: Klima-, Preis- und Beschäftigungseffekte des Klimabeitrags und alternativer Instrumente.* Technical report, Politikberatung kompakt. Berlin, Germany.

Oei, P.-Y., H. Hermann, P. Herpich, O. Holtemöller, B. Lünenbürger, and C. Schult. 2020. „Coal phase-out in Germany -Implications and policies for affected regions.“ *Energy.*

Oei, P.-Y., and R. Mendelevitch. 2019. „Prospects for steam coal exporters in the era of climate policies: a case study of Colombia.“ *Climate Policy* 19 (1): 73–91. https://doi.org/10.1080/14693062.2018.1449094.

Oei, P.-Y., P. Yanguas-Parra, and C. Hauenstein. 2020. *COVID-19 - Final Straw or Deathblow for a Global Coal Industry at the Verge of Collapse.* Technical report, IAEE Energy Forum / Covid-19 Issue 2020. https://www.iaee.org/en/publications/newsletterdl.aspx?id=879.

Office of the Chief Economist. 2021. *Resources and Energy Quaterly. March 2021.* https://publications.industry.gov.au/publications/resourcesandenergyquarterlymarch2021/documents/Resources-and-Energy-Quarterly-March-2021.pdf.

Pai, S., J. Emmerling, L. Drouet, H. Zerriffi, and J. Jewell. 2021. „Meeting well-below 2°C target would increase energy sector jobs globally.“ *One Earth* 4 (7): 1026–1036. https://doi.org/10.1016/j.oneear.2021.06.005.

Pai, S., H. Zerriffi, J. Jewell, and J. Pathak. 2020. „Solar has greater techno-economic resource suitability than wind for replacing coal mining jobs.“ *Environmental Research Letters* 15 (3): 034065. https://doi.org/10.1088/1748-9326/ab6c6d.

Parry, I., S. Black, and N. Vernon. 2021. „Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies.“ (Rochester, NY).

Paulus, M., and J. Trüby. 2011. „Coal lumps vs. electrons: How do Chinese bulk energy transport decisions affect the global steam coal market?“ *Energy Economics* 33 (6): 1127–1137. https://doi.org/10.1016/j.eneco.2011.02.006.

Peh, G. 2020. *Indonesian Coal at the Mercy of the Dragon and Tiger*. Technical report. https://ieefa.org/wp-content/uploads/2020/06/Indonesian-Coal-at-the-Mercy-of-the-Dragon-and-Tiger_June-2020.pdf.

Peters, G. P., and O. Geden. 2017. „Catalysing a political shift from low to negative carbon.“ *Nature Climate Change* 7:619–621. https://doi.org/10.1038/nclimate3369.

Pfeiffer, A., C. Hepburn, A. Vogt-Schilb, and B. Caldecott. 2018. „Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement.“ *Environmental Research Letters* 13 (5): 054019. https://doi.org/10.1088/1748-9326/aabc5f.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker. 2016. „The ‘2°C capital stock’ for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy.“ *Applied Energy* 179:1395–1408. https://doi.org/10.1016/j.apenergy.2016.02.093.

Piggot, G. 2018. „The influence of social movements on policies that constrain fossil fuel supply.“ *Climate Policy* 18 (7): 942–954. https://doi.org/10.1080/14693062.2017.1394255.

Piggot, G., P. Erickson, H. van Asselt, and M. Lazarus. 2018. „Swimming upstream: addressing fossil fuel supply under the UNFCCC.“ *Climate Policy* 18 (9): 1189–1202. https://doi.org/10.1080/14693062.2018.1494535.

Piggot, G., C. Verkuijl, H. van Asselt, and M. Lazarus. 2020. „Curbing fossil fuel supply to achieve climate goals.“ *Climate Policy* 20:8:881–887. https://doi.org/10.1080/14693062.2020.1804315.

Ploeg, F. van der, and A. Rezai. 2020a. „Stranded Assets in the Transition to a Carbon-Free Economy.“ *Annual Review of Resource Economics* 12 (1): 281–298. https://doi.org/10.1146/annurev-resource-110519-040938.

