EUROPA-UNIVERSITÄT FLENSBURG

DOCTORAL THESIS

From Shore to Ship and Beyond: Co-Creative and Systematic Modelling Approaches to Sustainable Energy Transitions

Franziska Theresa Dettner

Supervisors
Prof. Dr. Olav Hohmeyer
Prof. Dr. Pao-Yu Oei

A thesis submitted in fulfillment of the requirements for the degree of Dr.rer.pol.

Energie-und Umweltmanagment
Interdisziplinäres Institut für Umwelt-, Sozial- und Humanwissenschaften

Flensburg, April 2025

Summary

Research on climate change dates back over 120 years. Early pioneers such as Svante Arrhenius and Charles Keeling linked rising CO_2 levels to warming temperatures, while later reports solidified the role of human activity in climate change. Since then, climate science has highlighted the catastrophic effects of climate change, including biodiversity loss and extreme weather events, which could result in irreversible damage. Furthermore, the economic impact of climate change caused by health crises and the loss of productivity is immense, with externalities hardly ever reflected in market prices.

The critical challenge of mitigating climate change requires an urgent and comprehensive transition of the global energy landscape. This thesis examines how open-source and co-creative energy system models can guide sustainable energy transitions by focusing particularly on renewable energy deployment and decarbonisation strategies. It provides insights into various sectors, including electricity generation, transportation and shipping, and highlights how emissions modelling and scenario analysis can inform policy and investment decisions.

The central aim of this thesis is to advance energy system modelling by emphasising transparency and accessibility through open-source frameworks. The thesis seeks to answer the core research question *How can co-creative approaches, technological innovations and policy frameworks be integrated to develop cost-effective, sustainable and widely accepted solutions for a 100 % renewable energy system, while ensuring sectoral compliance with global climate targets?*

The thesis employs systematic modelling approaches, first and foremost Energy System Analysis (ESA), a multidisciplinary approach that uses quantitative models to simulate energy systems at different scales and temporal resolutions. ESA allows for detailed exploration of greenhouse gas reduction pathways by modelling sector-specific energy use and evaluating the potential impacts of different decarbonisation strategies. In the context of this dissertation, two key methodological approaches within ESA are (1) co-creative scenario modelling and analysis, exploring the impact of diverse energy mix configurations within energy system modelling applying the Open Energy Modelling Framework (oemof) and (2) a customised emission model for mar-

itime shipping, developing a high-resolution inventory for air pollutant emissions in the North and Baltic Seas based on ship movement data and relevant emission factors. The open-source nature of both methodological approaches ensures reproducibility, enabling researchers and stakeholders to validate results and adapt findings for policy development and planning. At the same time, it facilitates the assessment of technical, economic, environmental, and social feasibility of various energy transition scenarios.

Key findings presented in this thesis are:

- **Renewable Energy and Decarbonisation Potential** The results of the applied ESA demonstrate that renewable energy, particularly wind and solar in combination with storage, can feasibly replace fossil fuels in electricity generation. In the context of maritime emissions, substituting conventional fuels with renewable alternatives such as E-methanol could reduce CO_2 emissions by up to 90 % by 2040. However, the scalability of these solutions depends on substantial investment in infrastructure and renewable capacity.
- **Importance of Scenario Modelling** Scenario modelling highlights the advantages of transparent, open-source approaches, as these allow real-time adjustments based on emerging data and stakeholder input. Co-creative scenario modelling can foster greater public engagement and ensure that modelled outcomes align more closely with community and industry needs. Scenario modelling supports the goal of a just and inclusive energy transition, as it provides multiple stakeholders with a platform to shape the scenarios and understand the trade offs involved.
- **Economic and Policy Implications** The research underscores the importance of establishing appropriate carbon pricing mechanisms and regulatory frameworks. For instance, the integration of maritime emissions into the EU Emissions Trading System (EU ETS) incentivise the adoption of low-carbon fuels by internalising the external costs of CO_2 emissions.
- **Open Science and Data Transparency** The thesis advocates for open data practices to increase scientific rigor, transparency and public trust. Open source models such as oemof and open source emission inventories for air pollutants provide a flexible foundation for continuous improvement and democratise access to essential tools for energy planning, particularly in regions with limited resources. By making both the models and data publicly accessible, the research supports equitable participation in the development of climate change mitigation solutions.

This thesis investigates the complex challenges and opportunities in advancing sustainable energy transitions through an integrated lens that spans technological, economic and social dimensions, as depicted in Figure 1. The research demonstrates that transitioning to renewable energy systems is not only feasible but also capable of de-

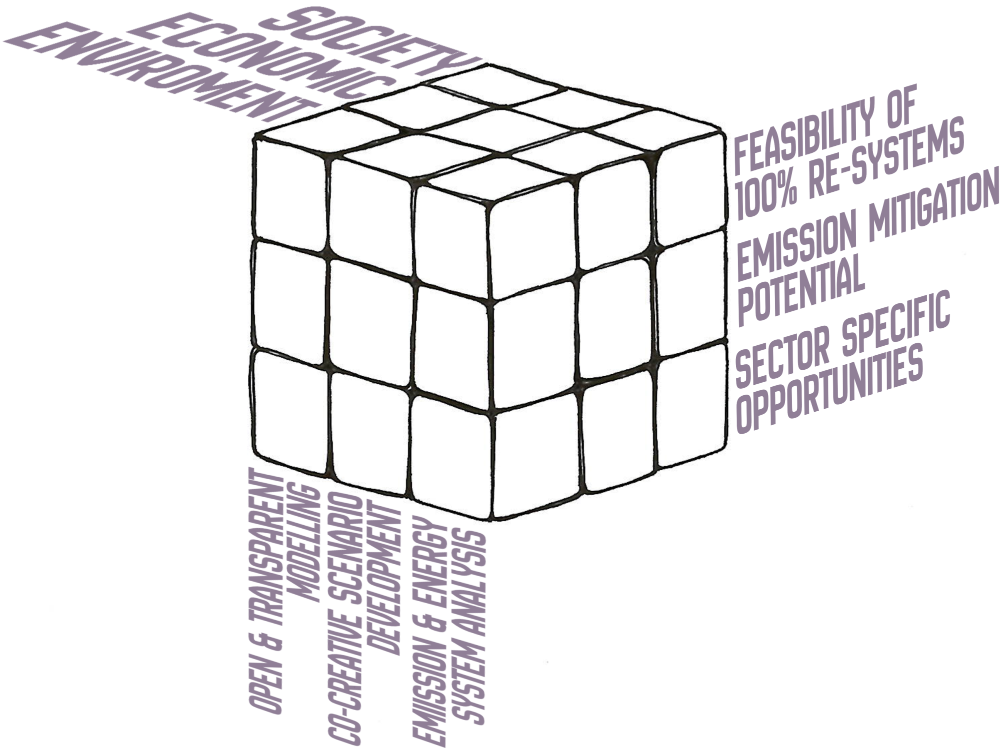


Figure 1: Unboxing the Energy Puzzle Connecting sustainability pillars and modelling pathways for sustainable energy transition.

livering significant environmental, economic and social justice benefits. However, the work acknowledges key limitations and areas for further investigation. Efficiency measures, such as demand-side management, and sufficiency, which aligns consumption with actual needs, were not comprehensively addressed, despite their critical importance in minimising energy demand and ensuring cost-effective transitions. Additionally, the external costs of energy systems and the complexities of long-term planning for fully renewable energy systems remain inadequately explored. The energy system models employed in this thesis highlight the need for improved approaches, as simplified assumptions, such as perfect foresight, often omit critical factors such as regional weather patterns, grid constraints, and integration costs. Similarly, in maritime energy transitions, infrastructure limitations and uncertainties in emissions modelling underscore the need for enhanced methods and systems to support alternative fuels. Social sustainability, a vital component of energy transitions, remains under-represented in techno-economic analyses. Achieving transformative energy solutions requires a broader integration of social considerations alongside technological and economic advancements. Despite these challenges, the findings of this thesis highlight the critical role of sustainable energy systems as a foundation for climate change mitigation. Addressing the identified limitations and advancing interdisciplinary solutions is essential to realising the ambitious targets of global energy transitions.

With regard to the research question, Part I emphasises the necessity of a sustainable energy transition in the context of climate change. Achieving a 100 % renewable energy system that is both cost-effective and socially accepted requires a comprehensive, multi-faceted approach. Part II presents the individual publications, each addressing and answering distinct aspects of the overarching research question. Co-creative scenario modelling, as discussed in Chapter 3, enhances stakeholder engagement and acceptance by integrating diverse perspectives. The cost-optimal mix of energy sources, highlighted in Chapters 4 and 5, combines technologies such as solar, wind, and biomass (bagasse) with pumped hydro storage (PHS) and battery storage, to meet future electricity demands. The application of open-source emission inventories in the shipping sector (Chapter 6), ensure critical data transparency for meeting climate targets such as the Paris Agreement's 1.5°C goal (Chapter 7). Additionally, the sustainable production of future energy carriers, such as green hydrogen, must consider environmental, social, and economic factors across the entire value chain, underlining the need for integrated policy frameworks that promote long-term sustainability and innovation, as explored in Chapter 8. By integrating technological, economic and social dimensions, the collective research effort presented in this thesis emphasises the need for a holistic approach that goes beyond isolated interventions, as articulated in Part III.

This thesis makes a significant contribution to the field of sustainable energy transitions by demonstrating how open-source and co-creative modelling approaches can effectively support policy development and drive progress toward a low-carbon future. Through detailed analysis of sector-specific pathways, the research not only illustrates the viability of renewable energy solutions but also underscores the importance of transparency, accessibility and active stakeholder engagement in achieving global climate objectives. These elements collectively reinforce the thesis's potential to guide practical and impactful energy transition strategies.

Acknowledgements

Have no fear of perfection - you'll never reach it.

– Salvador Dali, *1904-1989*

Science has always fascinated me. The pursuit as well as the application of knowledge to understand the natural and social world guided by a systematic, evidence-based, methodology has given me a sense of calmness in a fast-changing and increasingly complex world. My time at university gave me the unique opportunity not only to look into different aspects of energy systems and their effects on society, it also gave me the time and space to explore the different dimensions of scientific work. For me, one of the most fascinating aspects is the area of science communication. The supply of information and evidence-based data in a world with fake-news, confusing statistics, increased complexity and an uncountable number of interconnections is becoming more and more important. Effective scientific communication informs non-experts about scientific findings and raises public awareness and interest in science. In this context, when addressing social problems — particularly those at the heart of energy transitions — acceptance and participatory approaches are essential for achieving real change.

This thesis represents a journey exploring various avenues of energy transitions; a bouquet tied together at its roots by a common thread of thoughts and values. I owe much of this journey's success to the support and inspiration provided by numerous individuals who deserve recognition. Their contributions have shaped this work, and I am grateful for the collaborative effort that has brought it to fruition. First and foremost, I would like to express my sincere gratitude to my doctoral supervisor Prof. Dr. Olav Hohmeyer for continuously believing in me and getting me to write my thesis in the first place. His passion for the environment, and especially the topic of external costs, sparked my research interest. I also wish to thank Prof. Dr. Pao-Yu Oei for his inspiring perspective on research, publications and energy transitions. A special recognition has to be given to Dr. Simon Hilpert, with whom I had the pleasure to work with on a number of publications and who's challenging and inspiring thoughts helped develop my analytic, systematic and connective thinking. His passion for research, science and a wide range of topics has always been infectious. Another special recognition has to be given to Dr. Marina Blohm, whose sympathy and pragmatism helped immensely in designing research approaches and sometimes simply getting through the day. I also wish to mention my friends, who with all their brilliance not only created a stunning research group at the Centre for Sustainable Energy Systems but also, unknowingly, inspired me to work as a scientific researcher myself - thank you Simon, Marion, Clemens, Ulf, Krischan and Frauke. I would like to thank my friends and my family for their steadfast support and belief in me throughout this process. Your support and encouragement, even during my moments of doubt, have been invaluable. First and foremost, I would like to thank Jonathan Mole for his utterly skilful and ruthless English academic writing support in a number of publications as well as this thesis.

Thanks to the Gesellschaft für Energie & Klimaschutz Schleswig-Holstein (EKSH) for awarding me a doctoral scholarship in 2021 to support the completion of research on climate-neutral shipping. Gratitude is also extended to the Research Committee of the Europa-Universität Flensburg for funding several open-access publications as part of this thesis.

Contents

Part II - Publications

Part III - Connecting the Dots

List of Tables and Figures

Tables

Figures

Part I - Introduction and Foundations

1

Introduction

The world has enough for everyone's need, but not enough for everyone's greed.

– attributed to Mahatma Ghandi, *1896-1848*

1.1 Context & Rationale

For over 120 years, research and science has helped us to understand the cause and effects of climate change. Beginning in 1896, Swedish chemist Svante Arrhenius recognised that the burning of coal could increase carbon dioxide (CO_2) levels and warm the climate (Arrhenius 1896). In the 1940s, the British coal engineer Guy Calledar discovered that the planet had warmed by 0.3 °C over the previous 50 years due to rising CO_2 levels (Callendar 1949). In 1958, Dr. Charles Keeling discovered that rising CO_2 levels are attributed to the use of fossil fuels, resulting in the Keeling Curve, which shows the continuous rise in atmospheric CO_2 concentrations since then (Monroe 2024). In 1967, the first computer model predicted the increase of global average temperatures by 2 °C, assuming a doubling in CO_2 concentrations (Manabe and Wetherald 1967). Only a year later, in 1968, scientists predicted the melting of the ice caps due to rising global temperatures (Mercer 1968). After the publication of the *The Limits to Growth* by the Club of Rome (Meadows et al. 1972), James Hansen, a NASA climate scientist, testified that the climate was warming, that greenhouse gases (GHGs) were the cause, and that human activity was responsible for the rising levels of GHGs (Shabecoff and Hansen 1988).

The establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 marked a new era of climate change research driving policy action. The first climate assessment report (IPCC 1990), confirmed that "emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases" (p.117). The findings of the second assessment report (IPCC 1995) strengthened the evidence for human-induced climate change. The fourth assessment report (IPCC 2007) noted that human-caused GHGs had increased by 70 % between 1970 and 2004 and that "anthropogenic warming could lead to some impacts that are abrupt or irreversible, depending upon the rate and magnitude of the climate change" (p. 53). The most recent assessment report further highlights the impacts of human-induced climate change (IPCC 2021). Historically, the largest driver of climate change is the consumption of fossil fuels, accounting for over 75 % of global GHG emissions and almost 90 % of all CO_2 emissions (UN 2024). The primary contributors to anthropogenic climate change are emissions from electricity and heat production (IPCC 2021, p.12).

The consequences of climate change are severe and wide-ranging, affecting ecosystems, weather patterns and human livelihoods. Rising temperatures contribute to more frequent and intense heatwaves, droughts and storms, while sea levels continue to rise, threatening coastal communities. Biodiversity loss is accelerating, with species struggling to adapt to shifting climates and habitats. These impacts disproportionately affect vulnerable populations, particularly in low-income and developing regions, exacerbating existing inequalities and global instability (see Chapter 8, *Poverty, Livelihoods and Sustainable Development* (IPCC 2021)). While some impacts of anthropogenic climate change are already visible, others may take some time to fully manifest themselves and could become irreversible if the rate and extent of climate change are not limited before critical thresholds are exceeded (IPCC 2001). Exceeding these thresholds, or tipping points, poses significant risks (IPCC 2021; Lenton et al. 2023). Several important Earth systems, such as the Greenland and West Antarctic ice sheets, coral reefs and permafrost, are at risk if these thresholds are crossed, potentially initiating a domino effect of accelerated damage (Levermann 2023; Lenton et al. 2023). The likelihood of triggering critical tipping points increases with a 3°C global temperature rise, with dire consequences such as continuous sea-level rise and ecosystem collapse (Schleussner et al. 2016).

Transgressing tipping points in climate systems also exacerbates global economic risks, with external costs arising from phenomena such as thawing permafrost and the dissociation of ocean methane hydrates. These externalities, captured by the social cost of carbon[1] (SCC), reflect the economic damages caused by each additional ton of CO_2 emissions, including health impacts, property damage and agricultural losses (Dietz et al. 2021). Dietz et al. (2021) suggest that crossing climate tipping points could increase the SCC by at least 25 % in conservative estimates and that there is a 10 % probability that transgressing these tipping points could more than double the SCC, significantly amplifying global economic risks. A spatial assessment reveals widespread

[1]The term social cost of carbon represents the estimated present value of the economic damage of carbon dioxide emissions or GHG equivalent emissions (Nordhaus 2017).

economic losses, with nearly all regions impacted (Dietz et al. 2021). Further economic research underscores the profound long-term impacts of climate change. A study by Willner et al. (2021) highlighted that expected temperature changes over the next 80 years could reduce economic growth in ways comparable to the effects of the past three decades, resulting in a 20 % income decline compared to a scenario where the economy is unaffected by climate change. This decline is driven by 40 % lower growth and a 50 % reduction in investment incentives, primarily due to concerns over diminished returns rather than explicit climate action. Additionally, a conservative estimate suggests that the global economy may face a 19 % reduction in income over the next 26 years, regardless of emissions pathways (Kotz et al. 2024). Within this short-term timeframe, these damages already surpass the costs of limiting global warming to 2°C by a factor of six and vary significantly afterwards based on emission decisions (Kotz et al. 2024).

Fossil fuel consumption imposes significant externalities not only through the climate impacts of GHG emissions, but also through the effects of air pollution. For example, emissions of nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulate matter (PM) from fossil fuel consumption contribute to approximately 5 to 6 million deaths annually worldwide (IEA 2016; Lelieveld et al. 2020). These externalities, whether climate impacts, health crises or economic burdens, are typically borne by society and are hardly ever reflected in market prices, leading to inefficient outcomes and substantial hidden economic impacts. The cumulative hidden costs of energy are staggering; Sovacool et al. (2021b, p. 16) estimates the global hidden costs of energy and mobility to be US$ 24.662 trillion, or 28.7 % of global GDP.

Given the knowledge about climate change and its consequences, as summarised in Figure 1.1, scientists and policy makers have aimed to develop policy and regulatory frameworks to combat climate change. The first major international policy discussion took place in 1979, primarily among scientists, at the first World Climate Conference. This led to the establishment of the World Climate Programme. The Earth Summit in Rio de Janeiro in 1992 saw discussions at governmental level and resulted in the signing of the United Nations Framework Convention on Climate Change (UNFCCC). The first international treaty to reduce global warming came into force in 1994 followed by the Kyoto Protocol in 1995 and the Paris Agreement in 2015. The aim of these treaties was and is to limit global warming to 2 °C, but preferably 1.5 °C above pre-industrial levels[2]. The EU Green Deal in 2019 and the Glasgow Climate Pact in 2021 stress the urgency to protect the climate. Before the Kyoto Protocol came into force, the EU's Emission Trading System was launched as the first and largest emission trading scheme

[2]Since 1850, the Earth's temperature has risen by an average of 0.06 °C per decade, totalling approximately 1.1 °C in 2023. However, since 1982, the rate has increased to 0.20 °C per decade. 2023 was the warmest year on record, 1.18 °C above the 20th-century average and 1.35 °C above the pre-industrial average (NOAA 2024).

and a pillar of EU climate policy (European Parliament 2024). The Conference of the Parties (COP) meeting in Baku in 2024 further highlighted the critical role of climate finance in enabling developing countries to transition to a low-carbon future (United Nations Framework Convention on Climate Change (UNFCCC) 2025).

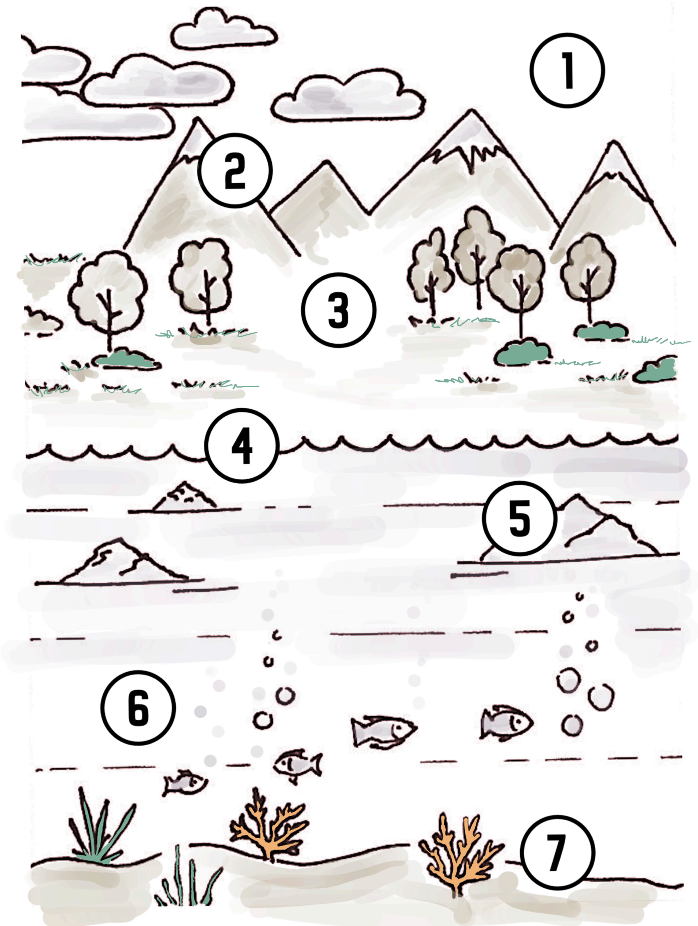


Figure 1.1: Empirical evidence of the impacts of global warming. (1) CO_2 levels unmatched for at least 2 million years, (2) Glacial retreat unmatched for over 2,000 years, (3) Last decade warmer than any period in at least 125,000 years, (4) Sea level rise faster than in any century over the past 3,000 years, (5) Arctic summer sea ice coverage smallest in the last 1,000 years, (6) Ocean warming faster than at any time since the last ice age and (7) Ocean acidification at highest levels in at least 26,000 years. Data according to IPCC (2021). Illustration inspired by Boehm and Schumer (2023).

1.2 Research Questions

Figure 1.2: Preliminary conceptual sketch framing the initial research perspectives of this thesis. This illustration was developed during the early phase of the research to situate the global energy system in relation to societal systems and environmental limits. It outlines the basic structure of energy demand and supply, along with the importance of storage and grid infrastructure. The ocean illustrates a curated set of keywords that emerged from the presented publications.

After reviewing the historical progression of research on climate change, its consequences, and the economic rationale of overarching climate policies, it is evident that limiting global warming to 1.5 °C requires swift and comprehensive mitigation measures across all GHG-emitting sectors. A key strategy for addressing climate change is the substantial reduction of GHG emissions through sustainable energy transitions, including inter alia the widespread deployment of renewable energy technologies, enhancements in energy efficiency and sufficiency measures. Achieving this requires identifying techno-economically viable solutions to environmental (and social) challenges. A methodological approach commonly adopted in industrialised countries to address these issues is Energy System Modelling and Analysis, which relies on the development and application of energy models. These models mathematically represent individual processes, sectors or entire energy systems at varying temporal and spatial resolutions, facilitating the analysis of GHG reduction potentials under different scenarios. To ensure transparency and equity in results, scenario modelling should adopt a co-creative and open-source approach to allow for the engagement of diverse stakeholders, thereby enhancing the accessibility and robustness of climate mitigation strategies. This thesis applies energy system modelling and energy system analysis (ESA) in various case studies to explore the multifaceted role and significance of sustainable energy transitions within an interdisciplinary approach, addressing all three pillars of sustainability — economy, environment and society. The case studies collectively highlight the interplay of technological, economic, environmental, and social dimensions in advancing sustainable energy transitions. There is a particular focus on addressing sector-specific challenges and opportunities in countries such as Jordan, Barbados, and in the Northern European shipping sector.

Within the context outlined above and by considering different sectors and the entire value chain of green hydrogen — an exemplary energy product that plays a crucial role in decarbonising hard-to-abate sectors such as industry and transportation — this thesis aims to answer the following overarching research question, as well as the subordinate questions (related publications and thesis chapters are provided in parentheses):

How can co-creative approaches, technological innovations and policy frameworks be integrated to develop cost-effective, sustainable and widely accepted solutions for a 100 % renewable energy system, while ensuring sectoral compliance with global climate targets?

- Does co-creative scenario modelling increase acceptance of energy system solutions? Chapter 3 (Komendantova et al. 2020)
- What is the cost-optimal energy mix, based on the current energy system, to meet the future electricity demand in Jordan? Chapter 4 (Hilpert et al. 2020a)
- What are suitable combinations of storage technologies and what is the role of pumped hydro storage (PHS) in a 100 % renewable energy (RE) system in Barbados? Chapter 5 (Harewood et al. 2022)
- What is the benefit of an open source–based emission inventory for maritime emissions? Chapter 6, (Dettner and Hilpert 2023a)
- What is the level of compliance of the Northern European shipping sector within the Paris Agreement's 1.5 °C goal? Chapter 7 (Dettner and Hilpert 2023b)
- Which sustainable criteria have to be considered for the production of green hydrogen? Chapter 8 (Blohm and Dettner 2023)

1.3 Structure of Thesis

This cumulative thesis is divided into three main parts. Part I provides the context and rationale for climate change research and explores the development of climate policies. It establishes the necessary theoretical foundation of sustainability and energy systems, with a focus on transformations, analysis, and modelling. Building on this foundation, the thesis transitions to a sector-specific application by examining maritime energy systems. This includes discussions on infrastructure, emission modelling and maritime policies. Lastly, it emphasises the significance and context of open data and open-source modelling approaches in addressing these challenges.

Part II contains six peer-reviewed publications in Chapters 3 to 8, as listed in Table 1.1. These publications address the research questions listed in Section 1.2. Chapter 3 used co-creative approaches to resolve opposing views and assess stakeholder preferences in the analysis of different scenarios for the Jordanian energy system using an open spreadsheet model and multi-criteria decision analysis. The publications in Chapters 4 and 5 applied the Open Energy Modelling Framework (oemof) to analyse cost-optimal and 100 % renewable energy systems and storage for electricity generation in Jordan and Barbados. Chapter 5 integrates the use of renewable electricity for shore-to-ship power supply of cruise ships and vehicles within an energy system model. Chapters 6 and 7 focus on energy demand and emissions of ships, establishing an open source emission inventory for Northern European shipping and determining the CO_2 emission mitigation potential. Touching upon the necessity to use alternative, carbon-neutral fuels for hard-to-abate sectors, such as shipping, Chapter 8 takes a broad view on the promising future carbon-neutral energy carrier green hydrogen within the overarching sustainability context, focusing on environmental and social criteria.

Part III summarises the methods and results of the individual publications on sustainable energy transitions and maritime energy system transitions, before addressing the overarching research question and highlighting both limitations and opportunities for further research.

Overview of Chapters and Personal Contribution

Cumulative dissertations offer a flexible approach, allowing researchers to publish their findings incrementally, gain recognition and receive feedback from the scientific community. However, it is crucial to clearly state the contribution of the author for each publication within the cumulative thesis. Given that all presented publications have (multiple) co-authors, detailing my specific role and input ensures transparency and clarity. Table 1.1 summarises my contributions as outlined in the CRediT authorship statements within the publications in Part II, while Table 1.2 provides an overview of the research questions, applied research approaches and scientific contributions of the respective papers.

Table 1.1: Overview of peer-reviewed publications and personal contribution.

Chapter	Publication and own contribution
3	**Water-Energy Nexus: Addressing Stakeholder Preferences in Jordan** Published as: Nadejda Komendantova, Leena Marashdeh, Love Ekenberg, Mats Danielson, Franziska Dettner, Simon Hilpert, Clemens Wingenbach, Kholoud Hassouneh and Ahmed Al-Salaymeh. 2020. „Water-Energy Nexus: Addressing Stakeholder Preferences in Jordan“. *Sustainability* 12(15), 6168, (July). `https://doi.org/10.3390/su12156168`.
	All authors led, organised and moderated the workshops as part of a GIZ project in Jordan from which this publication emerged. All authors thus contributed equally to this publication.
4	**Analysis of Cost-Optimal Renewable Energy Expansion for the Near-Term Jordanian Electricity System** Published as: Simon Hilpert, Franziska Dettner and Ahmed Al-Salaymeh. 2020. „Analysis of Cost-Optimal Renewable Energy Expansion for the Near-Term Jordanian Electricity System“. *Sustainability* 12(22), 9339, (November). `https://doi.org/10.3390/su12229339`.
	All authors contributed to validation, data curation and writing the original draft. Joint work with Simon Hilpert included investigation, writing the review and editing, as well as funding acquisition and formal analysis. Simon Hilpert worked on methodology, software development and visualisation.
5	**Open source modelling of scenarios for a 100 % renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles** Published as: André Harewood, Franziska Dettner, Simon Hilpert. 2022. "Open source modelling of scenarios for a 100 % renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles" *Energy for Sustainable Development* 68, 120-130 (June). `https://doi.org/10.1016/j.esd.2022.03.004`
	All authors contributed jointly to the conceptualisation, investigation and writing of the original draft. Collaborative work with André Harewood included resources, data curation, validation and formal analysis. Joint work with Simon Hilpert focused on methodology. Independent work was carried out on review and editing.
6	**Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea** Published as: Franziska Dettner and Simon Hilpert. 2023. "Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea" *Data* 8(5), 85 (May). `https://doi.org/10.3390/data8050085`
	Joint work with Simon Hilpert involved conceptualisation, methodology and formal analysis. Independent contributions included investigation, project administration and supervision, project acquisition and funding, as well as writing the original draft and reviewing and editing. Simon Hilpert contributed to software development, data curation, and visualisation.

Chapter	Publication and own contribution
7	**Modelling CO_2 emissions and mitigation potential of Northern European shipping** Published as: Franziska Dettner and Simon Hilpert. 2023. "Modelling CO_2 emissions and mitigation potential of Northern European shipping" *Data* 119, 103745 (June). https://doi.org/10.1016/j.trd.2023.103745
	Independent contributions include conceptualisation, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, writing of the original draft as well as review and editing. Simon Hilpert contributed to software development, validation, and visualisation.
8	**Green hydrogen production: Integrating environmental and social criteria to ensure sustainability** Published as: Marina Blohm, Franziska Dettner. 2023. "Green hydrogen production: Integrating environmental and social criteria to ensure sustainability" *Smart Energy* 11, 100112 (August). https://doi.org/10.1016/j.segy.2023.100112
	Joint work with Marina Blohm on conceptualisation and writing the original draft, reviewing and editing. Interviews conducted independently by Marina Blohm.

Table 1.2: Overview of research questions, focus, methodologies and scientific contributions.

Chapter	Core	Research Question	Research Focus	Research Approach	Scientific Contribution
3	*Water-Energy Nexus*	**Does co-creative scenario modelling increase acceptance of energy system solutions?**	Interdisciplinary analysis, capacity building, inter-sectoral energy systems (water and energy)	Energy system modelling, multi-criteria decision analysis, case study, workshops, open source and open development	Stakeholder engagement in sustainable energy planning
4	*Renewable Energy Expansion*	**What is the cost-optimal energy mix, based on the current energy system, to meet the future electricity demand in Jordan?**	Cost-optimal & 100 % RE systems, policy implications for renewable integration, storage	oemof, energy system modelling, scenario analysis, case study	Insights into economic feasibility and policy recommendations for the Jordanian energy system
5	*100 % RE System*	**What are suitable combinations of storage technologies and what is the role of PHS in a 100 % RE system in Barbados?**	Cost-optimal & 100 % RE systems, integration of shore-to-ship power, electric vehicles, economic diversification, energy security, storage	oemof, energy system modelling, scenario analysis, case study	Framework for 100 % sustainable energy transition on small island developing states (Barbados)
6	*Maritime Emissions Inventory*	**What is the benefit of an open source based emission inventory for maritime emissions?**	Data-driven approach to maritime emissions tracking	Emission modelling, data curation, statistical analysis, open emission inventory	Comprehensive & open dataset on North and Baltic Sea shipping emissions
7	*Maritime CO_2 Mitigation*	**What is the level of compliance of the Northern European shipping sector within the Paris Agreement's 1.5°C goal?**	Climate impact of shipping, emission reduction strategies, alternative fuels	Emission inventory, impact assessment, carbon budget, emission trading	Data-based evaluation of mitigation pathways for maritime transport
8	*Sustainable Green Hydrogen*	**Which sustainability criteria have to be considered for the production of green hydrogen?**	Integration of environmental and social sustainability in hydrogen production	Multi-criteria analysis, sustainability assessment, literature review, expert interviews	Framework for evaluating all sustainability dimensions of green hydrogen projects (with potential for application for other energy projects)

2

Theoretical Foundations

This chapter establishes the theoretical basis for the publications in Part II. It begins with a discussion of the concepts of transformation, transition and sustainability. It then explores energy systems, as well as the fields of energy system analysis, (open) energy system modelling and climate change policies. The chapter proceeds with an exploration of maritime energy systems, emissions modelling in maritime transport, and maritime policy. It then shifts its focus to open science, before concluding with a discussion on the scope of the publications.

2.1 Transformation or Transition?

The terms energy transition and energy transformation have emerged in political and scientific discussions, indicating the necessity for systemic change to establish a sustainable society in light of global issues such as climate change, resource depletion and increasing social inequality (Lu and Nemet 2020). The emphasis on *transformation* and *transition* reflects a mounting consensus that maintaining the status quo will not ensure that humanity remains within a safe operating space (Rockström et al. 2009). Both terms, according to Hölscher et al. (2018) express "the ambition to shift from analysing and understanding problems towards identifying pathways and solutions for desirable environmental and societal change" (p. 1) and refer to changes in complex adaptive systems. According to the IPCC (2023) a transition is "the process of changing from one state or condition to another in a given period of time" (p.129) and is mainly used to describe changes when focusing on complex adaptive systems in societal sub-systems, such as energy and transportation. Transformation, however, is commonly used to describe large-scale and fundamental changes in whole societies (Hölscher et al. 2018). Transitions and transformations are both complex and uncertain, but they follow specific patterns and mechanisms, such as path dependency, emergence and thresholds (Feola 2015).

Despite the identification of the two distinct terms transition and transformation, it can be assumed that they signify the same fundamental concept. However, Child and Breyer (2017) argue that alterations to physical forms and systems should be categorised as *transformations* while changes to extensive socio-technical systems should be categorised as *transitions*. The term transition is therefore used in this thesis.

2.2 Sustainability

> *Man soll keine alte Kleider wegwerffen / bis man neue hat / also soll man den Vorrath an ausgewachsenen Holtz nicht eher abtreiben / bis man siehet / daß dagegen gnugsamer Wiederwachs vorhanden.*
>
> – Hans Carl von Carlowitz (Carlowitz 1732, p.88)

There is significant scientific understanding that the challenges of climate change cannot be solved by technological advances, policies or individual countries alone (Leemans and Solecki 2013). The former IPCC Chair, Pachauri (2008) argues that global growth and development have progressed in a manner that is inherently unsustainable and climate change is only part of the problem. Furthermore, he emphasises the necessity to consider the connection between climate science and sustainability science. He also notes that climate change offers an opportunity to apply sustainability science in practice, thus serving as a bridge between these interconnected scientific fields.

> *"A communications gap has kept environmental, population, and development assistance groups apart for too long, preventing us from being aware of our common interest and realizing our combined power. Fortunately, the gap is closing. We now know that what unites us is vastly more important than what divides us. We recognize that poverty, environmental degradation, and population growth are inextricably related and that none of these fundamental problems can be successfully addressed in isolation. We will succeed or fail together. Arriving at a commonly accepted definition of 'sustainable development' remains a challenge for all the actors in the development process."* (Brundtland 1987, p. 38–39)

The Brundtland Report emphasises the challenge of an all-encompassing definition of sustainable development. However, the report is also considered to be the originator of the first definition of sustainable development; *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."* (Brundtland 1987, p. 16).

The concept of sustainability first appeared in modern scientific literature in the book *The Limits to Growth* (Meadows et al. 1972), which analysed economic development and qualitative-oriented economic growth with regard to population growth, industrialisation, malnutrition, exploitation of raw materials and the destruction of the living environment. This is reflected in Howarth's definition that sustainability is "the ability to be maintained at a certain rate or level" (Howarth 1997, p. 569). Since around 1990, the concept of sustainability has become established in various academic fields, such as ecology, climate science, engineering, urban planning, sociology, law, health and anthropology (Uiterkamp and Vlek 2007) and has developed within these different fields (Purvis et al. 2019). It is now widely agreed that sustainability encompasses a balance between environmental protection, social equity and economic needs and growth, ensuring that current actions do not compromise the future generation's ability to meet their needs.

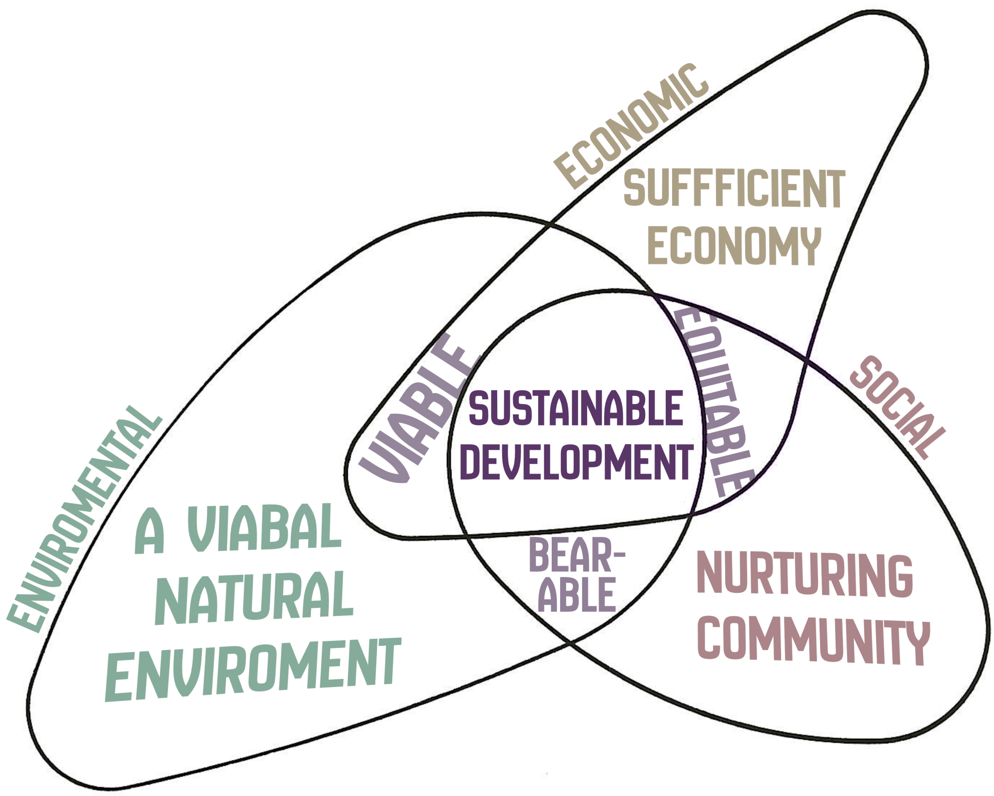


Figure 2.1: The Three Pillars of Sustainability.
Reinterpretation of the three pillars of sustainability based on Barbier (1987). Unlike the conventional depiction using three equal, overlapping circles, this version employs varied shapes and sizes, without implying relative importance, to reflect the heterogeneity and complexity within each pillar.

Three pillars[1] of sustainability, which were first postulated by Barbier (1987), namely *environment*, *society* and *economy*, are used in the sustainability debate. Agenda 21 (United Nations 1993) and Agenda 30 (United Nations 2015), the latter of which contains the United Nation's 17 sustainable development goals (SDGs), both acknowledge the three pillars of sustainability as a guiding principle of the concept.

The Venn diagram in Figure 2.1 illustrates the interconnected nature of the different constituent elements of the pillars. There is no clear hierarchy between the three pillars; however, the environmental dimension is usually thought to be the most important, as economy and society are constrained by environmental limits (Rockström et al. 2009).

Environmental Sustainability

People became aware of the environmental impacts of fossil fuels during the Great Smog of London in 1952 (Wilkins 1954). As a result, the environmental or ecological pillar of sustainability was the first to gain widespread attention. According to Goodland (1995), environmental sustainability is defined as the "maintenance of natural capital" (p.10). However, Morelli (2011) defines environmental sustainability as maintaining a balance that allows human needs to be met without exceeding ecosystems' regenerative capacity or compromising biodiversity. Environmental sustainability focuses on human interactions with natural systems, distinguishing it from the broader ecological perspective of interdependence. In the context of energy systems, it addresses two environmental services: the source function, which involves the utilisation of renewable and non-renewable resources, and the sink function, which pertains to pollution and waste assimilation. The impacts of environmental degradation and pollution, particularly the sink function, manifest both locally and globally, encompassing a range of issues beyond the greenhouse gas effect (Leemans and Solecki 2013). Air pollution is a local issue that has garnered increasing awareness due to its direct effects on public health and ecosystems (Friedrich and Voss 1993). To address these challenges, environmental sustainability is guided by core principles such as supporting societal needs, preserving biodiversity, aligning resource use with regenerative limits, promoting reuse and recycling, and ensuring that activities remain within planetary boundaries (Morelli 2011).

Economic Sustainability

Economic sustainability is a controversial topic and the most challenging pillar of sustainability to fully comprehend (Doane and MacGillivray 2001; Daly 1973). Political economists in the 1950s questioned the limits of economic and demographic growth and

[1]In the literature, the terms circles, dimensions, components or perspectives are also used instead of the term pillars.

addressed the inherent trade-offs between wealth generation and social justice (Purvis et al. 2019). At this time, economic development was predominantly guided by the notion of growth as a primary indicator of progress (Arndt 1981). Questions emerged in the publication of the *Limits to Growth* (Meadows et al. 1972) and other "no-growth" studies, marking the onset of a new paradigm of growth that is both robust and socially and environmentally sustainable (Brundtland 1987). In the realm of economics, sustainability and sustainable development are often delineated as the imperative to maintaining an enduring income for all from non-declining capital stocks (Spangenberg 2005). Consequently, within this perspective, the constancy of human-made, natural and social capital stocks (Pearce et al. 1992) is widely perceived as essential and frequently deemed sufficient to meet the economic criteria of sustainability and sustainable development (Pearce and Barbier 2000). However, expanding economic capital must not occur at the detriment of environmental or social capital. Therefore, economic sustainability entails not only the allocation of resources across time but also the guarantee of inter-generational equity (Jeronen 2023).

Social Sustainability

The social pillar of sustainability has remained rather undefined (Vallance et al. 2011; Eizenberg and Jabareen 2017) and is challenging to analyse. According to Åhman (2013), this has resulted in a "challenging conceptual confusion" (p. 1163). Whereas Eizenberg and Jabareen (2017) provide a framework for social sustainability which focuses on equity, safety, eco-prosumption and urban forms, Ly and Cope (2023) argue for adaptability, social inclusion, quality of life, security and equity. According to Murphy (2012) social sustainability focuses on the well-being of individuals and communities, ensuring equitable access to resources, opportunities and basic human rights. It promotes inclusive societies that foster social cohesion, participation and an awareness for justice and equity (Murphy 2012). This difference might be due to the unclear and elusive definition and delimitation and that social sustainability has so far been neglected in political decision-making processes (Boström 2012), despite there being a rising recognition of its relevance (Boyer et al. 2016).

2.3 Energy Systems

Energy systems are intrinsically linked to climate change as they serve as both a major driver of GHG emissions and a critical focus for mitigation and adaptation strategies.

Energy is essential to our daily lives, playing a critical role in economic growth and productivity (Owusu and Asumadu-Sarkodie 2016). As Lloyd (2017, p. 54) notes, energy is intricately connected to nearly every aspect of human development, forming an indispensable component of any energy system by driving the entire process. Energy can be derived from various sources, which are broadly categorised as renewable or non-renewable. Renewable energy sources include solar energy, wind energy, hydro power, geothermal energy, biomass and other more rarely used sources such as ocean energy (tidal or wave energy). Non-renewable energy sources include fossil fuels such as coal, oil and natural gas, which are formed from the remains of ancient plants and animals. Fossil fuels are burned to release energy in the form of heat, which can be used to generate electricity or power engines. Nuclear energy is another form of non-renewable energy, derived from fission of heavy atomic nuclei in nuclear reactors or deuterium-tritium fusion reaction, involving the merging of light atomic nuclei.

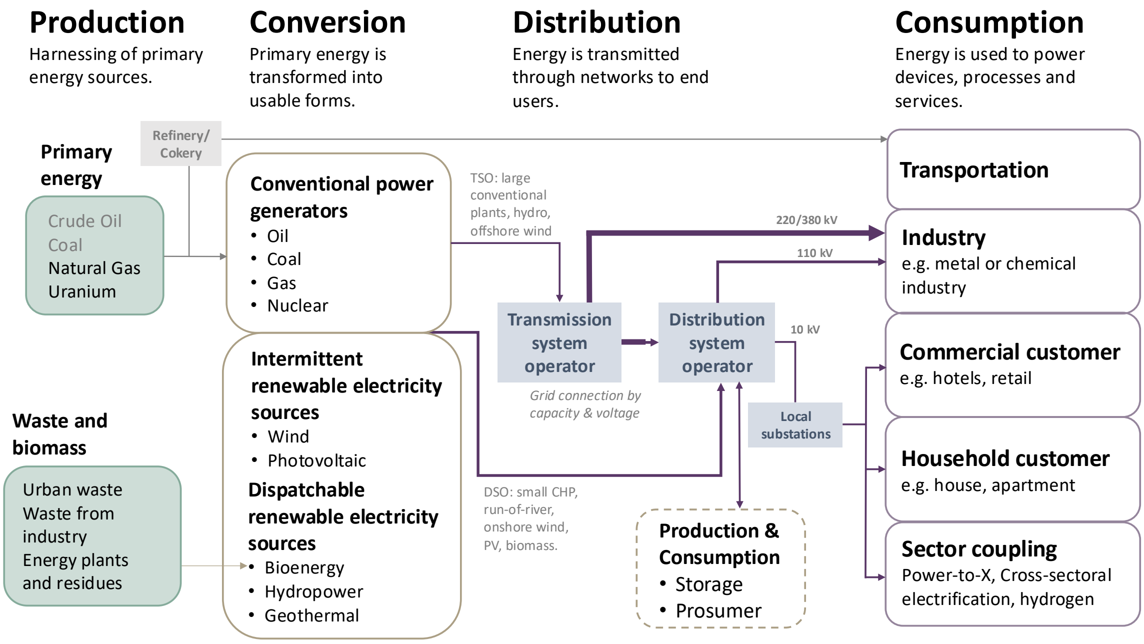


Figure 2.2: The electricity value Chain: from production to consumption. Electricity is generated in power plants, traded via markets, transmitted through grids and finally sold to end users. While this process may appear linear, it is embedded in a multi-layered system involving technical infrastructure, financial transactions, legal frameworks and political influence. This graphic provides a simplified overview and does not claim to reflect the full complexity of the energy economy. Illustration inspired by Graebig et al. (2023).

An energy system primarily serves to deliver energy services to end-users (Groscurth et al. 1995) and consists of essentially four components: production, conversion, distribution and consumption (Bruckner et al. 2014), as depicted in Figure 2.2. Energy systems provide an integrated set of technical as well as economic activities, which operate within a complex societal framework (Hoffman and Wood 1976).

The first component within an energy system, energy *production* often refers to the initial phase of acquiring energy resources and is essentially the extraction and harnessing of energy carriers, such as fossil fuels or renewables. However, it should be noted that energy can neither be created nor destroyed. This fundamental principle of nature is known as the first law of thermodynamics. In formal terms, it states that the total amount of energy in a closed system remains constant. However, energy can be converted from one form to another.

The second fundamental component of an energy system is conversion, which encompasses the transformation of energy from one form into another. For example, the combustion of coal converts chemical energy into thermal energy. This thermal energy, in the form of high-pressure steam, is subsequently transformed into mechanical energy through turbine rotation, which then drives a generator to produce electrical energy. In a lamp, this electrical energy is further transformed into radiant energy, producing light. However, energy conversions are typically accompanied by transformation losses, predominantly in the form of heat (Graebig et al. 2023).

The third component is energy *distribution*, which encompasses the transmission of electrical power from generation facilities to end-users. This is carried out by means of an electrical energy grid, crucial infrastructure within energy systems that ensures a consistent and reliable supply of electricity by equilibrating supply and demand and regulating the flow of electricity. In the context of the electrical energy grid, energy storage technologies such as batteries, thermal storage systems and pumped hydro storage play a vital role in addressing the intermittency associated with renewable energy sources. These storage solutions capture surplus energy during peak production periods and release it during high demand or reduced generation, thereby maintaining stability and reliability in energy supply.

The fourth component of an energy system is energy *consumption*, which pertains to the utilisation of energy across various sectors, including residential, commercial, industrial and transportation. In residential settings, energy is employed for heating, cooling, lighting and for operating appliances. Industrial energy use involves processes related to manufacturing, machinery operation and heating. The transportation sector relies on energy predominantly in the forms of fossil fuels and electricity to operate vehicles, aircraft and ships. Sector coupling, as shown in Figure 2.2, is also a relevant part of the energy system as a systemic approach that connects the electricity sector with end-use sectors such as heating, transport and industry through integrated conversion, storage and consumption paths.

The final component(s) of an energy system, which are not part of the sequence described above but are important for all components, are policies, regulations and management practices and data flows that govern the operation of the energy system along the entire value chain.

2.3.1 Energy System Transition

It is widely accepted that alterations to global energy systems are required to deal with global warming and the effects of air pollution. The primary strategy for mitigating climate change is the significant reduction of GHG emissions through the widespread adoption of renewable energy technologies and increased energy efficiency. The transition to renewable energy sources has seen the world's renewable capacity increase by 50 % between 2022 and 2023 (IEA 2024). Nevertheless, there may be discrepancies when it comes to the exact combination of technologies and policy measures used within energy systems to improve sustainability and tackle climate change (Child and Breyer 2017). In discussions concerning sustainable energy system transitions, three distinct guiding strategies exist: efficiency, consistency and sufficiency (Bundestag 1998). In essence, efficiency advocates for minimising resource usage per service output, consistency emphasises the adoption of eco-friendly technologies and structures, and sufficiency focuses on curbing excessive consumption. However, the definitions and interpretations of these strategies frequently diverge, sparking varied viewpoints and occasionally contentious debates (Behrendt et al. 2018). Energy transitions are therefore always set between political, social and economic reasoning (Sovacool et al. 2021a).

The field of energy transition research is rapidly expanding and diversifying in terms of topics and publications (Köhler et al. 2019). The number of publications increased by a factor of 50 between 2008 and 2020, with 67 % of them dealing with policy issues (Lu and Nemet 2020). The earlier focus on electricity and transportation has widened to include societal domains such as food, water, heat and buildings. There has also been a geographical expansion beyond Northern European countries (Köhler et al. 2019), although as of 2019 still only about 25 % of articles discussed energy transitions in developing countries (no more recent figures available).

2.3.2 Energy System Analysis

Energy system analysis is a multidisciplinary approach designed to address complex energy planning challenges by integrating various aspects such as fuel substitution, energy-economy interactions and competition for investment between energy and other sectors. ESA characterises energy supply and demand flows within a society using the systems approach by examining the interactions between system components rather than isolating individual components (Nakata et al. 2011). Based on Bertalanffy's

General Systems Theory, energy systems analysis takes a holistic view of problems and emphasises the relationships and interdependencies within a system in order to understand its overall behaviour (Bertalanffy 1969).

According to Brown and Sovacool (2007), ESA was originally used to maximise efficiency in countries where the consumption threshold had been passed. The consumption threshold within energy systems refers to the point at which energy consumption reaches a level that exceeds either the available energy supply, technological capabilities or environmental constraints (Brown and Sovacool 2007). This threshold is crucial for understanding when an energy system becomes inefficient, resources are exhausted or infrastructure is overloaded. According to Brown and Sovacool (2007), studies have shown that advanced societies differ significantly in their per capita energy consumption. Surveys suggest that while a threshold of high energy consumption is necessary for industrialisation, once this threshold is exceeded there is considerable flexibility in terms of energy requirements to maintain living standards.

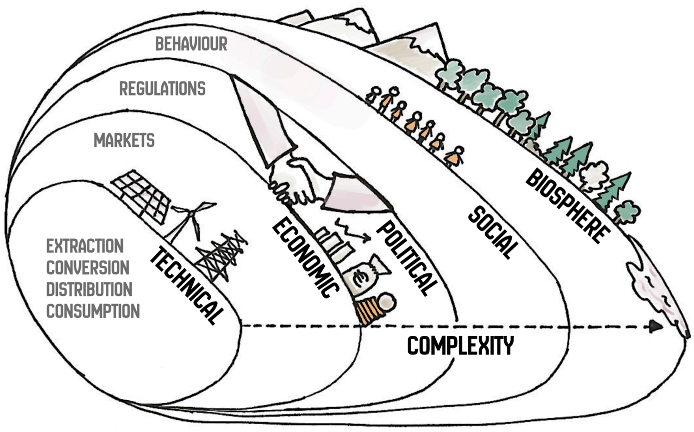


Figure 2.3: Multidimensional construct of the energy system. Concept based on Jaccard (2006), illustration inspired by Hilpert (2022a).

During the energy crisis in the 1970s, more refined ESA evolved, challenging the assumption that energy consumption and economic well-being are in a constant relationship with each other (Brown and Sovacool 2007). The kind of analysis used today is predominantly concerned with producing forecasts of the future by characterising future scenarios that utilise alternative energy sources (Brown and Sovacool 2007). ESA can determine, for example, which storage system is best suited for an energy system, which subsidies are required for renewable energies, the cost-optimal energy mix, and which consequences occur in energy system designs if external costs of energy are taken into account. The necessary information can be acquired from interdisciplinary analysis, drawing upon various scientific disciplines such as modelling, physics, engineering, law or sociology (Groscurth et al. 1995). In general terms, ESA can be defined as the interdisciplinary field that integrates engineering, economics, environmental science and policy analysis to analyse, model and optimise the structure, operation and performance of energy systems, with the aim of supporting informed decision-making towards sustainable energy transitions. Figure 2.3 illustrates the socio-political-techno-economic energy system as it operates within and depends upon the biosphere. It emphasises the interconnectedness of all three pillars of sustainability within the context energy systems.

There is complexity in accounting for cross-sectoral interactions, technological advancements, economic impacts and policy influences, as well as the difficulty in capturing long-term energy transition dynamics and global energy market fluctuations. Recent approaches of ESA have aimed to incorporate sufficiency measures, as there is a growing scientific consensus that techno-economic sustainability measures have to be complemented by sufficiency measures to reach the goal set within the Paris Agreement (Spangenberg and Lorek 2019).

2.3.3 Energy System Modelling

Addressing the global climate crisis is an imperative task that cannot be deferred until an indisputable scientific solution is identified, particularly considering the possibility that such a solution may remain elusive. In this context, utilising energy models within ESA can facilitate informed decision-making by enhancing the comprehension of energy systems. Energy models are used to calculate the future energy requirements and demand of a country or region. The models are generally used with certain assumptions about specific boundary conditions, such as the availability of (renewable) energy sources, the development of economic activities, demographic trends or energy prices on the global markets (Herbst et al. 2012). Careful interpretation of the output of models is necessary, as often, controversial issues in energy science and energy policy about the prospects, feasibility and impact of future energy supply and demand can be traced back to the different types of energy models used (Herbst et al. 2012).

In the context of energy system modelling, *scenarios*, *models* and *model generators* are essential. *Scenarios* are narratives that describe plausible future energy systems, combining quantitative data with qualitative narratives (Spaniol and Rowland 2019; Dieckhoff 2015). Scenarios are not predictions but an exploration of a range of possible outcomes based on current knowledge and assumptions (Dieckhoff and Grunwald 2016). Scenarios use *models* to quantify potential future developments (Strachan et al. 2009). While all scenarios involve models, not all models are used for scenarios (Aigner-Walder and Döring 2022). Models are a simplified representation of real-world systems used to simulate various futures. They consist of inputs (variables), outputs (results) and mathematical equations that link the two. Models in ESA can be empirical (based on data) or structural (based on theoretical relationships). These models can be generated using tools such as *generators* or *modelling frameworks*. Frameworks vary depending on their analytical approach, methodology and mathematical foundation. They can be top-down (macro-economic, aggregated) or bottom-up (technology-specific, detailed). Models can be differentiated between equilibrium models, optimisation models or simulation models (Hedenus et al. 2013; Herbst et al. 2012; Connolly et al. 2010), input-output models (Ansell and Cayzer 2018; Liu et al. 2019; Zhang et al. 2019) or economic models (Dagoumas and Barker 2010; Pretis 2020). Models can be predictive for short-term planning or exploratory (focusing on various geographical scopes and time horizons) for long-term policy analysis.

2.3.4 Climate Change Policies

Decision-makers require evidence-based approaches to anticipate future scenarios, with models serving as a foundation for informed policymaking to drive long-term sustainability. Policies for energy systems that support climate change mitigation incorporate emission reduction targets, including those in the Paris Agreement and net-zero carbon laws, alongside carbon pricing mechanisms such as carbon taxes, carbon budgets and cap-and-trade systems. This section focuses on carbon budgets, a representative market-based policy mechanism, as explored in Chapter 7. The remaining carbon budget sets the maximum GHG emissions permissible to avoid that global warming exceeds a specified limit, typically 1.5°C or 2°C above pre-industrial levels. The remaining budget in 2020 to remain within the 1.5°C limit was between 400 and 500 gigatonnes (Gt) of CO_2, according to the IPCC (2023). The current, as of January 2025, remaining budget according to the Mercator Research Institute on Global Commons and Climate Change (MCC) (2023) is 191.45 Gt, leaving about 4.5 years, until the CO_2 budget is depleted.

Carbon budgets are based on historical emissions, current annual emissions and projected future emissions, and form the basis for emissions caps in cap-and-trade systems. Within these systems, governments set a cap on total GHG, aligned with the carbon budget. Emission allowances are allocated to entities, either freely or through auction and are reduced over time to achieve gradual emission cuts. Entities that emit less than their allowance may sell the surplus, while those needing additional capacity can purchase allowances from others, creating a financial incentive to innovate and reduce emissions. At the end of each compliance period, entities must surrender allowances to cover their emissions or face penalties. The cap-and-trade system offers a cost-effective path to emissions reduction, drives innovation and generates revenue. A prominent example is the European Union Emissions Trading System (EU ETS), which operates across sectors and countries within the EU, including all CO_2 emissions from electricity and heat generation, as well as energy intensive industry sectors, aviation and shipping (EC 2024).

2.4 Maritime Energy Systems

Sector-specific climate change mitigation efforts are essential to ensure that Paris Agreement targets are met. Maritime transport is vital for the global economy and is one of the most energy-efficient modes of transport. Ships and port infrastructure and maritime energy systems form a crucial subset of energy systems, reflecting the specialised requirements and innovations of the maritime sector. This section discusses the integration of maritime energy systems within the larger context of energy systems, shipping emissions, policies and the modelling of shipping emissions as a necessary tool for emission reduction analysis.

2.4.1 Infrastructure and Technology

Ships are integrated within land-based energy systems through interconnected infrastructure and technology. From an infrastructure perspective, ports serve as key hubs for connecting ships to the energy grid, as they often provide shore-to-ship power, enabling ships to plug into the local grid when docked rather than relying on their auxiliary engines to generate electricity, which reduces fuel consumption and emissions (Borkowski and Tarnapowicz 2012). To facilitate this, the port's electrical infrastructure must be modified to enable power supply to different types of ships, and the local grid and energy supply must be designed to accommodate the increased load and demand, as examined by Harewood et al. (2022) in Chapter 5.

In terms of technology, both maritime and land-based energy systems primarily rely on fossil fuels for energy generation. Traditionally, oil-based fuels accounted for over 99 % of the total energy consumption in international shipping, while bio fuels met less than 0.5% of the energy demand in 2022 (IEA 2023). Due to a demand for more sustainable practices, maritime and land-based energy systems face similar market dynamics, driven by fluctuating fuel prices, regulatory pressures and technological advancements. Maritime energy systems, similar to land-based energy systems, are increasingly integrating renewable energy. For maritime systems this includes the use of hybrid and fully electric ships. As electric ships are not feasible for all applications, ship owners are increasingly exploring alternative fuels. This is crucial, as after 2040 only renewable fuels will comply with the Fuel EU Maritime according to Christodoulou and Cullinane (2022).

Fuels

The introduction of alternative fuels and advanced technologies is underway, but challenges persist due to the high cost and long lifespan of ships, as well as regulatory uncertainties (IEA 2023). The choice of future maritime fuels depends on several factors, including environmental regulations, cost-effectiveness, availability, safety and technological development. Future maritime fuels can be broadly categorised into two main groups: hydrogen-based carriers, such as E-hydrogen and E-ammonia, and synthetic hydrocarbons, such as E-LNG, E-diesel and E-methanol (Lindstad et al. 2021). Among these, E-ammonia and E-methanol are currently considered to be the most promising alternatives (Lindstad et al. 2021), as both (as well as e-FT Diesel) could enable the 2050 FuelEU Maritime GHG target to be met (Ingwersen et al. 2025).

Lindstad et al. (2021) assessed the potential role of E-fuels in maritime applications. E-methanol was found to offer a well-to-wake CO_{2eq} emission reduction potential of 99 %, followed by E-ammonia with a reduction potential of 94 %. According to Lindstad et al. (2021), considering energy consumption, as of 2021, E-methanol required 6.5 kWh of energy per kWh delivered at the propeller (well-to-wake), with a likely minimum value of 5.9 kWh. This outperformed E-diesel, which had a minimum value of 6.3 kWh/kWh, suggesting that transitioning the global maritime fleet to E-diesel would result in a threefold increase in shipping's energy demand. E-ammonia performs slightly better, requiring 4.2 kWh/kWh, while the most efficient green fuel, battery electricity, only requires 1.5 kWh/kWh (Lindstad et al. 2021).

Renewable E-methanol has also gained considerable attention due to its compatibility with existing infrastructure. However, its environmental and economic performance varies significantly depending on the source of hydrogen and carbon used in its production. Methanol can be derived from electrolysis (e-H_2) and sustainable carbon sources such as direct air capture (DAC) or biomass (BC), which have lower life-cycle GHG emissions. However, options such as DAC-E-methanol (DAC-EM), while promising from a climate perspective, face major cost barriers, particularly due to the high energy and capital requirements of DAC technology, which can account for over 50% of the total fuel cost (Li et al. 2024). However, DAC-EM is less sensitive to fluctuations in carbon pricing due to its inherently low greenhouse gas emissions. This could enhance its competitiveness under stricter carbon pricing regimes. DAC-EM remains economically challenging due to the early-stage development of DAC technology.

Generally, the annual operating costs of alternative maritime fuels are highly sensitive to the price of renewable electricity. In a high-cost renewable energy scenario, fuel expenses can account for up to 80 % of the total annual costs per kilowatt for E-methanol (Lindstad et al. 2021). Under these conditions, hydrocarbon E-fuels, such as E-LNG, E-methanol and E-diesel, can triple the total annual cost of operating a medium-sized tanker or bulker compared to one fuelled by marine gas oil. In contrast, the use of E-ammonia and E-hydrogen result in approximately a twofold increase in total annual costs. However, in a low renewable electricity price scenario, the cost gap between hydrocarbon E-fuels and E-ammonia/E-hydrogen narrows significantly, with only a 20 % difference in total annual expenditure (Lindstad et al. 2021).

Considering environmental impacts, Ingwersen et al. (2025) assessed twelve different categories of marine fuels. Their comparative analysis revealed that E-ammonia has the lowest environmental impact in eight of the twelve categories, while E-methanol has the highest toxicity levels. It was found that, eutrophication in marine environments is the highest for E-methanol (even higher than for fossil fuels), whereas acidification and terrestrial eutrophication are the highest for E-ammonia. E-methanol also ranks highest for human toxicity (both carcinogenic and non-carcinogenic) and land use, with all E-fuels exhibiting high land use impacts during their production phase. Additionally, E-ammonia has the highest water usage, driven by fuel production.

In summary, both E-ammonia and E-methanol are viable options for decarbonised marine fuels. They both offer distinct benefits and challenges depending on specific use cases and regional factors. While both require high initial investments, they provide the greatest flexibility in fuel choice over the medium and long term (Lindstad et al. 2021). E-ammonia stands out in the analysis of cost-effectiveness in environmental and economic terms (Ingwersen et al. 2025). However, in the publication in Chapter 7, E-methanol was selected for a case analysis to assess the functionality of the developed model in Chapter 6 and the calculation of its carbon reduction potential. The primary factor influencing this choice was that E-methanol can be blended into existing fuel supply chains and utilised within the current shipping fleet infrastructure, which might make hydrocarbon E-fuels cost-competitive with E-ammonia under low renewable electricity price scenarios (Lindstad et al. 2021). Additionally, E-ammonia is currently (as of 2025) considered the most immature of all technologies (Ingwersen et al. 2025).

2.4.2 Emissions from Ships

According to the European Commission and Directorate-General for Climate Action (2019), global shipping emitted 1,076 million tonnes of CO_2 in 2018, representing about 2.9 % of global human-induced emissions, with projections suggesting a possible increase of up to 130 % of 2008 levels by 2050. This stems from the industry's heavy reliance on fossil fuels as well as the high volume of goods transported by sea, as around 90 % of global trade is via maritime routes (IMO 2020a). At the EU level, maritime transport is responsible for 3 to 4 % of the EU's total CO_2 emissions with over 124 million tonnes of CO_2 emitted from shipping in 2021 (European Commission and Directorate-General for Climate Action, 2019). In 2022, global CO_2 emissions from ships grew by 5 %, continuing the rebound from the temporary decline during the COVID-19 pandemic. According to a study by Transport & Environment (2021), shipping could account for about 10 % of global GHG emissions by 2050, if current growth rates persist.

The emissions from ships do not only include GHGs, such as CO_2 and methane (CH_4), but also air pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), black carbon (BC), ash, carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) (Shi et al. 2023). According to Shi et al. (2023), evidence is gathering that ship-emitted air pollutants have a significant impact on atmospheric chemistry, clouds and ocean biogeochemistry. Partanen et al. (2013) indicated that the elevated sulphur content in marine fuel contributed to an estimated 19,000 to 91,000 premature deaths annually in coastal areas prior to the introduction of the EU's Sulphur Emission Control Area (SECA). Mueller et al. (2023) analysed global health impacts attributed to air pollution (external effects) from shipping, identifying the highest concentrations along major shipping routes and near ports, with the most severe health effects observed among coastal populations and an estimated 265,000 premature deaths worldwide in 2020.

Emission Modelling

Emission modelling of ships is often necessary due to the frequent absence of direct onboard measurement data, requiring the use of estimation methods to assess emissions accurately. However, results have to be treated carefully as for example Chu-Van et al. (2018) showed with onboard measurements that emission factors for inter alia CO and PM were significantly higher during ship manoeuvring than cruising.

Maritime emission modelling can be used to create maritime emission inventories, which provide insights into the quantity and types of pollutants emitted from ships, and their spatial distributions. Subsequent analysis can reveal potential health and environmental impacts and the effectiveness of various emission reduction measures and technologies. Maritime emission inventories can be particularly useful in projecting future emissions if they consider techno-economic and socio-ecological factors, such as fuel switching, efficiency and sufficiency measures and changes in trade volumes. Additionally, they can aid the analysis of energy demands for shore-side power connections in port areas, a requirement that has been enforced in Germany since 2023 (BMWK 2019).

There are two types of (maritime) energy system and emission models: top-down and bottom-up. While energy system models usually focus on the optimisation or forecast of energy demand and supply, emission models focus on the quantification of GHG and air pollutant emissions for scenario analyses. Historically, top–down models were used, which estimate emissions from ships using aggregated data, such as total fuel consumption or cargo volume, often combined with average emission factors (Corbett and Fischbeck 1997; Corbett et al. 1999; Eyring 2005). Top–down models are less data intensive than bottom-up models but provide less detailed insights. Since 2004, with the introduction of the Automatic Identification System (AIS), and the availability of ship activity (movement) data, highly accurate but data-intensive bottom–up models have been used (Gon and Hulskotte 2010; Jalkanen et al. 2014; Jalkanen et al. 2016; Johansson et al. 2017; Karl et al. 2019).

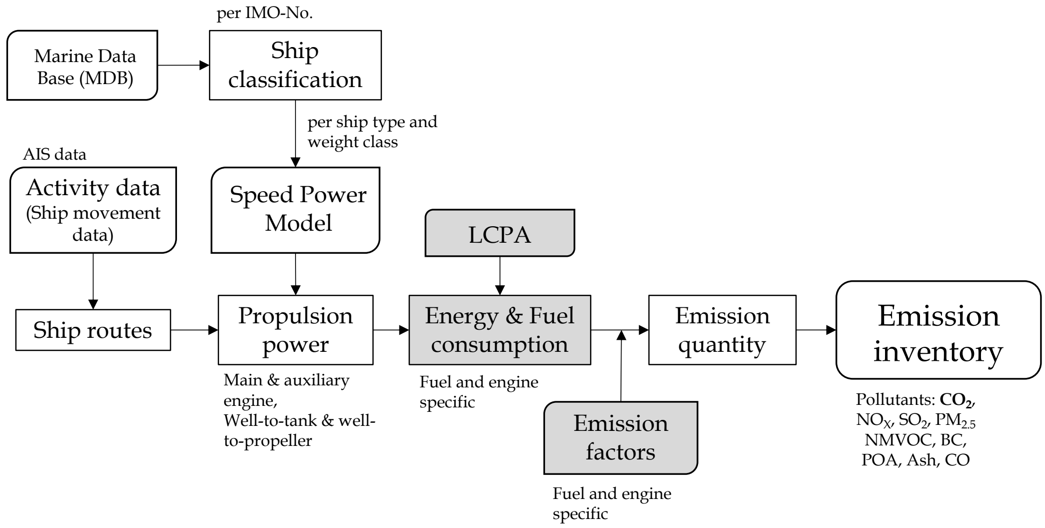


Figure 2.4: Modelling approach for emissions from ships.
This figure illustrates the detailed data flow and steps involved in the emission modelling process for ships as developed, applied and fully introduced in Chapter 6.

Bottom-up models typically consist of two main key components, as depicted in Figure 2.4 (highlighted in grey, except the life cycle performance analysis (LCPA)). First, there are the ship's fuel consumption data, derived from activity data, such as speed, location, timestamp and unique identifier, and ship specifics. Second, there are emission factors, coefficients that represent the average emissions per unit of activity, such as emissions per ton of fuel burned or per nautical mile travelled. Emission factors vary by ship type, fuel type, engine type and operating conditions (Schwarzkopf et al. 2021). As emissions data from actual measurements are not usually available, the emission quantities are calculated using emission factors. These have a certain level of uncertainty, as analysed in Chapter 7. To assess the spatial distribution of emissions, models incorporate geographical information about shipping routes, port locations and emission-sensitive areas (Aulinger et al. 2016).

Challenges for maritime emission modelling primarily include data availability and the accuracy of emission factors. Accurate modelling depends on detailed and up-to-date data on ship activities and fuel consumption, which can be challenging to obtain as they are often proprietary. The complexity of shipping operations, such as the variability in ship types, fuel type, engine technology and operational patterns is difficult to reflect within models. The most commonly used models for emission modelling of ships are introduced in Chapter 6. The Ship Traffic Emission Assessment Model (STEAM) by the Finnish Meteorological Institute has been widely used to determine emission quantities in the Baltic Sea (Jalkanen et al. 2014), in the Danish Straits (Jalkanen et al. 2012), European Waters (Jalkanen et al. 2016), the Northern European Emission

Control Area (ECA) (Johansson et al. 2013) and globally (Johansson et al. 2017). More recently, the MariTEAM Model was used to analyse global shipping emissions from a well-to-wake perspective (Kramel et al. 2021). The preparation of the publication in Chapter 6 was carried out in close cooperation with the Helmholtz-Zentrum *hereon*. hereon's Modular Ship Emission Model (MoSES) and its resulting emission inventory (Schwarzkopf et al. 2021) serve as a key reference in Schwarzkopf et al. (2022) and provide a comparative benchmark for the inventory detailed in Chapter 6.

Since 2023, there have been a number of publications dealing with the modelling of emissions from ships. Chen et al. (2023) focused on predicting fuel consumption for harbour vessels using machine learning and comparing the predictions to traditional linear regression models as used with IMO (2020a). The Artificial Neural Network outperformed other models, showing significant accuracy improvements (up to 62 %) when meteorological factors were included (Chen et al. 2023). Chen et al.'s work highlights the value of machine learning in extracting complex relationships from high-dimensional data for more accurate fuel consumption predictions for ships. The integration of real-time data, machine learning and big data analytics is expected to further enhance the accuracy and usability of emission models of ships. Senol and Seyhan (2024) investigated ship and tugboat emissions during berthing manoeuvres at ports. Using data from over 300,000 readings in a ship simulator, they calculated emissions using bottom-up methods. A significant correlation was found between emissions and the pilots' demographics and experience. A machine learning model with 73 % consistency was developed to predict emissions, offering a tool for strategic planning and cost-effective emission mitigation in port operations. The most recent Ship Emission Inventory Model by Yi et al. (2025), offers ship emission inventory data at a high spatio-temporal resolution (0.1° × 0.1°) for the years 2013 and 2016–2021. It was developed using a bottom-up approach with emission quantities calculated from ship movement data, similar to the publication in Chapter 6. Results from 30 billion AIS data records include a substantial reduction in SO_2 and $PM_{2.5}$ emissions, 81.3 % and 76.5 % respectively, due to existing fuel-switching policies (Yi et al. 2025).

2.4.3 Maritime Legislation, Regulation, Policies and Schemes

Maritime energy systems are subject to strict policies, regulations and schemes designed to reduce environmental impact and ensure safety. Intermediate targets for climate change mitigation set by the International Maritime Organisation (IMO), aim to achieve a 20 – 30 % reduction in CO_2 emissions by 2030 and a 70 – 80 % reduction by 2040, based on 2008 levels (IMO 2020a). The IMO also aims for 5 – 10 % of energy used by ships to come from zero- or near-zero-emission technologies by 2030 (IMO 2023). However, the IMO's GHG report highlights limited progress, with CO_2 emissions increasing by 6 % between 2012 and 2018 (IMO 2020a). As of April 2025, the

IMO has approved draft regulations introducing a global marine fuel standard and emissions pricing to achieve net-zero GHG emissions from shipping by around 2050. The framework combines mandatory limits and financial mechanisms, with adoption expected in 2025 and enforcement from 2027 (*Draft revised MARPOL Annex VI* 2025).

The IMO has set four pillars for regulation, the SOLAS (1974, the International Convention for the Safety of Life at Sea), STCW (1978, the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers), MARPOL (1973, the International Convention for the Prevention of Pollution from Ships and amendment in 1978, Annex VI to impose a limit of 0.5 % on sulphur levels in fuels used by all operating ships) and MLC (2006, the Maritime Labor Convention to protect the seafarers' rights). The MARPOL is the main global agreement aimed at reducing marine pollution from ships, both accidental and operational.

European maritime legislation reflects the EU's commitment to environmental sustainability, safety, market competition and the welfare of maritime workers (EC 2020). The Fit for 55 package, introduced in 2021 as part of the European Green Deal, encompasses revised and new EU climate policies, including (1) the EU Emission Trading System Directive, (2) the FuelEU Maritime Regulation, (3) the Alternative Fuels Infrastructure Regulation, and (4) the Energy Taxation Directive. Some measures to implement the revised targets are still pending. Adopted in July 2023, the FuelEU Maritime Regulation ((EU) 2023/1805) promotes renewable, low-carbon fuels and clean energy technologies essential for sectoral decarbonisation. From January 2024, maritime CO_2 emissions are included in the EU ETS, covering ships over 5,000 gross tonnage calling at European Economic Area ports. The scheme mandates a 50 % coverage of CO_2 emissions from voyages to/from non-EU ports and a 100 % coverage from intra-EU voyages, gradually increasing from 40 % coverage in 2024 to full coverage by 2026 (European Union 2024).

2.5 Open Science

> *Information is the oil of the 21st century, and analytics is the combustion engine.*
>
> – Peter Sondergaard, Economist, 2011

Since the 1990s, the topic of climate change has moved from academic discourse to the public arena, generating widespread interest (Gong 2022). This reflects Kuhn's concept of paradigm shifts, where scientific revolutions emerge from changes in societal and scientific perspectives (Kuhn 1962). Kuhn argued that paradigm shifts, fundamental changes in scientific understanding, drive progress through a mix of sociological forces, enthusiasm and scientific innovation. This is reflected today in the growing demand for transparency and public engagement in science and has sparked a new paradigm: the open science movement. This shift, particularly in open data, emphasises accessible data as essential for transparency and collaboration, marking a profound transformation in scientific research (Gong 2022).

2.5.1 Open Energy System Modelling

According to Morrison (2018), the open energy modelling revolution originated in Germany and the USA, with Germany having, as of 2017, the leading number of frameworks, projects, datasets and wikis related to open energy modelling. This may be due to the advanced *Energiewende* in Germany (Morris and Jungjohann 2016). For some years, it has become increasingly common to use open energy system models to support public policy development (Wiese et al. 2014; Pfenninger 2017; Pfenninger et al. 2018). Three distinct drivers can explain this paradigm shift towards open energy system modelling; *public transparency*, *scientific reproducibility* and *open development* (Morrison 2018). Therefore, an idealised open modelling process combines open data, open source development and open access dissemination, guaranteeing transparency, reproducibility and open development throughout the entire modelling process (see Figure 2.5).

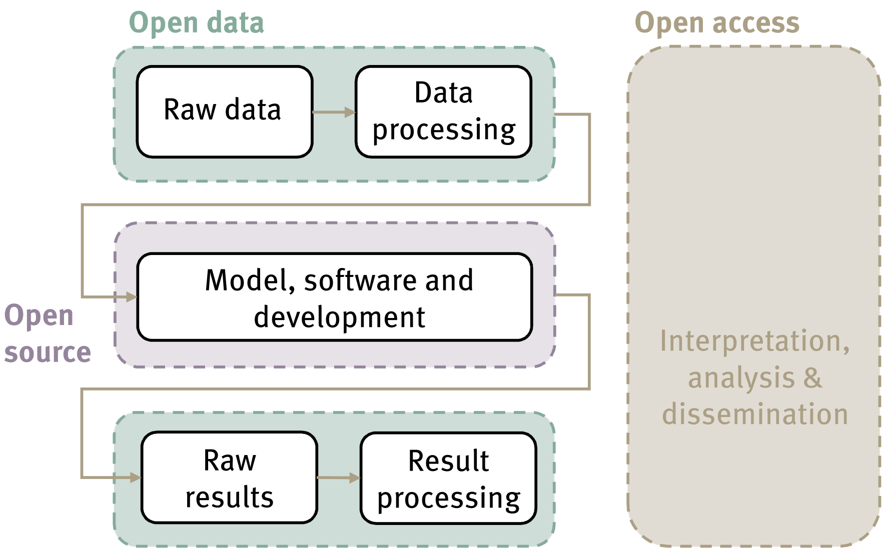


Figure 2.5: Open modelling process. Schematic representation of an idealised modelling process. Inspired by Hilpert (2022a), who in turn refers to the original framework by Pfenninger et al. (2018, p. 64). Open access matters at every step of the process.

The lack of transparency in closed energy system models is a significant problem as it tends to conceal and perpetuate errors (Pfenninger 2017). Making models and code accessible and comprehensible to users enables replication (Cao et al. 2016). According to Peng (2011), replication is "the ultimate standard by which scientific claims are judged." (p. 1126). Researchers should allow others to scrutinise, validate and build upon their work. Transparency not only strengthens the credibility of scientific findings but also encourages the development of best practices in research (Cao et al. 2016). This is increased and enhanced by open development methods and practices, such as unrestricted participation, contribution and extreme transparency (Morrison 2018).

Open source modelling projects are often developed by a global community of contributors. These contributors bring diverse perspectives and expertise to the table, leading to more innovative and comprehensive models. McGookin et al. (2021) examined progress in democratising key decision-making processes and the benefits and challenges of participatory methods in energy system modelling and planning. A key finding of the research was that only around 10 % of all studies analysed included some form of collaboration with non-academic stakeholders, and furthermore, in 36 % of the studies analysed there was only one interaction. This indicates a lack of progress in the democratisation of modelling processes. Nonetheless, the collaborative nature of open source development ensures that models evolve rapidly, incorporating the latest research and technological advancements while being transparent and constantly reviewed.

One example of open source modelling is the Open Energy Modelling Framework *oemof* (Hilpert et al. 2018). This open-source, Python-based framework is designed to model energy systems and support energy system analysis. oemof provides tools and libraries to simulate, optimise and analyse energy systems (Hilpert et al. 2018), and is used within Chapter 4 and 5 of this thesis. The highly modular and flexible features of oemof allow users to define their own energy systems to include, for example, renewable energy sources, conventional power plants, and energy storage systems. oemof, as an open-source project itself, was collaboratively programmed. It allows anyone to contribute, modify and use the code, which ties in with the social sustainability pillar of energy modelling and the promotion of transparency.

The development of open source energy system models also connects to the idea of the collaborative commons (Rifkin 2014). This ties in with Raworth's assertion that the sector of modelling will play an important role in the age of sustainability, alongside the state and conventional economy (Raworth 2017). Open source models are typically free, making them accessible to a broad range of researchers, including those at institutions with limited financial resources. This democratisation of access is critical for fostering a more equitable research landscape (Brown 2022).

The values and principles of open energy system modelling can be effectively applied to emission modelling. Energy system models simulate energy production, demand and distribution, creating scenarios with diverse energy mixes. Emission models, in turn, quantify the environmental impacts of these scenarios, covering GHG and other air pollutants. By linking energy outputs with emissions data, these models support enforceable regulations, such as carbon pricing, and provide opportunities for iterative feedback and continuous improvement. For this thesis, a sector-specific application was undertaken with the modelling of shipping emissions. The comprehensive ship emission inventory, made publicly accessible in csv format and presented in Chapter 6, captures the entire CO_2 pathway from ship movement data and energy consumption across various life-cycle stages to emission quantification and scenario development. Following the principle shown in Figure 2.5, while the raw input data initially required anonymisation due to proprietary ship-specific identifiers (IMO numbers), a version of the movement dataset is now also available. This demonstrates that open data can emerge from proprietary sources without compromising data quality.

2.6 Scope of Publications

This section outlines the aspects discussed in Part I that are reflected in the academic publications presented in Part II. As previously noted, energy systems are undergoing significant technological, economic, social and scientific transitions, accompanied by paradigm shifts. The complexity of energy system modelling, analysis and interpretation is increasing. This growing complexity is closely linked to the principles of open science, which, in the face of climate change, facilitates the identification of solutions aligned with the three pillars of sustainability.

Environmental sustainability is addressed in all publications through the analysis of transitions to renewable energy systems, aimed at reducing and mitigating the emission of CO_2 and air pollutants. The economic pillar of sustainability is considered in techno-economic energy system models and analyses in the publications in Chapters 4 and 5. However, within the publications in Part II, energy systems (and sub-systems) are viewed not only as techno-economic systems but also as complex social systems. As such, their analysis is inherently multidisciplinary, drawing on both quantitative and qualitative methods. Energy system analysis tools, particularly computational models, play a vital role in supporting the design of sustainable energy systems but are not ends in themselves. Therefore, Chapter 3 adopts a participatory approach to energy system analysis, scenario design and the assessment of participants' preferences for criteria influencing energy system analysis and the resulting recommendations for action. Consequently, Chapter 3 strengthens the social pillar of sustainability within energy system analysis as well as Chapter 8, which assessed multiple dimensions of sustainability criteria for the production of green hydrogen.

The principles of open science were applied in all publications. oemof was applied in the publications in Chapter 4 and in Chapter 5. Chapter 6 presents an open-source emissions inventory for shipping in the North and Baltic Sea, which was subsequently applied in the scenario analysis within the publication in Chapter 7. In all publications contained in this thesis, publicly available energy or emission models were therefore used or created and proprietary tools were excluded (where possible).

Part II - Publications

3

Water-Energy Nexus: Addressing Stakeholder Preferences in Jordan[1]

Nadejda Komendantova
Leena Marashdeh
Love Ekenberg
Mats Danielson
Franziska Dettner
Simon Hilpert
Clemens Wingenbach
Kholoud Hassouneh
Ahmed Al-Salaymeh

[1]published as: Nadejda Komendantova, Leena Marashdeh, Love Ekenberg, Mats Danielson, Franziska Dettner, Simon Hilpert, Clemens Wingenbach, Kholoud Hassouneh and Ahmed Al-Salaymeh (2020): Water-Energy Nexus: Addressing Stakeholder Preferences in Jordan. *Sustainability*, 12, 6168-6184

sustainability

MDPI

Article

Water–Energy Nexus: Addressing Stakeholder Preferences in Jordan

Nadejda Komendantova [1,*], Leena Marashdeh [2], Love Ekenberg [1,3], Mats Danielson [1,3], Franziska Dettner [4], Simon Hilpert [4], Clemens Wingenbach [4], Kholoud Hassouneh [2] and Ahmed Al-Salaymeh [2]

1 International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria; lovek@dsv.su.se (L.E.); mats.danielson@su.se (M.D.)
2 Mechanical Engineering Department, University of Jordan, 11942 Amman, Jordan; leena_marashdeh@yahoo.com (L.M.); k.hassouneh@ju.edu.jo (K.H.); salaymeh@ju.edu.jo (A.A.-S.)
3 Department of Computer and Systems Sciences, Stockholm University, P.O. Box 7003, SE-164 07 Kista, Sweden
4 Energy and Environmental Management, Europe University Flensburg, Auf dem Campus 1, 24943 Flensburg, Germany; Franziska.Dettner@uni-flensburg.de (F.D.); simon.hilpert@uni-flensburg.de (S.H.); clemens.wingenbach@uni-flensburg.de (C.W.)
* Correspondence: komendan@iiasa.ac.at; Tel.: +43-676-83-807-285

Received: 24 June 2020; Accepted: 27 July 2020; Published: 31 July 2020

check for updates

Abstract: The water and energy sectors are fundamentally linked. In Jordan, especially in the face of a changing climate, the water–energy nexus holds a number of challenges but also opportunities. A key point in exploring synergies is the identification of such, as well as the communication between the water and energy sectors. This paper promotes the importance of using a co-creative approach to help resolve opposing views and assessing stakeholder preferences in the context of the water–energy nexus in Jordan. A computer-supported, co-creative approach was used to evaluate stakeholder preferences and opinions on criteria and future scenarios for the energy and water sector in Jordan, identifying common difficulties and possibilities. The criteria describe socio-ecological aspects as well as techno-economic aspects for both systems. Discussing a set of preliminary scenarios describing possible energy and water futures ranked under a set of sector relevant criteria, a consensus between both stakeholder groups is reached. The robustness of results is determined, using a second-order probabilistic approach. The results indicate that there are no fundamental conflicts between the energy and water stakeholder groups. Applying a participatory multi-stakeholder, multi-criteria framework to the energy-water nexus case in Jordan promotes a clear understanding of where different stakeholder groups stand. This understanding and agreement can form the basis of a joint water–energy nexus policy used in the continued negotiation process between and within national and international cooperation, as well as promoting and developing acceptable suggestions to solve complex problems for both sectors.