———. 2020b. „The risk of policy tipping and stranded carbon assets.“ *Journal of Environmental Economics and Management* 100:102258. https://doi.org/10.1016/j.jeem.2019.102258.

Power, T. M., and D. S. Power. 2013. „The Impact of Powder River Basin Coal Exports on Global Greenhouse Gas Emissions.“ *San Francisco, CA: Energy Foundation,* 22.

PPCA. 2017. *Powering Past Coal Alliance | Working towards the global phase-out of unabated coal power.* https://poweringpastcoal.org.

Pradhan, S., W. M. Shobe, J. Fuhrman, H. McJeon, M. Binsted, S. C. Doney, and A. F. Clarens. 2021. „Effects of Direct Air Capture Technology Availability on Stranded Assets and Committed Emissions in the Power Sector.“ *Frontiers in Climate* 3.

Praetorius, B., M. Kaiser, S. Körzell, and A. Grothus. 2019. „Reflexionen nach der Schlacht. Erfahrungen aus der Kohlekommission.“ *Politische Ökologie,* no. 156, 51–60.

Puerto-Chaves, L. M., and F. Corral-Montoya. 2022. „The political economy of coal in light of climate and mineral-energy policies: A case study from Colombia.“ In *The Political Economy of Coal.* Routledge.

Quiggin, J. 2017. *The Economic (non)viability of the Adani Galilee Basin Project.* The Australia Institute. https://australiainstitute.org.au/wp-content/uploads/2020/12/The-economic-non-viability-of-the-Adani-Galilee-Basin-Project.pdf.

Rauner, S., N. Bauer, A. Dirnaichner, R. V. Dingenen, C. Mutel, and G. Luderer. 2020. „Coal-exit health and environmental damage reductions outweigh economic impacts.“ *Nature Climate Change,* 1–5. https://doi.org/10.1038/s41558-020-0728-x.

Rečková, D., L. Rečka, and M. Ščasný. 2017. *Coal Transition in the Czech Republic.* Technical report, An historical case study for the project “Coal Transitions: Research and Dialogue on the Future of Coal”. https://coaltransitions.files.wordpress.com/2016/09/coal_cz_v04.pdf.

Reddy, P., and A. Rosencranz. 2018. „Challenging the Proposed Carmichael Mine Before the UN.“ *Environmental Policy and Law* 48:31–36. https://doi.org/10.3233/EPL-180047.

Reitzenstein, A., R. Popp, P.-Y. Oei, H. Brauers, N. Stognief, C. Kemfert, J. Kurwan, and T. Wehnert. 2022. *Structural change in coal regions as a process of economic and social-ecological transition - Lessons learnt from structural change processes in Germany.* Technical report. Dessau-Roßlau: Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/structural-change-in-coal-regions-as-a-process-of.

REN21. 2022. *Renewables 2022 Global Status Report.* Technical report. Paris. https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Full_Report.pdf.

Rentier, G., H. Lelieveldt, and G. J. Kramer. 2019. „Varieties of coal-fired power phase-out across Europe." *Energy Policy* 132:620–632. https://doi.org/10.1016/j.enpol.2019.05.042.

Rentschler, J., and M. Bazilian. 2017. „Reforming fossil fuel subsidies: drivers, barriers and the state of progress." *Climate Policy* 17 (7): 891–914. https://doi.org/10.1080/14693062.2016.1169393.

Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, et al. 2022. „Mitigation pathways compatible with long-term goals." In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge (UK) and New York, NY, (USA): Cambridge University Press.

Richter, P. M., R. Mendelevitch, and F. Jotzo. 2018. „Coal taxes as supply-side climate policy: a rationale for major exporters?" *Climatic change* 150 (1-2): 43–56. https://doi.org/10.1007/s10584-018-2163-9.

Rinscheid, A., and R. Wüstenhagen. 2019. „Germany' s decision to phase out coal by 2038 lags behind citizens' timing preferences." *Nature Energy* 4 (10): 856–863. https://doi.org/10.1038/s41560-019-0460-9.