Keywords: water–energy nexus; Jordan; energy policy; multi-criteria decision analysis; participatory governance and co-creation; compromise-oriented policy solutions

1. Introduction

The water and energy sectors are interconnected and fundamentally linked. Energy generation requires water. Water treatment and transportation consume energy. The newfound understanding of the water–energy nexus can identify challenges and opportunities. One key factor here is a comprehensive dialogue between sectors. A participatory governance approach, as presented here, including multi-criteria decision analysis, aids in exploring synergies and facilitates dialogue in the first place.

Jordan is facing several energy and environmentally related problems as one of the driest countries on earth. With 150 m^3/year, it has one of the lowest levels of water resource availability per capita [1]. Water scarcity will become a more pressing issue in the context of climate change with unpredictable intensity, duration, and frequency of precipitations, rising temperatures, and evaporation rates. Additionally, there are challenges regarding current patterns of water usage in the country as well as the large number of Syrian refugees in Jordan [2]. The sustainability of water supply in Jordan is not only affected by depleting water reserves but also by growing electricity tariffs. Water pumping systems are consuming 15% of the total electricity, making the Water Authority of Jordan (WAJ) the largest electricity consumer [3]. In the last decade, tariffs for electricity were growing steadily whereas tariffs for water remained the same. The division between revenues in the form of water tariffs and expenses in the form of costs for electricity threatens the financial sustainability of WAJ.

Given the number of possible synergies, there is currently limited dialogue between the two sectors, leading to very few cooperations between the water and energy sectors. A water–energy nexus in Jordan could, for example, mean renewable energies providing the electricity needed for water pumping systems. Existing feasibility studies show that such solutions could significantly reduce electricity generation costs [4]. The saved budget can be used for, e.g., investments in improved water pumping systems to avoid water losses. In the energy sector, the utilization of existing water basins as hydro energy storage systems, given suitable geographical features, can facilitate further deployment of renewable energies. However, implementations of participatory governance solutions require trade-offs in both water and energy policies.

This paper discusses how a participatory governance approach can contribute to and increase sustainability in the water sector as well as the energy sector. The results described here are the outcome of stakeholders' interactions at a workshop with relevant parties of the Jordanian water and energy sectors such as the Water Authority of Jordan (WAJ), National Electric Power Co (NEPCO), Energy & Minerals Regulatory Commission (EMRC), Aqaba Water Company (AWC), Ministry of Energy and Mineral Resources (MEMR), Ministry of Water and Irrigation (MWI), and Yarmouk Water Company (YWC) as well as scientific partners such as University of Jordan (UJ) and international participants such as Europa Universität Flensburg (EUF) and International Institute for Applied systems analysis (IIASA) in Amman, Jordan in October 2019. The workshop was supervised by GIZ, EUF, IIASA, and UJ and established in expert-led break-out groups, discussing techno-economic aspects of the energy and water system followed by a multi-criteria decision analysis (MCDA) to evaluate social-ecological aspects, preferences on a number of criteria important for both sectors as well as technical specifications and synergies for systems' solutions.

2. Background

The water–energy nexus is a complex problem that requires upgrading existing infrastructure, changes in legal and institutional frameworks, new technological solutions, and new forms of cooperation between various stakeholders involved in the energy and water sectors. There is no fixed definition for the water–energy nexus. It merely describes the interdependencies between the water and energy sectors. The first generation of nexus research focused on quantitative input-output modelling to empirically demonstrate interdependencies and options for optimizing resource management; currently, the number of scientific works on how nexus approaches are conditioned by property rights regimes, economic growth strategies based on resource extraction, and the ability to externalize environmental costs to other regions and states [5].

It became and is becoming increasingly necessary to respond to the production and consumption trade-offs, which have emerged with the increase of scarcity and competition over the last decades. The nexus highlights the need to study and develop the use and management of both resources in a joint way. Prerequisite to technological solutions, infrastructure developments, or even legal frameworks in the nexus context is a profound understanding of joint challenges and opportunities and the will to cooperate between the relevant stakeholders. This is facilitated through participatory governance methods and multi-criteria decision-making exercises to find a consensus and important criteria for the nexus.

While studying the energy-water nexus in the Middle East and North African region, [6] a highly skewed coupling of water and energy was found, with a relatively weak dependence of energy systems on freshwater, but a strong dependence of water abstraction and production systems on energy.

2.1. The Energy Sector

Currently, about 39% of the primary energy is used for electricity generation, with smaller shares for transport, heating, industrial use, and others. In 2018, renewable energy projects contributed to 10.8% of the generated electricity and 23% of the total installed capacity [7]. In 2018; about 82% of Jordan's electricity was supplied by imported oil, 12% by imported natural gas, while only about 8% were covered by renewable energy resources [8], which is an increase from only 2% (Renewable Energy Sources) RES in 2013 [9]. The aim for 2020 is to generate 20% of electricity by RES, 15% by oil shale, and to reach 30% renewable energy generation by 2022 [9]. Table 1 below lists some key figures from the energy sector in recent years.

Table 1. Key figures from the energy sector in recent years.

	Peak Load (MW)	Available Capacity (MW)	Generated Energy (GWh)	Consumed Energy (GWh)	Loss Percentage (%)
2014	3050	4189	18,269	15,419	14.40
2015	3470	4455	19,012	16,178	14.89
2016	3250	4465	19,661	16,700	13.77
2017	3220	4529	20,824	17,504	13.10
2018	3205	5236	20,692	16,392	13.30

Source: Ministry of Energy and Mineral Resources, 2019; NEPCO, 2018; EDAMA, 2019.

One of the targets of the energy policy in Jordan, which is reflected in two major documents, the updated National Energy Strategy (2015–2025) and National Master Plan of the Energy Sector (2007–2020), is to reduce the nation's dependence on imported energy sources.

The sustainability of the energy sector in Jordan, on the other hand, is influenced by the ongoing energy transition. In 2019, the Ministry of Energy declared to pause further development of renewable energy sources because of insufficient grid capacities and lacking technical abilities to manage demand peaks due to the volatility of electricity generation from renewable energy sources [10]. This solution is unsustainable, in the light of potential electricity demand growth due to growing needs for, e.g., cooling and desalinization, especially considering the abundance of renewable energy sources in the country. Furthermore, one major aim of the Jordan energy security policy is a reduction of energy import dependencies, which could be achieved with a higher share of renewable energy in the system or utilizing domestic fossil energy sources, such as oil shale [11].

2.2. The Water Sector

The water policy in Jordan is mainly driven by concerns about the current and future water supply. Currently, Jordan is among the 18 countries in the world with the highest risk of water scarcity. Competition for the use of the water resource can lead to conflicts between water users in irrigation and agriculture as well as in energy generation and private consumption [12]. Water supply and sanitation in Jordan can be specified by severe water scarcity exacerbated by forced immigration [13].

Jordan shares surface and groundwater resources with neighbouring countries. The surface water is shared through the water flows from the Yarmouk and Jordan Rivers to the Dead Sea. In the 1940s and 1950s, Jordan's river flow was 1.2 billion m^3 annually but in 2016, the flow was limited to 150 MCM (million m^3) because of the excessive use, diversion, and damming of the Jordan River's water by neighbouring countries. The share of the Jordan and Yarmouk river water for Jordan was stipulated in agreements between Jordan and upstream neighbouring countries, however, these quantities are not being realized. The groundwater of Jordan is shared with Saudi Arabia through Disi Aquifer, a signed agreement to share the aquifer between the two countries [4].

Risks to energy and water security are recognized globally as one of the most serious and significant risks. In 2016, the World Economic Forum conducted a ranking of global risks. Three out of the top five risks are concerned with energy (a failure of climate change mitigation and adaptation, or a severe energy price shock) or water (water crises). Given all the interrelationships between water and energy, it is apparent that the subject has to be approached in an integrated way. Still, the delivery chains of water and energy are mostly managed in 'silos,' where the silos not only represent different professions and sectors but also different institutions. It is apparent that the infrastructures of energy and water have to be designed and operated in a more integrated way [14]. Additionally, there are several cases from various countries where requirements for water by energy generation became an issue of serious social conflict [15]. While studying various cases of conflicts above water energy usage, scientific evidence shows that localized challenges for the water–energy nexus are diminished when considered from broader perspectives, while regionally important challenges are not prioritized locally [16].

There is a number of potential international projects to increase the water supply of Jordan such as Red Sea–Dead Sea Project (RSDSP). This is an international project which includes three beneficiary parties: Jordan, Israel, and Palestine. The major aim of this project is to save the Dead Sea from environmental degradation and to provide desalinated water to reduce water shortage in Jordan. However, the implementation of the project is currently delayed because of political tensions between the participating countries.

Jordan has an annual availability of water of less than 150 m^3 per person. Jordan's per capita water availability has decreased from 3,600 m^3/year in 1946 to 150 m^3/year in the present, putting the nation far below the 500 m^3/year level as defined by the WHO [3].

The water policy framework in Jordan is well-developed and includes a number of specified policies such as Water Demand Management Policy or Groundwater Sustainability Policy. Currently, implementation is a key challenge. The policy targets are mainly shaped by the National Water Strategy for the period 2016–2023, including the financial sustainability of the water sector, enhanced services of water and wastewater, supply of water to meet the demand for all uses as well as water resource sustainability and protection [4].

Jordan's water withdrawal or water demand, which is the annual amount of water withdrawn, amounts to 1.1 billion m^3 per year. "Water consumption" or "water use" is the portion of water use that is not returned to its original water source after being withdrawn. The sources of water in Jordan are 27% surface water, 14% treated wastewater, and 59% groundwater. The available renewable water resources for different purposes are around 853 MCM annually, while the estimated water demand quantity for all sectors is 1412 MCM in 2017, of which 54% is used for the agriculture sector, 52% for the domestic sector, and 3% for the industry sector. In 2016, there were 33 different Wastewater Treatment Plants (WWTPs) discharging approximately 137 MCM per year of effluent. This volume combined with the decreased volumes of freshwater is available for irrigated agriculture [3].

Greywater reuse has been practiced in Jordan for a long time. A report by the Center for Development Research in 1999 estimated that 60% of the households in Amman and 30% in rural Jordan reused water within the household. However, there are some barriers to implement greywater reuse systems in an extensive way in Jordan, which include: (1) hydraulic systems in Jordanian houses which include, in most cases, the pipes of greywater which are not separated from blackwater pipes; (2) characteristics of wastewater in Jordan which are different from other countries because the average salinity of municipal water supply is 580 ppm of TDS and the average domestic water consumption is low; (3) low cost of water as the water sector in Jordan is highly subsidized and the domestic consumers are not paying the actual costs of the water. The low prices of water reduce the effective 'financial savings' to be made by reusing greywater.

Rainwater is being harvested in many Jordanian houses. The Ministry of Public Works and Housing (MPWH), in cooperation with MWI, has included rainwater harvesting in the new water and sanitation plumbing code [17]. This code illustrates where and how rainwater harvesting is feasible and cost-effective. However, for customers paying at the low water tariff, the preliminary feasibility analysis indicated that the harvesting system is not economically feasible when compared to utility water supply [18].

Groundwater contributes to around 59% of the total water supply, which makes around 618.8 MCM per year. The groundwater mainly comes from 12 major groundwater basins. Six of these basins are already over-exploited [2]. There is a high risk that the country's aquifers will be completely depleted by 2030 because of the impacts of climate change and unsustainable water usage. The impacts of global warming, such as an increase in temperature, less frequent precipitation, and an increase in the intensity of extreme weather events, affect water quality and quantity [19]. According to the Global Freshwater Initiative, the precipitation in Jordan will decline by 30% in comparison to the current level, and the occurrence of drought will triple by the year 2100 as a result of climate change. It is projected that by 2025, the water demand in Jordan will exceed the available water resources by more than 26%. According to the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR), the decrease in water availability will be particularly severe after the year 2040 [20].

Around 42% of the drinking water for Amman stems from water sources situated 20 to 76 km away. As these sources are elevated up to about 1,200 m, they consume around 14% of the total electricity generated in Jordan, which amounts to 1,685 GWh.

Currently, the average electricity consumption per cubic meter of billed water is 4.31 kWh/m^3 [4]. Water pumping is the largest energy consumer in the water sector as the water system in Jordan has to rely mainly on resources located at a considerable distance from urban areas.

The reliability of the water supply is influenced by growing energy tariffs. Electricity consumption by the water sector continues to grow due to groundwater depletion that requires pumping water from lower levels, water desalination projects, and overall increased water demand. Currently, the revenues in the water sector are sufficient to cover around 70% of the total operation and maintenance costs, which also include capital costs, depreciation, and recovery. In the year 2017, electricity costs constituted 43% of the total operation and maintenance costs of the water sector and the electricity bill amounted to 161 million Jordanian Dinar (JD). The electricity tariffs continue to grow since in the year 2017, the water sector purchased electricity with a tariff of 0.094 JD per kWh, and in the year 2018, the electricity tariffs jumped to 0.140 JD per kWh, according to the conducted interview with the Former Head of finance and International Cooperation Directorate at Water Authority of Jordan-WAJ [21]. However, the published tariff for water pumping is 0.115 JD per kWh for the period from July 1, 2018 until now, according to the official website of Electricity Distribution Co (EDCO).

Moreover, a significant share of electricity is wasted because of the inefficiencies and physical losses mentioned above. For example, in the year 2017, the estimated non-revenue water was estimated at 48% with corresponding energy losses. Furthermore, administrative inefficiencies account for more than 50% of these losses and the remaining losses are due to physical losses from the networks [3].

2.3. Challenges and Opportunities

The water–energy nexus is mainly regulated by the Energy Efficiency and Renewable Energy Policy for the Jordanian Water Sector which was published in 2015 by the Ministry of Water and Irrigation of Jordan. It has two main targets: the reduction of energy consumption billed water by 15% and an increase of the share of renewable energy sources in the power generation for the water sector by 10% until 2030 in comparison with the year 2018.

There are a number of possible synergies between the water and energy sectors, but each of them has associated benefits, risks, and costs that require trade-offs in decision-making and policies as well as coordinated actions for implementation. These options include international and national cooperation and the implementation of renewable energies in the water sector. For example, renewable energy projects such as solar pumps can be an option to contribute to sustainability in the water sector while reducing the specific power consumption.

Due to the high cost of energy used within the water sector, the Ministry of Water and Irrigation (MWI) aims to improve the performance and sustainability of the water sector through improving the energy efficiency in water facilities in order to decrease the specific power consumption for water supply and introducing renewable energy technologies to protect the environment and to reduce energy price volatilities in the water sector [4].

Another approach is the multiple wastewater recovery, which is nowadays one of the most desirable options. The technology is also mature and feasible. Such an approach can save water. It can also help to reduce production costs and energy demand by eliminating unnecessary treatment and long-range conveyance, as it typically aims at local reuses. There are different wastewater reuse goals such as direct potable use, indirect potable use, non-potable uses, and industrial uses which are connected with various requirements and various technological options [22]. However, the wastewater treatment facilities are among the major energy consumers at the municipal level worldwide and make a significant fraction of the municipal energy bill. On the other hand, wastewater and its by-products contain energy in different forms: chemical, thermal, and potential. Here, new technologies could help to optimize water usage. For instance, recovery of the energy content of process residuals could allow significant additional energy recovery and increased greenhouse emissions abatement [23].

Pumped hydropower plants (PHS) can be another, most beneficial synergy to contribute to the sustainability of the energy sector. PHS plants offer the opportunity to store large quantities of energy, and the flexible management of water pumping can greatly contribute to shaping energy demand profiles by shifting loads from peak consumption hours to peak production hours. Water can be used to store energy in the dams along the Jordan Valley and in Aqaba. The King Talal, Wadi al Arab, and Mujib Dams could provide 500 MW power and store 3,000 MWh/day [2]. The implementation of these projects faces two major challenges; primarily, high investment costs and secondly, a necessary change in the energy tariff scheme to ensure financial sustainability.

Technological solutions for the joint challenges of the water and energy sectors are not the focus of this paper; however, in expert sessions during an on-site workshop in Amman, Jordan, in October 2019, a number of possible options were discussed. The solution with the highest potential according to local stakeholders is the deployment of water pumping systems powered by photovoltaic (PV) as well as pumped hydroelectricity storage systems. Among the other options discussed were in-pipe hydro solutions, floating PV to reduce evaporation rates of water as well as reducing the current 60% of water losses (non-revenue water), constraint zero feed-in for renewable energy to facilitate hybrid systems and desalination plants to meet the increasing water demand. Desalination, however, was not voted to be of the main interest.

2.4. Projects

There are two large-scale international cooperation projects, which are currently under consideration. The Red Sea–Dead Sea Water Conveyance project (RSDS) and the Interconnected Gulf Grid project.

The RSDS project is envisaged to become one of the main sources to meet the increased water demand in Jordan. The major aim of this project is to save the Dead Sea from environmental degradation and to provide desalinated water to reduce water shortages in Jordan. The project includes the construction of a desalination plant in the north of Aqaba city, with a capacity of 80−100 m^3/year of desalinated water, conveying the brine to the Dead Sea in order to reduce the decline of its water level. The project faces two major challenges, one being the international cooperation, especially with

Israel and Palestine, which is not resolved yet, delaying the process since 2013 due to political tension between the parties. The second challenge is the high investment costs of around 11 billion US dollars.

The Interconnected Gulf Grid is another project. In addition to the existing electrical interconnection line with Egypt and Palestine, the National Electric Company (NEPCO) signed a memorandum of understanding with Gulf Cooperation Council Interconnection Authority (GCCIA) during 2016 to conduct technical and economic feasibility studies for electric interconnection with Gulf [9]. In 2019, Jordan, Egypt, and the GCCIA agreed to form a joint technical committee and draft a memorandum of understanding to frame the basics for implementing a power connection project between the Arab Gulf countries' power grid and Europe's power grid through Jordan and Egypt [10]. The Jordanian Energy Minister stated that this project will have positive impacts such as improving the electric system's stability, economies, and enhancing energy exchange.

3. Methodology

The difficulties within the water–energy nexus are connected with existing conflicts between various stakeholders. Therefore, water–energy governance needs the development of cooperation schemes and compromised solutions on contested issues, design, and implementation processes. This can lead to conflicts in decision-making processes, in which some parties are trying to exclude others, resulting in winners and losers. Decision-making processes can also lead to inefficiencies when benefits from synergies in water and energy policy schemes and efforts are ignored and lost. When well applied, a participatory governance methodology can integrate views, visions, and opinions of different stakeholder groups. Such a methodology tends to be more sustainable, less prone to conflict, and better balanced, even though it might be more time-consuming for stakeholders to engage.

The framework of the participatory approach in this paper is a decision analytical approach in a multi-stakeholder and multi-criteria environment, supported by elaborated decision analytical tools and processes. The framework includes various scientific tools and methodologies such as methods for elicitation of stakeholder preferences, a decision engine for strategy evaluation, mechanisms for risk analyses, a set of processes for negotiation, and a set of decision rule mechanisms and processes for combining these items. Such a framework has been shown to be useful for decision-making processes such as agenda settings and overall processes, goals, strategies, policies, sub-strategies, part-policies, understanding of consequences and effects, qualifications and sometimes quantifications of the components, negotiation protocols as well as decision rules and processes [24–28].

3.1. Data

The framework included three steps to collect data for the analysis. The first step was an extensive literature review including scientific analyses, strategies, and reports to identify relevant questions for interviews with key stakeholders of the water and energy sectors.

The second step consisted of in-depth qualitative interviews (between one to two hours), which were conducted in the period between August and October of 2019. The majority of interviews were conducted in person while some interviews were conducted via Skype. Altogether, seven experts from the German International Cooperation (GIZ), the Water Authority of Jordan, the Ministry of Water and Irrigation as well as Dorsch International Consultants were interviewed, identifying key challenges and criteria for Jordan's energy and water nexus.

The third step included a workshop, which was conducted on the 21st and 22nd of October 2019 in Amman, Jordan. The workshop was joined by 37 representatives of the water and energy sector. The water sector was represented by the Water Authority Jordan (WAJ), Dorsch Engineering Consulting, Aqaba Water Company (AWC), the Ministry of Water and Irrigation (MWI), Jordan Valley Authority (JVA), Jordan Water Company Miyahuna, Jordan Water Management Initiative (WMI) and Yarmouk Water Company (YWC). The energy sector was represented by the National Electric Power Company (NEPCO), the Energy and Minerals Regulatory Commission (EMRC), and the Ministry of Energy and Mineral Resources (MEMR). In a plenary session, the background of the energy–water nexus in Jordan was introduced as well as the MCDA methodology and modelling approach. In three groups, one represented by energy sector stakeholders and two from the water sector, the MCDA methodology was applied. The participants were then subsequently split into three break-out groups, regardless of sector, for a moderated discussion about joint synergies and challenges of the energy–water nexus.

3.2. Process

The interactions with stakeholders in this context were in a co-creative format. The concept of co-creation has existed in many contexts over the years as a process for active involvement of end-users in various stages of planning and production [29]. As argued, for instance in [30,31], the underlying understanding is that co-creation (or co-production) will improve the efficiency of processes, yield faster response times, make them more secure by reducing human errors and increase inclusion, democracy, and participation, as the process ideally provides the same opportunities to different actors. There is also a growing body of evidence that trust is a key issue in the successful deployment of any kind of infrastructure and that participatory governance and co-production methods increase the level of trust [32,33].

Another component is a decision analytical tool for evaluating the multi-stakeholder decision problem, allowing to make preference assessments. One of the problems with standard methods is that numerically precise information is seldom available and most decision-makers experience difficulties with entering realistic information [24,25]. There have been many suggestions for handling the requirements for decision-makers to provide precise information, such as approaches based on capacities, sets of probability measures, upper and lower probabilities, interval probabilities and utilities, evidence and possibility theories, as well as fuzzy measures [34–37].

The computational complexity can, however, be problematic. This is extensively discussed in, for example, [38,39]. We suggest here an implemented method for integrated multi-attribute evaluation under risk, subject to incomplete or imperfect information. The software originates from our earlier work on evaluating decision situations using imprecise utilities, probabilities, and weights, as well as qualitative estimates between these components derived from convex sets of weight, utility, and probability measures. Therefore, for the evaluation of the stakeholders' preferences [40–43], the software DecideIT was used.

The software manages imprecise utilities, probabilities, and weights, as well as qualitative estimates between these components derived from convex sets of such measures [39]. Furthermore, higher-order distributions for better discrimination between the possible outcomes are introduced to managing belief mass over the output intervals, giving a measure of how plausible it is that an alternative outranked the remaining ones, and thus provide a robustness measure.

Danielson and Ekenberg compare a number of state-of-the-art methods and, utilizing a simulation approach, discuss the underlying assumptions and robustness properties while demonstrating how the ranking evaluation procedure provides a better result than hitherto popular methods, e.g., from the SMART family as well as AHP [44,45].

The method also includes the P-SWING method, suggested in [46]. P-SWING consists of an amended swing-type technique while allowing for intermediate comparisons as well, allowing for analyses of solution robustness. The multi-criteria decision problem is evaluated as a multi-linear problem calculating weighted averages over the polytopes spanned up by the ordering constraints, or, more precisely, equations of the format $E(A_j) = \sum w_i v_{ij}$, where w_i is the weight variable of criterion i and v_{ij} is the value variable of strategy j under criterion i. The value $E(A_j)$ is computed by solving successive optimization problems by the software, see [47] for mathematical details [48].

The ranking of criteria and scenarios could be represented as a matrix of choice, where trade-offs between scenarios can be identified as well as the most popular and accepted scenarios.

The application of the decision framework includes the following stages:

- Development of relevant criteria, which were determined based on available literature examining the water and energy sectors in Jordan, their targets, challenges, and existing strategies to achieve policy targets.
- Presentation of an overview of the socio-economic and environmental background on energy and water issues in Jordan, introducing previously set criteria.
- Discussion with stakeholders in interviews and during the workshop in a plenary manner to collect feedback on the selection of criteria, to find out whether criteria should be added or removed.
- Ranking of criteria according to their importance to the stakeholders and relative importance in relation to other criteria.
- Ranking of previously developed preliminary scenarios describing possible energy and water futures with regard to their importance to stakeholders and relative importance in relation to other scenarios.
- Quantification of criteria based on the ranking of criteria and of scenarios.
- Identification of trade-offs between sector ratings of criteria and favourable scenarios for each stakeholder group.

3.3. Criteria

The interviews and a review of background literature identified 25 criteria of relevance for the energy and water sectors in Jordan. Furthermore, the criteria were clustered and cumulated based on their similarities into 12 overarching criteria, which were discussed during the stakeholder workshop. These criteria were classified into four major groups: economic, environmental, technical, and institutional/regulatory. The definitions of the criteria were discussed and further developed together with the stakeholders during the workshop.

The group of economic criteria includes annual system costs per kWh. This criterion, in turn, includes three sub-criteria, namely investment, operation and maintenance costs as well as tariffs. The investment criterion includes all costs connected with planning, preparation, and construction of energy or water-related infrastructure. It also includes all other related investment costs. The operation and maintenance criterion summarizes all costs connected with the operation and maintenance of water and energy infrastructure. The tariffs criterion includes tariffs for water and energy paid by private and industrial/institutional consumers. Annual system costs per kWh should be the basis for tariffs.

The group of institutional and regulatory criteria includes two criteria: transboundary political feasibility and internal institutional feasibility. The transboundary political feasibility criterion includes all issues connected to transboundary cooperation over resource availability such as water management issues or the functioning of interconnected critical infrastructures. This criterion also includes political dialogue with neighbouring countries. The internal institutional feasibility criterion includes all efforts necessary for dialogue and cooperation in a horizontal perspective between various ministries or on the coordination of donor efforts or in a vertical perspective between local, regional, and national levels of governance. It also includes the need to change, adapt, and streamline existing legal and institutional frameworks for water–energy issues, as well as the necessary capacity-building efforts.

The group of technical criteria includes two criteria: security of energy supply and security of water supply. The security of energy supply criterion includes all issues connected with the safety of the social functioning of critical energy supply infrastructures as well as reliable energy generation, transmission, and distribution, including covering supply and demand gaps, intermittency risks and protecting energy critical infrastructure from various natural and man-made hazards. The security of the water supply criterion includes the same issues as listed above, concerning the water sector and infrastructure.

The group of environmental criteria also includes two criteria: local environmental impacts and global environmental impacts. The local environmental impacts criterion includes pressure on local land, air, water, soil, and other kinds of environmental resources resulting from extraction, generation, transmission, and distribution of energy and water services. The global environmental impact criterion relates to the same issues, which have an impact from a global perspective.

3.4. Scenarios

During the workshop, participants weighted not only the criteria they found to be most relevant and important for Jordan's energy and water sectors but also ranked previously developed preliminary scenarios. Based on literature reviews, driven by two main dimensions—water and energy—possible futures were envisioned. The two dimensions can be described by future developments, be it of political, economic, or technological nature. The scenario is a creation of a new future situation, independent of former developments. Here, backcasting rather than forecasting was used, defining a desired future and how to achieve it. The different futures open up the scenario funnel from positive extreme scenarios, alternative futures, trend scenarios, and negative extreme scenarios on the future horizon to 2040. In this case, for a baseline scenario, this may entail expected trends and developments as stated in NEPCO's and WAJ's annual reports.

The energy dimension can have three main expected futures:

- ***Baseline Energy (BE)*** is following expected trends and developments as stated in the NEPCO annual reports, e.g., the demand is expected to increase by an average of 3% annually from 3057 MW. This might include large scale PV and wind installations, as well as small scale nuclear. A higher priority is given to oil shale development, with a 470 MW expected to be operational in 2020, with a focus on energy independence as well as achieving a higher share of power generated from renewable energies, expected to cover 30% of the demand by 2022 [9]. Difficulties: security of energy supply; grid stability; power cut-offs and possible after-effects.
- ***Low Imports (LI),*** originally called ***No Imports(NI)***, was adjusted during the workshop following stakeholder's feedback. The low import assumption is based on findings of the MENA-Select project, aiming at energy independence, with up to 78 GW of installed capacity needed, including substantial wind (15 GW) and solar (25 GW) installations, as well as geothermal plants (3.5 GW). Large-scale CSP projects (20 GW) are needed as well as biomass (0.5 GW). Key in this scenario are extensive storage capacities, as envisioned in the MENA-Select project with 18 GW and 40 GWh respectively. Difficulties: sourcing of biomass; grid stability increasingly difficult with a large share of volatile energy sources introduced; large scale RE developments needed (high costs). It retains the acronym **NI** in the figures and tables below.
- ***Interconnected Gulf System (IGS)***is based on the NEPCO annual report of 2018. Electrical interconnections are possible with Egypt (550 MW), Palestine (26 MW), Iraq and Saudi Arabia to use the strengths of an interconnected electricity system. The currently (as of NEPCO, 2018) active interconnectors are with Egypt and Palestine, the others are stalled due to current prevailing conditions in the region. Difficulties: political tensions; a need for transboundary international cooperation.

The water dimension can be described by:

- ***Baseline Water (BW)***. In the baseline future, which is driven by securing water supply, deeper and additional wells, as well as dams to cover the increasing water demand are considered. A high priority is given to desalination and reduction in water losses. This scenario follows expected trends and planning processes already in the works in the water sector while analysing the expected changes in energy inputs. Difficulties: environmental impacts (disposal of brine from desalination); energy security including the effect of power cut-offs on water supply.
- ***Smart Operation (SO)***. Uses synergies of the water and energy sectors, e.g., using excess energy of electricity system for water pumping (smart operation of pumps), solar-powered water pumping or energy storage through the medium of water-pumped hydroelectricity storage. Difficulties: sector dialogue; internal institutional cooperation.

The combination of both dimensions resulted in six different combined scenarios, five of which were considered during the ranking processes (Table 2).

Table 2. Energy and water dimensions of different scenarios.

		Energy Dimension		
		Baseline Energy (BE)	**Low Imports (NI)**	**Interconnected Gulf System (IGS)**
Water dimension	Baseline Water (BW)	BW_BE	BW_NI [1]	BW_IGS
	Smart Operation (SO)	SO_BE	SO_NI	SO_IGS

[1] BW_NI was not considered in the rankings due to infeasibility.

In a subsequent analysis, the presented scenarios need to be filled with context and definitive figures. The MENA-Select project already offered various energy-driven scenarios developed by local stakeholders. In discussions with water and energy stakeholders, the possible futures needed to be further elaborated, and technological solutions were included [46].

4. Results

The results of four rounds of ranking as well as the ranking in the group of energy sector stakeholders showed the prevalence of economic and security rationales, namely, ranking the criterion of average annual system costs per kWh the highest. The availability of resources was ranked as the second most important criterion. The ranking was followed by security of energy and water supply and by internal institutional feasibility and transboundary political feasibility. All environmental criteria such as local and global environmental impacts were ranked at the very bottom. The local environmental impacts were ranked higher than global impacts. The same outcome considering environmental criteria having the lowest ranking was observed during all rounds of ranking with slight differences; as in some rounds, local environmental impacts were ranked higher and during other rounds, the global environmental impacts were ranked higher (see Figure 1 below).

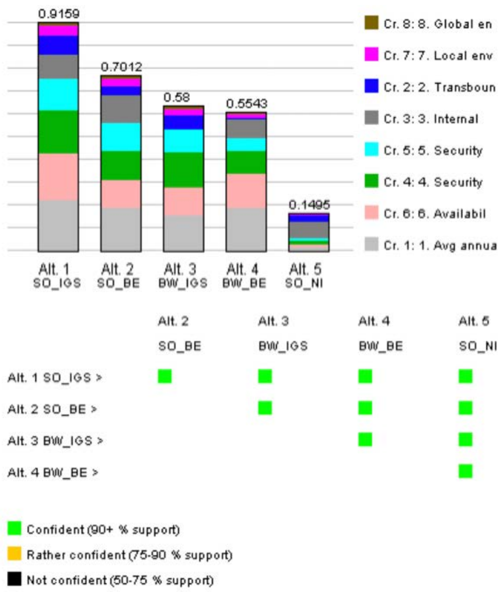


Figure 1. Results of MCDA (multi-criteria decision analysis) ranking for the group of energy sector stakeholders.

The average annual system cost per kWh was not only ranked the highest but significantly higher than other criteria. Figure 1 shows that this criterion has a weight of over 20% in all scenarios.

For the energy stakeholder group, the most preferred scenario is SO_IGS followed by SO_BE. These scenarios were followed by BW_BE and BW_IGS. Interestingly, the SO_NI scenario, which foresees a high share of domestically generated renewable energy sources, was considered the least preferable option, which is contradictory to the aim of utilizing domestic fuel sources such as oil shale and gaining energy independence.

The results of the ranking among the two groups of water energy stakeholders, as well as the results for the energy stakeholder group, are already described above and were more heterogeneous not only between the two groups but also within one group. For both groups, availability of service and security of water supply were the two most important criteria (Figures 2 and 3). Jointly, these two criteria weigh almost 50% for some of the scenarios (e.g., BW_BE). Environmental criteria such as local and global environmental impacts were ranked at the bottom. However, one group ranked global environmental impacts higher and another group ranked local above global impacts.

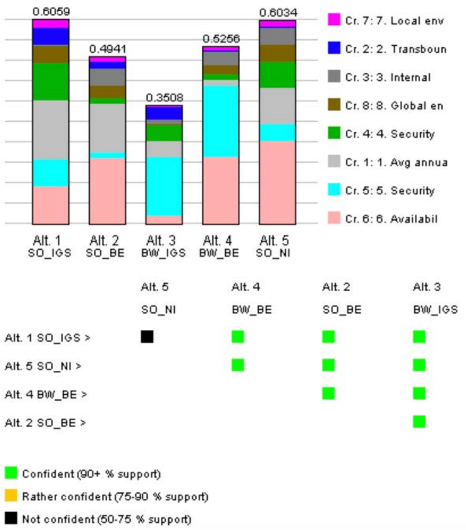


Figure 2. Results of MCDA ranking among the first group of water sector stakeholders.

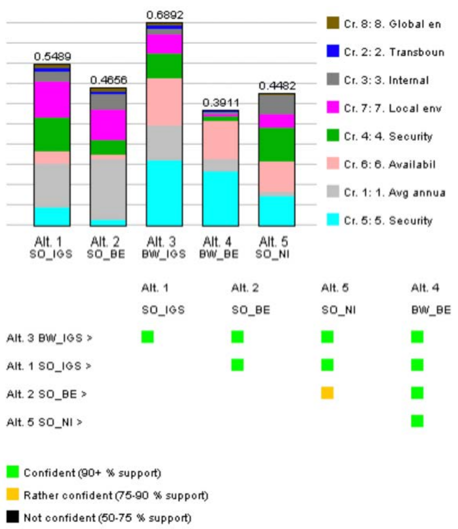


Figure 3. Results of MCDA ranking among the second group of water sector stakeholders.

For the first group of water stakeholders, the ranking was dominated by economic and security criteria such as availability of service, security of water supply, average annual system cost per kWh and security of energy supply. Annual average energy system costs per kWh ranked slightly higher than energy security.

Consideration of lower average annual energy system costs, involving an interconnected gulf grid and electricity trade in the region, made SO_IGS the most preferable scenario in both groups, of energy and water stakeholders. The weights of economic and security criteria in this scenario make up almost 80% of the entire preferences. The same is observed for SO_NI, where economic and security criteria are dominating. However, in this scenario, the role of the availability of services is weighted much higher than the role of the average annual system cost.

The results on energy security also demonstrated a clear preference for domestically available resources as they are perceived to offer more security in terms of supply and vulnerability to political tensions and import risks. The availability of services also got a significant weight in the BW_BE scenario, where the economic and security criteria are dominating.

Interestingly, in the water stakeholder group, a strong polarization of opinions could be observed between contrasting scenarios. One scenario involved high energy imports and the other relies on domestically available energy resources with low imports. This means that the discussion about energy options involving imports from other countries over domestically available resources is a contested issue. The discussion was mainly driven by the availability of services, the readiness to accept political risk, and further, to accept higher average annual energy system costs in order to obtain a more secure energy supply solution. Domestically available energy sources are perceived as being more secure as their supply does not involve energy imports and political risks. However, in the context of Jordan, the domestically available energy source is oil shale, which has high instalment costs and being a fossil fuel, also high external effects and social costs of energy, adding to an environmentally harmful extraction.

The results for the abovementioned group showed that SO_IGS was the most preferable scenario followed by SO_NI with conflicting opinions between the scenarios regarding the energy dimension. The two following scenarios involve baseline energy futures such as BW_BE and SO_BE. BW_IGS is considered as the least preferable scenario of all.

For the second water group, the security of water supply was perceived as the most important criterion followed by average annual energy system cost per kWh and availability of services. Local environmental impacts were ranked much higher by this group than by any other group. This criterion plays a significant role in the SO_IGS scenario as well as the SO_BE scenario. Security of water supply plays an important role in both scenarios, which involve the baseline water dimension as well as in the SO_NI scenario.

The results for the second water group showed that both scenarios involving IGS on the energy dimension are the most preferable scenarios, with BW_IGS the most preferable scenario and SO_IGS the second most preferable. These scenarios are followed by scenarios involving smart operation in the water dimension, viz. SO_BE and SO_NI. BW_BE was considered to be the least preferable scenario.

The results for all three stakeholder groups show an overarching preference for the Interconnected Gulf System in the energy dimension. Additionally, SO (Smart Operation) is being ranked as the most preferable and second most preferable for all three groups concerning the water dimension (see Table 3 below).

Table 3. MCDA results for all groups of stakeholders.

Ranking	1st	2nd	3rd	4th	5th
Energy group	SO_IGS	SO_BE	BW_IGS	BW_BE	SO_NI
Water group 1	SO_IGS	SO_NI	BW_BE	SO_BE	BW_IGS
Water group 2	BW_IGS	SO_IGS	SO_BE	SO_NI	BW_BE

There are two conflicting opinions apparent. Within water group 1 between IGS and NI on the energy side (see the black square in Figure 2 indicating no clear ranking outcome between SO_IGS and SO_NI), as well as between the two water groups regarding SO or BW as to the most preferable for the water dimension. There seems to be no strong conflict between the energy and water groups regarding the energy dimension since all three groups prefer IGS. However, the conflict between water group 1 and the energy group should be further investigated since the NI energy dimension is considered to be the second most favourable option by water group 1, whereas it was considered the least favourable option by the energy stakeholder group.

5. Summary and Concluding Remarks

The presented results regarding water–energy nexus governance in Jordan can increase the sustainability of the water and energy sectors. Using a computer-supported co-creative approach for evaluating stakeholder preferences on criteria and possible future scenarios of the sectors, joint challenges, opportunities, and preferences were identified. The MCDA approach allowed to value and rank socio-economic aspects as well as techno-economic criteria for both systems and joint scenarios.

The here presented detailed analysis of preliminary scenarios describing possible energy and water futures ranked under a set of water and energy sectors' relevant criteria, indicated that there is no fundamental conflict in opinions between the energy and water sectors. Each scenario's performance was also evaluated with respect to the robustness of the results, where the entire ranges of possible alternative values and criteria weights are considered. Using second-order probabilistic considerations, it was furthermore analysed how plausible it is that a scenario outranks the remaining ones. The analysis of multi-stakeholder multi-criteria situations of this kind requires elaborated calculations, which is why a decision methodology and a software tool for large-scale decisions were used to support the evaluation. The results also indicate that the ranking results are quite stable.

The main problems in the water sector are water scarcity, the high electricity consumption for water pumping, and the low water tariff, as current tariffs do not allow water utilities to recover all their costs. The energy sector suffers from different problems such as excess in generation capacity at a high cost compared to the electricity produced through renewable energy projects, its commitment to long-term agreements to purchase fuel and oil shale projects as a result of predictions, and expectations of increased demand for electric power.

The most preferred scenario by different groups is SO_IGS. This indicates that the two sectors find connecting with other countries to be the most preferable solution to mitigate the problems of both sectors. Through this option, Jordan will play a regional role by connecting to other countries to export the excessive electricity which may enable the energy sector to generate profits and stop the losses. The smart operation scenario will enable the use of innovative energy technologies, such as load shifting, energy storage, water pumping without electricity grid connection, and energy recovery through small hydropower plants.

The water and energy sectors are fundamentally linked. In Jordan, especially in the face of a changing climate, a water–energy nexus holds a number of challenges but also opportunities. A key point in exploring synergies is the identification of such, as well as the communication between the water and energy sectors. The nexus is a complex problem, which requires new forms of cooperation between various stakeholders involved in the energy and water sectors to avoid lasting conflicts and inefficiencies. Employing a participatory multi-stakeholder, multi-criteria framework to the energy–water nexus case in Jordan promotes a clear understanding of where different stakeholder groups stand; especially in the context of the energy–water nexus, where common challenges and synergies need to be identified. The previously poor communicative situation between the energy and water sectors was improved through the presented approach facilitating dialogue and discussion. Furthermore, the sectors were able to develop joint solutions for common problems. This understanding and agreement can form the basis of a joint water–energy nexus policy used in the continued negotiation process between and within national and international cooperation, as well as promoting and developing acceptable suggestions to solve complex problems for both sectors.

Author Contributions: Authors contributed equally to the conceptualisation, data collection, methodology and writing of this paper. All authors have read and agreed to the published version of the manuscript.

Funding: We are grateful to GIZ and H2020 Co-Inform project for funding of data collection, development of methodology and writing of this paper.

Conflicts of Interest: We declare no conflict of interests.