Rioux, B., P. Galkin, F. Murphy, and A. Pierru. 2015. *Economic Impacts of Debottlenecking Congestion in the Chinese Coal Supply Chain.* Technical report, KAPSARC Discussion Paper. Riyadh, Saudi Arabia. https://www.kapsarc.org/wp-content/uploads/2015/10/KS-1523-DP017A-Economic-Impacts-of-Debottlenecking-Congestion-in-the-Chinese-Coal-Supply-Chain.pdf.

Ritchie, H. 2021. *When will countries phase out coal power?* https://ourworldindata.org/coal-phase-out.

Rogelj, J., D. Huppmann, V. Krey, K. Riahi, L. Clarke, M. Gidden, Z. Nicholls, and M. Meinshausen. 2019. „A new scenario logic for the Paris Agreement long-term temperature goal." *Nature* 573 (7774): 357–363. https://doi.org/10.1038/s41586-019-1541-4.

Rogelj, J., A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, et al. 2018. „Scenarios towards limiting global mean temperature increase below 1.5 °C.“ *Nature Climate Change* 8 (4): 325–332. https://doi.org/10.1038/s41558-018-0091-3.

Rosenbloom, D., and J. Markard. 2020. „A COVID-19 recovery for climate.“ *Science* 368 (6490): 447–447. https://doi.org/10.1126/science.abc4887.

Rosewarne, S. 2016. „The transnationalisation of the Indian coal economy and the Australian political economy: The fusion of regimes of accumulation?“ *Energy Policy* 99:214–223. https://doi.org/https://doi.org/10.1016/j.enpol.2016.05.022.

Runfola, D., A. Anderson, H. Baier, M. Crittenden, E. Dowker, S. Fuhrig, S. Goodman, et al. 2020. „geoBoundaries: A global database of political administrative boundaries.“ *PLOS ONE* 15 (4): e0231866. https://doi.org/10.1371/journal.pone.0231866.

Ruppert Bulmer, E., K. Pela, A. Eberhard-Ruiz, and J. Montoya. 2021. *Global Perspective on Coal Jobs and Managing Labor Transition out of Coal: Key Issues and Policy Responses.* Technical report. Washington, DC. http://hdl.handle.net/10986/37118.

Sabatier, P., and H. Jenkins-Smith. 1988. „Advocacy coalition model of policy change and the role of policy oriented learning therein,“ 129–168.

Sabatier, P., and C. Weible. 2007. „The Advocacy Coalition Framework: Innovations and Clarifications.“ In *Theories of the Policy Process,* second edition, 189–220. New York.

Sartor, O. 2018. *Implementing coal transitions: Insights from case studies of major coal-consuming economies.* Technical report. https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%5C%20Iddri/Rapport/201809-Synthesis%5C%20Report%5C%20Iddri-COALTRANSITIONS-def.pdf.

Saunois, M., A. R. Stavert, B. Poulter, P. Bousquet, J. G. Canadell, R. B. Jackson, P. A. Raymond, et al. 2020. „The Global Methane Budget 2000–2017.“ *Earth System Science Data* 12 (3): 1561–1623. https://doi.org/10.5194/essd-12-1561-2020.

Saygin, D., J. Rigter, B. Caldecott, N. Wagner, and D. Gielen. 2019. „Power sector asset stranding effects of climate policies.“ *Energy Sources, Part B: Economics, Planning, and Policy* 14 (4): 99–124. https://doi.org/10.1080/15567249.2019.1618421.

Schlissel, D., T. Sanzillo, and S. Feaster. 2018. *IEEFA Outlook 2018 - U.S. Coal: More Market Erosion is on the Way.* Technical report. Cleveland, Ohio, USA. http://ieefa.org/wp-content/uploads/2018/01/U.S.-Coal-More-Market-Erosion-_-February-2018.pdf.

Schlissel, D., and D. Wamsted. 2018. *Holy Grail of Carbon Capture Continues to Elude Coal Industry.* Technical report. http://ieefa.org/wp-content/uploads/2018/11/Holy-Grail-of-Carbon-Capture-Continues-to-Elude-Coal-Industry_November-2018.pdf.

———. 2022. *Carbon Capture' s Methane Problem.* Technical report. https://ieefa.org/resources/carbon-captures-methane-problem.