References

1. World Bank Group. *The Cost of Irrigation Water in the Jordan Valley (English)*; Water Partnership Program (WPP): Washington, DC, USA, 2016. Available online: http://documents.worldbank.org/curated/en/275541467993509610/The-cost-of-irrigation-water-in-the-Jordan-Valley (accessed on 1 July 2020).
2. Ministry of Water and Irrigation of Jordan. *Water Yearbook: Hydrological Year 2016–2017*; Ministry of Water and Irrigation of Jordan: Amman, Jordan, 2018.
3. Ministry of Water and Irrigation of Jordan. *Jordan Water Sector: Facts and Figures*; Ministry of Water and Irrigation of Jordan: Amman, Jordan, 2017.
4. Ministry of Water and Irrigation of Jordan. *National Water Strategy 2016–2025*; Ministry of Water and Irrigation of Jordan: Amman, Jordan, 2016.
5. Keulertz, M.; Sowers, J.; Woertz, E.; Mohtar, R. The water-energy-food nexus in arid regions. In *The Oxford Handbook of Water Politics and Policy*; Oxford University Press: Oxford, UK, 2016.
6. Siddiqi, A.; Anadon, L.D. The water–energy nexus in Middle East and North Africa. *Energy Policy* **2011**, *39*, 4529–4540. [CrossRef]
7. Ministry of Energy and Mineral Resources. *Renewable Energy Program in Jordan*; Ministry of Energy and Mineral Resources: Amman, Jordan, 2019.
8. EDAMA Association. *Recommendations for Energy Sector Strategy*; EDAMA Association: Amman, Jordan, 2019.
9. National Electric Power Co (NEPCO). *Annual Report*; National Electric Power Co (NEPCO): Amman, Jordan, 2018.
10. *Grid's 'Technical Challenges' Prompt Freeze in Green Energy Projects*; Jordan Times: Amman, Jordan, 2019.
11. Ministry of Energy and Mineral Resources. *National Energy Strategy (2015–2025)*; Ministry of Energy and Mineral Resources: Amman, Jordan, 2015.
12. Sesma-Martín, D. Cooling water: A source of conflict in Spain, 1970–1980. *Sustainability* **2020**, *12*, 4650. [CrossRef]
13. Haddadin, M.J. A Jordanian socio-legal perspective on water management in the Jordan River—Dead Sea Basin. In *The Jordan River and Dead Sea Basin. NATO Science for Peace and Security Series C: Environmental Security*; Lipchin, C., Sandler, D., Cushman, E., Eds.; Springer: Dordrecht, The Netherlands, 2009.
14. Olsson, G.; Lund, P. Water and energy—Interconnections and conflicts. *Glob. Chall.* **2017**, *1*, 1700056. [CrossRef]
15. Sesma-Martín, D. The river's light: Water needs for thermoelectric power generation in the Ebro River Basin, 1969–2015. *Water* **2019**, *11*, 441. [CrossRef]
16. Scott, C.A.; Pierce, S.A.; Pasqualetti, M.J.; Jones, A.L.; Montz, B.E.; Hoover, J.H. Policy and institutional dimensions of the water–energy nexus. *Energy Policy* **2011**, *39*, 6622–6630. [CrossRef]
17. USAID-IDARA. *Water Residential Guide*; USAID-IDARA: Amman, Jordan, 2014.
18. USAID-IDARA. *Rainwater Harvesting Study Report*; USAID-IDARA: Amman, Jordan, 2011.
19. United Nations Development Programme. Jordan's Third National Communication Report on Climate Change. 2014. Available online: https://www.undp.org/content/dam/jordan/docs/Publications/Enviro/TNC%20jordan%20pdf.pdf (accessed on 25 June 2020).
20. United Nations Economic, Social Commission for Western Asia (ESCWA). Arab Climate Change Assessment Report—Main Report. 2017. Available online: https://www.unescwa.org/sites/www.unescwa.org/files/events/files/riccar_main_report_2017.pdf (accessed on 25 June 2020).
21. Elayyan, W. (Former Head of finance and International Cooperation Directorate at Water Authority of Jordan-WAJ) in interview with the authors. 23 August 2019.
22. Capodaglio, A. Fit-for-purpose urban wastewater reuse: Analysis of issues and available technologies for sustainable multiple barrier approaches. *Crit. Rev. Env. Sci. Technol.* **2020**, 1–48. [CrossRef]
23. Capodaglio, A.; Olsson, G. Energy Issues in Sustainable Urban Wastewater Management: Use, Demand Reduction and Recovery in the Urban Water Cycle. *Sustainability* **2020**, *12*, 266. [CrossRef]
24. Fasth, T.; Bohman, S.; Larsson, A.; Ekenberg, L.; Danielson, M. Portfolio Decision Analysis for Evaluating Stakeholder Conflicts in Land Use Planning. *Group Decis. Negot.* **2020**, *29*, 321–343. [CrossRef]
25. Danielson, M.; Ekenberg, L.; Larsson, A.; Riabacke, M. Weighting under ambiguous preferences and imprecise differences in a cardinal rank ordering process. *Int. J. Comput. Intell. Syst.* **2014**, *7*, 105–112. [CrossRef]

26. Komendantova, N.; Ekenberg, L.; Marashdeh, L.; Al-Salaymeh, A.; Linnerooth-Bayer, J.; Danielson, M. Are Energy security concerns dominating over environmental concerns? Evidence from stakeholder participation process on energy transition in Jordan. *Climate* **2018**, *6*, 88. [CrossRef]
27. Komendantova, N.; Schinko, T.; Patt, A. De-risking policies as a substantial determinant of climate change mitigation costs in developing countries: Case study of the Middle East and North African region. *Energy Policy* **2019**, *127*, 404–411. [CrossRef]
28. Komendantova, N.; Riegler, M.; Neumueller, S. Of transitions and models: Community engagement, democracy, and empowerment in the Austrian energy transition. *Energy Res. Soc. Sci.* **2018**, *39*, 141–151. [CrossRef]
29. Rowe, G.; Frewer, L. Public participation methods: A framework for evaluation. *Sci. Technol. Hum. Values* **2000**, *25*, 3–29. [CrossRef]
30. Arnstein, S.R. A ladder of citizen participation. *J. Am. Plan. Assoc.* **1969**, *35*, 216–224. [CrossRef]
31. Zillman, D.N.; Lucas, A. *Human Rights in Natural Resources*; Pring, A., Ed.; Oxford University Press: Oxford, UK, 2002.
32. Renn, O. *Risk Governance: Coping with Uncertainty in a Complex World*; Earthscan: London, UK, 2008.
33. Komentantova, N.; Neumuller, S. Discourses about energy transition in Austrian climate and energy model regions: Turning awareness into action. *Energy Environ.* **2020**. [CrossRef]
34. Dubois, D. Representation, propagation, and decision issues in risk analysis under incomplete probabilistic information. *Risk Anal.* **2010**, *30*, 361–368. [CrossRef]
35. Rohmer, J.; Baudrit, C. The use of the possibility theory to investigate the epistemic uncertainties within scenario-based earthquake risk assessments. *Nat. Hazards* **2010**, *56*, 613–632. [CrossRef]
36. Shapiro, A.F.; Koissi, M.C. Risk Assessment Applications of Fuzzy Logic. 2015. Available online: https://www.casact.org/education/annual/2015/presentations/C-13-Shapiro.pdf (accessed on 25 June 2020).
37. Dutta, P. Human health risk assessment under uncertain environment and its SWOT analysis. *Open Public Health J.* **2018**, *11*, 72–92. [CrossRef]
38. Danielson, M. Handling imperfect user statements in real-life decision analysis. *Int. J. Inf. Technol. Decis. Mak.* **2004**, *3*, 513–534. [CrossRef]
39. Danielson, M.; Ekenberg, L. Computing upper and lower bounds in interval decision trees. *Eur. J. Oper. Res.* **2007**, *181*, 808–816. [CrossRef]
40. Danielson, M.; Ekenberg, L. A Framework for analysing decisions under risk. *Eur. J. Oper. Res.* **1998**, *104*, 474–484. [CrossRef]
41. Danielson, M.; Ekenberg, L.; Larsson, A.; Sundgren, D. Second-order risk constraints in decision analysis. *Axioms* **2014**, *3*, 31–45.
42. Caster, O.; Norén, N.; Ekenberg, L.; Edwards, R. Quantitative benefit-risk assessment using only qualitative information on utilities. *Med. Decis. Mak.* **2012**, *32*, E1–E15. [CrossRef] [PubMed]
43. Ding, X.S.; Danielson, M.; Ekenberg, L. Disjoint programming in computational decision analysis. *J. Uncertain Syst.* **2010**, *1*, 4–13.
44. Danielson, M.; Ekenberg, L. The CAR method for using preference strength in multi-criteria decision making. *Group Decis. Negot.* **2016**, *25*, 775–797. [CrossRef]
45. Danielson, M.; Ekenberg, L. A Robustness Study of state-of-the-art surrogate weights for MCDM. *Group Decis. Negot.* **2017**, *26*, 677–691. [CrossRef]
46. Danielson, M.; Ekenberg, L. An improvement to swing techniques for elicitation in MCDM methods. *Knowl. Based Syst.* **2019**, *168*, 70–79. [CrossRef]
47. Danielson, M.; Ekenberg, L.; Larsson, A. A second order-based decision tool for evaluating decisions under conditions of severe uncertainty. *Knowl. Based Syst.* **2020**, *191*, 105219. [CrossRef]
48. Danielson, M.; Ekenberg, L.; Komendantova, N. A multi-stakeholder approach to energy transition policy formation in Jordan. In *Group Decision and Negotiation in an Uncertain World. GDN 2018*; Lecture Notes in Business Information Processing; Chen, Y., Kersten, G., Vetschera, R., Xu, H., Eds.; Springer: Cham, Switzerland, 2018; Volume 315, pp. 190–202. [CrossRef]

4

Analysis of cost-optimal renewable energy expansion for the near-term Jordanian electricity system[1]

Simon Hilpert
Franziska Dettner
Achmed Al-Salaymeh

[1]published as: S. Hilpert, F. Dettner, A. Al-Salaymeh (2020): Analysis of cost-optimal renewable energy expansion for the near-term Jordanian electricity system. *Sustainability*, 2020, 12, 9339.

sustainability

MDPI

Article

Analysis of Cost-Optimal Renewable Energy Expansion for the Near-Term Jordanian Electricity System

Simon Hilpert [1,*], Franziska Dettner [1] and Ahmed Al-Salaymeh [2]

1 Department of Energy and Environmental Management, Auf dem Campus 1, Europa Universität Flensburg, 24941 Flensburg, Germany; franziska.dettner@uni-flensburg.de
2 Mechanical Engineering Department, University of Jordan, Amman 11942, Jordan; salaymeh@ju.edu.jo
* Correspondence: simon.hilpert@uni-flensburg.de; Tel.: +49-461-805-3067

Received: 11 October 2020; Accepted: 6 November 2020; Published: 10 November 2020

check for updates

Abstract: Jordan is affected by an ever changing environment in the midst of climate change, political challenges, a fast growing economy and socio-economic pressures. Among other countries in the Middle East and Northern Africa, Jordan is facing a number of electricity related challenges, such as a rising energy demand, high dependency on fossil fuel imports and management of local, fossil and renewable resources. The paper presents an analysis based on an open source optimisation modelling approach identifying a cost-optimal extension of the Jordanian electricity system with growing demand projections until 2030 utilising pumped hydro energy storage and determining the costs of different CO_2 mitigation pathways. The results highlight the large potential of renewable energy for the cost effective, environmentally friendly and energy independent development of the Jordanian electricity sector. A share of up to 50% renewable energy can be achieved with only a minor increase in levelised cost of electricity from 54.42 to 57.04 $/MWh. In particular, a combination of photovoltaic and pumped hydro storage proved to be a superior solution compared to the expansion of existing shale oil deployments due to high costs and CO_2 emissions. Aiming for a more than 50% renewable energy share within the electricity mix calls for substantial wind energy deployments. In a system with a renewable energy share of 90%, wind energy covers 45% of the demand.

Keywords: energy system modelling; open science; GHG mitigation; pumped hydro storage; scenario analysis

1. Introduction and Background

Jordan is, in the midst of global warming and socio-political pressures, at an energy crossroads. Despite being in the middle of several oil-rich countries in the Middle East, Jordan is struggling to increase energy independence, being reliant almost entirely on fossil fuel imports. Despite having substantial renewable energy resources to increase energy independence and reduce greenhouse gas emissions, the most recently published energy strategy for 2040 [1] is more than conservative regarding their aims to increase the renewable energy share. Prior to the Arab Spring, Jordan relied almost entirely on natural gas imports from Egypt for electricity generation, which were disrupted in 2013 [2]. To satisfy energy demands, Jordan consequently switched to a petroleum based system. The government introduced substantial fuel subsidies to meet the increased costs and make energy available and affordable for the population [3], resulting in major governmental debt.

Between 1960 to 2011, six regional conflicts had direct or indirect effects on the energy sector in Jordan, namely, the Six Day War, the Lebanese Civil War, the Iraq–Iran War, the First Gulf war, the invasion of Iraq and the Egyptian revolution [4]. More recently, Jordan has been facing additional challenges concerning the energy and water sectors, such as a low level of foreign investment and substantial population growth due mainly to migration from war stricken Syria [5,6]. Unfortunately, there is a lack of literature dealing with the roles of foreign policy and politics and energy security in the case of Jordan. This rapidly changing and highly uncertain environment underlines the necessity for highly flexible energy system analysis tools to swiftly adjust to new circumstances.

1.1. Electricity Supply and Demand

Regardless of being in the midst of several oil-rich countries, Jordan struggles to secure its own energy resources for improved energy independence. Only recently, local oil shale resources were exploited, and a minor share of locally extracted natural gas was introduced to the system [7]. Table 1 introduces the installed capacities of Jordan's electricity system as of 2018 and the near-term forecast for 2023. In 2011, 97% of Jordan's energy needs were covered by oil and gas, consuming 19% of the Jordanian gross domestic product (GDP) [8] and only 2% were covered by renewable energy sources [9]. More recent, figures show that 19% of the installed capacity is covered by renewable energy power plants with 10.7% of the electricity generation of 2018 being covered by renewable energy sources [7]. Within the National Energy Masterplan for 2007–2020 [10] a reduction of energy dependency from 82% to 40% in 2020 was envisioned, which was not achieved, as Jordan is still importing 94% of its oil and gas to meet energy needs [11]. In 2018, 15% of the total electrical power consumption was used for water pumping, 45% in the residential sector, 22% in the industrial sector, 15% for commercial purposes and 2% for street lighting [12]. However, Jordan holds large renewable energy potential [5].

Table 1. Installed capacities in MW of Jordan's electricity system in 2018 based on NEPCO data [7] and for 2023 based on [1] with planned projects and retirements of conventional units (CC: combined cycle gas turbine, GT: gas turbine, DE: diesel engine, ST: Steam turbine)

	CC	GT	ST	DE	Shale-ST	Wind	PV	Hydro
2018	2740	83	602	814	-	280.4	698.4	12
2023	2567	83	363	810	470	663	1144	12

In 2018 the Jordanian peak load amounted to 3205 MW, which meant a decrease by about 3.4% from 3320 MW in 2017 [7]. NEPCO (National Electric Power Company) expects an increase of 1.9% by 2019 and a further 3% increase annually between 2019 and 2040 [7,12]. This means an electricity demand increase from 20,143 GWh to 38,261 GWh in 2040. Omary et al. [13] analyse the peak power demand development in three scenarios. The business as usual scenario assumes that the demand for electrical energy will grow continuously according to the growth of the last decade, reaching 25.3 TWh in 2030. The upper scenario assumes a higher increase with 30.3 TWh in 2030. The lower peak demand development path assumes a much lower demand of 15.8 TWh. Earlier studies examining potential future energy systems for Jordan, such as [14], expected an electricity demand of 106 TWh in 2050. This is due to the demand development between 2007 and 2013, showing a steady growth of electricity loads with an actual increase in consumption of 6.8% on average per year in the mentioned time period [8,12,15]. This was predicted to resume with a projected growth rate of 7.4% annually between 2014 and 2020 within the Master Strategy for Energy in Jordan [10], leading to an overestimation of the current demand. However, the most recent study from the Jordanian University of Science and Technology from 2019 [16] estimates a higher demand of 82.4 TWh for 2050 partly because of an electrification of other sectors. The unexpected demand decrease between 2018 and 2019, however, lead to a halt in the development of renewable energy projects. Before 2018, Jordan was progressing with the installation of renewable energies, becoming a leader in the Middle East on renewable developments. However, Jordan suspended renewable auctions and licenses for projects of 1 MW as of January 2019, due to concerns related to grid capacities [17]. Even considering a strictly fossil fuel based system, the future rising demand needs to be addressed, giving more stress to the grid, invalidating the argument of lacking grid capacity. Additionally, Jordan cancelled the tender for the first planned electrical storage project for renewable energy in 2020, inter alia due to the uncertain financial situation because of the global pandemic.

1.2. Strategies and Targets

A number of energy strategies were developed in Jordan: among others, the most relevant are the Energy Strategy 2030, the Energy Sector Strategy 2015–2025, the National Renewable Energy Action Plan, the National Energy Efficiency Action Plan and the Climate Change policy. However, some aims and visions are contradictory and incompatible, and previously set targets and goals were revised and neglected. For example the National Master Strategy of the Energy Sector for 2007–2020 and the National Strategy for the Development of Renewable Energy Resources stated the aim of 10% electricity generation based on renewable energies (wind and solar) by 2020, increasing to 20% by 2025. However, the latest energy strategy released in 2019 for 2018–2030 [1] aims in the baseline scenario at 21% for 2030, which indicates no evolution of the previously developed strategy. The penetration of renewable energy (RE) in the primary energy supply is predicted to increase from 3% in 2017 to 5% in 2020, reaching 6% in 2025 with no further increase up to 2030 in the reference case scenario [1]. The most ambitious scenario, increased sustainability, aims at 11% renewable penetration rate in 2030. Still, the energy import dependency will be as high as 73% in this scenario and between 92–94% in the reference case and business as usual scenario. As a least cost solution the share of renewable energy will not exceed 2.6 GW by 2030 (38% of installed capacity) with respect to the 2.4 GW of existing permits, and 5.7 GW by 2050 (47% of installed capacity). Contrary to the previous energy strategy and annual reports, which included the development of a nuclear power plant with a capacity of 220 or 660 MW being operational by 2026 [7], the revised strategy [1] does not foresee the development of nuclear energy.

Regarding CO_2 emission reduction targets, the revised energy strategy [1] envisions a CO_2 reduction of 10% by 2030; however, it fails to name a reference year. This goes along with the Intended Nationally Determined Contribution (INDC)[18], which aims at reducing greenhouse gas (GHG) emissions by 14% until 2030, again lacking a reference year. The mentioned 14% will be unconditionally full-filled by the country's own means at a maximal 1.5% reduction compared to a business as usual scenario. In comparison, the European Union's (EU) target is a reduction by 40% in 2030 compared to 1990 levels, and carbon neutrality by 2050 [19]. The temporary freeze in new renewable energy projects puts even this unambitious target at risk.

1.3. Research Question

The situation in Jordan puts strong emphases on energy independence and energy security because of the political and economical difficulties in the region. The research questions in this paper deal with the techno-economic assessment of the mid-term feature (2030). Therefore, we present an open source model based on the Open Energy Modelling Framework (oemof) [20] for the Jordanian electricity system. With the model the following research questions will be answered: (1) What is the cost-optimal mix, based on the current system, to meet the future electricity demand? (2) How can the future electricity demand be met by renewable energies in combination with pumped hydro and battery storage? (3) What are the costs of different RE shares in the electricity system?

2. State of the Art

2.1. Future Scenarios

The most recent study depicting the current Jordanian electricity system, as of 2018, underlines the number of challenges Jordan is facing, especially considering the current and coming energy demands [13]. The study does not offer any scenarios where energy storage is utilised, but does emphasise and suggest that the use of renewable energy resources could play a major role in a carbon relieved and more energy independent Jordanian energy system for 2030. Another recent study on electricity generation for Jordan was conducted by the University of Jordan, identifying mainly different scenarios in the face of two main issues, which are economic reasoning and geopolitical uncertainties [21]. Using GAMS, the study identified Combined Cycle Gas Turbine (CCGT) units mainly fired by natural gas in combination with PV and wind as the optimal choices with 70%, 19% and 11% shares respectively in 2018, changing to 10%, 71% and 19% in 2035. Dawoud et al. [21] recommend providing integrated storage options, without introducing concrete possibilities. Researchers from the school of energy systems with LUT Unjversity, Finland, [22] conducted an in-depth analysis of energy security of a 100% renewable energy transition in Jordan by 2050, projecting renewable electricity generation to increase from 0.1 TWh in 2015 to 110.7 TWh in 2050, 92% being covered by solar energy. Therefore, levelised cost of electricity (LCOE) develop from 78 EUR/MWh in 2015 to 61 EUR/MWh in 2050. For the calculation of scenarios an expansion model with 5 year time periods and an hourly resolution within each year is applied. The study recognises the importance of energy storage within a renewable system, introducing battery storage from 2025 onwards, with an installed capacity of 1 GWh increasing to approximately 67 GWh in 2050. Additionally, a compressed air energy storage (CAES) is included in the system in 2030, with a capacity of 31 TWh in 2050. Another study by the Jordan University of Science and Technology from 2019 [16] established various scenarios using EnergyPlan and LEAP, with one being 100% renewable, while others integrated natural gas, oil shale and nuclear power. The 100% renewable scenario was introduced with a high share of concentrated solar power (CSP), 10.6 GW, wind power of 4.5 GW and 25 GW of PV to cover the predicted demand of 2050 (82.4 TWh respective 14,350 MW peak load), and introduced a 90 GWh storage system to meet dispatchability problems. Kiwan and Al-Garibeh [16] found that the 100% is also economically feasible, with cumulative expansion cost of the renewable system amounting to $60 Billion compared to $52 Billion for the conventional system.

Within the MENA-Select (Sustainable Electricity Trajectories) project, participatory scenarios for the future Jordanian energy system for 2050 were established with local stakeholders [14]. In the other participating countries, Tunesia and Morocco, 100% renewable energy scenarios were considered and investigated; however, Jordanian stakeholders did not explore this possibility. The lowest CO_2 emissions were achieved within the no imports scenarios, reliant heavily on wind and PV (15 GW, 25 GW) as well as CSP (20 GW) and oil and gas (5 GW and 4 GW). Here, the largest energy storage (batteries) was modelled, with a capacity of 18 GW and an energy capacity of 40 GWh. Although this scenario is by far the most expensive, it was ranked the most preferable by local stakeholders due to the increased energy independence. However, due to changing developments, these scenario are not suitable to give guidance for the near and mid-term future. In another consecutive study, IIASA (International Institute for Applied Systems Analysis), among others [23], identified that energy security is preferable for all stakeholders over environmental concerns, which might be why a 100% renewable option is not as relevant for Jordan as for other countries.

2.2. Pumped Hydro Storage

The possibility of a pumped hydro storage system for Jordan was analysed within the Renewable Energy and Energy Efficiency Program for Jordan [24,25]. Pumped hydro storage (PHS) can facilitate a smoother integration of renewable, volatile energy sources into the national electricity system, if geographical features are beneficial. In Jordan, out of ten water reservoirs, three were identified to hold potential for pumped storage plants, namely, Mujib, King Talal and Wadi Arab. Mentioned here is the need for further studies to investigate the energy storage demand within the energy system, to verify assumptions. The study, however, did not analyse the integration of a pumped hydro storage into the Jordanian electricity system. The current energy strategy [1] advises in the increased sustainability, minimum dependency and rational use of energy scenario, a PHS of 220 MW to be introduced by 2025, to avoid renewable energy curtailment. Furthermore, the strategy selects Mujib as the only cost effective option. Generally speaking, a number of studies have been conducted that have identified the benefits of hybrid pumped hydro and battery storage for renewable energy based power systems, e.g., most recently [26]. In the Jordanian context, a number of studies have analysed in detail the renewable energy potential, such as a study by the Tafila Technical University [27] revising the renewable situation in Jordan in 2005. Here, a strong case for pro renewable energy was made, regarding energy security, energy independence and potentially lowered costs due to less operation and maintenance, as well as the environmental benefits in contrast to conventional energy sources. A more recent study of 2019 [28] explored the possibility of a combination of wind and pumped hydro storage within the Jordanian energy system. The team from the Yarmouk University, the University of Jordan and Texas A&M University used a Matlab optimisation toolbox to find the cost-optimal solution, showing that a combined wind and hydro storage system is economically, environmentally and technically more efficient than conventional power generation with CO_2 emissions and conventional grid energy purchases being reduced by almost 25%.

2.3. Contribution

As the State of the Art section shows, several modelling and scenario efforts have been made around the future Jordanian energy system. However, there is not an open source energy system modelling approach for Jordan, nor have the defined research questions been addressed. To our knowledge, no studies analysed how the existing energy system can be extended by renewable energy sources in combination with pumped hydro and battery storage to meet the expected rising energy demand in Jordan. In fast changing environments, open source models with open data can be of great value to adapt in a short manner. Additionally, the presented open source model can be used to assess similar research questions for any other country. Therefore, the presented work not only contributes to the scientific debate on decarbonisation of energy systems for climate change mitigation in Jordan, but also builds an important bridge for capacity building and development cooperation for other countries. The tool can facilitate a discussion among different sectors, e.g., the water and energy sectors, to identify joint solutions for common problems.

3. Mathematical Model

The developed and applied model is a linear (mixed-integer) optimisation model for the Jordanian electricity system. It is based on the open source package oemof-tabular [29]. In the following, endogenous (optimisation) variables are shown in bold to differentiate between these and exogenous model variables. The model minimises total operational cost for the time horizon T and all units $u \in U$, and annualised investment cost of all units $i \in I$, along with storage investments of all storage $s \in S$ for the Jordanian electricity system. Elements of the sets for the scenarios are listed in the Appendix A. The respective objective function is given below in Equation (1). The implemented model as well as the input data are provided in the Supplementary Material.

$$\min : \overbrace{\sum_{t\in T}\sum_{u\in U} c_u^{opex}\mathbf{p}_{u,t}}^{\text{operational cost}} + \overbrace{\sum_{i\in I} c_i^{capex,p}\mathbf{p}_i^{nom}}^{\text{power inv. cost}} + \overbrace{\sum_{s\in S} c_s^{capex,e}\mathbf{e}_s^{nom}}^{\text{energy inv. cost}} \tag{1}$$

The operational costs are calculated based on the efficiency η_u of a unit u and its fuel cost c_u^{fuel} according to Equation (2). Annualised investment costs c^{capex} are calculated based on the lifetime n, weighted cost of capital (WACC) i and specific investment cost of a technology $CAPEX$, along with the fixed operation and maintenance cost FOM in Equation (3). The scenario specific values for this study are found in Table 2 in the next section.

Table 2. Scenario assumptions for the year 2030. Renewable energy profiles (FLH) have been calculated based on renewables.ninja [30,31]. For calculation of annualised investment, weighted cost of capital (WACC) 5% was applied in all scenarios.

	η_u (-)	FOM (%/c^{capex})	CAPEX ($/kW)	c_u^{fuel} ($/MWh$_{th}$)	FLH (h)	Lifetime (Years)
Wind	1	3	1182 [32]	-	2050	20
PV	1	2	750 [32]	-	1912	20
CCGT	0.48 [1]	3.5	800 [1]	20.5	-	30
GT	0.33 [1]	3.5	550 [1]	20.5	-	30
ST	0.38 [1]	3.5	1300 [1]	20.5	-	30
DE	0.33 [1]	3.5		20.5	-	30
Oil shale ST	0.32 [1]	3	3720 [16]	25.2	-	30
Battery (power)	0.86[33]	3	306 [33]	-	-	10
PHS (power)	0.80[33]	1.5	1500 [34]	-	-	60
	(-)	(%/CAPEX)	($/kWh)	($/kWh$_{th}$)	(h)	
Battery (energy)	1	0	285 [33]	-	-	10

$$c^{opex_u} = \frac{c_u^{fuel}}{\eta_u} \tag{2}$$

$$c^{capex} = CAPEX \cdot \frac{(\mathrm{i} \cdot (1+\mathrm{i})^n)}{((1+\mathrm{i})^n - 1)} \cdot (1 + FOM) \tag{3}$$

Demand must equal the sum of supply of all producing units, as described in Equation (4). Note that in the case of the storage units, p can also take negative values when the storage is charging.

$$\sum_{u \in U} \mathbf{p}_{u,t} = d_t + \mathbf{p}_t^{excess} \qquad \forall t \in T \tag{4}$$

For all investment units, the supply is limited by the installed nominal power $\mathbf{p}_i^{nom}$ described in Equation (5).

$$0 \le \mathbf{p}_{i,t} \le \mathbf{p}_i^{nom} \qquad \forall i \in I, t \in T \tag{5}$$

$$\underline{p}_i \le \mathbf{p}_i^{nom} \le \overline{p}_i \qquad \forall i \in I \tag{6}$$

The energy storage balance in Equation (7) is applied for all modelled storage types. The balance includes standing losses η^{loss} as well as charge and discharge efficiencies $\eta^{in/out}$.

$$\mathbf{e}_{s,t} = \mathbf{e}_{s,t-1} \cdot \eta_s^{loss} - \frac{\mathbf{p}_{s,t}^{out}}{\eta_s^{out}} + \mathbf{p}_{s,t}^{in} \cdot \eta_s^{in} \qquad \forall s \in S, t \in T \tag{7}$$

Additionally, the power of the storage is limited by the optimised nominal power shown in Equation (8).

$$-\mathbf{p}_s^{nom} \le \mathbf{p}_{s,t} \le \mathbf{p}_s^{nom} \qquad \forall s \in S, t \in T \tag{8}$$

For all RE technologies, i.e., PV and wind, the power output is determined by Equation (9) where $c_t^{profile}$ is the time-dependent normalised generation profile of the unit $i \in I$. The profile data can be obtained from measurements, calculated from re-analysis weather data or directly obtained from databases such as renewables.ninja [30,31].

$$\mathbf{p}_{i,t} = c_{i,t}^{profile} \mathbf{p}_i^{nom} \qquad \forall i \in I, t \in T \tag{9}$$

Analogously to Equations (5) and (6), the energy storage level and its maximum investment level are bounded as shown in Equations (10) and (11).

$$e_s^{min} \cdot \mathbf{e}_s^{nom} \leq \mathbf{e}_{s,t} \leq \mathbf{e}_s^{nom} \qquad \forall s \in S, t \in T \tag{10}$$

$$0 \leq \mathbf{e}_s^{nom} \leq \overline{e}_s \qquad \forall s \in S \tag{11}$$

For all conventional units $c \in C$, upper and lower limits for the total energy supply over the time horizon T can be bounded with Equations (12) and (13).

$$\sum_{t \in T} \mathbf{p}_{c,t} \geq \underline{E}_c \qquad \forall c \in C \tag{12}$$

$$\sum_{t \in T} \mathbf{p}_{c,t} \leq \overline{E}_c \qquad \forall c \in C \tag{13}$$

To model RE penetration within the system by an exogenously defined RE share an additional constraint is introduced. The renewable energy share is defined by Equation (14) by the share of conventional technologies $c \in C$.

$$\sum_{t \in T} \sum_{c \in C} x_c^{flow}(t) \leq (1 - RE^{share}) \cdot c_l^{amount} \tag{14}$$

4. Scenario Assumptions

Within this study four different scenarios are modelled to analyse the future Jordanian electricity system. Based on NEPCO forecast, the demand for all scenarios is 28 TWh [7].

The **BASE scenario**, considering the existing power park of 2023 shown in Table 1, is a lower bound to the capacity expansion. The **CONT scenario** includes fossil fuel contracts for minimum gas consumption as well as operational constraints for the existing shale-oil power plant. The operation of the shale-oil unit is exogenous, set to 7500 h full load hours. For natural gas, 24 TWh_{th} annual gas consumption is set in the model. All other assumptions are the same as in the BASE scenario. As the energy independence in Jordan plays an important role, an **AUT scenario**, wherein only local resources can be utilised, has been added. Finally, the **GRE scenario** is an unconstrained electricity mix optimisation (greenfield planning approach). Therefore lower bounds on the investment of units were set; all costs and technical parameters were the same as in the BASE scenario. For all scenario setups, different shares of RE are modelled with Equation (14).

Costs and Technology Parameter

Table 2 summarises the cost and technology assumptions for all scenarios. For battery storage units a power to energy ratio of 1/6 was used; for PHS a ratio of 1/10 has been used in all scenarios. The PHS potential in this paper was derived from the work of [17]. According to the study, three (Mujib, Wadi Arab and King Talal) out of ten dams operated by the Jordan Valley authority are suitable for PHS installations. For these dams only an upper reservoir needs to constructed. Due to geological limitations, the aggregated PHS potential is restricted to 3750 MWh. Cost estimations for these PHS storage units are based on reference [34].

5. Results

5.1. Cost-Optimal Mix

The results of the scenarios for the cost-optimal mix are presented in Figures 1 and 2. The CONT and BASE scenarios result in a similar technology mix with RE shares of around 33%. Compared to the current power park, almost no additional investment in conventional units is required to meet the future demand. Instead, PV is expanded by capacity of 4.27 GW while wind capacity is not expanded for the cost-optimal mix. The GRE scenario shows that without current restrictions, the optimal mix consists of 3.74 GW of CCGT followed by 4.47 GW of PV and 0.99 GW of GT. The only scenario where storage units are installed is the AUT scenario. With 375 MW the PHS potential is fully exploited, and an additional 1.28 GW of battery storage is installed. The RE share of above 60% is significantly higher compared to the other scenarios. In addition to substantial PV capacity of 6.78 GW, wind capacity of 3.58 GW and oil shale capacity of 2.88 GW of are installed.

Except for the AUT scenario with 10.27 TWh_{el} of shale oil based supply, most electricity is still supplied by conventional units in the cost-optimal mix. For the cost-optimal case with no constraints on the RE share, 16.41 TWh is supplied by CCGT in the BASE scenario. With the contracts applied, the oil shale unit supplies 3.53 TWh, which causes a drop in the CCGT supply to 14.01 TWh. In both cases, around 8.16 TWh is produced by PV units. Notably, emissions of the cost-optimal AUT scenario (9.42 million t), with a RE share of above 60%, are similar to the CONT scenario (9.62 million t) with a RE share of about 30%, as emission factors of shale oil are higher and efficiency is lower compared to CCGT units. Emissions within the BASE and GRE scenarios are lower with 7.93 and 8.27 million t respectively.

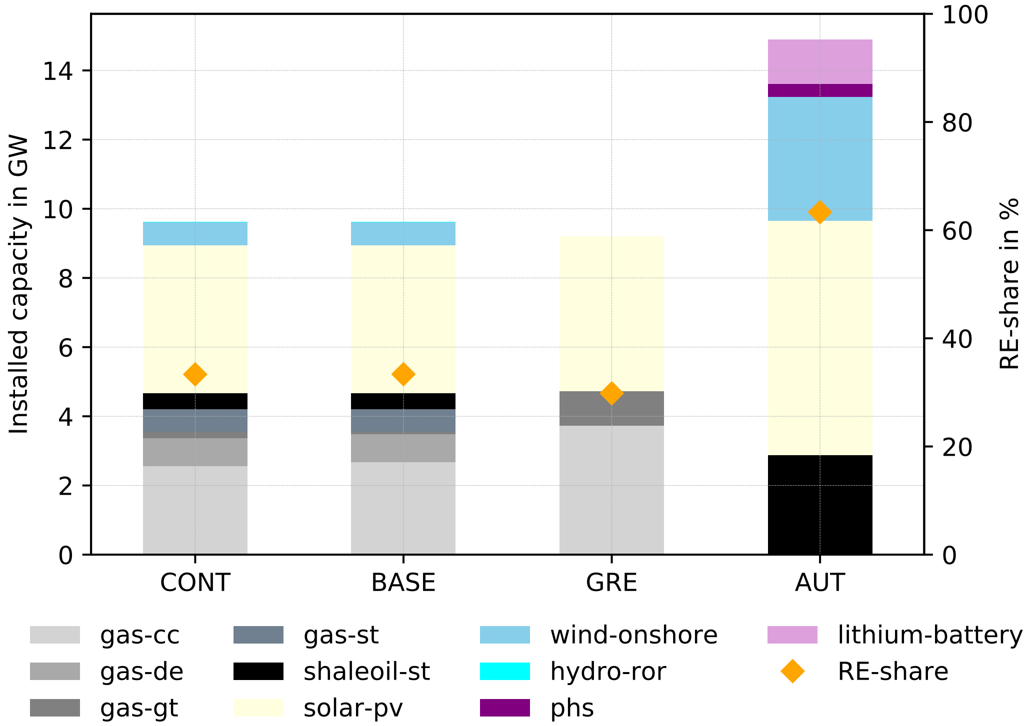


Figure 1. Installed capacities in the four scenarios and the cost-optimal case in GW (left axis) and renewable energy (RE) share in percent (right axis).

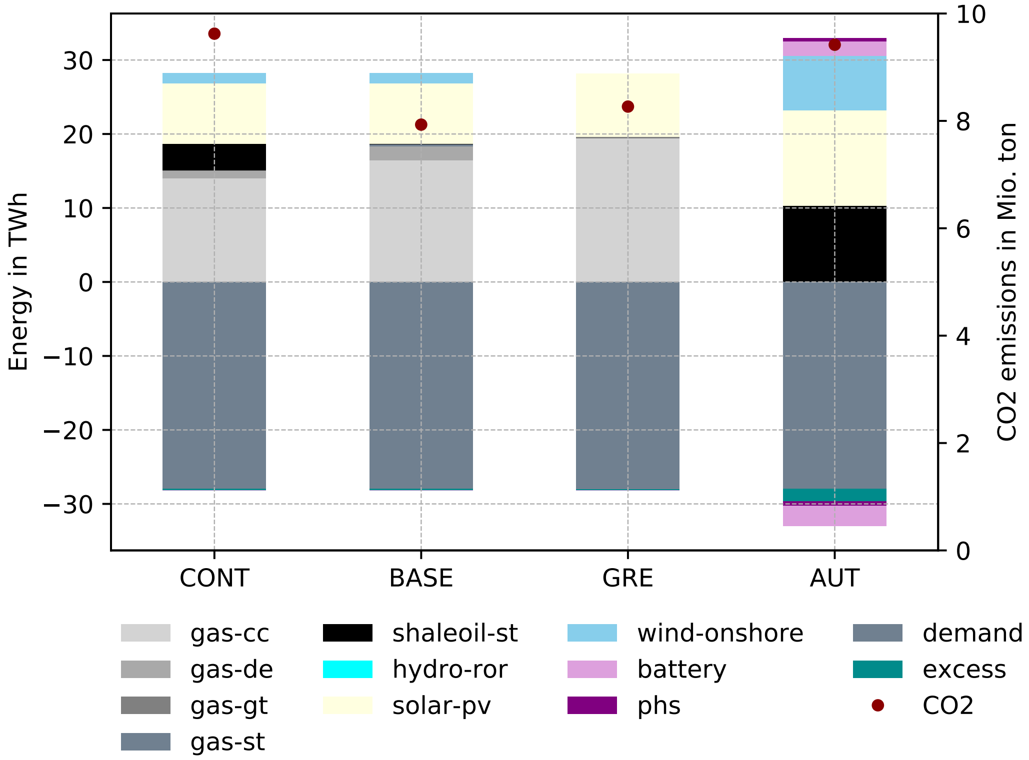


Figure 2. Supply and demand in the four scenarios and the cost-optimal case in TWh (left axis) and CO_2 emissions in million ton (right axis).

5.2. Varying Renewable Energy Shares

Figure 3 shows the installed capacities for 2030 for all scenarios with different RE shares. Detailed data are provided in the Appendix A. As described above, the cost-optimal mix in all scenarios already features a RE share 30% or above. Due to the lower bound on the gas consumption in the CONT scenario, higher shares of RE are not feasible within this setup. Compared to the status quo (2023), results show a significant increase in PV followed by wind investment in the BASE scenario to meet the increased demand of 28 TWh. In addition, minor investment in CCGT was chosen in the BASE scenario up to a RE share of 50%. This shows that due to the differences in marginal cost, additional CCGT investment is preferred instead of dispatching the shale-oil unit. PHS storage investment becomes relevant for RE shares of above 40% and the potential is fully exploited at shares above 50%. For up to 70% RE share, no additional storage than PHS is required to integrate the RE. Above 80% RE, investment in battery storage starts to increase significantly with over 3.15 GW installed capacity in the BASE-90 scenario and 3.82 GW in the AUT scenario.

Compared to the BASE scenario, a similar pattern with regard to installed capacities under different RE shares can be observed within the GRE scenario. However, in particular for shares above 80% RE, total conventional capacities are lower. Despite higher investment in shale oil, PV plays a bigger role than wind within the AUT scenario. In BASE-90 9.95 GW PV and 8.99 GW wind are installed compared to 10.89 GW PV and 6.93 GW in the AUT-90 case.

The energy supply, energy demand and corresponding CO_2 emissions are shown in Figure 4. For higher shares of RE, wind energy becomes more relevant and the need for additional battery storages increases significantly. In addition, limited (long) term storage options and missing transmissions to neighbouring countries cause high curtailment. In the BASE-90 scenario, over 35% of the RE production is curtailed. Due to higher storage capacities, curtailment is lower in the AUT scenarios.

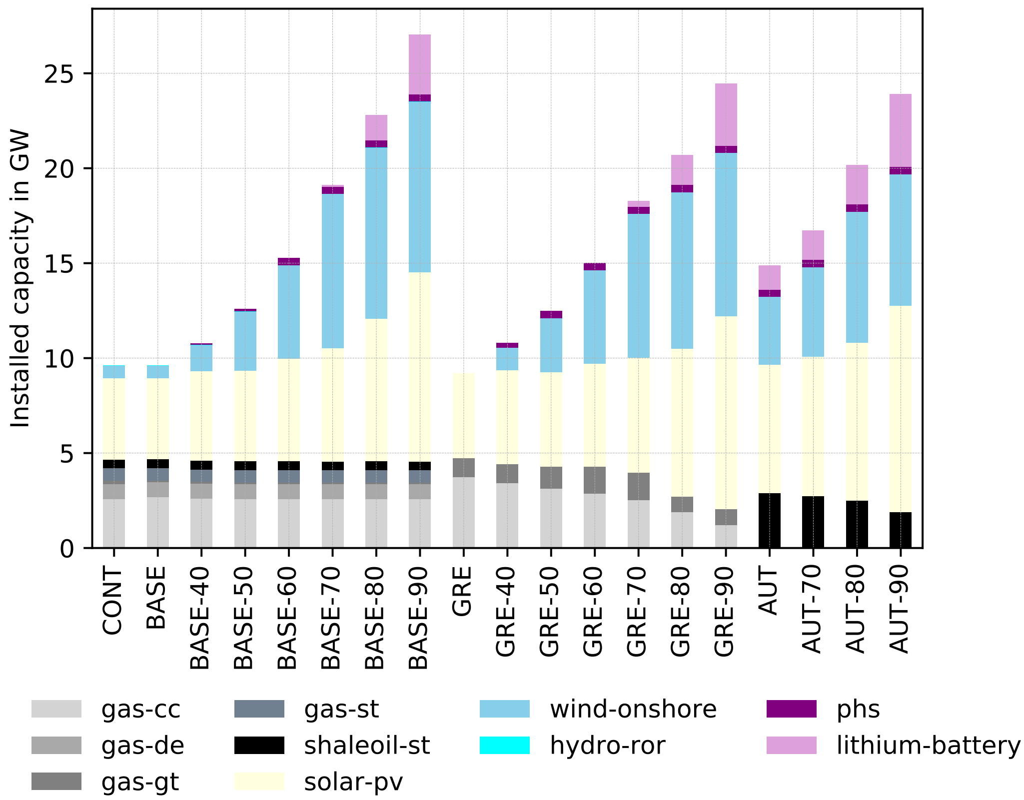


Figure 3. Installed capacities for all scenarios and varying renewable energy shares.

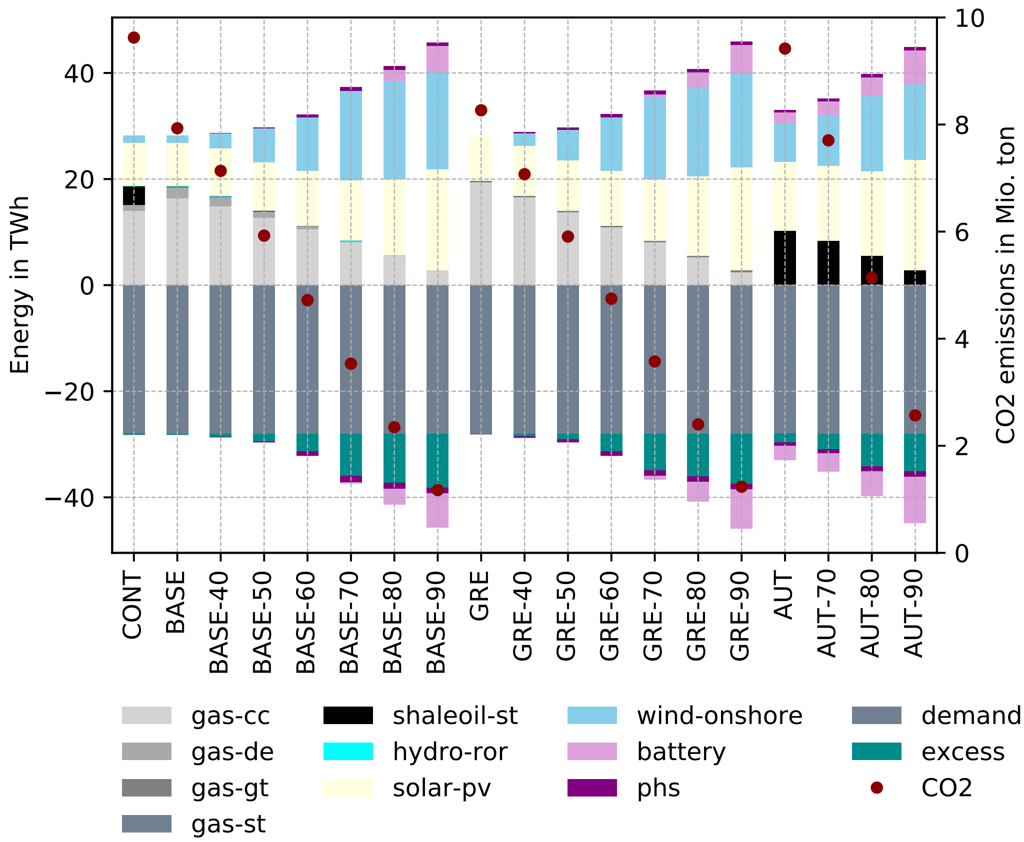


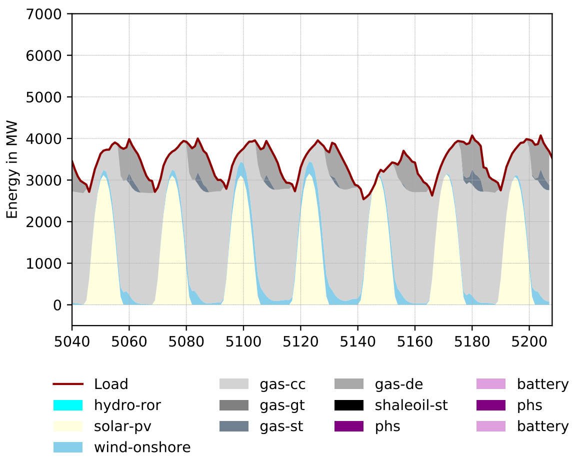
Figure 4. Supply/demand (left axis) and CO_2 emissions (right axis) for all scenarios.

With these results, three different stages within the system can be identified for the BASE scenarios: (1) low shares for up to 50% RE where PV supply is dominating; (2) medium share of RE between 60% and 80% where wind is higher than PV; and (3) high shares of above 80% where PV is equal to or more prevalent than wind. This shows the energy system's dynamic. PV has lower single technology cost of electricity and integrates well until a certain level of RE penetration is reached. After this point, the system value of wind starts to increase because it can supply electricity when PV is not available. Despite excellent solar resources and low cost, up to about 50% of the electricity supply comes from wind for scenarios of 90% RE share. A similar pattern can be identified within the GRE scenario. In contrast, the AUT scenarios feature higher storage capacities and therefore also in all cases higher PV supply than wind.

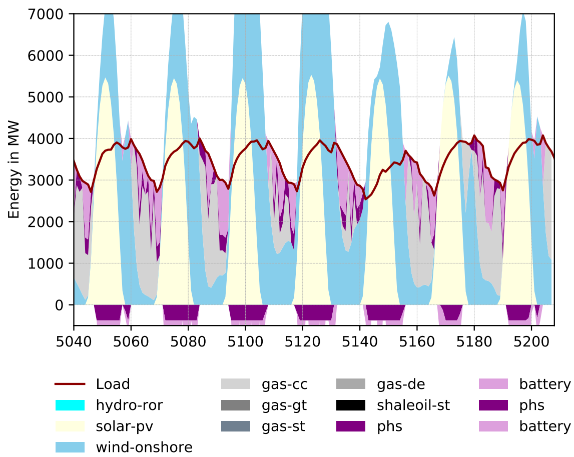
A major difference between the CONT and the BASE scenarios is the resulting level of CO_2 emissions. Due to the shale-oil unit, emissions are significantly higher for the CONT scenario.

5.3. System Operation

Figure 5 shows the dispatch of units for the BASE-40 and BASE-80 scenario. Within the system displayed in Figure 5a, mainly PV supply is consumed during the day while in the evening peaks and during the night CCGT and GT units are providing electricity. Storage operation is not required to integrate the RE. In contrast, Figure 5b shows the electricity system with a 80% RE supply. Here, consequences of increased RE supply can be observed. Storage operation increases notably, integrating wind and solar supply during the day and shifting this electricity to the evening peak. In addition, the high excess of RE during the day is also clearly visible.



(**a**) BASE-40



(**b**) BASE-80

Figure 5. Dispatch of supply and demand in a week of the year for two different RE shares within the BASE scenario.

For the same scenarios, the aggregated state of charge of the PHS units is shown in the heat map plot in Figure 6. The PV integrating pattern with fully charged storage units during the day and empty storage units in the morning is visible. It can be observed that the storage is operated more intensively in the case with higher share of RE. During the summer months, the storage is fully charged during the whole day in the BASE-40 scenario, whereas this can not be observed in the BASE-80 scenario.

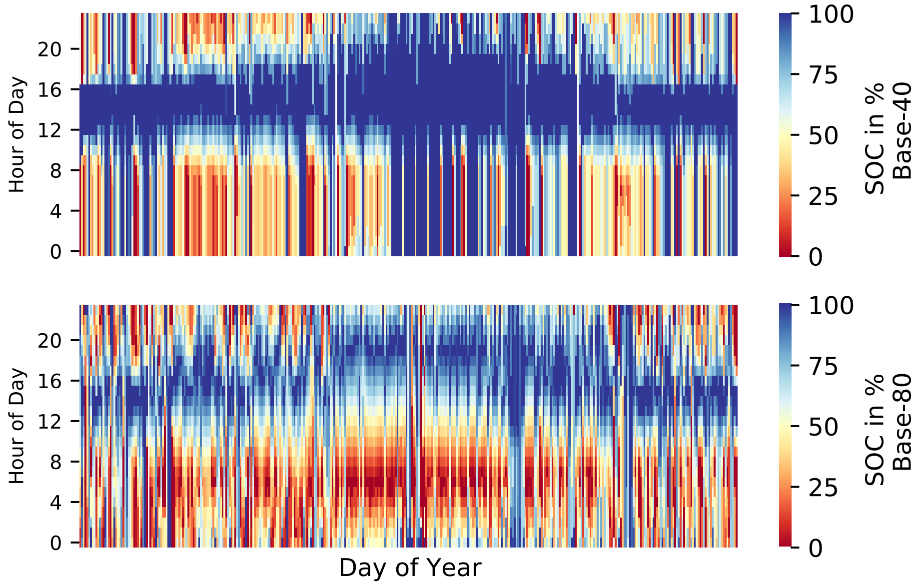


Figure 6. Aggregated SOC of pumped hydro storage (PHS) of BASE-40 (top) and BASE-80 (bottom) scenario.

5.4. Costs

Figure 7 shows the levelised cost of electricity (LCOE) for varying RE shares. LCOE has been calculated by dividing the total annualised investments and operational costs by the electricity demand covered. Note that for renewable energy systems, additional costs occur for integrating the intermittent electricity into the system, as discussed in [35].

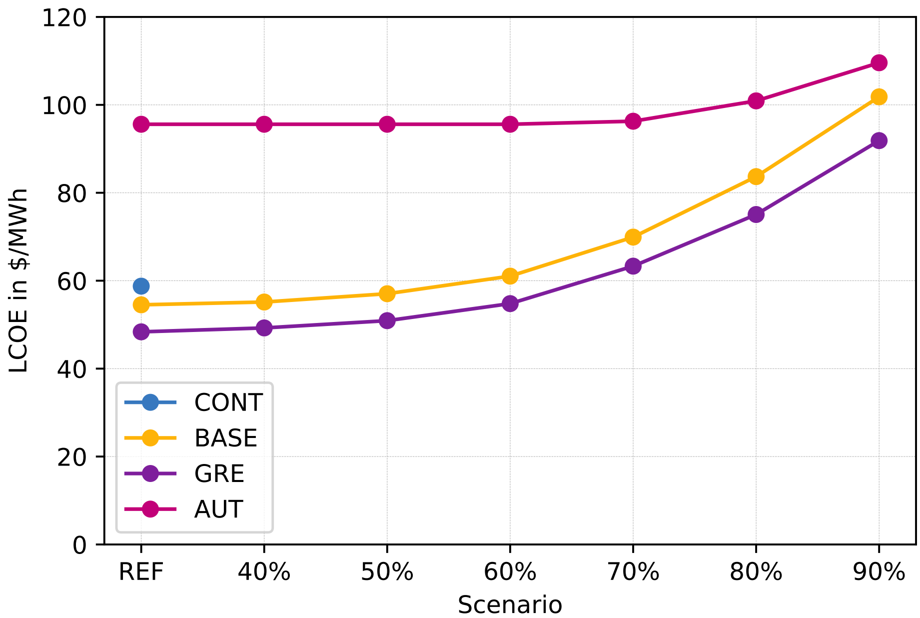


Figure 7. LCOE for different scenarios and RE shares.

Clearly, the AUT scenario comes with the highest cost, as autarchy has a high price. However, as it already features a RE share of above 60% in the cost-optimal mix, the increase in cost towards a 90% RE share setup is rather low in relative terms. The second highest cost for the cost-optimal case can be found within the CONT scenario with oil shale supply. The green field planning scenario GRE highlights that a combination of CCGT and RE is more cost efficient. The LCOE of the BASE and GRE setup do not differ significantly. With regard to rising RE shares, it can be observed that up to 50% RE can be achieved with a very small increase in LCOE from 54.52 to 57.04 $/MWh in the BASE scenario. For a RE share of up to 90%, LCOE increases almost to values twice as high as that in the cost-optimal case. The effects of higher storage requirements and thus additional investment costs and high excess electricity with curtailment can be reasons for these figures.

While PV has the lowest LCOE as a single piece of technology, the majority of the investment costs in scenarios with high shares of RE are caused by wind energy deployments and battery storage. The distribution of investment costs depicted in Figure A1 in the Appendix A shows that a combination of technologies within a system that strives for high RE shares has a different value compared to a single technology solution.

6. Discussion

The disruption of natural gas supply in 2011 caused by the Arab spring proved the unreliability and instability of the Jordanian energy system. Ever since, the country has failed to increase energy independence. With abundant renewable energy resources, a combination of PHS and RE energy and efficient CCGT units is the most cost effective way for gaining increased energy independence and simultaneously reducing GHG emissions.

6.1. Comparison with Other Studies

The presented results indicate a high share of RE within a cost-optimal energy system to meet the increased energy demand in Jordan by 2030 compared to what is envisioned within existing strategies, such as in references [1,7,18]. The herein determined cost-optimal energy mix includes a share of above 30% of RE by 2030, in all scenarios. In addition, the presented study also identified a greater role of wind energy and PHS for the Jordanian electricity system, contrary to [13], which underlined the importance of RE, while neglecting PHS utilisation though. Compared to [21], analysing the cost-optimal energy mix combining CCGT with PV and wind (10%, 71% and 19% in 2035), the calculated results indicate a lower share of PV—29.2% within cost-optimal mix of BASE scenario.

The integration of PHS is vital to a system with high renewable energy shares. The necessity of PHS and long-term battery storage to increase the share of RE and increase energy independence is recognised by [21,22]. The authors of [22] aim for 100% renewable energy supply by 2050, integrating 1 GWh of battery storage in 2025 up to 67 GWh in 2050; in this study 0.69 GWh PHS is necessary within the BASE scenario, with a RE share of 40%, and only with a share of above 70% RE does the battery storage become necessary. A RE share of 90% within the BASE scenario makes 3750 GWh PHS storage necessary. Along with [1], PHS is identified as an option to avoid or limit curtailment of renewable energies.

Supporting [27], the results clearly show reduced CO_2 emissions within the cost-optimal setting, which includes in all scenarios 30% or more RE and the high potential of further reductions due to the high potential of renewable energies within Jordan. Additionally, [28] proposed the combination of wind and PHS to be economically, environmentally and technically more efficient than conventional power generation in regard to CO_2 emissions. This is supported in this study.

As analysed within [4], a diversification of energy generation can have beneficial effects on the energy security of Jordan. According to this analysis, most relevant measures are continuing the decrease of imported energy through the utilisation of domestic energy resources such as oil shale and renewable sources (wind and PV). While this is certainly true for wind and PV, shale oil is environmentally and economically not recommendable, as shown within the here presented analysis. Instead, under the assumption of a growing electricity demand, PHS in combination with PV and wind energy can provide a secure, environmentally beneficial and cost effective energy supply.

Results show that shares of up to 50% RE share can be achieved by a slight increase in LCOE. Due to required storage investment and curtailment of RE, there is a high increase of LCOE for shares of up to 90%. However, it is important to note that an integrated electricity system of countries in the MENA region could reduce system costs significantly, as shown by [36]. Such integration will also help to reduce curtailment. Similarly, smart sector integration of the water and electricity sector is another option to increase RE penetration in the Jordanian energy system. Jordan, as one of the water-scarcest countries on the planet [37], has a high energy demand for the water sector, which is likely to increase in the coming years due to increased need for water pumping because of lowered water levels as well as the need for desalination of water as an additional source of fresh water.

6.2. Limitations of the Study

The study applied an open source investment model to analyse the future Jordanian electricity system. However, results need to be read in light of the modelling limitations. First of all, it is important to note that no transmission to neighbouring countries and Jordan's grid has been modelled. While the former can help to provide a solution with lower cost, due to reduced excess and lesser storage requirements, as discussed above, the latter can actually counteract these effects. In particular, curtailment and storage dispatch can be higher to keep the system balanced within the country on the distribution and transmission grid levels. Hence, storage units may be cost efficient within scenarios of shares below 40% RE.

Another important point is the cost-optimal dispatch based on perfect competition, where the existing contracts with independent power producers (IPP) need to be considered. While gas contracts have been integrated, additional contracts may exist that do not allow for a reduction of conventional power plant operation, and therefore limit RE expansion.

6.3. The Value of Open Source Tools

The context-specific boundaries, such as existing contracts, power plant characteristics and grid constraints, are important factors when modelling an electricity system. However, that information is not always available for scientists. In addition, political and economic dynamics can change fundamental assumptions, such as price and demand developments, in a short period of time. Therefore, open source approaches are of high value for further investigations. In addition to changes of basic assumptions and input data of this study, the model can be improved or extended. Among others, the applied Open Energy Modelling Framework (oemof) [20,29] provides the opportunity for detailed power plant modelling with minimum up and down times, part load efficiencies and linear optimal power flow grid modelling. Such functionalities could be integrated inside the developed model as well. The same holds for the PV and wind profiles, as [16] states, the exact renewable profiles which are technically feasible in Jordan have not been quantified yet.

7. Conclusions

The paper presents an analysis based on an open source optimisation modelling approach of the Jordanian electricity system in 2030. Results highlight and confirm the great potential of renewable energy for cost effective, environmentally friendly and more energy independent development in Jordan. Up to 50% renewable energy within the electricity system can be achieved with only a slight increase of levelised cost of electricity from 54.52 to 57.04 $/MWh. In particular, photovoltaic installations in combination with pumped hydro storage, as a low cost storage technology, seem to be a superior solution compared to the expansion of shale oil deployments due to high costs and CO_2 emissions. For higher shares of renewable energy, wind energy can play an important role, making up above 45% of the renewable energy supply in a 90% renewable energy based system.

However, high shares of renewable energy within the electricity mix require the analysis of long term storage options and grid expansion to neighbouring countries to avoid high costs as well as extensive curtailment of renewable energy. In addition, the water–energy sector cooperation using flexible desalination can be an important step to integrate renewable produced electricity and attenuate water stress at the same time. Within the transformation process, fossil fuel contracts pose a challenge, as they may hamper renewable energy expansion and increase integration cost. Modelling the scenario with existing long term gas contracts shows that renewable energy shares above 33% cannot be achieved, even under a growing electricity demand, by 2030. Therefore, strategic planning with a long term perspective is important for the Jordanian electricity system.

Supplementary Materials: The following are available online at https://github.com/znes/oemof-jordan/releases/tag/paper.

Author Contributions: Conceptualization, S.H.; methodology, S.H.; software, S.H.; validation, S.H. and F.D. and A.A.; formal analysis, S.H.; investigation, S.H. and F.D.; resources, S.H. and A.A; data curation, S.H. and F.D. and A.A.; writing—original draft preparation, S.H. and F.D. and A.A.; writing—review and editing, S.H. and F.D.; visualization, S.H.; supervision, S.H.; project administration, S.H.; funding acquisition: S.H. and F.D.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), grant number 81243459.

Acknowledgments: We acknowledge financial support for the article processing charge by the state of Schleswig-Holstein, Germany within the funding programme OpenAccess-Publikationsfonds. This work has been carried out during sabbatical leave granted to the co-author Ahmed Al-Salaymeh from the University of Jordan during the academic year 2019/2020. In addition, authors would like to thanks Clemens Wingenbach who was head of the project administration.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CAES	Compressed Air Energy Storage
CC	Combined Cycle
DE	Diesel Engine
FOM	Fixed operation and maintenance
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product
GHG	Green house gas
IIASA	International Institute of Applied Systems Analysis
INDC	Intended Nationally Determined Contribution
LEAP	Low Emission Analysis Plattform
LCOE	Levelised Cost of Electricity
MENA	Middle East and Northern Africa
NEPCO	National Electric Power Company
GT	Gas Turbine
PV	Photovoltaic
oemof	Open Energy System Modelling Framework
RE	Renewable Energy
ST	Steam Turbine
WACC	Weighted average cost of capital

Appendix A. Results

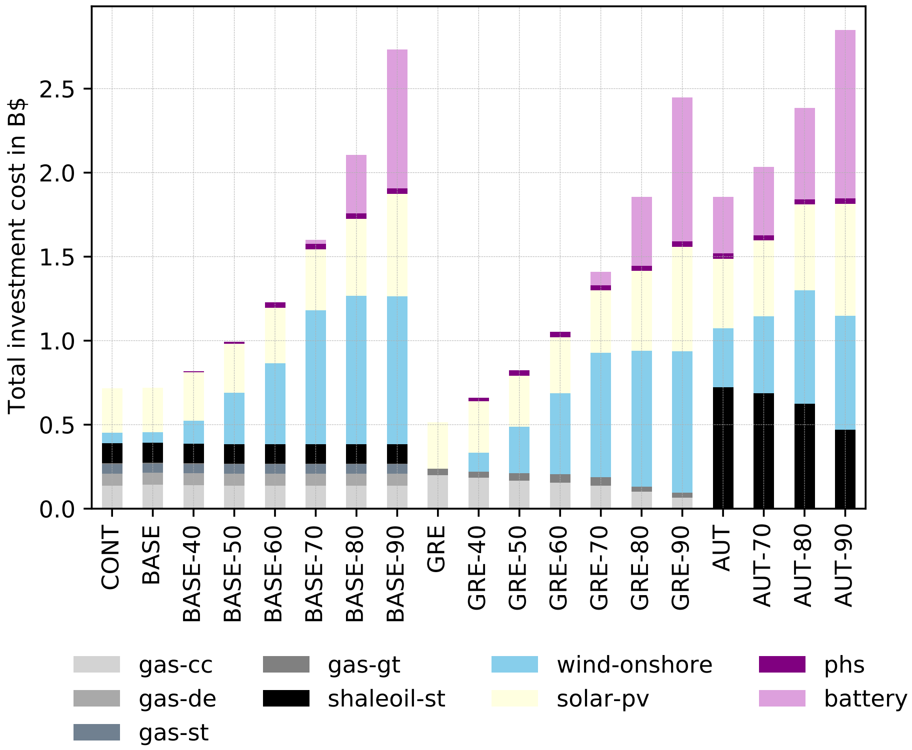


Figure A1. Annualised investment cost within all scenarios in Billion US $.

Table A1. LCOE in US $/MWh

	REF	40%	50%	60%	70%	80%	90%
CONT	58.76	-	-	-	-	-	-
BASE	54.52	55.15	57.04	61.04	69.92	83.68	101.83
GRE	48.37	49.26	50.91	54.79	63.31	75.06	91.87
AUT	95.59	95.59	95.59	95.59	96.28	100.91	109.58

Table A2. Annualised investment cost in million US $.

	Gas-cc	Gas-de	Gas-st	Gas-gt	Shaleoil-st	Wind-Onshore	Solar-pv	phs	Battery
CONT	138.27	70.9	55.67	7.02	118.09	64.77	261.93	0.00	0.00
BASE	144	70.9	55.67	3.07	118.09	64.77	262.27	0.00	0.00
BASE-40	140.08	70.9	55.67	3.07	118.09	135.65	288.44	5.56	0.00
BASE-50	138.27	70.9	55.67	3.07	118.09	303.45	293.54	10.43	0.00
BASE-60	138.27	70.9	55.67	3.07	118.09	479.53	332.55	30.16	0.00
BASE-70	138.27	70.9	55.67	3.07	118.09	795.27	365.10	30.16	21.22
BASE-80	138.27	70.9	55.67	3.07	118.09	881.53	460.03	30.16	346.41
BASE-90	138.27	70.9	55.67	3.07	118.09	878.64	610.81	30.16	826.25
GRE	201.19	0	0	36.84	0.00	0.00	274.11	0.00	0.00
GRE-40	184.21	0	0	37.23	0.00	113.16	304.40	19.88	0.00
GRE-50	167.89	0	0	43.4	0.00	277.35	304.91	30.16	0.00
GRE-60	154.26	0	0	52.39	0.00	480.34	333.36	30.16	0.00
GRE-70	136.23	0	0	53.36	0.00	738.83	372.42	30.16	77.48
GRE-80	102.57	0	0	29.37	0.00	807.10	477.83	30.16	410.32
GRE-90	64.84	0	0	31.69	0.00	841.63	622.36	30.16	855.80
AUT	-	-	-	-	724.27	349.56	416.02	30.16	335.34
AUT-70	-	-	-	-	686.15	460.42	451.38	30.16	406.25
AUT-80	-	-	-	-	626.15	673.96	511.25	30.16	543.04
AUT-90	-	-	-	-	471.19	676.66	668.73	30.16	1001.05

Table A3. Installed capacities in MW.

	Gas-cc	Gas-de	Gas-gt	Gas-st	Shaleoil-st	Solar-pv	Wind-Onshore	Hydro-ror	phs	Battery
CONT	2567	810	189	636	470	4267	663	12	0	0
BASE	2673	810	83	636	470	4272	663	12	0	0
BASE-40	2600	810	83	636	470	4698	1388	12	69	0
BASE-50	2567	810	83	636	470	4781	3106	12	129	0
BASE-60	2567	810	83	636	470	5417	4908	12	375	0
BASE-70	2567	810	83	636	470	5947	8140	12	375	80
BASE-80	2567	810	83	636	470	7494	9023	12	375	1320
BASE-90	2567	810	83	636	470	9950	8993	12	375	3150
GRE	3735	0	994	0	0	4465	0	0	0	0
GRE-40	3420	0	1005	0	0	4958	1158	0	247	0
GRE-50	3117	0	1172	0	0	4967	2839	0	375	0
GRE-60	2863	0	1414	0	0	5430	4916	0	375	0
GRE-70	2529	0	1440	0	0	6066	7562	0	375	295
GRE-80	1904	0	793	0	0	7784	8261	0	375	1564
GRE-90	1203	0	855	0	0	10,138	8615	0	375	3263
AUT	0	0	0	0	2882	6777	3578	0	375	1278
AUT-70	0	0	0	0	2730	7353	4712	0	375	1548
AUT-80	0	0	0	0	2492	8328	6898	0	375	2070
AUT-90	0	0	0	0	1875	10,893	6926	0	375	3816

Table A4. Energy supply and demand in TWh.

	Gas-cc	Gas-de	Gas-gt	Gas-st	Shaleoil-st	Hydro-ror	Solar-pv	Wind-Onshore	Battery	phs	Demand	Excess	phs-cos	Battery-cos
CONT	14.01	1.07	0.00	0.06	3.53	0.02	8.16	1.36	0.00	0.00	−28.0	−0.21	0.00	0.00
BASE	16.41	1.94	0.01	0.29	0.01	0.02	8.17	1.36	0.00	0.00	−28.0	−0.21	0.00	0.00
BASE-40	14.85	1.71	0.00	0.23	0.01	0.02	8.99	2.85	0.00	0.05	−28.0	−0.63	−0.08	0.00
BASE-50	12.73	1.13	0.00	0.13	0.00	0.02	9.14	6.37	0.00	0.14	−28.0	−1.45	−0.23	0.00
BASE-60	10.55	0.61	0.00	0.04	0.00	0.02	10.36	10.06	0.00	0.56	−28.0	−3.33	−0.88	0.00
BASE-70	8.05	0.33	0.00	0.02	0.00	0.02	11.37	16.69	0.15	0.72	−28.0	−7.99	−1.15	−0.21
BASE-80	5.58	0.02	0.00	0.00	0.00	0.02	14.33	18.50	2.18	0.69	−28.0	−9.30	−1.07	−2.95
BASE-90	2.80	0.00	0.00	0.00	0.00	0.02	19.03	18.44	4.80	0.63	−28.0	−10.25	−0.98	−6.49
GRE	19.44	0.00	0.20	0.00	0.00	0.00	8.54	0.00	0.00	0.00	−28.0	−0.19	0.00	0.00
GRE-40	16.60	0.00	0.20	0.00	0.00	0.00	9.48	2.38	0.00	0.20	−28.0	−0.55	−0.31	0.00
GRE-50	13.77	0.00	0.23	0.00	0.00	0.00	9.50	5.82	0.00	0.38	−28.0	−1.10	−0.60	0.00
GRE-60	10.90	0.00	0.30	0.00	0.00	0.00	10.38	10.08	0.00	0.57	−28.0	−3.35	−0.89	0.00
GRE-70	8.10	0.00	0.30	0.00	0.00	0.00	11.60	15.51	0.50	0.67	−28.0	−6.93	−1.06	−0.69
GRE-80	5.32	0.00	0.28	0.00	0.00	0.00	14.89	16.94	2.68	0.65	−28.0	−8.05	−1.03	−3.68
GRE-90	2.47	0.00	0.33	0.00	0.00	0.00	19.39	17.66	5.42	0.61	−28.0	−9.49	−0.98	−7.41
AUT	0.00	0.00	0.00	0.00	10.27	0.00	12.96	7.34	2.00	0.42	−28.0	−1.62	−0.66	−2.70
AUT-70	0.00	0.00	0.00	0.00	8.40	0.00	14.06	9.66	2.53	0.50	−28.0	−2.95	−0.78	−3.42
AUT-80	0.00	0.00	0.00	0.00	5.60	0.00	15.93	14.14	3.48	0.59	−28.0	−6.11	−0.92	−4.71
AUT-90	0.00	0.00	0.00	0.00	2.80	0.00	20.83	14.20	6.40	0.60	−28.0	−7.14	−0.96	−8.73

Appendix A.1. Mathematical Symbols

Table A5. Sets used in the model description and values of these sets used within the applied scenarios.

Symbol	Index	Description	Elements of Sets in Scenarios	Unit
T	t	Timesteps	{1...8760}	h
R	r	Renewable units	{Wind, PV}	MW
C	c	Conventional units	{CCGT, GT, ST, DE, Oil-shale ST}	MW
S	s	Storage units	{Battery, PHS}	MW, MWh
I	i	Investment units	Scenario dependet	-
U	u	All supply units ($R \cup C \cup S$)	-	-

Table A6. Optimisation variables used in the model description.

Symbol	Description
$\mathbf{p}_t$	Power output at timestep t
$\mathbf{p}^{nom}$	Upper limit of power output
$\mathbf{e}_{s,t}$	Storage level of storage s at timestep
$\mathbf{e}_s^{nom}$	Upper limit of storage output
$\mathbf{p}_t^{excess}$	Excess variable

Table A7. Exogenous model variables used in the model description.

Symbol	Description
$\overline{p}_i$	Upper power investment limit of unit i
$\underline{p}_i$	Lower power investment limit of unit i
$\overline{e}_s$	Upper energy investment limit of storage s
d_t	Electricity demand at timestep t
η_s^{loss}	Standing loss of storage s
η_s^{in}	Charge efficiency of storage s
η_s^{out}	Discharge efficiency of storage s
c_u^{opex}	Operational expenditure of unit u
$c_i^{capex,p}$	(Annualised) power expenditure of unit i
$c_s^{capex,e}$	(Annualised) energy capital expenditure of storage s
$c_r^{profile}$	Generation profile of renewable energy unit r
e_c	Emission factor of power output of unit c

References

1. Tigas, K.; Giannakidis, G.; Perrakis, K.; Kafantaris, N.; Mandoulidis, P. *Development of Energy Strategy in Jordan for 2018–2030 and Prospects up to 2050*; Technical Assistance 2016/380-325; European Union: Brussels, Belgium, 2019.
2. Wenzel, T.; Asen, J. Market Info Jordan—Photovoltaics. Technical Report, Deutsche Energie-Agentur GmbH (dena) -German Energy Agency, Berlin. 2014. Available online: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/3205_Market_Info_Jordan_Photovoltaic.pdf (accessed on 31 August 2020).
3. Aziz, A.; Jellema, J.; Serajuddin, U. *Energy Subsidies Reform in Jordan: Welfare Implications of Different Scenarios*; World Bank: Washington, DC, USA, 2015; [CrossRef]
4. Alshwawra, A.; Almuhtady, A. Impact of Regional Conflicts on Energy Security in Jordan. *Int. J. Energy Econ. Policy* **2020**, *10*, 45–50, [CrossRef]
5. Komendantova, N.; Irshaid, J.; Marashdeh, L.; Al-Salaymeh, A.; Ekenberg, L.; Linnerooth-Bayer, J. *Background Paper: Country Fact Sheet, Jordan—Energy and Development at a Glance, 2017*; Background Paper; Internationals Konversionszentrum Bonn: Bonn, Germany, 2017.
6. Ayasreh, E.A.; Bin Abu Bakar, M.Z.; Khosravi, R. The political concept of energy security: The case of Jordan. *Hum. Soc. Sci.* **2017**, *44*, 199–218.

7. NEPCO. *Annual Report 2018*; Technical report; National Electric Power Company: Amman, Jordan, 2018. Available online: https://www.nepco.com.jo/store/docs/web/2018_en.pdf (accessed on 17 August 2020).
8. NEPCO. *Annual Report 2017*; Technical report; National Electric Power Company: Amman, Jordan, 2017. Available online: https://www.nepco.com.jo/store/docs/web/2017_en.pdf (accessed on 31 August 2020).
9. Mohammed, D. Improved Regulatory & Institutional Framework for Energy Efficiency in Jordan. Legislative Aspects & Development Opportunities. In Proceedings of the 5th International Forum on Energy for SD-Tunis, Hammamet, Tunisia, 4–6 November 2014.
10. HKJ. *Updated Master Strategy of Energy Sector in Jordan for the Period (2007–2020)*; Summary; Hashemite Kingdom of Jordan: Amman, Jordan, 2007.
11. Abu-Rumman, G.; Khdair, A.I.; Khdair, S.I. Current status and future investment potential in renewable energy in Jordan: An overview. *Heliyon* **2020**, *6*, e03346, [CrossRef] [PubMed]
12. Almuhtady, A.; Alshwawra, A.; Alfaouri, M.; Al-Kouz, W.; Al-Hinti, I. Investigation of the trends of electricity demands in Jordan and its susceptibility to the ambient air temperature towards sustainable electricity generation. *Energy Sustain. Soc.* **2019**, *9*, 39, [CrossRef]
13. Al-omary, M.; Kaltschmitt, M.; Becker, C. Electricity system in Jordan: Status & prospects. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2398–2409, [CrossRef]
14. Zelt, O.; Krüger, C.; Blohm, M.; Bohm, S.; Far, S. Long-Term Electricity Scenarios for the MENA Region: Assessing the Preferences of Local Stakeholders Using Multi-Criteria Analyses. *Energies* **2019**, *12*, 3046, [CrossRef]
15. Danielson, M.; Ekenberg, L.; Komendantova, N. A Multi-stakeholder Approach to Energy Transition Policy Formation in Jordan. In *Group Decision and Negotiation in an Uncertain World*; Lecture Notes in Business Information Processing; Chen, Y., Kersten, G., Vetschera, R., Xu, H., Eds.; Springer: Cham, Switzerland, 2018; pp. 190–202, [CrossRef]
16. Kiwan, S.; Al-Gharibeh, E. Jordan toward a 100% renewable electricity system. *Renew. Energy* **2020**, *147*, 423–436, [CrossRef]
17. Emiliano, B. Jordan suspends renewables auctions, new licenses for projects over 1 MW. *PV Magazine, 28 January 2019.*
18. HKJ. *Intended Nationally Determined Contribution (INDC)*; Technical report; Hashemite Kingdom of Jordan: Amman, Jordan, 2015.
19. European Council. *2030 Climate and Energy Policy Framework*; European Council conclusions EUCO 169/14; European Council: Brussels, Belgium, 2014.
20. Hilpert, S.; Kaldemeyer, C.; Krien, U.; Günther, S.; Wingenbach, C.; Plessmann, G. The Open Energy Modelling Framework (oemof)—A new approach to facilitate open science in energy system modelling. *Energy Strategy Rev.* **2018**, *22*, 16–25, [CrossRef]
21. Dawoud, F.; Al-Salaymeh, A.; Abuzeid, O. Electricity Generation Scenarios for Jordan (2018–2035). *Indian J. Sci. Res.* **2019**, *10*, 16.
22. Azzuni, A.; Aghahosseini, A.; Ram, M.; Bogdanov, D.; Caldera, U.; Breyer, C. Energy Security Analysis for a 100% Renewable Energy Transition in Jordan by 2050. *Sustainability* **2020**, *12*, 4921, [CrossRef]
23. Komendantova, N.; Ekenberg, L.; Marashdeh, L.; Al Salaymeh, A.; Danielson, M.; Linnerooth-Bayer, J. Are Energy Security Concerns Dominating Environmental Concerns? Evidence from Stakeholder Participation Processes on Energy Transition in Jordan. *Climate* **2018**, *6*, 88, [CrossRef]
24. Homschmied-Carstens, S. *Report on the Analysis of Pumped-Storage Hydropower Potential in Jordan*; Technical Report; The Renewable Energy and Energy Efficiency Programme/Technical Assistance (Reee II Ta) Jordan: Amman, Jordan, 2018.
25. Alasis, E.; Homscheid-Carstens, S.; Schmitt, A.; Frobeen, H.; Uhrakeye, T.; Mik, J. Pre-Feasibility Study of Pumped-Storage Hydropower Potential in Jordan & at Mujib Reservoir. In Proceedings of the MENA-SELECT Project Regional Conference, Dead Sea, Jordan, 29–30 January 2018.
26. Javed, M.S.; Zhong, D.; Ma, T.; Song, A.; Ahmed, S. Hybrid pumped hydro and battery storage for renewable energy based power supply system. *Appl. Energy* **2020**, *257*, 114026, [CrossRef]
27. Hrayshat, E.S. Analysis of renewable energy situation in Jordan. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1873–1887, [CrossRef]
28. Al-Masri, R.A.; Chenoweth, J.; Murphy, R.J. Exploring the Status Quo of Water-Energy Nexus Policies and Governance in Jordan. *Environ. Sci. Policy* **2019**, *100*, 192–204, [CrossRef]

29. Hilpert, S.; Günther, S.; Söthe, M. Oemof Tabular. 2020. Available online: https://github.com/oemof/oemof-tabular (accessed on 1 October 2020).
30. Pfenninger, S.; Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **2016**, *114*, 1251–1265, [CrossRef]
31. Staffell, I.; Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **2016**, *114*, 1224–1239, [CrossRef]
32. Schröder, A.; Kunz, F.; Meiss, J.; Mendelevitch, R.; von Hirschhausen, C. *Current and Prospective Costs of Electricity Generation until 2050*; Data Documentation; Deutsches Insititut für Wirtschaftsforschung: Berlin, Germany, 2013.
33. Mongird, K.; Fotedar, V.; Viswanathan, V.; Koritarov, P.; Balducci, B.; Hadjerioua, J. *Energy Storage Technology and Cost Characterization Report*; Technical Report; US Department of Energy: Washington, DC, USA, 2019. Available online: https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf (accessed on 7 September 2020).
34. Lacal Arantegui, R.; Jaeger-Waldau, A.; Vellei, M.; Sigfusson, B.; Magagna, D.; Jakubcionis, M.; Perez Fortes Maria Del, M.; Lazarou, S.; Giuntoli, J.; Weidner Ronnefeld, E.; et al. *ETRI 2014—Energy Technology Reference Indicator Projections for 2010–2050*; EUR—Scientific and Technical Research Reports; Publications Office of the European Union: Luxembourg, 2014; [CrossRef]
35. Ueckerdt, F.; Hirth, L.; Luderer, G.; Edenhofer, O. System LCOE: What are the costs of variable renewables? *Energy* **2013**, *63*, 61–75. [CrossRef]
36. Aghahosseini, A.; Bogdanov, D.; Breyer, C. Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030. *Energy Strategy Rev.* **2020**, *28*, 100466, [CrossRef]
37. Al-Ansari, N.; Alibrahiem, N.; Alsaman, M.; Knutsson, S. Water Demand Management in Jordan. *Engineering* **2014**, *6*, 19–26, [CrossRef]

5

Open source modelling of scenarios for a 100% renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles[1]

André Harewood
Franziska Dettner
Simon Hilpert

[1]published as: A. Harewood, F. Dettner, S. Hilpert (2022): Open source modelling of scenarios for a 100% renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles. *Energy for Sustainable Development*, 68, 120-130

Energy for Sustainable Development 68 (2022) 120–130

Contents lists available at ScienceDirect

Energy for Sustainable Development

Open source modelling of scenarios for a 100% renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles

André Harewood, Franziska Dettner *, Simon Hilpert

Department of Energy and Environmental Management, Europa-Universität Flensburg, Auf dem Campus 1, 24943 Flensburg, Germany

A R T I C L E I N F O

Article history:
Received 24 August 2021
Revised 7 February 2022
Accepted 12 March 2022
Available online 31 March 2022

Keywords:
Energy transition
100% renewable systems
SIDS
Transport electrification
Open source energy modelling
Shore-to-ship power

A B S T R A C T

The high dependence on imported fuels and the potential for both climate change mitigation and economic diversification make Barbados' energy system particularly interesting for detailed transformation analysis. An open source energy system model is presented here for the analysis of a future Barbadian energy system. The model was applied in a scenario analysis, using a greenfield approach, to investigate cost-optimal and 100% renewable energy system configurations. Within the scenarios, the electrification of private passenger vehicles and cruise ships through shore-to-ship power supply was modelled to assess its impact on the energy system and the necessary investment in storage. Results show that for most scenarios of a system in 2030, a renewable energy share of over 80% is achieved in cost-optimal cases, even with a growing demand. The system's levelised costs of electricity range from 0.17 to 0.36 BBD/kWh in the cost-optimal scenarios and increase only moderately for 100% renewable systems. Under the reasonable assumption of decreasing photovoltaic investment costs, system costs of a 100% system may be lower than the current costs. The results show that pumped hydro-storage is a no-regret option for the Barbadian power system design. Overall, the results highlight the great potential of renewable energy as well as the technical and economic feasibility of a 100% renewable energy system for Barbados.

Introduction & background

Energy is key for the well-being and development of all societies. Especially Small Island Developing States (SIDS) are facing numerous social, economic and environmental challenges when it comes to energy. Smaller market size in comparison to larger developed nation counterparts makes diversifying conventional power generation almost impossible, which favours large utility monopolies. In addition, most SIDS lack natural fossil resources and have difficulty diversifying economically (UNDP, 2018). Also, SIDS, including Barbados, are playing an increasingly important role pushing for climate action. With a dependence of more than 95% on fossil fuel imports, Barbados faces economic vulnerabilities that translate into high electricity prices (Henderson, 2013). At the same time, Barbados is the first island in the English-speaking Caribbean to commit to using 100% renewable energy (Henry et al., 2015). The heavy reliance on fuel imports for energy generation and transportation has affected and is affecting the nation's economic growth and social development. Barbados has favourable wind and solar resources to aim for a high share of renewable energy sources in the electricity sector as well as the potential to electrify other relevant fossil fuel based sectors.

Most energy system modelling at the international level and in the SIDS is done with closed black-box energy system models (ESMs). Typically, these are pre-set models and the source code is unavailable for third party review (Hilpert et al., 2018; Pfenninger & Staffell, 2016). This makes the analysis of the raw data and the methods used impossible for external analysis, especially for policy planning agencies and researchers. However, under the principles of the Open Energy Modelling (openmod) initiative, the data, code and documentation for the model used in this analysis is shared publicly. Open science should be the standard to promote transparency in scientific investigations. Increased openness is also significant to foster open and frank dialogue between SID state governments and the lending agencies that often require energy modelling investigations as a prerequisite for policy based loans (Atteridge & Savvidou, 2019). Whereas only a few studies address the possibility of a 100% RES for Barbados, none utilise an open source energy system model to create transparent and reproducible results. This study fills the above mentioned research gap by developing an open energy system model based on the Open Energy Modelling Framework (oemof) (Hilpert et al., 2018) for Barbados. This allows to determine,

* Corresponding author.
E-mail addresses: andre-gr.harewood@studierende.uni-flensburg.de (A. Harewood), franziska.dettner@uni-flensburg.de (F. Dettner), simon.hilpert@uni-flensburg.de (S. Hilpert).

https://doi.org/10.1016/j.esd.2022.03.004
0973-0826/

which share of renewable energies is technically and economically feasible in the future electricity system of Barbados in 2030, as well as modelling not yet electrified sectors, such as passenger transport and the cruise tourism sector. Applying a greenfield approach to energy system modelling, which removes all boundary conditions by today's systems to achieve the best overall system performance (Geidl et al., 2006), the present analysis is an indispensable prerequisite for future, detailed power system planning.

For an in depth analysis and a more profound understanding of the Barbadian energy system, including currently installed capacities, demand analysis, renewable energy potentials and political framework conditions please consult the supplementary material. The most relevant information is summarised below. Weather conditions in Barbados are promising for a cost efficient RES. The dynamic of average wind and solar daily capacity factors is shown in Fig. 1 based on selected weather years.