Schoemaker, P. J. H. *Scenario Planning: A Tool for Strategic Thinking.* https://sloanreview.mit.edu/article/scenario-planning-a-tool-for-strategic-thinking/.

SEI, IISD, Climate Analytics, ODI, and UNEP. 2019. *The Production Gap Report 2019.* Technical report. http://productiongap.org/.

SEI, IISD, ODI, Climate Analytics, CICERO, and UNEP. 2019. *The Production Gap: The discrepancy between countries' planned fossil fuel production and global production levels consistent with limiting warming to 1.5°C or 2°C.* Technical report. https://productiongap.org/2019report/.

SEI, IISD, ODI, E3G, and UNEP. 2020. *The Production Gap Report 2020.* http://productiongap.org/2020report.

———. 2021. *The Production Gap Report 2021.* Technical report. http://productiongap.org/2021report.

Selby, J. 2018. „The Trump presidency, climate change, and the prospect of a disorderly energy transition.“ *Review of International Studies,* 1–20. https://doi.org/10.1017/S0260210518000165.

Seto, K. C., S. J. Davis, R. B. Mitchell, E. C. Stokes, G. Unruh, and D. Ürge-Vorsatz. 2016. „Carbon Lock-In: Types, Causes, and Policy Implications.“ *Annual Review of Environment and Resources* 41 (1): 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.

Setzer, J., and R. Byrnes. 2020. *Global trends in climate change litigation: 2020 snapshot.* Technical report. London. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2020/07/Global-trends-in-climate-change-litigation_2020-snapshot.pdf.

Shearer, C., N. Mathew-Shah, L. Myllyvirta, A. Yu, and T. Nace. 2018. *Boom and Bust 2018: Tracking the Global Coal Plant Pipline.* Technical report. https://endcoal.org/wp-content/uploads/2018/03/BoomAndBust_2018_r6.pdf.

Shearer, C., L. Myllyvirta, A. Yu, G. Aitken, N. Mathew-Shah, G. Dallos, and T. Nace. 2020. *Boom and Bust 2020: Tracking the global coal plant pipeline.* Technical report. https://endcoal.org/wp-content/uploads/2020/03/BoomAndBust_2020_English.pdf.

Siefken, S. T. 2016. „Expertenkommissionen der Bundesregierung.“ In *Handbuch Politikberatung,* edited by S. Falk, M. Glaab, A. Römmele, H. Schober, and M. Thunert, 1–17. Springer Reference Sozialwissenschaften. Wiesbaden: Springer Fachmedien.

Sinn, H.-W. 2008. „Public policies against global warming: a supply side approach.“ *International Tax and Public Finance* 15 (4): 360–394. https://doi.org/10.1007/s10797-008-9082-z.

Söderholm, P., R. Hildingsson, B. Johansson, J. Khan, and F. Wilhelmsson. 2011. „Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050.“ *Futures,* Special Issue: Energy Futures, 43 (10): 1105–1116. https://doi.org/10.1016/j.futures.2011.07.009.

Solana, J. 2020. „Climate change litigation as financial risk.“ *Green Finance* 2 (4): 344–372. https://doi.org/10.3934/GF.2020019.

Somanathan, E., T. Sterner, T. Sugiyama, D. Chimanikire, N. Dubash, J. Essandoh-Yeddu, S. Fifita, et al. 2014. „National and Sub-national Policies and Institutions.“ In *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Sovacool, B. K., J. Axsen, and S. Sorrell. 2018. „Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design.“ *Energy Research & Social Science* 45:12–42. https://doi.org/10.1016/j.erss.2018.07.007.

Sovacool, B. K., J. Kim, and M. Yang. 2021. „The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities.“ *Energy Research & Social Science* 72:101885. https://doi.org/10.1016/j.erss.2020.101885.

Sovacool, B. K., and J. Scarpaci. 2016. „Energy justice and the contested petroleum politics of stranded assets: Policy insights from the Yasuní-ITT Initiative in Ecuador.“ *Energy Policy* 95:158–171. https://doi.org/10.1016/j.enpol.2016.04.045.