The relevance of bioenergy for a 100% RES in Barbados to complement the wind and solar potential has been noted in Espinasa et al. (2016); GOB (2019) and IRENA (2016), among others. Bagasse as a residue from the sugar production process can be used for the generation of bio-energy Marshall (2019). As an island system aiming for a 100% renewable energy supply, it is natural to include sectors traditionally powered by fossil fuels in the modelling. The passenger transport sector as well as the cruise sector as an important tourism sector with a total contribution of almost 40% to the GDP as well as the national employment in 2015 is included in the modelling approach.

Research question

The Barbadian situation puts a strong emphasis on climate change mitigation because of the small island characteristics and economical challenges connected to the fuel import dependency. The research questions in this paper are connected to a techno-economic assessment of the energy future of 2030 and built on Section 2. A representative year was selected with perfect foresight to model the system and its costs. Neither the transition nor cost during transition are included, as this is not the goal of the chosen approach. This is a trade-off between complexity and simplicity. For this purpose, an open source model based on the Open Energy Modelling Framework (oemof) was developed, utilising a greenfield modelling approach, aiming to answer the following research questions:

(1) What is the cost-optimal share of renewable energy sources technically feasible for the Barbadian electricity system?
(2) What are suitable combinations of storage technologies and particularly the role of PHS in a 100% RES for Barbados?

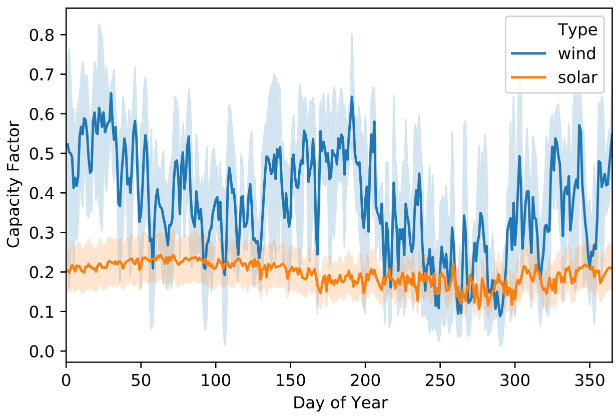


Fig. 1. Average wind and solar daily capacity factor and 95% confidence interval of four years (2002, 2004, 2010 , 2014) based on *Renewables.Ninja* (Pfenninger & Staffell, 2016) data for location at 13.32 latitude and −59.6321 longitude.

(3) What are the techno-economic effects in the electricity system due to the electrification of the passenger transport sector and shore-to-ship power supply for cruise ships in Barbados?

State of research

Several studies have highlighted the impact of fossil fuel dependency on the SID state characteristics that directly and indirectly exacerbate the need for sustainable development. This compromises the ability of Barbados to invest in sustainable development initiatives to reduce the dependency. According to Blechinger and Richter (2014), Caribbean islands face several barriers for the development of renewable energy technologies, which can be clustered in technical, economic, political and social.

Scenario analyses have been conducted on possible futures for the Barbadian electricity system solely in studies on behalf of the Government of Barbados. A first investigation was carried out under the Sustainable Energy Framework (SEF 2010) for Barbados (IADB, 2010a). In 2010, a 100% RES was not yet an official policy target for the Government and was therefore not analysed. The study results led to the initial policy target of 29% of renewable energy in the electricity mix for Barbados in 2030 (IADB, 2010b). However, the report did not publish modelling code, tools or methodologies. The Government also consulted the International Renewable Energy Agency (IRENA) for scenario analysis of the power generation sector, which recommended a share of 76% renewable energy instead of a 100% RES. The study did not consider pumped hydro-storage (PHS) as a viable storage option to support the 100% RES, but battery storage technologies (IRENA, 2019). The viability of the 100% RE scenario depends on utilising a biomass potential of 54 MW, which would require 16 million tonnes of sugarcane per year from 20,000 ha of land (IRENA, 2016). However, as recent as 2016, only 7000 ha of arable land for sugarcane production were available (Lind et al., 2018). A study conducted by Hohmeyer (2017) examined the possibility of a 100% RES using PHS to achieve a dispatch with lower levelised costs of electricity. All scenarios employed between 200 and 260 MW of wind and PV, as well as 11 MW of solid waste combustion. The scenarios varied only in the extent of biomass utilisation and technology for bio energy generation. Within the Barbados National Energy Policy (BNEP) 2019 (GOB, 2019), scenario analysis was also conducted to examine possible dispatch options. Although, a 100% RE system remains the goal for Barbados, the purpose of the scenario analysis was to examine possible dispatch options of a 76% RE system, centred on IRENA (2016), using a multi-criteria approach based on environmental, economic and social considerations (GOB, 2019). IRENA (2016) is the only study to examine an optimised dispatch with renewables, conventional generators and battery storage using LEAP and OSeMOSYS. Table A.3 summarises key figures of the previously introduced scenario analyses.

Scientific contribution

Models of a 100% RES for Barbados exist, are, however, based on closed energy system models, which pose challenges associated with the inability to reproduce the outputs for external examination. Previous studies are also heavily depended on external aid, without which investment in most SIDS energy sectors would be non-existent (Niles & Lloyd, 2013). Donor agencies have the technical, legal and professional capacities to draft policies and review institutional structures. This may also lead to the development of energy policies as a prerequisite or condition to further access funds from the donor or loan agency. When using closed models as seen in the development of the SEF 2010 for Barbados, the findings are solely presented as final results, without scrutiny from third parties.

Open access research may be more beneficial for the Barbadian energy system by improving transparency, generating and fostering the re-usability of results as well as adding scientific value to discussions on carbon neutral energy systems. The greater openness offered by oemof (Hilpert et al., 2018), in the form of open source code and raw model results, can address the problem of external donor agencies and the possibility of biased results. As shown in Section 2, none of the previous studies considered high shares of RE, the possibility of PHS nor a combination of multiple storage types. Additionally, the study at hand is the first to assess the possibility of electrifying one of the most relevant revenue sectors for Barbados, the cruise ship tourism sector. Analysing shore-to-ship renewable power can benefit the country and the society as a whole with lower GHG emissions as well as reduced air pollution levels and increased health standards. The investigation focuses on examining various possible scenarios for a cost-optimal integration of RE into the energy system, as well as analysing the possibility of a 100% RES. Furthermore, the presented open source model can be used to address similar research questions for other SIDS energy systems. Therefore, the presented model does not only contribute to the scientific debate of decarbonising energy systems to mitigate climate change, but can also mark an important step for capacity building and sustainable development in other SIDS through open, unbiased dialogue.

Mathematical model

To assess the future energy system, a bottom-up optimisation linear programming model is applied. The model has been implemented based on the model generator oemof-solph (Krien et al., 2020) using the oemof-tabular interface (Hilpert et al., 2021), which are both part of the Open Energy Modelling Framework (oemof) (Hilpert et al., 2018). A similar model has been applied for the analysis of the Jordanian energy system (Hilpert et al., 2020).

In the following mathematical description, endogenous (input) variables are printed in bold to distinguish them from exogenous model variables. The model minimises total operational costs for the time horizon T and annualised investment costs of units $u \in U$ as well as storage investment costs of all storages $s \in S$ for the Barbadian electricity system. The respective objective function is given below in Eq. 1.

$$\min : \overbrace{\sum_{t \in T} \sum_{u \in U} c_u^{opex} \mathbf{p}_{u,t} \cdot \tau}^{\text{operational cost}} + \overbrace{\sum_{u \in U} c_u^{capex,p} \mathbf{p}_u^{nom}}^{\text{power inv.cost}} + \overbrace{\sum_{s \in S} c_s^{capex,e} \mathbf{e}_s^{nom}}^{\text{energy inv.cost}} \tag{1}$$

The operational costs c_u^{opex} are calculated based on the efficiency η_u of a unit u and its fuel cost c_u^{fuel} according to Eq. 2. Annualised investment costs c^{capex} are calculated based on the lifetime n, weighted cost of capital $wacc$ and the specific investment cost of a technology $capex_u$ as well as the fixed operation and maintenance cost fom in Eq. 3.

$$c_u^{opex} = \frac{c_u^{fuel} + c_u^{var}}{\eta_u} \tag{2}$$

$$c_u^{capex} = capex_u \cdot \frac{(wacc \cdot (1 + wacc)^n)}{((1 + wacc)^n - 1)} \cdot (1 + fom) \tag{3}$$

The demand must equal the sum of supply of all producing units as described in Eq. 4. Note, that for the storage units, p can also take negative values when the storage is charging. The total demand in every time step is composed of different loads such as households, electrical vehicles and cruise ships with their specific patterns and is assumed to be inelastic.

$$\sum_{u \in U} \mathbf{p}_{u,t} \cdot \tau = \sum_{l \in L} d_{l,t} \cdot \tau + \mathbf{p}_t^{excess} \cdot \tau \qquad \forall t \in T \tag{4}$$

For all investment units, the supply is limited by the installed nominal power $\mathbf{p}_i^{nom}$ described in Eq. 5, which is bounded by a lower and upper investment limit as shown in Eq. 6.

$$0 \le \mathbf{p}_{u,t} \le \mathbf{p}_u^{nom} \qquad \forall u \in U, t \in T \tag{5}$$

$$\underline{p}_i \le \mathbf{p}_u^{nom} \le \overline{p}_i \qquad \forall u \in U \tag{6}$$

The energy storage balance in Eq. 7 is applied for all modelled storage types. The balance includes standing losses η^{loss} as well as charge and discharge efficiencies $\eta^{in/out}$.

$$\mathbf{e}_{s,t} = \mathbf{e}_{s,t-1} \cdot \eta_s^{loss} - \frac{\mathbf{p}_{s,t}^{out}}{\eta_s^{out}} \cdot \tau + \mathbf{p}_{s,t}^{in} \cdot \eta_s^{in} \cdot \tau \qquad \forall s \in S, t \in T \tag{7}$$

Additionally, the power of the storage is limited by the optimised nominal power shown in Eq. 8.

$$-\mathbf{p}_s^{nom} \le \mathbf{p}_{s,t} \le \mathbf{p}_s^{nom} \qquad \forall s \in S, t \in T \tag{8}$$

For all volatile RE technologies, i.e. PV and wind, the power output is determined by Eq. 9 where $c_{v,t}^{profile}$ is the time dependent normalised generation profile of the unit $v \in V$.

$$\mathbf{p}_{v,t} = c_{v,t}^{profile} \mathbf{p}_v^{nom} \qquad \forall v \in V, t \in T \tag{9}$$

Analogous to Eq. 5 and 6, the energy storage content and its maximum investment is bounded as shown in Eq. 10 and 11.

$$e_s^{min} \cdot \mathbf{e}_s^{nom} \le \mathbf{e}_{s,t} \le \mathbf{e}_s^{nom} \qquad \forall s \in S, t \in T \tag{10}$$

$$0 \le \mathbf{e}_s^{nom} \le \overline{e}_s \qquad \forall s \in S \tag{11}$$

The dispatchable renewable units $d \in D$ are modelled with a conversion process as described in Eq. 12.

$$\mathbf{p}_{d,t} = \eta_d \cdot \mathbf{h}_{d,t} \qquad \forall d \in D, \forall t \in T \tag{12}$$

The conversion process allows to introduce the input of fuel h, which can then be bounded for a time horizon within Eq. 13. This equation allows to model (annual) resource limitations in biomass or waste.

$$\sum_{t \in T} \mathbf{h}_{d,t} red \cdot \tau \le \overline{h}_c \qquad \forall d \in D \tag{13}$$

To model RE penetration within the system by an exogenously defined RE share, an additional constraint is introduced. The renewable energy share is defined within Eq. 14 by the share of conventional technologies $c \in C$.

$$\sum_{t \in T} \sum_{c \in C} \mathbf{p}_{c,t} \cdot \tau \le \left(1 - RE^{share}\right) \cdot \sum_{l \in L} c_l^{amount} \tag{14}$$

Finally, the excess supply within the model is limited by two equations. Eq. 15 limits the excess power in every time step by to 10% of the peak demand d^{peak} of the year, while Eq. 16 limits the excess energy for the whole time horizon.

$$\mathbf{p}_t^{excess} \le 0.1 \cdot d^{peak} \qquad \forall t \in T \tag{15}$$

$$\sum_{t \in T} \mathbf{p}_t^{excess} \cdot \tau \le 0.1 \cdot \sum_{l \in L} c_l^{amount} \tag{16}$$

Scenario assumptions

The analysis considers ten scenarios, of which the main parameters are summarised in Table 1 and Table 2. All scenarios are modelled in a cost-optimal (without Eq. 14) and a 100% renewable case, where Eq. 14 applies with a value of 1 for the RE^{share} parameter.

A greenfield approach is applied, which is a standard procedure in energy system modelling. Greenfield planning largely neglects the

Table 1
Overview of scenario assumptions including demand and technical parameters. All scenarios, except SQ, consist of base demand, electric vehicle demand and cruise demand as in the REF scenario - with variations as stated in parameters.

Scenario	Symbol	Parameter	Value
Status-quo	SQ	Base demand	943 GWh
Reference	REF	Base demand	943 GWh
		EV demand, controlled charging	265 GWh
		Cruise demand	44.15 GWh
High demand	HD	Base demand +1.2%/a	1321.3 GWh
Restricted biomass	RB	Biomass potential −50%	328 GWh_{th}
		Waste potential −50%	109 GWh_{th}
No PHS	NPHS	No PHS investment	–
Cost variations			
Low oil price	LOP	Oil price −50%	59.2 $/kWh
Electric vehicle uc	EVUC	EV demand, uncontrolled charging	265 GWh
Low RE costs	LRC	Long term wind costs	2900 $/kW
		Long term PV-distributed costs	2100 $/kW
		Long term PV-utility costs	1500 $/kW
Medium RE costs	MRC	Medium term wind costs	3335$/kW
		Medium term PV-distributed costs	3150 $/kW
		Medium term PV-utility costs	2250 $/kW
High bagasse cost	HBC	Higher bagasse investment costs	18,400 $/kW

constraints given by today's system and future planning, except for natural limits such as wind and solar resources (Geidl et al., 2006). Most of the currently installed power plants will retire in 2030 due to age. The first scenario represents the status-quo (SQ) on the demand side and is primarily designed for the comparability of results with other studies and therefore does not consider electrification of sectors other than energy generation. The second scenario is used as a reference scenario (REF) for the remaining scenarios and includes the electrification of passenger transport vehicles and cruise ships.

The electricity demand in Barbados was modelled based on the assumptions of the Integrated Resource Plan (BL&P, 2014). Although, the document has not been updated since IRENA, 2016, it remains the primary source of information on generation and future demand of the Barbadian energy system. IRENA (2016), Hohmeyer (2017) and GOB (2019) were used to validate and compare the final demand in the target year 2030. The annual hourly load profile was simulated from a sample 7-day hourly demand curve from 2014, as outlined within Hohmeyer (2017). The total future system demand for 2030 was set at 943 GWh, which is the current demand of 2019. The demand increased only marginally from 912 GWh in 2013 and, as stated in BL&P (2014), is not expected to increase substantially due to demand side management and energy efficiency measures in the residential and commercial sector. The high demand scenario (HD), assumes, analogous to BL&P (2014), an expected growth in residential, commercial and industrial demands between 2012 and 2030 of 1.2% annually, which generates an annual system demand of 1321.3 GWh for 2030.

The demand profiles for the electrification of the transport sector and the cruise ships are analysed as separate profiles to the annual system demand. All scenarios, except SQ and EVUC, use the same demand profiles for the electrification of sectors as well as the same base demand (expect HD) with varying dispatchable renewable generation, PHS and battery storage and costs to address uncertainties.

On the renewable supply side, wind, solar, biomass (bagasse) and waste are considered in all scenarios with varying capacities. Based on Hohmeyer (2017), the annual potential of biomass and waste is limited in the REF scenario to 656 GWh_{th} and 218 GWh_{th} respectively (169 GWh_{el} and 74 GWh_{el}). The generation profiles for wind and solar are based on the *Renewables.Ninja* project (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016). The conventional units considered are low and medium speed diesel generators (lsce and msce) fired with heavy fuel oil (hfo). A combination of fuel efficient lsce and smaller msce is considered as a viable solution for Barbados, according to (BL&P, 2014). The model and the scenario input data are publicly available on GitHub (Hilpert & Harewood, 2021).

Cruise and vehicle demand

The demand profiles for electric vehicles and shore-to-ship charging for cruise ships were created as separate demand profiles, as depicted in Fig. 2.

At the time of the present analysis, no information regarding the energy consumption nor the demand profile of cruise ships in Barbados were publicly available. However, Hoyte (2016) has conducted an extensive study of the cruise industry demand in Barbados, which is used in this research as well as information from the local port authority (BPI, 2020). Analysis of the port data shows, that cruise ships typically dock for a period of 5 to 20 h, with 92% docking longer than 10 h. About 50% of all recorded cruise arrivals (431 in 2018) docked between 10 and 12 h, only 7.7% stayed less than 10 h. The large majority of all ships arrived between 5:00 and 10:00 am (see Fig. C.9). A 12 h demand profile for the docking time of one generic ship was applied, using a peak demand of 12 MW, multiplied by the actual arrival data from 2018 BPI (2020). Within the first 2 h after docking with peak demand, the demand drops to low demand, increasing again to peak demand at the end of the docking time. A peak demand of 15 MW was assumed

Table 2
Cost and technical data for supply units in the REF scenario with costs in BBD. wacc - weighted average cost of capital, η - efficiency, fom - fixed operation and maintenance, vom - variable operation and maintenance. Values from (BL&P, 2014, p. 76/92) for generation technologies and Mongird et al. (2019) for storage units.

		capex	Life	Wacc (−)	η			
		($/kW)	(a)		(%)	Fom (%)	Vom ($/MWh)	Size (MW)
Carrier	Technology							
Wind	Onshore	3500	20		0.07	100.0	4.0	0 1
Solar	pv-distributed	5400	20		0.07	100.0	1.0	0 -
	pv-utility	3900	20		0.07	100.0	1.0	0 1
Lithium	Battery	2500*	12		0.07	94.9	3.0	0 -
Hydro	phs	5000	45		0.07	89.4	1.0	0 -
hfo	lsce	2853	30		0.07	46.4	4.0	12 31.7
	msce	2344	25		0.07	43.9	7.0	18 17.1
Bagasse	st	8000	25		0.07	25.3	3.6	15 25
Waste	ocgt	18,000	20		0.07	34.1	3.9	15 13.5

Note: A sensitivity analysis for wacc of 4% and 10% is included to reflect uncertainties in assumptions.
* Storage cost in include 100 $/kW and 600 $/kWh with a E/P ratio of four.

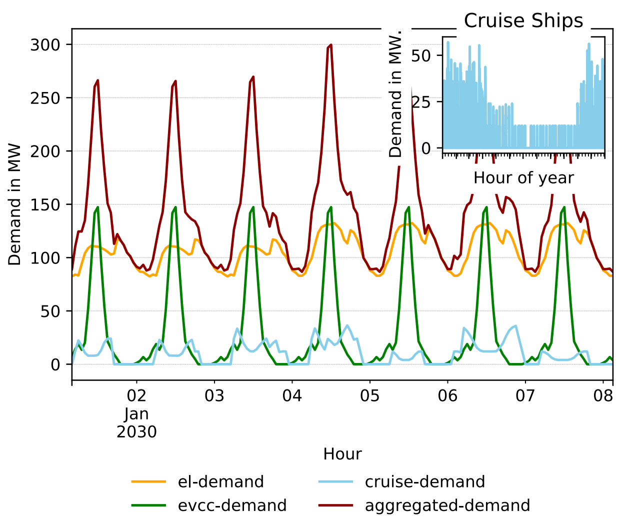


Fig. 2. Modelled load patterns of electricity demand, electric vehicles and cruise ships for one week (main figure) and the cruise ship daily average for a whole year (small figure upper right).

for all cruise ship types Hoyte (2016). The seasonal pattern in the annual demand from cruise ships is clearly visible in Fig. C.10.

On Barbados, there were 94,100 registered vehicles as of 2016 (IRENA, 2016). Just over 81% are passenger vehicles, followed by light and heavy goods vehicles (11.2%), private taxis and minibuses (3%) as well as rental cars (2.7%). Following IRENA (2016), only the electrification of the largest share of vehicles, passenger transport, was considered. Within the model, in all scenarios but the SQ scenario, an electrification rate of 80% by 2030 was assumed, which is in-keeping with the goals of the BNEP 2019. Controlled charging is mapped in all scenarios but SQ and EVUC, where peak demand occurs around noon. The annual demand of 265.4 GWh as well as the daily load profile was modelled after IRENA (2016) and Gay et al. (2018). As a comparison, a scenario with uncontrolled charging (EVUC) is set up, where the charging peak occurs around 6:00 pm.

The electrification scenarios cause a higher total demand and an altered aggregated demand pattern. Fig. 2 shows the first week of 2030 with three different modelled load patterns as well as the aggregated demand with values of the REF scenario .

Results

Installed capacities and energy balance

The results of this study have to be critically read in the light of the used method and model. Fig. 3 depicts the installed capacities per supply technology. In all scenarios, independent of the cost-optimal or the 100% renewable energy (RE) case, RE sources are the substantial share of the overall installed capacity. Wind energy has the highest capacities ranging from around 168 MW in the LRC-scenario to 371 MW in the HD-100 scenario. Within the SQ scenario, 211 MW wind capacity compared to 269 MW in the REF scenario are necessary to cover the increased demand due to the electrification of passenger transport and cruise ships. Additionally, much higher conventional capacities are needed in the REF scenario (169 MW msce) compared to the SQ scenario (76 MW), as well as increased PHS (46 MW respective 18 MW). The maximum possible PV-utility potential of 80 MW is exploited in all scenarios, but SQ and SQ-100. Due to its investment cost, PV-distributed reaches high capacities only in the 100% scenarios, either due to cost reductions (MRC-100, LRC-100), higher demand (HD-100) or a restricted biomass potential (RB-100). Within the scenario of uncontrolled EV charging, no distributed PV is installed due to the higher costs of integrating PV electricity.

Despite their high investment costs, bagasse capacities around 30 MW can be found in all cost-optimal scenarios, except RB with 15 MW and no investment with a lower oil price (LOP) or higher investment cost of biomass (HBC). The reason are the significantly lower fuel costs of bagasse compared to heavy fuel oil, which has lower investment cost but high operational cost. Hence, for the LOP scenario, no bagasse investment is cost-optimal. In all 100% RE scenarios, bagasse capacity increases to values ranging from 60 MW in the RB-100 scenario to 96 MW in the HD-100 scenario. Installed capacities within SQ compared to REF are almost identical, with 30 MW (74 MW respective 84 MW in the 100% cases). The lower bagasse investment in the RB-100 scenario due to the restricted biomass potential is compensated by high PHS capacities. In all 100% scenarios, PHS capacity is above 95 MW (except 3~7 MW in SQ). However, an installed capacity of 143 MW and 152 MW highlights the relevance of the PHS in the case of restricted biomass potential (RB-100) and uncontrolled EV charging (EVUC-100), respectively. Due to the large PHS capacity in the 100% scenarios, battery storage capacity is only required for up to 15 MW in cost-optimal cases. Lithium batteries also become important within the EVUC scenarios, to meet the shifted charging demand in the evening and PV peak during the day. Also, within the REF scenarios, batteries are applied (1 MW REF and 11.6 MW REF-100), whereas in the SQ scenarios, no battery capacities are necessary. If there is no PHS investment (NPHS), battery capacities of 56 MW in the cost-optimal and 101 MW need to be included. No conventional capacities exist in the 100% scenarios. In the cost-optimal scenarios values of conventional installed capacities are ranging from 76 MW in the SQ scenario to 271 MW in the LOP scenario. Investment in waste units can only be observed for 100% RE scenarios due to the high investment costs of 18.000 BBD/kW. Investment in lithium batteries is necessary in the NPHS scenarios, as well as, the EVUC scenarios, where the PV generation pattern cannot compensate for the increased demand from electric vehicles. The corresponding energy balance and RE-share is shown in Fig. 4.

The cost-efficient investment of renewable energy leads to high RE-shares above 80% in most cost-optimal scenarios (except for the LOP with 46% and HBC with 68%) with a maximum of around 93% in the LRC scenario. With the favourable capacity factor of wind and its therefore large installed capacities, the demand is covered mainly by wind, followed by conventional supply in the cost-optimal scenarios. Only with a reduction in PV cost (LRC, MRC), PV supplies the second largest share of electricity in the cost-optimal cases. Bagasse and waste supply only increase slightly from the cost-optimal to the 100% cases.

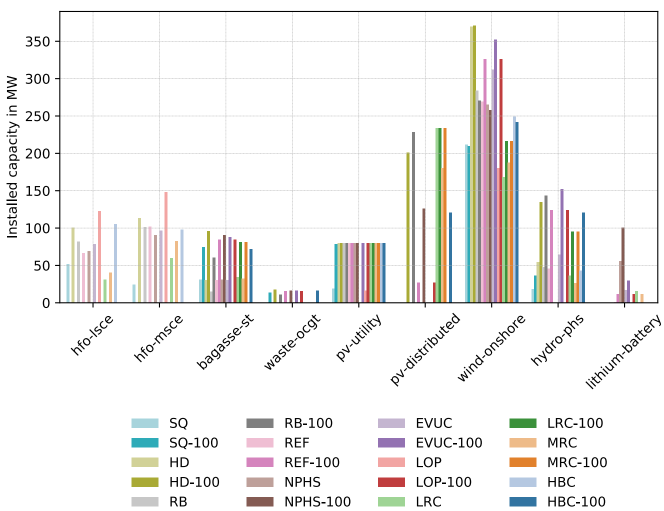


Fig. 3. Installed capacities for all scenarios in the cost-optimal and 100% RE setup.

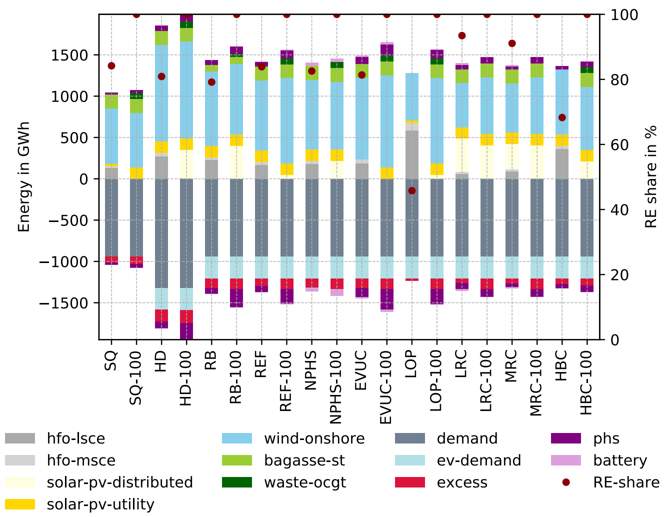


Fig. 4. Energy supply and demand balance (left axis) and renewable energy share (right axis) for all scenarios.

A. Harewood, F. Dettner and S. Hilpert Energy for Sustainable Development 68 (2022) 120–130

Dispatchable operation

To analyse the system operation, PHS storage and bagasse dispatch is shown in Fig. 5 for the REF and REF-100 scenarios. The PHS is mainly charged in the afternoon, due to the high PV supply, shifting energy into the night and morning. A seasonal shift between the month with lower wind supply can be observed. While absolute PHS increases from about 46 MW in REF to over 124 MW in REF-100, the pattern remains the same. In contrast, both the maximum supply and the pattern of bagasse change from the cost-optimal REF to the 100% REF-100 scenario. In the REF scenario, bagasse operates in full load during many hours of the year, while in the 100% scenario, bagasse operates as a peaking and back-up component in the system to supply electricity during periods of low RE supply (e.g. when wind drops and PV is not available). Bagasse is less utilised in the summer months with high PV and wind supply and lower demand due to the absence of cruise ships, but also at the beginning of the year with high wind supply.

The operation of the dispatchable components underlines the need for a highly flexible operation to incorporate and manage long periods of no production, as evident in the drop of wind electricity generation, and full-load production in other periods.

Costs

Investment costs play a crucial role, due to the Barbadian economic challenges, such as debt accumulation due to increasing and volatile prices of fossil fuels, limited sources of foreign exchange and a heavy dependence on external aid and donors. Fig. 6 shows the annualised investment cost per technology for all scenarios. 100% RE systems typically require higher investment cost than the cost-optimal systems. Total annualised investment costs range from 126 Mio. BBD in the SQ to 204 Mio. BBD in the HBC (247 Mio. BBD in HD) in the cost-optimal cases and from 192 Mio. BBD (SQ) to 393 Mio. BBD (HBC-100) (410 Mio. BBD in HD-100) in the 100% RE scenarios. The costs range from 199 Mio. BBD to 293 Mio. BBD in the REF respective REF-100. It must be noted, that operational costs are significantly lower in the 100% RE systems due to the low or zero marginal cost of wind and PV, as well as lower cost for bagasse compared to heavy fuel oil, expect within HBC-100. While the share of energy provided from dispatchable renewable energies and storage is low, compared to the energy provided by volatile resources such as wind and photovoltaics, their share in the total investment costs is significantly high in the scenarios with 100% renewable

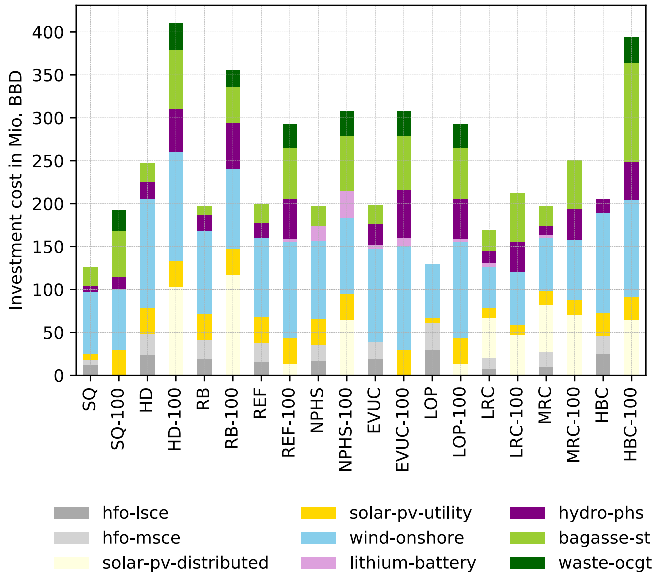


Fig. 6. Investment cost per technology for all scenarios in the cost-optimal and the 100% renewable energy setup.

energies. Lower RE costs, as in the LRC-100 and MRC-100 scenarios, lead to no investment in waste, whereas all other 100% scenarios rely on a waste investment. The increase in bagasse investment costs (HBC) leads to no investment in bagasse in the cost-optimal case, while in the HBC-100 scenario, higher investments are made in PV plants compared to the REF-100 scenario to compensate for the higher investment costs.

One main driver for installed capacities and associated required capital is the demand, which is demonstrated by comparing the investment costs of the REF and the HD scenario. Another main driver are the costs required for flexibility, which is indicated by high investment costs for the HBC-100 scenario compared to the REF-100 scenario.

LCOE and impact of financing costs (wacc)

LCOE have been calculated with three different assumptions for wacc (low 4%, base 7% and high 10%). For all cases, the resulting systems' levelised cost of electricity (LCOE) show a moderate increase from cost-

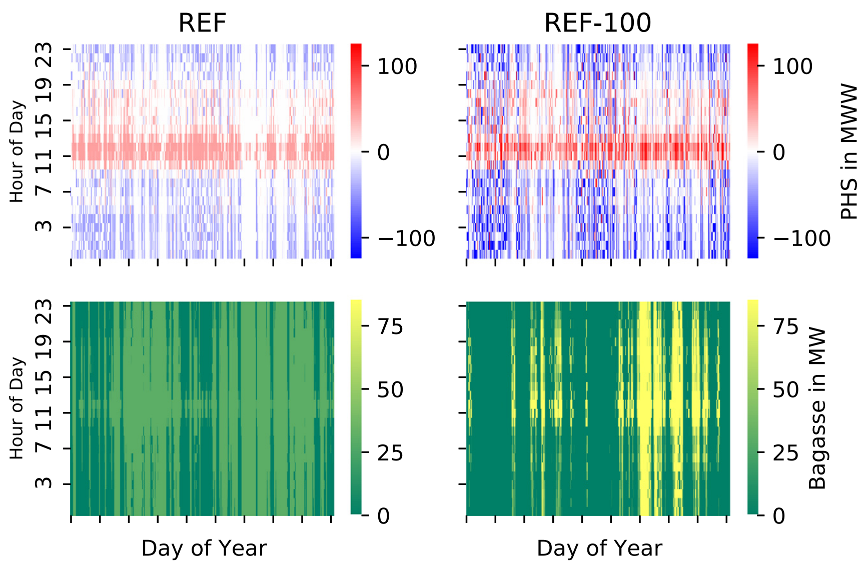


Fig. 5. Heatmap for the operation of PHS (top) and bagasse (bottom) in the REF (left) and the REF-100 (right) scenario.

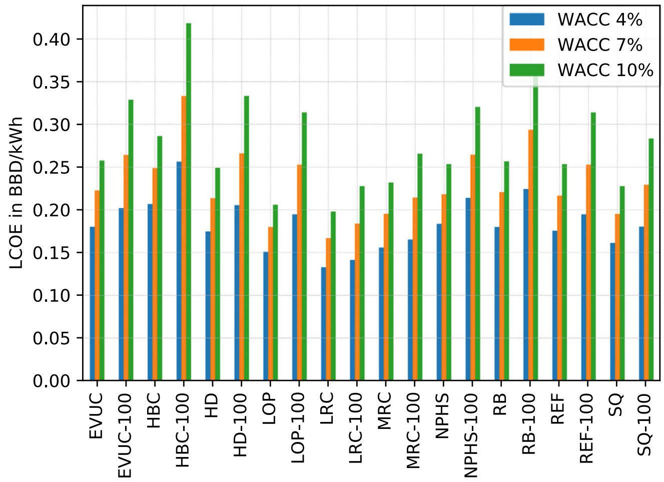


Fig. 7. System LCOE for all scenarios in the cost-optimal case (COPT) and the 100% renewable energy case (100RE) in BBD per kWh with wacc of 4%, 7% and 10%.

optimal to 100% RE systems (Fig. 7). However, this increase is higher if renewable flexibility is expensive (HBC), restricted (RB) or the cost of fossil generation are low compared to renewable generation (LOP).

With the base value of 7% wacc, the lowest LCOE for the cost-optimal case occurs in the LOP scenario (0.18 BBD/kWh), while the highest cost-optimal system LCOE can be identified for the HBC scenario with 0.25 BBD/kWh. In the 100% RE scenarios, low LCOE of 0.18 BBD/kWh can be identified within the LRC scenario. In the reference scenario REF-100 costs are higher with 0.25 BBD/kWh but still significantly lower than for HBC-100 with 0.33 BBD/kWh. The general pattern is the same for all wacc assumption. However it is clearly visible, that with wacc of 4% the LCOE decreases. On average the LCOE decrease by 22.6% for 100% RE cases and 18.2% in COPT scenarios. In contrast, higher wacc of 10% cause an average increase in LCOE of 24.21% (100% RE) and 16.5% (COPT) respectively.

Fig. 8 shows the impact of different wacc on the invested capacities. Generally, a varying wacc has a larger impact in COPT compared to 100% RE scenarios. In the COPT case, lower wacc of 4% causes a higher share of renewable energies, particularly noticeable in higher wind and PHS investment and decreased battery investment compared to the base case of a 7% wacc.

Assuming a higher wacc of 10%, the opposite effect becomes apparent. However, the NPHS scenario shows, that a higher wacc reduces investment in dispatchable units, bagasse and hfo, and wind capacities, which is compensated by increased battery capacity. With low wacc of 4%, fossil investment is reduced significantly in favour of higher PHS capacities. In a 100% RE system, the high wacc causes a shift from wind to PV investment, with the opposite effect for a low wacc. Analysing storage options, with a high wacc investment in battery is favoured over PHS. The opposite effect, albeit not as drastic, is visible in some scenario settings with a low wacc. As the chosen 7% wacc in the base case is already rather high, this underlines, that PHS is a robust solution on a way to 100% RE for Barbados. The sensitivity analysis furthermore shows the importance of low and solid renewable energy financing options, especially for countries like Barbados.

Discussion

The results clearly indicate high potential shares of renewable energies in cost-optimal energy systems for 2030. The electrification of the cruise ship and transport sector is possible but requires additional investment capital, particularly for PHS and additional wind capacities. The high demand from electric vehicles reflected in the modelling results as well as the charging patterns pose a challenge for a future sustainable Barbadian energy system. If electric vehicle charging is uncontrolled, more storage is needed. This only leads to a slight increase in investment costs and LCOE. This underlines the role of demand response measures and energy policies to harness peak renewable energy generation. In the transport sector, a reduction in demand could be achieved by increasing the share of public transport and improving the infrastructure for (electric) bicycles to change the modal split. Additionally, an optimisation of the charging habits and the different effects controlled and uncontrolled charging have, needs to be further analysed and optimised, to counteract times with low renewable energy potential. This is highlighted within the modelling results, as higher RE shares are achieved within the REF scenario (controlled charging) compared to the EVUC scenario (uncontrolled charging). However, marginally higher investment costs are necessary within the REF scenario, respective the EVUC system. The present study suggests priority on the expansion of the wind capacity as it has a higher system value than PV. Whereas

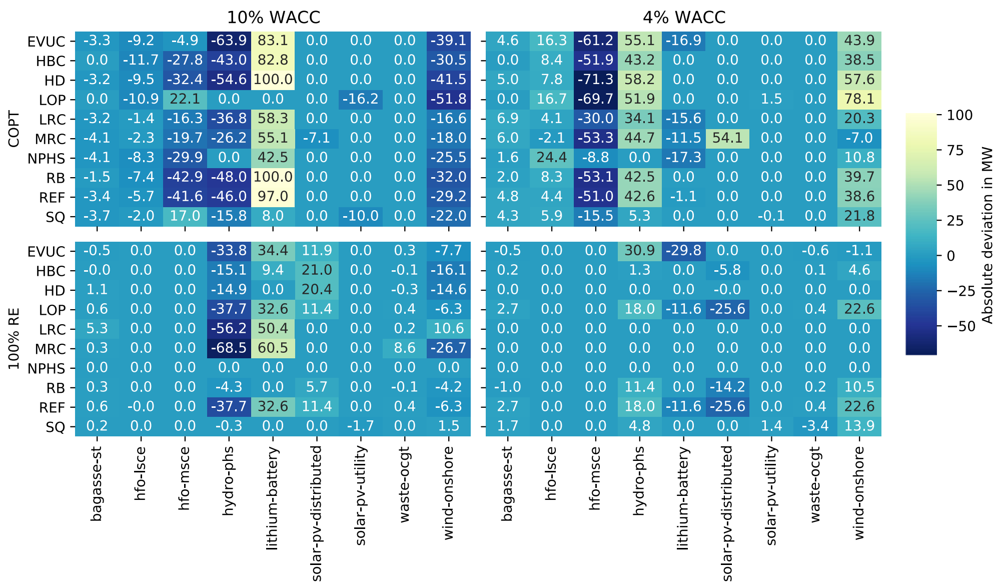


Fig. 8. Deviation of installed capacities in MW with wacc of 10% (right) and 4% (left) compared to the reference case of 7% for the cost optimal (COPT) and the 100% RE case in all scenarios.

the technology LCOE for wind and PV are similar, a system with high wind capacities can achieve lower overall system LCOE. Wind power therefore forms an important pillar for the future renewable energy system for Barbados, regardless the seasonal variations within the wind resource, which are challenging.

Demand-side management (DSM) was not considered in this study. However, this can be seen as a valuable option for renewable energy integration, which should be explored in future analyses. As the model is based on oemof-solph (Krien et al., 2020), a DSM component can be included. First estimates of DSM Savings can be used from the Integrated Resource Resilience Plan for Barbados Activity B, Draft Report (Mott MacDonald, 2021). Future analysis can also include detailed grid planning, electricity planning and stronger economic analysis. These can underline and strengthen the arguments for 100% renewable energy.

Costs

Estimates showed, that in 2013, fuel costs alone made up 73% (0.413 BBD/kWh) of the total electricity production costs (0.566 BBD/kWh) in Barbados (Hohmeyer, 2017). In 2015, the purchase of international oil cost the Barbadian economy 377 million BBD, resulting in high electricity costs passed to the public in the form of the Fuel Clause Adjustment (Hohmeyer, 2015). A higher renewable energy share does not necessarily result in higher electricity costs. With the likely future reduction in RE cost, as modelled in the LRC and MRC scenarios, a RE share of more than 90% is possible, while keeping system LCOE below 0.20 BBD/kWh (for LRC even in the 100% scenario). Reaching a share of 100% RE comes with only a slight increase in LCOE from 0.18 to 0.20 BBD/kWh (REF). However, these values do not reflect integration costs, such as grid and balancing costs or taxes, but solely system generation costs. This needs to be considered and analysed in further detail. Regardless, the respective required (annual) investment costs of the HD scenario are 47.6 Mio. BBD per year higher than in the REF scenario. These cost can be interpreted to be available for a 40% demand reduction. Although the LCOE may not differ largely between the HD and REF scenario, higher capital investment is required. As supported in previous studies, there is a sharp increase in investment costs as the energy system approaches a 100% RE. By assuming a higher than usual lifetime and nominal efficiencies of new technologies, is it feasible to build newest available technologies or built older, cheaper plants, they will be running in part-load anyway so they won't cover the nominal efficiencies, however this means that conservative cost optimal with regard to 100% systems, intertwined with grid etc.

Flexibility

Lack of or expensive flexibility within an energy system can lead to significant problems, especially when demand increases, the flexibility potential is restricted. In Barbados, flexibility is provided by biomass (bagasse) and waste and will play a significant role for investment costs and LCOE in the future energy system. Further research is necessary to determine how much of the currently installed capacity might be used as flexible generation units. In addition, the use of biomass may be limited due to operational requirements in systems with high shares of RE.

Limitation of study

The results of this study have to be critically read in the light of the used method and model. Within the model supply units are aggregated and not represented as individual units. In addition, grid constraints and spinning reserves are not considered. Another important restriction of the model is the applied perfect-foresight approach, which particularly matters within the context of the specific Barbadian weather pattern. The drop in wind supply in autumn in combination with restricted biomass resources and storage capacities requires long-term planning of dispatchable power plant operation and storage management. While the perfect-foresight approach allows to optimise this operation for a whole year, it will be much more challenging in reality. The maximum installed capacities are constrained, due to meteorological and geographical conditions. The wind resource was capped at 472 MW in keeping with the recommendations of Rogers (2017). The solar resource is constrained at 234 MW at the residential level. Without studies to support the expansion of utility scale solar on the island, this potential was constrained to 80 MW for all scenarios. Considering utility-scale PV is the cheapest renewable resource and was always selected by the model and used at maximum potential, it is vital to verify the assumed potential.

The assumptions made, may lead to rather optimistic results in terms of capacities and costs. The costs for the integration of renewable energies, such as grid expansion and back-up capacities for stable system operation, must be added to the costs presented in this study. While integration costs are highly context specific literature values suggest that these costs can range of 35 to 50% of the total generation costs Hirth et al. (2015). The challenges of long-term operational planning under resource constraints in 100% RE systems also need to be considered.

Value of open source

The boundaries and specifications posed within the context of Barbados, such as load profiles and possible resource capacities are key factors when analysing electricity systems. This information, however, is not always available to the public nor to scientists. Additionally, future economic and political developments can change fundamentally within a short period of time altering assumptions taken within the model. The applied Open Energy Modelling Framework offers the possibility to flexibly adjust input data and thus quickly and transparently adapt to changing circumstances without reducing the traceability of results.

Shore-to-ship power

The study describes shore-to-ship demand based on the annual arrival of cruises ships and varies with the tourist season over the course of the year. The cruise ship demand contributes significantly to the total energy demand of Barbados. The cruise ship demand pattern is almost complementary to the wind generation profile, which further supports the suitability of this resource for the Barbadian energy system. However, more research examining how renewable energy sources can optimally meet the daily cruise ship demand through e.g. scheduled docking times by the system operator, would be beneficial.

Conclusion

Due to good renewable energy resources and future cost developments, a cost-optimal system design in Barbados already features a share of over 80% renewable energy, assuming a future reduction in RE costs with current oil prices. Even with increased demand due the electrification of cruise ships and passenger transport, a renewable energy share of over 80% is achieved, with only slightly increased system LCOE (0.22 BBD/kWh respective 0.20 BBD/kWh). Particularly the energy potentials of waste and bagasse and the flexible operation of these systems need to be validated to ensure a stable 100% RE-system for the future. In the case of Barbados, imported bio-diesel for backup may be required due to the specific wind and solar pattern. Nonetheless, PHS can lower the costs of a 100% renewable set-up, additionally reducing the consumption of resources needed for batteries. The value of pumped hydro is only slightly affected by higher costs of renewable energy sources, lower oil prices or a demand reduction. Therefore, when aiming for 100% RE, the results indicate that PHS is a no-regret option for the Barbadian energy systems design. An open source energy system model as introduced here for the island of Barbados marks an important step towards decarbonising SIDS. By using an open source model, the problems of external donor agencies and the possibility of biased results, especially in the context of Small Island Developing States, are addressed. The study additionally underlines the feasibility of RE systems, even with an increasing demand including the electrification of sectors other than electricity generation.

Data availability

The model is available at https://github.com/znes/oemof-barbados/releases/tag/v0.2.

CRediT authorship contribution statement

André Harewood: Conceptualization, Resources, Data curation, Validation, Formal analysis, Investigation, Supervision, Project administration, Writing – original draft. **Franziska Dettner:** Conceptualization, Resources, Data curation, Validation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Simon Hilpert:** Conceptualization, Software, Methodology, Investigation, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

André Harewood and therefore his work is supported by the National Development Scholarship Scheme Barbados by the Ministry of Education, Technological and Vocational Training.

Appendix A. Scenario studies summary

Table A.3
Overview of key values from scenario studies on renewable energy in Barbados, current as of study year.

	BL&P (2014)	IRENA (2016)	Hohmeyer (2017)	GOB (2019))
Curr. capacity	239.1 MW_{2012}	241.5 MW_{2015}	240 MW	n/a
Exp. capacity	293.3 MW_{2036}	450 MW_{2030}	395 MW	n/a
Curr. demand	980 GWh/a_{2012}	n/a	912 GWh/a_{2013}	11,297 BOE per day
Exp. demand	903–1986 GWh/a_{2036}	998 GWh/a_{2030}	1350 GWh/a	n/a
Curr. generation	n/a	1092 GWh/a_{2015}	970 GWh/a_{2013}	n/a
Exp. generation	n/a	998 GWh/a_{2030}	n/a	1600 GWh
Curr. peak demand	163 MW_{2011}	158 MW_{2015}	150 MW	n/a
Exp. peak demand	208.1 MW_{2011}	145 MW_{2030}	140–300 MW_{2036}	n/a
Exp. share of RE	1.2–29%	max. 76%	100%	76%
Storage	wind with 10% battery	150 MW $battery_{2035}$	3 GWh_{2035} PHS	–
Biomass	25 MW	18 MW (for 100% 54 MW)	25–40 MW (35 GWh)	39 MW_{2035}
Waste potential	60 MW $_{2035}$	2.2 MW	11 MW	40 MW (WtE)
Solar (PV)	–	60 MW_{2030}	219 MW - 265 MW_{2035}	195 MW_{2037}
Wind	–	15 MW_{2030}	219–265 MW_{2035}	127 MW_{2037}
Natural Gas	n/a	n/a	n/a	49 MW_{2037}
Electrification rate vehicles	–	20% -50% EV	100% EV	100% EV
Cruise ship demand	n/a	n/a	n/a	n/a

Appendix B. Mathematical symbols

Table B.4
Sets used in the model description and values of sets used within the applied scenarios.

Symbol	Index	Description	Elements of sets in scenarios	Unit
T	t	Time steps	{1..0.8760}	h
V	v	Volatile renewable units	{wind-onshore, pv-utility, pv-distributed}	MW
D	d	Dispatchable renewable units	{bagasse-st, waste-ocgt}	MW
C	c	Conventional units	{hfo-lsce, hfo-msce}	MW
L	l	Load types	{cruise-ship, ev, el-demand}	MW
S	s	Storage units	{lithium-battery, PHS}	MW, MWh
U	u	All supply units	R U C U S U D	–

Table B.5
Optimisation variables used in the model description.

Symbol	Description
$\mathbf{e}_{s,t}$	Storage level (energy) of storage s at time step t
$\mathbf{e}_s^{nom}$	Nominal storage level (energy of full storage) of storage s
$\mathbf{h}_t$	Fuel consumption at time step t
$\mathbf{p}_t$	Power output/input at time step t
$\mathbf{p}^{nom}$	Upper limit of power output
$\mathbf{p}_t^{excess}$	Excess variable

Table B.6
Exogenous model variables used in the model description.

Symbol	Description
τ	Length of time step (in hours)
$\overline{p}_i$	Upper power investment limit of unit *i*
$\underline{p}_i$	Lower power investment limit of unit *i*
$\overline{e}_s$	Upper energy investment limit of storage *s*
$d_{l,\,t}$	Electricity demand of type *l* at time step *t* d^{peak} Total electricity peak demand within the year
$\overline{h}_d$	Maximum fuel consumption of unit d
η_s^{loss}	Standing loss of storage *s*
η_s^{in}	Charge efficiency of storage *s*
η_s^{out}	Discharge efficiency of storage *s*
c_u^{opex}	Operational expenditure of unit *u*
$c_i^{capex,\,p}$	(Annualised) power expenditure of unit *i*
$c_s^{capex,\,e}$	(Annualised) energy capital expenditure of storage *s*
$c_v^{profile}$	Generation profile of volatile renewable energy unit *v*
RE_v^{share}	Renewable energy share between 0 and 1.

Appendix C. Cruise demand

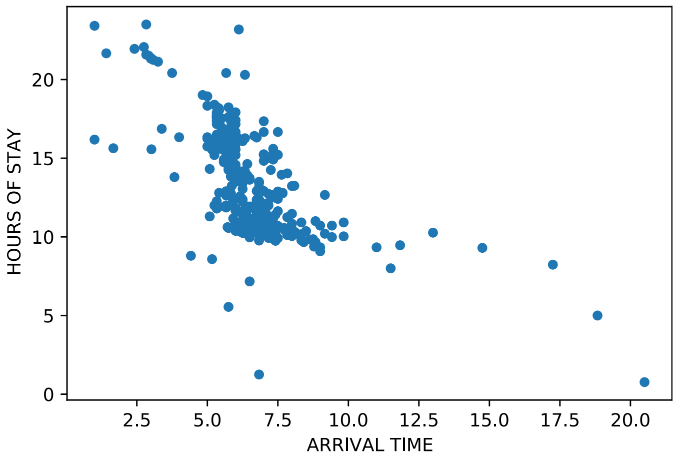


Fig. C.9. Arrival times and duration of stay of cruise ships in the port of Barbados for 2018 (analysis based on BPI (2020)).

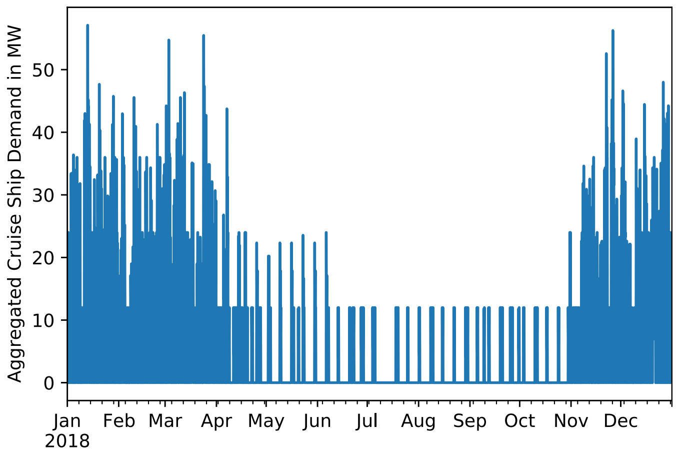


Fig. C.10. Cruise demand for 2030, modelled from detailed port statistics based on actual arrivals and duration of stay of 2018 (analysis based on BPI (2020)).

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2022.03.004.

References

Atteridge, A., & Savvidou, G. (2019). Development aid for energy in Small Island Developing States. *Energy, Sustainability and Society*, *9*, 10.

BL&P (2014). *Integrated Resource Plan (IRP) 2012. Technical Report Barbados Light and Power Co.* Barbados: Ltd. Bridgetown.

Blechinger, P., & Richter, K. (2014). *Barriers and solutions to the development of renewable energy technologies for power generation on Carribaen island states.* Workshop Presentation Reiner Lemoine Institut.

BPI (2020). *Port Statistics 2010–2019.*

Espinasa, R., Gischler, C., Humpert, M., Gonzalez Torres, C., & Sucre, C. (2016). *Achieving Sustainable Energy in Barbados: Energy Dossier.*

Gay, D., Rogers, T., & Shirley, R. (2018). Small island developing states and their suitability for electric vehicles and vehicle-to-grid services. *Utilities Policy*, *55*, 69–78.

Geidl, M., Favre-Perrod, P., Klöckl, B., & Koeppel, G. (2006). *A greenfield approach for future power systems.*

GOB, G. o. B (2019). Barbados National Energy Policy 2019–2030. *Offical policy document BNEP*. Bridgetown, Barbados: The Ministry of Energy & Water Resources Trininty Business Complex.

Henderson, V. (2013). *SIDS DOCK: Facilitating the Transformation of the SIDS Energy Sector to Enable climate Change Adaptation: "25-50-25 By 2033".*

Henry, L., Bridge, J., Henderson, M., Keleher, Kevin, Kirchhoff, M., Goodwin, Geoff, Namugayi, D., Morris, M., Oaks, B., Dalrymple, O., Shrake, S., Ota, A., Azevedo, Laura, Blue, B., Boucher, Z., Boege, S., Hager, Laura, Mack, Tahja, Thompson, Katherine, & Chavez, Melissa (2015). Key factors around ocean-based power in the Caribbean Region, via Trinidad and Tobago. *Journal Abbreviation: Renewable and Sustainable Energy Reviews Publication Title: Renewable and Sustainable Energy Reviews.*, *50*.

Hilpert, S., & Harewood, A. (2021). oemof-Barbados. Version 0.2 used for this work. https://github.com/znes/oemof-barbados/releases/tag/v0.2.

Hilpert, S., Kaldemeyer, C., Krien, U., Günther, S., Wingenbach, C., & Plessmann, G. (2018). The Open Energy Modelling Framework (OEMOF) - a new approach to facilitate open science in energy system modelling. *Energy Strategy Reviews*, *22*, 16–25.

Hilpert, S., Dettner, F., & Al-Salaymeh, A. (2020). Analysis of cost-optimal renewable energy expansion for the near-term jordanian electricity system. *Sustainability*, *12*, 9339.

Hilpert, S., Günther, S., & Söthe, M. (2021). Introducing Data packages for Reproducible Workflows in Energy System Modeling. *Journal of Open Research Software*, *9*, 6.

Hirth, L., Ueckerdt, F., & Edenhofer, O. (2015). Integration costs revisited – an economic framework for wind and solar variability. *Renewable Energy*, *74*, 925–939.

Hohmeyer, O. (2015). A 100% renewable Barbados and lower energy bills: A plan to change Barbados' power supply to 100% renewables and its possible benefits. *Discussion Papers 5 ISSN: 2192–4597 Center for Sustainable Energy Systems (CSES/ZNES)* (pp. 2192–4597). Flensburg. Issue: System Integration Department Munketoft.

Hohmeyer, O. (2017). *Economic Analysis to Facilitate the Establishment of a Stable Price for Electricity from Renewable Sources. Technical Report ME 36_1_2 T54.* Bridgetown, Barbados: Global Sustainable Energy Consultants Ltd Issue: ME 36_1_2 T54.

Hoyte, D. (2016). Shore-to-ship Power for Cruise Ships on '100% Renewables' in the Bridgetown Port, Barbados. *Master's Thesis Centre for Resource Management and Environmental Studies (C.E.R.M.E.S)*. The University of the West Indies - Cave Hill Campus-Faculty of Science and Technology.

IADB (2010a). *Support for Sustainable Energy Framework for Barbados (SEFB) I. Technical Report (BA-L1022).* Bridgetown: Inter-American Developement Bank Barbados.

IADB (2010b). *Sustainable Energy Framework for Barbados.* Bridgetown: Plan of Operation Inter-American Developement Bank Barbados.

IRENA (2016). *Barbados Energy Roadmap. Technical Report International Renewable Energy Agency United Arab Emirates.*

IRENA (2019). *Renewable Power Generation costs in 2018. Technical Report International Renewable Energy Agency Abu Dhabi.*

Krien, U., Schönfeldt, P., Launer, J., Hilpert, S., Kaldemeyer, C., & Pleßmann, G. (2020). oemof.solph—a model generator for linear and mixed-integer linear optimisation of energy systems. *Software Impacts*, *6*, Article 100028.

Lind, M., Bjorn-Andersen, N., Watson, R., Ward, R., Bergmann, M., Rylander, R., ... Santén, V. (2018). *The potential Role of PortCDM in Cold Ironing.*

MacDonald, Mott (2021). Integrated Resource & Resiliency Plan for Barbados. *Technical Report Draft Report.* Brighton: Inter-American Development Bank.

Marshall, R. (2019). *Bio-Digestion: Benefits to Barbados: Central Bank of Barbados's Biodigestion Conference 2019.* Panel Discussion.

Mongird, K., Fotedar, V., Viswanathan, V., Koritarov, P., Balducci, B., & Hadjerioua, J. (2019). *Energy Storage Technology and cost Characterization Report. Technical Report US Department of Energy.*

Niles, K., & Lloyd, B. (2013). Small Island developing States (SIDS) & energy aid: Impacts on the energy sector in the Caribbean and Pacific. *Energy for Sustainable Development*, *17*, 521–530.

Pfenninger, S., & Staffell, I. (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy*, *114*, 1251–1265.

Rogers, T. (2017). A Desktop Study into the Wind Resource in Barbados. *Technical Report The University of the West Indies Cave Hill Campus Bridgetown, Barbados.*

Staffell, I., & Pfenninger, S. (2016). Using bias-corrected reanalysis to simulate current and future wind power output. *Energy*, *114*, 1224–1239.

UNDP (2018). High-level Political Forum on Sustainable Developement. *Technical Report United Nations Developement Programme.*

6

Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea[1]

Franziska Dettner
Simon Hilpert

[1]published as: Dettner,F., Hilpert, S. (2023): Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea *Data*, 8, 85.

data MDPI

Data Descriptor

Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea

Franziska Dettner * and Simon Hilpert

Centre for Sustainable Energy Systems, Europa Universität Flensburg, Auf dem Campus 1b, 24943 Flensburg, Germany
* Correspondence: franziska.dettner@uni-flensburg.de; Tel.: +49-(0)461-805-3034

Abstract: A high temporal and spatial resolution emission inventory for the North Sea and Baltic Sea was compiled using current emission factors and ship activity data. The inventory includes seagoing vessels over 100 GT registered with the International Maritime Organization traversing in the North and Baltic Seas. A bottom-up approach was chosen for the compilation of the inventory, which provides emission levels of the air pollutants CO_2, NO_x, SO_2, $PM_{2.5}$, CO, BC, Ash, NMVOC, and POA, as well as the speed-dependent fuel and energy consumption. Input data come from both main and auxiliary engines, as well as well-to-tank and tank-to-propeller emission and energy and fuel consumption quantities. The georeferenced data are provided in a temporal resolution of five minutes. The data can be used to assess, inter alia, the health effects of maritime emissions, the social costs of maritime transport, emission mitigation effects of alternative fuel scenarios, and shore-to-ship power supply.

Dataset: znes/KlimaSchiff, https://zenodo.org/record/6951672. The code for the underlying calculations and post-processing functions are available under the BSD 3-Clause licence on https://github.com/znes/KlimaSchiff.

Dataset License: CC-BY.

Keywords: emission modelling; AIS data analysis; maritime emission pollution; emission quantification

check for updates

Citation: Dettner, F.; Hilpert, S. Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea. *Data* **2023**, *8*, 85. https://doi.org/10.3390/data8050085

Academic Editor: Marco Helbich

Received: 24 March 2023
Revised: 21 April 2023
Accepted: 24 April 2023
Published: 1 May 2023

1. Introduction

Approximately 3% of global carbon dioxide (CO_2) emissions and a substantial amount of other harmful air pollutant emissions originate from international maritime shipping [1]. Maritime transport is expected to increase significantly in the coming years, and according to the International Maritime Organization (IMO), maritime CO_2 emissions could increase by 50–250% by 2050 under a business-as-usual scenario [2]. For the analysis of guidelines and emission limits, as well as the climate and health impacts of shipping emissions, a comprehensive and transparent maritime emission inventory that is particularly accessible to non-modelers is required.

2. Summary

The study presented in this paper used maritime activity data (compiled from Automatic Identification Systems (AIS) data) in the North Sea and Baltic Sea in 2015 to quantify air pollutant emissions. These were calculated for all ships over 100 GT at 5 min intervals, resulting in the EUF (Europa University Flensburg) emission inventory, which is temporally and spatially highly resolved. A bottom-up approach was used to consider the nine leading air pollutants (CO_2, NO_x, $PM_{2.5}$, SO_2 (sulphur dioxide), POA (primary organic aerosols), ash (mineral ash), CO (carbon monoxide), NMVOC (non-methane volatile organic compounds), and black (or elemental) carbon (BC)), as well as speed-dependent fuel and energy consumption. The inventory includes emissions from both main and auxiliary engines and energy and fuel consumption values for the well-to-tank and tank-to-propeller stages. The presented EUF (Europa Universität Flensburg) emission inventory is available in csv-format and offers policy makers and non-modelers, in particular, an important starting point for their own analyses. The EUF inventory provides a high resolution and is therefore particularly suitable use in chemical transport models (prior conversion to netCDF files is necessary). Furthermore, the inventory includes the pollutants PM, BC, CO, and Ash, which are not provided as standard in other inventories.

Emission inventories are indispensable tools for environmental impact assessments and more generally for air pollution prevention measures through policy development and implementation. In addition, they can be used for the calculation of pollutant concentrations. The inventory presented here is particularly useful for the analysis of future emissions, which take into account techno-economic and socio-ecological aspects (e.g., fuel switching, efficiency and sufficiency measures, and changes in trade volumes), and the analysis of energy requirements for shoreside power connections in port areas, which will become mandatory in Germany from 2023 [3].

2.1. Literature Review

Before 2004, the calculation of maritime emissions was mostly carried out by estimating fuel consumption through the amount of bunkered fuel oil. Initial studies were carried out by Corbett et al. [4–7] and Eyring et al. [8]. Detailed analysis of ship emissions was made possible with the introduction of the Automatic Identification System (AIS) in 2004 and the subsequent availability of historical ship activity data. The first studies based on AIS data analyzed air pollutants from the Port of Rotterdam in 2009 [9] and for the OSPAR II region in 2011 [10]. One of the best known models used to analyze ship emissions in the European context is the Ship Traffic Emission Assessment Model (STEAM), which was developed by the Finnish Meteorological Institute. STEAM has been used to determine emission quantities in the Baltic Sea [11], in the Danish Straits [12], European Waters [13], the Northern European Emission Control Area (ECA) [14], and globally [15]. Most recently, the MariTEAM Model was used to analyze global shipping emissions from a well-to-wake perspective [16].

The Helmholtz-Zentrum Hereon is a leader in chemical transport modeling of pollutant emissions, as well as in the compilation of emission inventories, and has worked intensively on emissions from maritime transport [17–20]. Hereon's modular ship emission model (MoSES) was used to compile a comprehensive maritime emission inventory for the North Sea and Baltic Sea region for 2015 [21].

2.2. Research Objective and Contribution

While there are some open-source maritime emissions models and inventories such as STEAM [11,12] and the IMO GHG Emissions Calculator [22], the inventory presented here addresses, in particular, the issues of transparency and reproducibility. Some inventories may not provide sufficient detail or transparency about their methodology or data sources, which may make it difficult for users to verify the accuracy of the estimates or compare the results with other studies.

The aim of this study was to provide a comprehensive data set of maritime emissions for the North Sea and Baltic Sea with scenario capabilities. The anonymization and interpolation of the data allow open-source publication as csv-files, to make them available to (non-)modelers for their own analysis of, e.g., the health effects of maritime emissions, the social costs of maritime transport, emission mitigation effects of alternative fuel scenarios, and shore-to-ship power supply. The study aims to provide a valuable tool for policy-makers, researchers, and stakeholders to evaluate the environmental impact of maritime transport and to develop policies to reduce its negative effects.

3. Methods

3.1. Activity Data

The introduction of the AIS marked the beginning of digitization in the shipping industry. Since the end of 2004, it has been mandatory for every ship over 100 GT to be equipped with an AIS transmitter, which emits a signal every 6 s, providing, for example, the IMO identification number (unique identifier), the position (longitude/latitude), and a time stamp. Companies such as MarineTraffic, Vesselfinder, and IHS Fairplay collect and store these AIS signals and sell historical data. HELCOM (Baltic Marine Environmental Protection Commission) provide AIS data for the Baltic Sea region free of charge for research purposes. The presented emission inventory is based on high-temporal-resolution HELCOM [23] (Baltic Sea) and Vesselfinder [24] (North Sea) AIS data for 2015, covering the area between 65° N, −5° W, 48.3° S and 30.7° E, corresponding with the European Sulphur Emission Control Area (SECA). The AIS data for the Baltic Sea can be requested from HELCOM and are available for purchase from Vesselfinder for the North Sea.

3.2. Ship Routes

Consideration of shipping routes is an essential part of the emissions modeling of the shipping sector. Shipping routes can influence emission modeling by, inter alia, determining the type of fuels used, depending on the regulations and availability in the respective region. For the analyzed area, the SECA regulations apply.

Ship routes in the Baltic Sea and North Sea in 2015 were created from the acquired AIS data for all ships identified by their IMO number as being above 100 GT. Each route consists of segments that were formed from two consecutive AIS data points, using the following steps:

- Sorting of ship point data (longitude/latitude) by time stamp.
- Calculation of the distance between two consecutive time stamps using the Haversine equation.
- Calculation of the time duration between the two consecutive time stamps.
- Calculation of the speed of the ship between the time stamps based on time and distance.
- The spatial density of received AIS signals is significantly lower in the open sea than in coastal areas. To mitigate this, a method of rearrangement and interpolation to uniform 5 min time intervals of AIS signals is employed.
- When the calculated speed of a ship falls below 1 knot, the ship's speed is set to 0 knots. This is done based on the assumption that the ship is neither docking nor maneuvering, and that only the auxiliary engine is active at such low speeds. By setting the ship's speed to 0 knots in these situations, it is possible to differentiate between periods of inactivity and periods of slow movement, and accurately track the ship's location and activity. This was confirmed by analysis of the AIS Vesselfinder data, as the navigational status was on average (as of June 2015) 0.7 knots (at anchor) and 0.4 knots (moored) [25].
- As a necessary simplification, any data points with a calculated speed greater than 15 m/s (equivalent to approximately 29 knots) are removed. This is done to address artifacts that may arise from erroneous longitude/latitude data, particularly when the time difference between two points is short but the distance between them is high, resulting in implausible vessel speeds. If a vessel departs from the area under analysis, the route calculation is interrupted, as it may not be possible to interpolate between two positions due to an extended route outside the area of interest, which could span several hours. The route calculation is also interrupted if the ship is at the edge of the area of interest and the distance between the calculated points is greater than 300 m. When the ship re-enters the area of interest, the route calculation is restarted. It is worth noting that ships may sometimes travel at speeds greater than 15 m/s, due to current effects. This factor is not accounted for in the presented model.

Figure 1 shows the annual gridded CO_2 emissions in the area under consideration. This initial result is a basic plausibility check for the bottom-up calculation of ship routes and emissions. The main and well-known shipping routes (cf. [26]) are clearly identifiable from the AIS-data-generated routes.

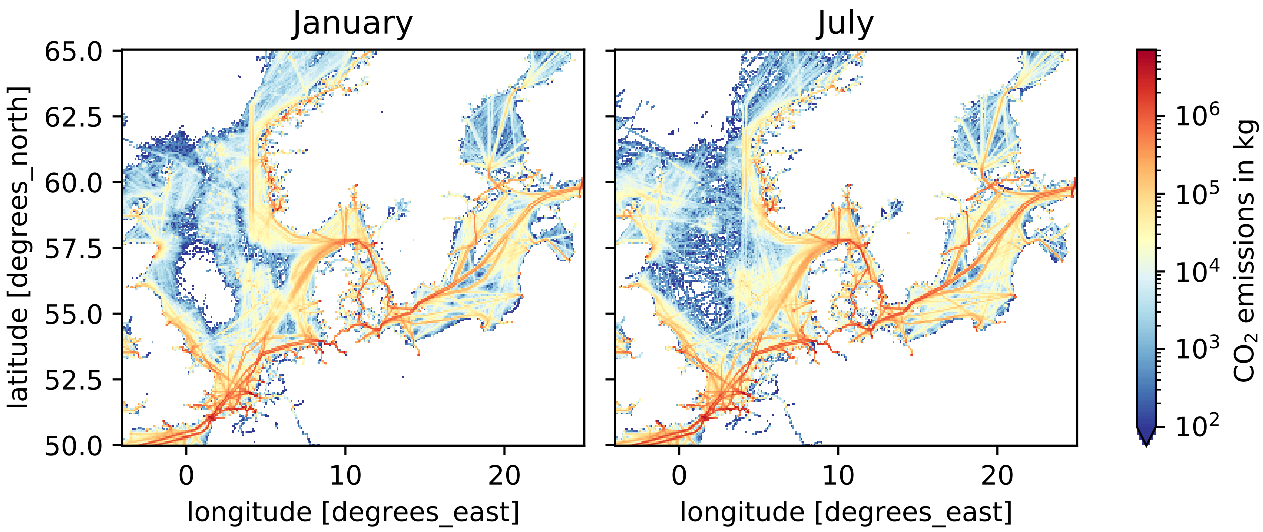


Figure 1. CO_2 emissions in kg in the North Sea and Baltic Sea for January and July, 2015.

3.3. Ship Types and Characteristics

Decisive factors determining the emissions from individual ships are primarily the ship type, size, age, and engine configuration. The Maritime Data Base (MDB) hosted by Vesselfinder, which includes 18,309 IMO identification numbers in the given area, was used to cluster the ships using the listed AIS type [24] (The MDB offers a range of information for each IMO identification number: Name, Built (Year), Flag, Type (AIS-Type), Status, GT (Gross Tonnage), DWT (Deadweight tonnage), LOA (Length over all), LPP (Length between perpendiculars), Beam and Draft.). Based on the AIS ship types, standardized ship types, and the expertise of shipbuilders [27], nine generic ship types were classified in this study: CarCarrier, Container, RoRo, Bulker, RoPax, MPV (Multi Purpose Vessel), Tanker, Cruise, and Diverse (The ship class Diverse is mainly composed of 20% tugs, 25% fishing vessels and 16% offshore supply/tugs. Tugs have a high installed power, but rarely use it due to high berthing times (70–80%) and therefore are not defined as a separate class.). If the MDB did not specify the AIS type for a particular IMO identification number, the ship was assigned to the Diverse ship type. A statistical analysis of the MDB data provided the weight distribution within each ship type. Based on this and international ship sizes (weight classes), between two and four weight classes were defined per ship type. The Tanker and Container size classes are based on the international ship classes Handy Size (1), Handy Max (2), PanMax (3), and SuezMax (4). Table 1 shows the set ship types by size class (weight classes) (1–4).

The ship types additionally differ in their engine configuration. A ship usually uses two sets of engines: the main engine(s), which provides the required propulsion power, and the auxiliary engine(s), which supply electrical power to the ship's electrical system via generators [27]. Both engine sets run at different loads and have different engine characteristics and corresponding fuel consumption and associated emissions during operation. In general, a distinction is made between slow-speed, medium-speed, and high-speed diesel engines [28]. The decisive factor here is the engine speed. Slow-speed engines operate from 70 rpm up to 300 rpm, as is the case for most large two-stroke engines found on ships. Medium speed engines typically operate from approximately 300 rpm to 900 rpm [27].

Table 1. Ship characteristics in type and size (weight) classes 1–4, based on statistical analysis of the MDB [25] and ship building expertise [27].

Type	Unit [1]	Main Engine [2]	Auxiliary Engine	1	2	3	4
RoPax	GT	medium	medium	0–24,999	from 25,000		
CarCarrier [3]	GT	slow	medium	0–39,999	from 40,000		
RoRo	GT	medium	medium	0–24,999	from 25,000		
Cruise	GT	medium	medium	0–24,999	from 25,000		
Diverse	GT	medium	medium	0–1999	from 2000		
Container [4]	GT	slow	medium	0–17,499	17,500–54,999	55,000–144,999	from 145,000
Tanker	DWT	slow	medium	0–34,999	35,000–49,999	50,000–119,999	from 120,000
Bulker	DWT	slow	medium	0–34,999	35,000–49,999	50,000–119,999	from 120,000
MPV	DWT	slow	medium	0–11,999	from 12,000		

[1] Weight classes are measured in GT (gross tonnage) or DWT (dead weight tonnage), depending on the type of ship. [2] Engine configuration differs between medium- or slow-speed diesel engines, depending on the type of ship. It is assumed that all ships within a particular class have the same engine configuration. [3] Typical size specifications for pure car carriers (PCC), in terms of the number of transported cars, was translated into GT. [4] Typical sizes of TEU (twenty foot equivalent unit, standard for container ships) or PanMax, SuezMax, etc., were translated into GT.

3.4. Energy and Fuel Consumption

The required power for propulsion was calculated using a speed–power curve (SPC) per ship type and size class [27], which determines the power consumption of each ship type as a function of speed. The calculation determines the required propeller power P_D [29]. The input variables are class-specific values, such as average length, width, and draft (arithmetic average of all ships with the set size class from the MDB). The SPC is simple to use and calibrate. It should be noted that the models represent generic, and thus average, ship types; the suitability of the application for modeling a single ship is dependent on the context and it is not intended.

The auxiliary engine in all ships is assumed to be a medium-speed diesel engine. For simplification, it is assumed that the auxiliary diesel power is essentially constant over all speeds [27]. Power values are based on EEDI specifications [1]. Even though the power can increase at higher speeds, due to, for example, seawater cooling or the operation of lube oil pumps, this effect should influence the overall results by less than 1% [27].

For the calculation of expended energy and fuel consumption, a proprietary life cycle performance analysis (LCPA) tool was used. The tool was developed jointly by the Flensburger-Schiffsbaugesellschaft Gmbh (FSG), BALance Technology Consulting, SSPA Sweden, Teknologian tutkimskeskus VTT, IFEU, and Det Norske Veritas [30,31], to support the generation of ship designs. The LCPA model is made available by BALance Technology Consulting and is available for purchase (LCPA). In the context of the present analysis, the LCPA was made available by the project partners of the FSG. The LCPA tool and SPC model were coupled to determine the fuel mass flow, which is calculated using the assumed power of the engine, together with the mechanical or electrical efficiencies and the specific fuel consumption for a certain time period. The energy expended was derived from the amount of fuel consumed and its calorific value (This step cannot be published, however can be traced and reproduced using the efficiency approximations of the ship's engines and the calculated propeller power within the SPC) [31]. It is assumed that all ships use low-sulfur marine gas oil (LSMGO) (lower heating value (LHV) 42.675 kJ/kg) with a sulfur content of less than 0.1%, in line with IMO regulations within the European Sulphur Emission Control Area (SECA) [32].

3.5. Emission Calculation

Tank-to-propeller pollutant emissions are determined using activity-based emission factors that relate to the fuel or energy consumption, in combination with the navigational phase of the ship [33]. There are three navigation phases, as a distinction is made between underway, maneuvering, and hoteling/at berth (maneuvering and hoteling are often analyzed as one).

The calculation of NO_x, SO_2, $PM_{2.5}$, and CO_2 was performed within the LCPA model [31]. Due to the closed-source nature of the tool, only the qualitative calculation process is described. CO_2 emissions were calculated from the carbon fraction of the used fuel (LSMGO, 3206 t_{CO_2}/t_{fuel}) [31]. SO_2 emissions were determined using the acidification potential, based on the fuel sulfur content (0.1%) and stoichiometric combustion to SO_2 in the energy converter [31]. PM emissions were calculated using the equation $PM = 0.2 + 0.6 \cdot S$ (g/kWh) for internal combustion engines [2,31], where S is the sulfur content of the fuel used. NO_x emissions were assumed to be in line with the official MARPOL tier regulations [2], depending on the ship construction date (see Table 2). The Tier I guideline was assumed for all ships built before 2000 [34], as this was set close to the actual pollutant levels before 2000 [27].

Table 2. Nitrogen oxide guidelines in the North Sea and Baltic Sea ECA (Emission Control Area) according to the IMO [2], MARPOL Annex VI. n = engine's rated speed in revolutions per minute (rpm).

		Total Weighted Cycle Emission Limit (g/kWh)		
Tier	**Ship Construction Date on or after**	**n < 130**	**n = 130–1999**	**n > 2000**
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.2)}$	7.7
III	1 January 2021	3.4	$9 \cdot n^{(-0.2)}$	2.0

POA, NMVOC, Ash, BC, and CO emissions were calculated using literature-based emission factors, together with the fuel or energy consumption determined within the LCPA tool. A variety of emission factors for maritime applications can be found in the literature [13,19,21,33,35–38]. A key study is EMEP CORINAIR, the Guidance Document for Air Pollutant Emissions Inventory published by the European Environment Agency (EEA) [39]. The 2019 version of the guide [33] provides activity-based emission factors for shipping (last update 12/2021 [37]). All of the emission factors used, as well as an extensive literature review of additional emission factors for sensitivity analyses related to engine types, are available in the Zenodo repository [40].

Speed-related emissions $e(v)$ in kg were calculated from selected emission factors ef and E or F, the ship's energy and fuel consumption, respectively, using Equations (1) and (2).

$$e(v) = ef \cdot E(v) \quad (1)$$

$$e(v) = ef \cdot F(v) \quad (2)$$

In addition to the activity-based (tank-to-propeller) emissions, the life cycle emissions of the fuel used (well-to-tank) were also analyzed. The LCPA tool provides well-to-tank emissions of NO_x, SO_2, $PM_{2.5}$, and CO_2 [31]. A full life cycle analysis can be used to evaluate the overall impact of a fuel, in terms of greenhouse gas and pollutant emissions, including all phases from production to use. The typical well-to-tank life stages of marine fuels include extraction, transportation, conversion, carriage, and bunkering. The LCPA software used the UMBERTO [41] life cycle software to determine the emission factors for well-to-tank emissions [30,31].

3.6. Processing

The introduced steps and data sets are brought together as follows. The individual steps can be traced in the publicly available code [29].

- Classification of each ship by IMO number, according to scenario-specific ship type and depending on age and scenario year, and unique assignment of the model via ship type and size class.
- Randomization of IMO numbers, in order not to be able to trace back to the proprietary AIS data.
- Integration of scenario-specific (e.g., year for NO_x regulation) models, including emissions and fuel consumption depending on speed.
- Calculation of all emissions, energy consumption, and related parameters for a 5 min interval, using interpolation based on the model's supporting values and the average speed of the ship during each 5 min interval.
- Generation of an hourly georeferenced emission inventory for further analysis.

Figure 2 summarizes the methodological steps used to compile the inventory.

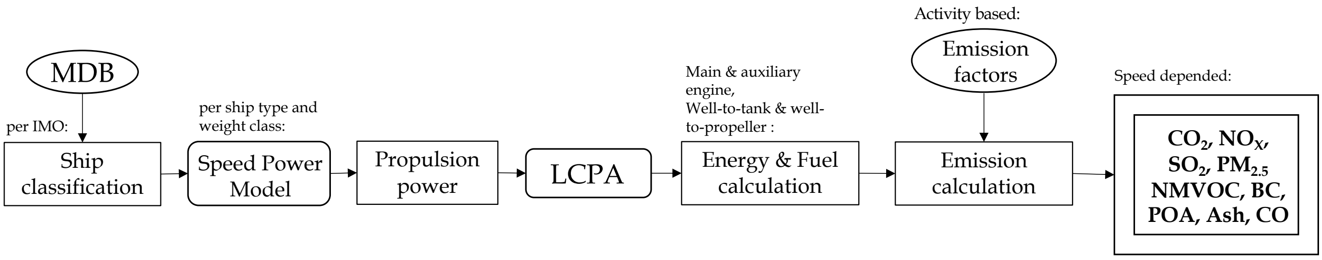


Figure 2. Schematic overview of the methodological steps utilized in the development of the EUF emission inventory, displaying the relevant processing steps within the square boxes. The input data for each step are contained within the circles and squares with rounded corners, the final output is shown in the double square. MDB = Maritime Data Base, LCPA = life cycle performance assessment.

4. Data Description

All input and output data can be accessed via the Zenodo data repository [40]. The supporting model code is available on GitHub [29].

(1) The CSV file *emission model* includes hourly emission quantities (well-to-tank and tank-to-propeller) and energy expended for the speed of the specific vessel type and size.

- **Type** (column A): Ship type definition in three components separated by an underscore (_): (1) the ship type (see Table 1), (2) the size class 1–4 [40], and (3) the age-dependent NO_x regulation, Tier I, Tier II, or FS (future scenario, equivalent to Tier III), e.g., ropax_2_tier 1 represents a RoPax vessel in size class 2 (above 25,000 GT), which was built before 01/01/2011.
- **Engine** (column B): Propulsion (main) engine or lectric (auxiliary engine) of a ship.
- **Speed (m/second)** (column C): The calculated speed over ground of a ship.
- **Energy (well-to-tank) (J)** (column D): Energy expended for the production, transportation, and distribution of the fuel used for propulsion.
- ***Pollutant*** **(well-to-tank) (kg)** (columns E–H): CO_2, SO_x, NO_x and PM emissions during production, transportation, and distribution of the fuel consumed (for SQ-2015 LSMGO).
- **Energy (J)** (column I): Energy expended for the propulsion of the ship per speed.
- **Fuel Consumption (kg)** (column J): Tank-to-propeller fuel consumption.
- ***Pollutant*** **(kg)** (columns K-S): Tank-to-propeller emission of CO_2, SO_x, NO_x, PM, BC, ASH, POA, CO, and $NMVOC$.

(2) The emission inventory *ship_emissions_YYYYMMDD* is available as 396 csv files, one for each day in 2015 and December 2014. These contain the following data records:

- **UniqueID** (column A): Unique identifier of ship. Due to the use of proprietary input data (AIS), the originally used unique identifier (IMO-number) was replaced with a random number.

- **Type** (column B): See the description for type in the emission model input descriptor list above.
- **Datetime** (column C): Date and time stamp following the format YYYY-DD-MM HH:MM:SS.
- **Lat** (column D): Calculated latitudinal position of the ship in decimal degrees.
- **Lon** (column E): Calculated longitudinal position of the ship in decimal degrees.
- **Speed_calc** (column F): Calculated speed in m/s from the calculated distance at a 5 min time interval .
- **Propulsion-Energy (Well to tank) (J)** (column G): Energy expended for the production, transportation, and distribution of the fuel used in the main engine.
- **Electrical-Energy (Well-to-tank) (J)** (column H): Energy expended for the production, transportation, and distribution of the fuel used in the auxiliary engine.
- **Propulsion-*Pollutant* (Well-to-tank) (kg)** (columns I, K, M, and O): CO_2, SO_x, NO_x, and PM ($PM_{2.5}$) emissions from the production, transportation, and distribution of the fuel needed by the main engine for propulsion in the respective time interval.
- **Electrical-*Pollutant* (Well to tank) (kg)** (columns J, L, N, and P): CO_2, SO_x, NO_x, and PM ($PM_{2.5}$) emissions from the production, transportation, and distribution of the fuel needed by the auxiliary engine in the respective time interval.
- **Propulsion-Energy (J)** (column Q): Energy content of the fuel used for propulsion (tank-to-propeller) of the main engine in the respective time interval.
- **Electrical-Energy (J)** (column R): Energy content of the fuel used for the auxiliary engine (tank-to-propeller) in the respective time interval.
- **Propulsion-Fuel Consumption (kg)** (column S): Fuel consumption for the propulsion (main engine) of the vessel in the respective time interval.
- **Electrical-Fuel Consumption (kg)** (column T): Fuel consumption for the hoteling load (auxiliary engine) of the vessel in the respective time interval.
- **Propulsion-*Pollutant* (kg)** (columns U, W, Y, AA, AC, AE, AG, AI, and AK): CO_2, SO_x, NO_x, *PM, BC, ASH, POA, CO, NMVOC* emissions from the main engine during operation (tank-to-propeller) of the ship.
- **Electrical-*Pollutant* (kg)** (columns V, X, Z, AB, AD, AF, AH, AJ and AL): CO_2, SO_x, NO_x, *PM, BC, ASH, POA, CO, NMVOC* emissions from the auxiliary engine during operation (tank-to-propeller) of the ship.

(3) In the interest of transparency and reproducibility, a number of supporting data sets are available on Zenodo [40]. The *speed-power-model.xlsx* file summarizes the assumed power (kW) for the main and auxiliary engines, as well as inputs for the SPC calculation (length (m), width (m), drauft (m), the shape-dependent variable c_b, the propulsion efficiency, and the wetted surface of the ship in m^2 specific to speed, ship type, and weight class. The *emission_factors.xlsx* file summarizes the emission factors specific to engine type, navigation phase, and pollutant, as well as an extensive, referenced list of factors for sensitivity analyses. The *analysis.xlsx* file contains additional information for further analyses of, for example, emission quantities as assessed within different models for cross-model comparisons. Additionally included is the time spent at a particular speed, as well as the number of ships considered in each ship and weight class. The *supplementary_material.pdf* file summarizes regulations and targets for maritime emissions [1,2]. This file also contains the equations used to calculate the propulsion power P_D.

(4) All related code, including static input data, is available on GitHub [29]. Within the folder *emission_model*, the *maximum_speed_per_type.csv* file lists the maximum possible speed in m/s [27]. The *ship_weightclass_mapper.csv* file assigns the different ship types and sizes to weight types (DWT or GT) and the lower and upper bounds of the weight classes connecting Tier I, II, and FS with the year of construction and the typical engine rpm for each specification. Both the *ship_type_fsg_mdb_mapper.xlsx* file and *short_long_name_mapper.xlsx* file are used for the preprocessing of ship type classification. Within the folder *lcpa-models* are *SensitivityAnalysis-ShipeTypeName-Rev2.csv* files, which are hourly emission models for

all ship types and sizes. The *scr* folder contains the model code itself, preprocessing steps and routines for result and input data analyses.