Spencer, T., M. Colombier, O. Sartor, A. Garg, V. Tiwari, J. Burton, T. Caetano, F. Green, F. Teng, and J. Wiseman. 2018. „The 1.5°C target and coal sector transition: at the limits of societal feasibility.“ *Climate Policy* 18 (3): 335–351. https://doi.org/10.1080/14693062.2017.1386540.

Steckel, J. C., O. Edenhofer, and M. Jakob. 2015. „Drivers for the renaissance of coal.“ *Proceedings of the National Academy of Sciences* 112 (29): E3775–E3781. https://doi.org/10.1073/pnas.1422722112.

Steffen, B. 2020. „Estimating the cost of capital for renewable energy projects.“ *Energy Economics* 88:104783. https://doi.org/10.1016/j.eneco.2020.104783.

Stognief, N., P. Walk, and P.-Y. Oei. 2022. „Political Economy of Climate and Energy Policies in the United Kingdom.“ In *The Political Economy of Coal: Obstacles to Clean Energy Transitions,* edited by M. Jakob and J. C. Steckel, 78–95. London: Routledge.

Stognief, N., P. Walk, O. Schöttker, and P.-Y. Oei. 2019. „Economic Resilience of German Lignite Regions in Transition.“ *Sustainability* 11 (21): 5991. https://doi.org/10.3390/su11215991.

Strefler, J., E. Kriegler, N. Bauer, G. Luderer, R. C. Pietzcker, A. Giannousakis, and O. Edenhofer. 2021. „Alternative carbon price trajectories can avoid excessive carbon removal.“ *Nature Communications* 12 (1): 2264. https://doi.org/10.1038/s41467-021-22211-2.

Stuart-Smith, R. F., F. E. L. Otto, A. I. Saad, G. Lisi, P. Minnerop, K. C. Lauta, K. van Zwieten, and T. Wetzer. 2021. „Filling the evidentiary gap in climate litigation.“ *Nature Climate Change* 11 (8): 651–655. https://doi.org/10.1038/s41558-021-01086-7.

Stutzer, R., A. Rinscheid, T. D. Oliveira, P. M. Loureiro, A. Kachi, and M. Duygan. 2021. „Black coal, thin ice: the discursive legitimisation of Australian coal in the age of climate change.“ *Humanities and Social Sciences Communications* 8 (1): 178. https://doi.org/10.1057/s41599-021-00827-5.

Suarez, I., and R. Gray. 2021. *With China’ s Withdrawal from Overseas Coal, the Pipeline for New Coal in Asia Could Drop to 22 GW—All of Which Will Likely Not Be Built.* Global Energy Monitor, CREA. https://globalenergymonitor.org/report/with-chinas-withdrawal-from-overseas-coal-the-pipeline-for-new-coal-in-asia-could-drop-to-22-gw-all-of-which-will-likely-not-be-built/.

Sussams, L., and A. Grant. 2015. *The US Coal Crash - Evidence for Structural Change.* Technical report. http://www.carbontracker.org/report/the-us-coal-crash/.

Svobodova, K., J. R. Owen, J. Harris, and S. Worden. 2020. „Complexities and contradictions in the global energy transition: A re-evaluation of country-level factors and dependencies.“ *Applied Energy* 265:114778. https://doi.org/10.1016/j.apenergy.2020.114778.

The Government of the Republic of Korea. 2020. *2050 Carbon Neutral Strategy of the Republic of Korea. Towards a Sustainable and Green Society 2050.* https://unfccc.int/sites/default/files/resource/LTS1_RKorea.pdf.

The White House. 2017. *Statement by President Trump on the Paris Climate Accord.* https://www.whitehouse.gov/the-press-office/2017/06/01/statement-president-trump-paris-climate-accord.

———. 2021. *FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies.* Technical report. Washington DC, USA. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

The World Bank. 2021. *State and Trends of Carbon Pricing 2021.* Washington, DC. http://hdl.handle.net/10986/35620.

———. *Coal rents (% of GDP).* https://data.worldbank.org/indicator/NY.GDP.COAL.RT.ZS?end=2020&start=1970&view=map.

Thomson, V. E., K. Huelsman, and D. Ong. 2018. „Coal-fired power plant regulatory rollback in the United States: Implications for local and regional public health.“ *Energy Policy* 123:558–568. https://doi.org/10.1016/j.enpol.2018.09.022.

Tong, D., Q. Zhang, Y. Zheng, K. Caldeira, C. Shearer, C. Hong, Y. Qin, and S. J. Davis. 2019. „Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target.“ *Nature,* https://doi.org/10.1038/s41586-019-1364-3.

Trout, K., G. Muttitt, D. Lafleur, T. V. d. Graaf, R. Mendelevitch, L. Mei, and M. Meinshausen. 2022. „Existing fossil fuel extraction would warm the world beyond 1.5 °C.“ *Environmental Research Letters* 17 (6): 064010. https://doi.org/10.1088/1748-9326/ac6228.

Trüby, J., and M. Paulus. 2012. „Market Structure Scenarios in International Steam Coal Trade.“ *The Energy Journal* 33 (3). https://doi.org/10.5547/01956574.33.3.4.

Trump, D. J. 2017. „Presidential Executive Order on Promoting Energy Independence and Economic Growth.“

Turnheim, B., and F. W. Geels. 2012. „Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913‑1997).“ *Energy Policy,* Special Section: Past and Prospective Energy Transitions - Insights from History, 50:35–49. https://doi.org/10.1016/j.enpol.2012.04.060.

UN. 2015. *Transforming our World: the 2030 Agenda for Sustainable Development.* Technical report. New York City.

UN Climate Change Conference UK. 2021. *Political Declaration on the Just Energy Transition in South Africa.* https://ukcop26.org/political-declaration-on-the-just-energy-transition-in-south-africa/.

UNEP. 2021. *Emissions Gap Report 2021: The Heat Is On –A World of Climate Promises Not Yet Delivered.* Technical report. Nairobi. https://www.unep.org/resources/emissions-gap-report-2021.

UNFCCC. 2015. *Paris Agreement.* Technical report. Paris.

———. 2016. *Just transition of the workforce, and the creation of decent work and quality jobs.* Technical report. Bonn, Germany. https://unfccc.int/resource/docs/2016/tp/07.pdf.

———. 2021. *Glasgow Climate Pact.* https://unfccc.int/sites/default/files/resource/cop26_auv_2f_cover_decision.pdf.

———. *Paris Agreement - Status of Ratification.* https://unfccc.int/process/the-paris-agreement/status-of-ratification.

Unruh, G. C. 2000. „Understanding carbon lock-in.“ *Energy Policy* 28 (12): 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7.

———. 2019. „The Real Stranded Assets of Carbon Lock-In.“ *One Earth* 1 (4): 399–401. https://doi.org/10.1016/j.oneear.2019.11.012.

Urgewald, R. Finance, 3. Japan, and 2. other NGO partners. 2022. *Who Is Still Financing the Global Coal Industry?* Technical report. Berlin. https://www.coalexit.org/sites/default/files/download_public/GCEL.Finance.Research_urgewald_Media.Briefing_20220209%5C%20%5C%281%5C%29.pdf.

Urpelainen, J., and T. Van de Graaf. 2018. „United States non-cooperation and the Paris agreement.“ *Climate Policy* 18 (7): 839–851. https://doi.org/10.1080/14693062.2017.1406843.

Vinichenko, V., A. Cherp, and J. Jewell. 2021. „Historical precedents and feasibility of rapid coal and gas decline required for the 1.5°C target.“ *One Earth* 4 (10): 1477–1490. https://doi.org/10.1016/j.oneear.2021.09.012.

Volcovici, V. 2018. „Coal firms plead to courts, Trump for West Coast export terminals.“ *Reuters.*

Walk, P., I. Braunger, J. Semb, C. Brodtmann, P.-Y. Oei, and C. Kemfert. 2021. „Strengthening Gender Justice in a Just Transition: A Research Agenda Based on a Systematic Map of Gender in Coal Transitions.“ *Energies* 14:5985. https://doi.org/https://doi.org/10.3390/en14185985.

Wamsted, D., S. Feaster, and K. Cates. 2020. *U.S. Coal Outlook 2020: Market Trends Pushing Industry Ever Closer to a Reckoning.* Technical report. Cleveland, Ohio, USA. https://ieefa.org/wp-content/uploads/2020/03/US-Coal-Outlook-2020_March-2020.pdf.

Wang, N., K. Akimoto, and G. F. Nemet. 2021. „What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects.“ *Energy Policy* 158:112546. https://doi.org/10.1016/j.enpol.2021.112546.

Wang, Q., S. Li, and R. Li. 2019. „Will Trump’s coal revival plan work? - Comparison of results based on the optimal combined forecasting technique and an extended IPAT forecasting technique.“ *Energy* 169:762–775. https://doi.org/10.1016/j.energy.2018.12.045.

Weber, J. G. 2020. „How Should We Think about Environmental Policy and Jobs? An Analogy with Trade Policy and an Illustration from U.S. Coal Mining.“ *Review of Environmental Economics and Policy* 14 (1): 44–66. https://doi.org/10.1093/reep/rez016.

Wehnert, T., T. Andreeva, H. Fekete, K. Lütkehermöller, L. Luna, and M. Vieweg. 2019. *Challenges of Coal Transitions: A comparative study on the status quo and future prospects of coal mining and coal use in Indonesia, Colombia and Viet Nam.* CLIMATE CHANGE 07. Dessau - Roßlau, Germany: German Environment Agency.

Welsby, D., J. Price, S. Pye, and P. Ekins. 2021. „Unextractable fossil fuels in a 1.5 °C world.“ *Nature* 597 (7875): 230–234. https://doi.org/10.1038/s41586-021-03821-8.

Western Interstate Energy Board. 2012. *Coal Ports.* http://westernenergyboard.org/topics/spotlight/coal-ports/.

Wing, I. S. 2009. „Computable General Equilibrium Models for the Analysis of Energy and Climate Policies.“ *International Handbook on the Economics of Energy.*

Wolff, F., D. A. Heyen, B. Brohmann, R. Grießhammer, K. Jacob, and L. Graaf. 2020. *Transformative environmental policy: Consistently promote and shape sustainable development.* Technical report. Dessau - Roßlau. https://www.umweltbundesamt.de/publikationen/transformative-environmental-policy-consistently.

Wright, H., and A. Fenton. 2020. *Green economic stimulus: Priority actions for central banks.* https://medium.com/@drhelenawright/green-economic-stimulus-priority-actions-for-central-banks-e15dfebcb425.

Yanguas Parra, P., F. Corral-Montoya, A. Furnaro, J. Hanto, C. Hauenstein, N. Malz, T. Mitterecker, P.-Y. Oei, and G. Quiceno. in preparation. „Perspective: Why a short-term relapse to coal could put exporting countries at risk."

Yanguas Parra, P., G. Ganti, R. Brecha, B. Hare, M. Schaeffer, and U. Fuentes. 2019. *Global and regional coal phase-out requirements of the Paris Agreement: Insights from the IPCC Special Report on 1.5°C.* Technical report. Berlin, Germany: Climate Analytics.

Yanguas Parra, P., C. Hauenstein, and P.-Y. Oei. 2021. „The death valley of coal –Modelling COVID-19 recovery scenarios for steam coal markets." *Applied Energy* 288:116564. https://doi.org/10.1016/j.apenergy.2021.116564.

York, R., and S. E. Bell. 2019. „Energy transitions or additions?: Why a transition from fossil fuels requires more than the growth of renewable energy." *Energy Research & Social Science* 51:40–43. https://doi.org/10.1016/j.erss.2019.01.008.

Zhou, S., B. Chen, W. Wei, Z. Liu, S. Song, K. Feng, and J. Li. 2022. „China's power transformation may drastically change employment patterns in the power sector and its upstream supply chains." *Environmental Research Letters* 17 (6): 065005. https://doi.org/10.1088/1748-9326/ac5769.

Zhou, X., C. Wilson, and B. Caldecott. 2021. *The energy transition and changing financing costs.* Technical report. https://www.smithschool.ox.ac.uk/sites/default/files/2022-02/The-energy-transition-and-changing-financing-costs.pdf.