5. Validation

Comparison with Existing Emission Inventories

Crucial in the creation of an emissions inventory through bottom-up modeling is the validation of the results obtained. There was no possibility of comparing the chosen assumptions and related results with actual emission measurements. Initial studies on measuring ship emissions using drones are underway [42], exemplified by the SCIPPER project [43] and efforts by the European Maritime Safety Agency (EMSA). However, only individual ships on a specific voyage can be measured. A cross-model comparison, however, allows a statement about the quality of the obtained results. Useful in this context are the MoSES [21] and STEAM models [13]. The two models have been used to create emission inventories for the North Sea and Baltic Sea area: MoSES [21] for 2015, STEAM—in this application—for 2011 [13]. Table 3 summarizes the emission quantities, reference year, and number of ships analyzed for these two inventories and the presented results of the EUF inventory.

Table 3. Result values from MoSES [21], STEAM [13], and the EUF inventory in Gg per year and respective deviations from the EUF results in %.

	MoSES	**EUF**	**STEAM**	**Diff MoSES (%)**	**Diff STEAM (%)**
Year	**2015**	**2015**	**2011**		
Number of Ships	**21,845**	**16,632**	**n/a**	**23.86**	**n/a**
SO_2	32.55	24.90	192.10	30.70	671.34
NO_x	897.97	818.00	806.20	9.78	−1.44
BC	13.89	0.44	n/a	3036.76	n/a
POA	17.96	11.62	n/a	54.50	n/a
MA	0.32	0.22	n/a	46.85	n/a
CO_2	44,886.43	34,931.98	35,740.00	28.50	2.31
CO	38.31	38.04	57.30	0.72	50.64
$PM_{2.5}$	29.83	13.94	38.30	113.98	174.74
NMVOC	11.12	17.32	n/a	−35.81	n/a

In general, a good agreement can be observed between the values from EUF, STEAM, and MoSES for most pollutants. The emission quantities from the STEAM and MoSES inventories tended to be higher than those from the EUF model. This can be explained, among other things, by the number of ships investigated in the area under consideration. Comparing the EUF and STEAM values, it can be seen that there was a significant deviation in SO_x emissions. This was largely due to the introduction of the 0.1% sulfur guideline in 2015, which can also partially explain the deviation in $PM_{2.5}$ emission results, as the reduced sulfur content in the fuel also reduced particulate matter emissions. Further comparative analyses are possible based on Hilpert et al. [40].

Figure 3 depicts a detailed comparison of emissions from the EUF and MoSES [21] inventory and the deviations of the results of MoSES from the EUF emission inventory in percent. There was a tendency for MoSES emission values to be higher than those in the EUF inventory, which may have been due to the number of ships considered and the different calculation approaches for energy consumption and related emissions. A comprehensive comparison of the selected fuel and energy modeling would be difficult, due to the different methodological paths chosen. However, CO_2 emissions are a stable indicator, since the carbon from the required fuel burns almost entirely to CO_2. The variation here is consistent with the variations in the number of ships considered. The SO_2 emissions are in the same order of magnitude for the MoSeS and EUF values. The differences in NO_x, POA, and Ash are within a reasonable range and can be justified by the different emission factors used. The differences in NMVOC and BC are striking. Contrary to the general trend, NMVOC emissions are higher in the EUF inventory. BC emissions, on the other hand, are an order of magnitude lower in the EUF emission inventory.

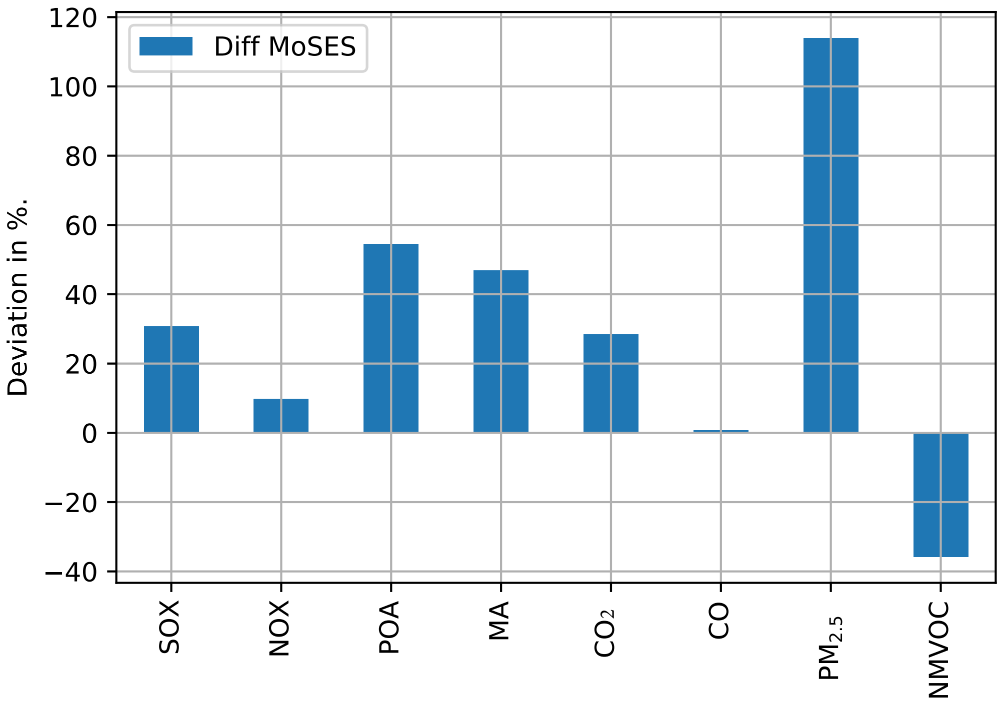


Figure 3. Deviation (in %) of values (emission quantity in the EUF inventory) to MoSES [21] for SQ-2015. MA = mineral ash.

The EUF model mainly uses fuel-based emission factors, while the emission factors within MoSES are related to the energy expended. MoSES uses a factor of 0.03 g/kWh for BC emissions from the main engine and 0.15 g/kWh for the auxiliary engine, as well as a adjustment of the factor to low loads of the engine. The EUF model uses the EEA's [37] factors (see Table 4). A more in-depth analysis that examines variances arising from energy expenditure is recommended.

Table 4. Emission factors used in MoSES [21] and EUF, FSC = fuel sulfur content (0.1%) and SFOC = specific fuel oil consumption.

Model	BC	POA	Ash	CO	NMVOC
MoSES	0.03 g/kWh	0.2 g/kWh	FSC · SFOC · 0.02 g/kWh	0.54 g/kWh	0.5 g/kWh
EUF	0.0329 kg/t	0.09 g/kWh	0.0002 kg/t	3.47 kg/t	1.52 kg/t

The analysis of the different values from STEAM, MoSES, and EUF show how crucial the choice of emission factors is. The factors for the EUF model were chosen based on an extensive literature review; particular emphasis was placed on the timeliness of the source. Nevertheless, there are large uncertainties that must be taken into account when interpreting the obtained results.

6. Discussion

Uncertainties

The results of this study must be viewed critically with regard to the methods and models used. The results are discussed concerning (1) (input) data (quality), and (2) the general modeling approach and connected assumptions.

(1) Uncertainties about the reliability of the emission inventories arise from the use of the closed-source LCPA model and raw AIS data, which are proprietary. This limits the reproducibility and transparency of the values generated. The creation of ship routes is influenced by the quality of the AIS data used and by the interpolation routines chosen. The AIS data used have a high data ranking (A or B are most accurate [24]), which makes the generated values more reliable. Since the end of 2018, satellite-processed AIS data are available, which can further increase the accuracy of results. Additionally, climate change may affect shipping routes by altering ocean currents and sea levels, and changing weather patterns. For example, changes in ocean currents could affect the efficiency of shipping routes, while rising sea levels could require modifications to port facilities and coastal infrastructure [44].

The LCPA model is a closed-source model. However it builds on the expertise of ship builders and environmental analysts. The emission values and associated calculation steps used within the LCPA model can be traced with sufficient accuracy.

(2) Within the general study approach, the chosen speed reduction criteria may also affect the results. Unlike other studies, such as used within the MoSES model [21], this study does not consider engine load for the calculation of fuel and power consumption. The speed–power curves take this into account, but the auxiliary engine is only partially responsive to the engine load and is simplified for modeling purposes. Unlike STEAM [11,12], the influence of waves and currents is not directly considered in the EUF model. However, the SPCs tend to have high power assumptions, so consideration of waves and currents was not considered essential. The loading condition of ships was not considered in the studies analyzed, such as [11,21]. Although some shipping companies may provide access to real-time data, this is often treated as confidential and not publicly available. As a result, the loading condition is not taken into account during the EUF analysis.

Generic ship types were defined, based on a complementary data set obtained from Vesselfinder, which can be compared with the AIS types from *Vesselfinder* [24]. Nevertheless, the integration of a more accurate ship type assignment system could further refine the emission values. Additionally, only ships over 100 GT were utilized in the EUF model, so the study does not provide an assessment of all emissions.

For future scenarios, fleet developments have to be taken into account. In 2017, maritime transport accounted for nearly 90% of international trade measured in tonne-kilometers [28]. Maritime trade volumes have tripled since 1980. The DNV expects seaborne trade to be 35% higher in 2030 than in 2017 and to increase by a further 12% before 2040. The UNCTAD [45] projected an average annual growth of 3.5% between 2019 and 2024, with the largest relative growth expected in the gas and container cargo sectors, each increasing by 135–150%. Bulk carriers are projected to increase by 40% by 2050, based on a combination of an increase in non-coal bulk trade and a possible reduction in coal shipments [45]. Looking specifically at the future development of container ships and their contribution to total emissions, it can be assumed that future emissions will increase disproportionately to the increase in goods transported.

7. Further Use of Data, Data Availability and User Notes

The data in the EUF emission inventory can be used to assess air pollution regulations and incorporate different emission control or propulsion technologies. The data can also be used in chemical transport modeling, to evaluate the air pollutant concentration resulting from maritime emissions. Subsequently, gridded population data could be used together with the results from chemical transport modeling to estimate the human health impacts of air pollutants. As the EUF inventory also provides fuel and energy consumption at a high resolution, new emission factors could be applied for different pollutants and the inventory could be expanded accordingly. The high spatial resolution of the data set makes it possible to analyze the shore-to-ship power demand for renewable energy to reduce emissions from the auxiliary engine at berth.

The code for the underlying calculations and post-processing functions are available under the BSD 3-Clause license [29]. The analysis uses Python as a programming language.

The emission inventory and all supporting data sets, with the exception of the AIS data, are available under an open license on Zenodo [40]. The data can be processed using Excel or any other data processing software capable of processing csv files, such as Python or R.

AIS data for the Baltic Sea can be obtained from HELCOM via a data agreement. The AIS data for the North Sea is proprietary data, which can be purchased from Vesselfinder. The LCPA model used is also proprietary, but the associated computational pathways are described qualitatively, allowing sufficient traceability of the results.

Author Contributions: Conceptualization, F.D.; methodology, F.D.; software, S.H.; formal analysis, F.D. and S.H.; investigation, F.D.; data curation, S.H.; writing—original draft preparation, F.D.; writing—review and editing, F.D.; visualization, S.H.; supervision, F.D.; project administration, F.D.; funding acquisition, F.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the EKSH (Society for Energy and Climate Protection Schleswig-Holstein). We acknowledge financial support by Land Schleswig-Holstein within the funding program Open Access-Publikationsfonds. No known financial gain for the funding giver is recognized.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are available at: https://zenodo.org/record/6951672, (accessed on 23 March 2023).

Acknowledgments: The authors would like to thank Rolf Nagel and Frank Borasch from the Flensburger Schiffsbau-Gesellschaft Nobiskrug. A special thanks goes to Jonathan Mole for his tireless and highly-skilled linguistic proofreading work.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

AIS	Automatic Identification System
BC	Black Carbon
CO	Carbon Monoxide
CO_2	Carbon Dioxide
c_b	shape dependent variable for prpulsion efficiency
DNV	Det Norske Veritas
ECA	Emission Control Area
EEA	European Environment Agency
EEDI	Energy Efficiency Design Index
EMEP	European Monitoring and Evaluation Programme
EMSA	European Maritime Safety Agency
EUF	Europa Universität Flensburg
e(v)	Speed related emissions
E	Energy Consumption
ef	Fuel Consumption
FSC	Fuel Sulphur Content
FSG	Flensburger Schiffbaugesellschaft
HELCOM	Helsinki Commission (Baltic Marine Environment Protection Commission)
IHS	IHS Markit
IMO	International Maritime Organisation

LCPA	Life Cycle Performance Assessment
LHV	Lower Heating Value
LOA	Length Overall
LSMGO	Low Sulfur Marine Gas Oil
MA	Mineral Ash
MARPOL	International Convention for the Prevention of Pollution from Ships
MDB	Maritime Data Base
MPV	Multi-Purpose Vessel
MoSES	Modular Ship Emission Model
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
OSPAR	Oslo-Paris Convention
P_D	Propulsion Power
PCC	Pure Car Carrier
$PM_{2.5}$	Particulate Matter
POA	Primary Organic Aerosol
RoRo	Roll-on/Roll-off
rpm	Revolutions Per Minute
SCIPPER	Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations
SECA	Sulphur Emission Control Area
SO_2	Sulfur Dioxide
SPC	Speed Power Curve
SFOC	Specific Fuel Oil Consumption
STEAM	Ship Traffic Emission Assessment Model
TEU	Twenty-foot Equivalent Unit
UNCTAD	United Nations Conference on Trade and Development

References

1. International Maritime Organization. *Fourth IMO Greenhouse Gas Study 2020*; Technical Report; IMO: London, UK, 2020.
2. International Maritime Organization. *Third IMO Greenhouse Gas Study 2014*; Technical Report; IMO: London, UK, 2015.
3. BMWK. *Verordnung über Netzentgelte bei der Landstromversorgung und zur Redaktionellen Anpassung von Vorschriften im Regulierungsrecht*; Verordnung 52; Bundesministerium für Wirtschaft und Energie: Bonn, Germany, 2019.
4. Corbett, J.J.; Fischbeck, P. Emissions from Ships. *Science* **1997**, *278*, 823–824. [CrossRef]
5. Corbett, J.J.; Fischbeck, P.S.; Pandis, S.N. Global nitrogen and sulfur inventories for oceangoing ships. *J. Geophys. Res.* **1999**, *104*, 3457–3470. [CrossRef]
6. Corbett, J.J.; Koehler, H.W. Considering alternative input parameters in an activity-based ship fuel consumption and emissions model: Reply to comment by Øyvind Endresen et al. on "Updated emissions from ocean shipping": Commentary. *J. Geophys. Res.* **2004**, *109*, D23. [CrossRef]
7. Corbett, J.; Ruwet, M.; Xu, Y.C.; Weller, P. Climate governance, policy entrepreneurs and small states: Explaining policy change at the International Maritime Organisation. *Environ. Politics* **2020**, *29*, 825–844. [CrossRef]
8. Eyring, V. Emissions from international shipping: 1. The last 50 years. *J. Geophys. Res.* **2005**, *110*, D17305. [CrossRef]
9. Van der Tak, C.; Cotteleer, A. *Emissions 2009: Netherlands Continental Shelf, Port Areas and Ospar Region II*; MARIN: Wagenigen, The Netherlands, 2011.
10. Van der Gon, H.D.; Hulskotte, J. *Methodologies for Estimating Shipping Emissions in the Netherlands—A Documentation of Currently Used Emission Factors and Related Activity Data*; Technical Report 500099012; Netherlands Environmental Assessment Agency: Bilthoven, The Netherlands, 2010.
11. Jalkanen, J.P.; Johansson, L.; Kukkonen, J. A Comprehensive Inventory of the Ship Traffic Exhaust Emissions in the Baltic Sea from 2006 to 2009. *AMBIO* **2014**, *43*, 311–324. [CrossRef] [PubMed]
12. Jalkanen, J.P.; Johansson, L.; Kukkonen, J.; Brink, A.; Kalli, J.; Stipa, T. Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. *Atmos. Chem. Phys.* **2012**, *12*, 2641–2659. [CrossRef]
13. Jalkanen, J.P.; Johansson, L.; Kukkonen, J. A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011. *Atmos. Chem. Phys.* **2016**, *16*, 71–84. [CrossRef]
14. Johansson, L.; Jalkanen, J.P.; Kalli, J.; Kukkonen, J. The evolution of shipping emissions and the costs of recent and forthcoming emission regulations in the northern European emission control area. *Atmos. Chem. Phys. Discuss* **2013**, *13*, 16113–16150. [CrossRef]
15. Johansson, L.; Jalkanen, J.P.; Kukkonen, J. Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. *Atmos. Environ.* **2017**, *167*, 403–415. [CrossRef]

16. Kramel, D.; Muri, H.; Kim, Y.; Lonka, R.; Nielsen, J.B.; Ringvold, A.L.; Bouman, E.A.; Steen, S.; Strømman, A.H. Global Shipping Emissions from a Well-to-Wake Perspective: The MariTEAM Model. *Environ. Sci. Technol.* **2021**, *55*, 15040–15050. [CrossRef] [PubMed]
17. Karl, M.; Jonson, J.E.; Uppstu, A.; Aulinger, A.; Prank, M.; Sofiev, M.; Jalkanen, J.P.; Johansson, L.; Quante, M.; Matthias, V. Effects of ship emissions on air quality in the Baltic Sea region simulated with three different chemistry transport models. *Atmos. Chem. Phys.* **2019**, *19*, 7019–7053. [CrossRef]
18. CNSS. *Clean North Sea Shipping—Key Findings and Recommendations*; Final Report; Clean North Sea Shipping: Newcastle upon Tyne, UK, 2014.
19. Aulinger, A.; Matthias, V.; Zeretzke, M.; Bieser, J.; Quante, M.; Backes, A. The impact of shipping emissions on air pollution in the greater North Sea region—Part 1: Current emissions and concentrations. *Atmos. Chem. Phys.* **2016**, *16*, 739–758. [CrossRef]
20. Matthias, V.; Aulinger, A.; Backes, A.; Bieser, J.; Geyer, B.; Quante, M.; Zeretzke, M. The impact of shipping emissions on air pollution in the greater North Sea region—Part 2: Scenarios for 2030. *Atmos. Chem. Phys.* **2016**, *16*, 759–776. [CrossRef]
21. Schwarzkopf, D.A.; Petrik, R.; Matthias, V.; Quante, M.; Majamäki, E.; Jalkanen, J.P. A ship emission modeling system with scenario capabilities. *Atmos. Environ. X* **2021**, *12*, 100132. [CrossRef]
22. IMO. Excel, International Maritime Organization. 2012. Available online: https://greenvoyage2050.imo.org/fleet-and-co2-calculator/ (accessed on 3 March 2023).
23. HELCOM. *Emissions from Baltic Sea Shipping 2006–2018*; MARITIME 19-2019 5-2; HELCOM: Lisbon, Portugal, 2019.
24. Vesselfinder. AIS Ship Types—AIS Data. 2022. Available online: https://www.vesselfinder.com/ (accessed on 23 April 2023).
25. Vesselfinder. Available online: https://www.vesselfinder.com/historical-ais-data (accessed on 23 March 2023).
26. EC. Baltic Sea Shipping Traffic Intensity. 2017. Available online: https://maritime-spatial-planning.ec.europa.eu/practices/baltic-sea-shipping-traffic-intensity (accessed on 23 April 2023).
27. Nagel, R. (Flensburger Schiffbau-Gesellschaft mbH & Co KG, Flensburg, Germany); Dettner, F. (Europa University Flensburg, Flensburg, Germany). Shipbuilding Expertise. Personal communication, 2021.
28. DNV-GL. *Martime Forecast to 2050*; Forecast; DNV GL: Høvig, Norway, 2017.
29. Hilpert, S. *znes/KlimaSchiff: V1.0 (V1.0)*; Zenodo, Source Code, BSD 3-Clause; Europa Universität: Flensburg, Germany, 2022. [CrossRef]
30. Thiem, C.; Liebich, A.; Münter, D. *Joules—Fuel Data Report, Identification, Physico-Chemical Properties and Well-To-Tank Data of Marine Fuels*; Confidential Report FP7-SST-2013-RTD-1; Flensburger Schiffbau-Gesellschaft mbH & Co KG: Hamburg, Germany, 2013.
31. Joules. *LCPA Tool incl. LCPA and LCA Description*; Confidential Report 21-1; Flensburger Schiffbau-Gesellschaft mbH & Co KG: Flensburg, Germany, 2014.
32. International Maritime Organization (IMO). *Safety for Gas-Fuelled Ships—New Mandatory Code Enters into Force*; IMO: London, UK, 2017.
33. European Environment Agency (EEA). *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019—Technical Guidance to Prepare National Emission Inventories*; EEA: Copenhagen, Denmark, 2019.
34. IMO. *Nitrogen Oxides (NOx)—Regulation 13*; IMO: London, UK, 2020.
35. Kristenen, H.O. Energy demand and exhaust gas emissions of marine engines. *Clean Shipp. Curr.* **2012**, *1*, 18–26.
36. Jun, P.; Gillenwater, M.; Barbour, W. *CO_2, CH_4, and N_2O Emissions from Transportation-Water-Borne-Navigation*; Technical Report; IPCC: Geneva, Switzerland, 2001.
37. EEA. *Emission Inventory International—1.A.3.d Navigation (Shipping) 2019, Update Dec. 2021*; Guidebook 2019 SNAP 08042-4; EEA: Copenhagen, Denmark, 2021.
38. Entec UK Limited. *Quantification of Emissions form Ships Associated with Ship Movements between Ports in the European Community*; Final Report; Entec UK Limited: Northwich, UK, 2002.
39. EEA. *EMEP/CORINAIR Emission Inventory Guidebook*; EEA: Copenhagen, Denmark, 2007.
40. Hilpert, S.; Dettner, F.; Nagel, R. Emission Inventory of maritime Shipping on the Baltic and North Sea in 2015 with scenario capabilities. *arXiv* **2022**, arXiv:2211.13129.
41. ifu hamburg. 2022. Available online: https://www.ifu.com/de/umberto/oekobilanz-software (accessed on 3 March 2023).
42. Winnes, H.; Moldanová, J.; Anderson, M.; Fridell, E. On-board measurements of particle emissions from marine engines using fuels with different sulphur content. *Proc. Inst. Mech. Eng. Part J. Eng. Marit. Environ.* **2016**, *230*, 45–54. [CrossRef]
43. SCIPPER. *SCIPPER—Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations*; Horizon2020; SCIPPER: Brussels, Belgium, 2021.
44. DOT. *The Potential Impacts of Climate Change on Transportation*; Summary and Discussion Paper; DOT Center for Climate Change and Environmental Forecasting: Washington, DC, USA, 2002.
45. UNCTAD. *Review of Maritime Transport*; Technical Report; United Nations Conference on Trade and Development: New York, NY, USA, 2019.

7

Modelling CO_2 Emissions and Mitigation Potential of Northern European Shipping[1]

Franziska Dettner
Simon Hilpert

[1]published as: F. Dettner, S. Hilpert (2023): Modelling CO_2 emissions and mitigation potential of Northern European Shipping *Transportation Research Part D: Transport and Environment*, 119, 103745

Transportation Research Part D 119 (2023) 103745

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Modelling CO_2 emissions and mitigation potential of Northern European shipping

Franziska Dettner *, Simon Hilpert

Europa-Universität Flensburg, Centre for Sustainable Energy Systems, Auf dem Campus 1, 24943 Flensburg, Germany

ARTICLE INFO

Keywords:
Maritime emissions
AIS-data analysis
Emission modelling
Carbon pricing
Paris agreement
EU-ETS

ABSTRACT

The European maritime shipping sector has a crucial role in reducing CO_2 emissions in order to meet the 1.5 °C target set in the Paris Agreement. This study uses state-of-the-art maritime emissions modelling to quantify CO_2 emissions in the North and Baltic Seas (34,932 t in 2015), and to assess the carbon mitigation potential of E-methanol when life-cycle emissions are taken into consideration. A reduction of 90% is possible by 2040 if all considered ships are replaced by ships powered by E-methanol. The assessment of a carbon budget for shipping in the North Sea and Baltic Sea (0.75 Gg for the period 2011–2011) shows that with a conservative estimate of annual carbon emissions, the budget will be consumed by 2030 if no countermeasures are taken.

1. Introduction & background

The European Union (EU) is the world's third-largest emitter of greenhouse gases (GHGs), such as CO_2, and consequently has a crucial role to play in achieving the 1.5 °C target of the Paris Climate Agreement. Since 1990, transport emissions in the EU have grown by 33% (DNV-GL, 2017). Transport, especially maritime transport, remains a key obstacle to achieving the EU's climate targets.

In 2018, the International Maritime Organisation (IMO)[1] set ambitious targets to reduce global maritime shipping CO_2 emissions by 40% by 2030 and by 50% by 2050, but these are neither binding nor do they include possible transformation pathways (IMO, 2020a). The shipping industry has longstanding fossil fuel infrastructure assets that are vulnerable to carbon lock-in effects, which ties it and the economy to CO_2 emissions for decades (Anderson and Bows, 2012). The calculation of maritime shipping emissions is of particular importance, as these are emitted into the marine atmospheric boundary layer (Kasibhatla et al., 2000), which serves as a useful environmental reference point (Davis et al., 2001) and emissions here can directly influence and change the composition of the atmosphere (Shi and Gullett, 2018).

This study quantifies CO_2 emissions from shipping in the North Sea and Baltic Sea and evaluates their compatibility with the Paris Climate Agreement. It is unique in its comprehensive examination of the costs, budget, and pricing of maritime transport carbon emissions in the North Sea and Baltic Sea regions using open source-based modelling which allows for own analysis. Its focus on the compatibility of shipping emissions with the Paris Agreement and carbon pricing to mitigate them makes it a valuable resource for reducing maritime transport CO_2 emissions and meeting the goals of the Paris Agreement.

* Corresponding author.
E-mail addresses: franziska.dettner@uni-flensburg.de (F. Dettner), simon.hilpert@uni-flensburg.de (S. Hilpert).

[1] Abbreviations used several times in the following article; International Maritime Organisation (IMO), Automatic Identification System (AIS), Energy Efficiency Design Index (EEDI), Greenhouse Gases (GHG), European Emission Trading Scheme (EU-ETS), Maritime Emission Trading Scheme (METS), Conference of the Parties (COP), Gross Tonnage (GT), Low-sulphur marine gas/diesel oil (LSMGO).

https://doi.org/10.1016/j.trd.2023.103745
Received 4 January 2023; Received in revised form 21 March 2023; Accepted 16 April 2023
Available online 25 April 2023
1361-9209/

This study quantifies the CO_2 emissions from shipping in the North Sea and Baltic Sea, assesses the compatibility of the European (North Sea and Baltic Sea) maritime shipping emission pathway within the Paris Agreement, and analyses carbon pricing, including the cost of environmental damage and CO_2 certificates.

1.1. Maritime policy framework

Within the Paris Agreement international shipping is not directly included, but it is addressed under the UNFCCC's subsidiary body, the International Maritime Organisation (IMO) (UNFCCC, 2016). The IMO is responsible for regulating greenhouse gas emissions from international shipping, and it has adopted a number of measures to reduce emissions from ships. The most relevant measure is the International Convention for the Prevention of Pollution from Ships from 1973, which was modified in 1978 into the MARPOL 73/78 protocol. Annex VI of the protocol, which came into force in 2013, details measures which could help to increase the energy efficiency of ships, including technical measures (e.g., the Energy Efficiency Design Index (EEDI)), which sets energy efficiency requirements for new ships, and operational measures (e.g., the Ship Energy Efficiency Management Plan (SEEMP)), which requires ships to develop and implement a plan to improve their energy efficiency over time (IMO, 2015).

In addition to these measures, the IMO has adopted an initial strategy on reduction of GHG emissions from ships. The strategy aims to reduce global CO_2 emissions from maritime shipping by 40% by 2030 and 50% by 2050 (IMO, 2021). This aim was consolidated, among other things, in the European Union's *Fit for 55* package (EC et al., 2019), which aims to reduce the EU's greenhouse gas (GHG) emissions by 55% by 2030. The strategy also includes specific short-term measures to reduce emissions from ships, such as the implementation of a new fuel oil standard, the development of a data collection system for fuel consumption, and the promotion of energy efficiency technologies and practices (EC et al., 2019), (IMO, 2020a).

A proposition also states, that from 2023, maritime shipping in the EU is to be subject to the European Union's Emission Trading Scheme (EU-ETS). Ships currently reporting CO_2 emissions under the EU Monitoring, Reporting and Verification (MRV) Regulation (2015/757) will have to purchase CO_2 emission certificates (IMO, 2015). All intra-EU emissions will be included in the EU-ETS, together with 50% of emissions from ships arriving in or leaving countries within the EU. This will increase to 100% by 2026 (EC et al., 2019). During COP 27, EU legislators ultimately agreed to include maritime shipping in the EU-ETS (as of 29/11/22). There will be a gradual implementation of the ETS. In 2025, ships will have to pay for 40% of their CO_2 emissions. This will increase to 70% in 2026 and 100% in 2027. All non-CO_2 emissions, such as nitrogen oxides, soot and methane, will be included in the ETS in the future. They will first be monitored (i.e. included in the MRV regulation) from 2024 and then included in the ETS from 2026 (i.e. 2027 will be the first year payments are made for non-CO_2 emissions from 2026). It is intended that ETS revenues from the sale of 20 million CO_2 certificates will go into the Innovation Fund and be used to renew shipping fleets to tackle the root of the problem and reduce emissions. The final negotiations on one of the biggest climate laws in Europe have yet to be concluded.

Overall, while international shipping is not directly included in the Paris Agreement (UNFCCC, 2016), the IMO's measures to reduce greenhouse gas emissions from ships are aligned with the goals of the Paris Agreement and contribute to global efforts to combat climate change.

1.2. Carbon budgeting and emission trading

Research on the abatement of carbon emissions from maritime shipping is relatively new. In 2007, the Federal Environment Agency in Germany commissioned a study to assess the inclusion of CO_2 emissions from international shipping in the EU-ETS (Kågeson, 2007). According to this study, "a ship would be liable for emissions from fuel bunkered during six months prior to a call at a participating port. With this design, emissions from the return voyages of ships involved in intercontinental traffic would automatically be covered, and shipowners and operators would gain nothing by calling at ports just outside the European Union. The geographical scope would thus be global, albeit limited to ships that call at ports of the European Union (and other participating states)." (Kågeson, 2007). Based on these assumptions, Kågeson (2007) shows that 6,200 million tons fewer CO_2 would be emitted between 2021 and 2035 in a business-as-usual scenario. A large proportion of the reduction would result from land-based sources paid for indirectly by the shipping sector. In 2008, Kågeson (2008) proposed a global cap and a trade system for CO_2 emissions from international maritime shipping. The study underlines the importance of targeting real CO_2 emissions and indicates that ownership within the maritime transport industry makes it difficult to allocate a carbon budget to each ship in the global fleet without potentially penalising countries of the global south (flag states).

A study by the Fridtjof Nansen Institute in Norway applied a multi-level reinforcement perspective to the process of including maritime shipping in the EU-ETS and found that its inclusion is in line with the broadening ambitions of the European Commission since the start of the ETS (Wettestad and Gulbrandsen, 2022).

A study by Traut et al. (2015) sets the carbon budget for maritime shipping in the period 2011–2100 at 33 Gt for a 2 °C warming scenario and 18 Gt for warming under 1.5 °C. This is based on approximately 60,000 ships globally in 2012. An analysis of data acquired by the EU-MRV regulation shows that the estimated baseline committed emissions value is equivalent to 85%–212% of the global maritime shipping's carbon budget required to meet the 1.5 °C target of the Paris Agreement (Bullock et al., 2020). Mellin et al. (2020) assessed the design of a Maritime Emission Trading Scheme (METS) and its impacts, basing the assessment on data collected within the EU-MRV regulation. If no countermeasures are taken, the MRV data are likely to capture the emission of about 178 Mt of CO_2 in 2026, whereas an approach based solely on intra-European Economic Area (EEA) shipping yields an emission value of only 75 Mt CO_2 (Mellin et al., 2020) .

A number of studies discuss the problem of emissions allocation in the shipping sector. Zhu et al. (2014) discuss the impact of a METS on fleet deployment and the mitigation of carbon emissions for container ship operators. Zhu et al. (2014) show that an METS can motivate operators to utilise new technologies, increase energy efficiency and even remove less efficient ships from service; however, the efficiency of a METS is pronounced when bunker fuel prices are high, which has a larger effect than applying a stricter certificate allocation. Based on the analysis of 38,000 oil tanker voyages over a 3-year period, a carbon allowance price of 10–50 USD per tonne would cost shipping companies between 0.3 and 1.4 billion USD per year (Cariou et al., 2021). Cariou et al. (2021) analysed that if lower carbon prices are considered, the METS still provides sufficient incentives for abatement measures, in particular for wind-assisted propulsion technologies for ships. An analysis by Gu et al. (2019) suggests that the implementation of a METS does not lead to emission reductions in short term scenarios. They state that only with low bunker prices and high allowance costs of a global METS can a more significant carbon decrease be expected in the short term.

Selin et al. (2021) analysed the national allocation of maritime shipping emissions with regard to five factors: flag, owner, operator, manager and bunker fuel country. For all factors, around 10 countries would be responsible for around 70% of carbon emissions. With an allocation scheme by owner, manager and operator, over 70% of the emissions are attributed to OECD countries. With an allocation by bunker this figure is 39%, and by flag countries 25% (Selin et al., 2021). Selin et al. (2021) finds that the best allocation mechanism, which meets the criteria of effectiveness and equity, would be one in which emissions are assigned to the countries of ship owners, which would be Japan, Greece, China, US, Germany, Singapore and Denmark. The most drastic increase in national carbon budgets would occur for the Marshall Islands (610%), Greece (105%), Cyprus (79%), Denmark (61%). For the EU27 area, the carbon budget would increase by 7% (Selin et al., 2021).

The UK leads the application of emissions allocation, which will include the share of emissions from international aviation and shipping in its carbon budgets from 2033 onwards (CCC, 2020).

1.3. The role of emission abatement measures

A study by Bows-Larkin et al. (2015) shows that, contrary to IMO reports, emissions from maritime shipping remain at a high level. Over the last decades, total global emissions from all sources have increased, while the share from maritime shipping has fallen. Emission reduction measures are generally distinguished between operational and technical measures. Shi (2016) argues that although technological measures are not sufficient to achieve maritime shipping emission reductions in the short-term, operational measures can lead to immediate emission reductions. Slow-steaming is identified as the most promising operational measure (Bows-Larkin et al., 2015). However according to Bows-Larkin et al. (2015) “only by opening out the possibility space to consider a step-change in technology and operations, as well as demand-side measures, can the sector sustain the level of cuts associated with making its fair and proportionate contribution to avoiding dangerous climate change.”. Walsh et al. (2017) analysis of maritime shipping emissions from a UK perspective shows that it is possible for a nation’s shipping sector to make a fair contribution to meeting global climate change commitments although a combination of mitigation measures is necessary.

Regarding technical measures, alternative fuels seem to be to most promising solution for reducing emissions. The analysis presented in this paper indicates that E-methanol is a promising emission abatement method. According to Nagel (2020), methanol (and ammonia) are discussed most prominently in the shipbuilding industry as an alternative fuel (additional information within Appendix B).

Horvath et al. (2018) analysed methanol as a future maritime shipping fuel and concluded that the payback time for methanol engines could be between 1.2 years and 15 years, depending on the price of marine gas oil (MGO). The study highlights that the results strongly depend on projected fuel prices; however, E-methanol was identified as the most feasible fuel for container ships and deep sea vessels in 2040. The projected prices are similar to fossil diesel with an imposed carbon tax. Lindstad et al. (2020) highlight the potential role of E-fuels for the maritime shipping sector, noting that the GHG reduction potential depends solely on abundant renewable electricity, and recommend the use of dual-fuel engines.

1.4. Contribution to scientific debate & research question

Thus study includes the analysis of the entire CO_2 pathway in Northern European shipping, spanning from ship movement data to energy consumption during different life-cycle phases, emission quantification and scenario analysis. The comprehensive dataset (emission inventory and scenario analysis), made publicly available in csv-format (Hilpert et al., 2022. Hilpert, 2022, Dettner and Hilpert, 2022), facilitates adjustments and custom analyses, also for non-modelling experts.

This study concentrates on the North and Baltic Seas, which represent one of the world’s most frequented marine areas, and offers an evaluation of not only CO_2 emissions from maritime shipping data but also places them within the framework of a European emission budget aimed at reaching the 1.5 °C target. The study investigates the potential of e-methanol as an alternative fuel to mitigate emissions and examines the costs of carbon pricing. This research accentuates the pressing need for immediate action in the (European) maritime sector to align with the emissions reduction goals.

Underlying research questions are:

- What is the carbon abatement potential of E-methanol as an alternative fuel for the international maritime shipping sector?
- What is the level of compliance of the maritime shipping sector within the Paris Agreement’s 1.5 °C goal?
- What carbon price is necessary to enable a swift transition to carbon neutral shipping?

2. Materials and methods

The area under consideration is the North European Sulphur Emission Control Area (SECA), as defined by the MARPOL Convention Annex VI, between 65°N, -5°W, 48.3°S and 30.7°E (BSH, 2015).

2.1. Emission inventory

This study is based on a temporally and spatially highly-resolved emission inventory for the North Sea and the Baltic Sea for all IMO registered seagoing vessels above 100 GT. The emission inventory was compiled using current emission factors and ship activity data for the year 2015. The activity data was provided by HELCOM (Baltic Sea) (helcom, 2019) and Vesselfinder (North Sea) (Vesselfinder, 2022), compiled from AIS data. The emission inventory includes air pollutant quantities of CO_2, NO_x, SO_2, $PM_{2.5}$, CO, BC, Ash, NMVOC, and POA, as well as speed-dependent fuel and energy consumption. The inventory distinguishes the emission, energy and fuel consumption quantities between main and auxiliary engines and between well-to-tank and tank-to-propeller life cycle stages. The data within the inventory is geo-referenced and provided at a five-minute resolution. Table 10 within Appendix A summarises the main methodological steps taken to compile the emission inventory (see also Fig. 1). The emission inventory, related code and calculations are available on Zenodo (Hilpert et al., 2022) and GitHub (Hilpert, 2022). The full methodology is described in detail within Dettner and Hilpert (2022).

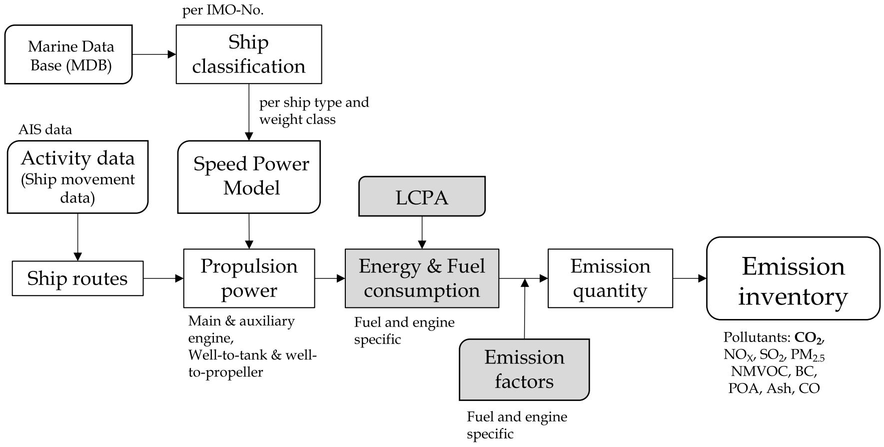


Fig. 1. Schematic overview of methodological steps used for the emission inventory. The rectangles with two rounded corners identify the *external input data and used calculation models*. The rectangle with rounded corners *emission inventory* represents the final result, and the square rectangles show the intermediate calculation steps, all made available on Hilpert et al. (2022). MDB provided by Vesselfinder (2022), LCPA = Life Cycle Performance Analysis Tool (by Joules, 2014, Nagel, 2020, Thiem et al., 2013). Methodology in detail in Dettner and Hilpert (2022).

2.2. Scenario analysis

The emissions inventory was used to evaluate the CO_2 mitigation and air pollutant reduction potentials of alternative fuels. E-methanol (background within Appendix B) was selected as a promising future fuel (Nagel, 2020), DNV-GL (2017) for analysis.

Assumptions

The emission, energy and fuel quantities for the base year, 2015, are contained in the Status-Quo Scenario (SQ-2015). Quantities for 2030 are provided in FS-2030 and for 2040 in FS-2040. The movement data from 2015 was used as the basis, and potential fleet developments were neglected (for information see e.g. IMO (2015), UNCTAD (2019) or DNV-GL (2017)). It is assumed that the considered ships will be replaced by a *future_ship* fuelled by E-methanol after a lifetime of 25 years (Nagel, 2020), (DNV-GL, 2017), (UNCTAD, 2019). By 2040, all ships will be renewed (Table 1).

It is assumed that E-methanol will be the standard operating fuel for all ships operating in FS-2040. In order to create a high temperature and high pressure environment for robust combustion, a pilot fuel is injected together with methanol (Dong et al.,

Table 1
Scenario description and share of methanol-fuelled ships.

Scenario	Year	Name	Share of methanol-fuelled Ships
Status quo	2015	SQ-2015	0%
Low emissions	2030	FS-2030_low	51%
High emissions	2030	FS-2030_high	51%
Low emissions	2040	FS-2040_low	100%
High emissions	2040	FS-2040_high	100%

Table 2
Scenario assumptions for FS-2030 and FS-2040 in a *high* and *low* scenario.

	CO_2	NO_x	SO_2	$PM_{2.5}$	BC	POA	CO	Ash	NMVOC
FS_low	LCPA	LCPA	LCPA	LCPA	0	0	0	0	0
FS_high	LCPA	LCPA	LCPA	- 95% SQ	0	SQ	SQ	0	SQ

Table 3
Production emissions (well-to-tank) for LSMGO (SQ-scenario) and methanol (FS-scenario) (Joules, 2014).

	Share RE	Energy expended		CO_2	SO_2	NO_x	PM
	%	kJ/kg_{fuel}	MJ/MJ_{fuel}	g/kg_{fuel}	g/kg_{fuel}	g/kg_{fuel}	g/kg_{fuel}
LSMGO	0.1	8,582	0.201	482.52	1.47	1.64	0.16
Methanol	99.8	22,486	2.339	−646.86	0.69	0.28	0.22

Table 4
CO_2 costs in EUR_{2020}/t_{CO2eq} for environmental damage costs, 1% time preference rate, increased valuation of welfare of present generation compared to future generations, 0% means equal distribution (UBA, 2020). Costs for CO_2 certificates within the EU-ETS (EU, 2018), in *low* (OECD, 2021) and *high* after the *ambitious* scenario from Pietzcker et al. (2021).

	Environmental damage costs 1% time preference rate	Environmental damage costs 0% time preference rate	EU-ETS low	EU-ETS high
Low	195	680	30	80
Medium	215	700	60	130
High	250	765	120	300

2020). Low-sulphur maritime gas oil (LSMGO) was selected as the pilot fuel for the future scenarios and is also the standard operating fuel for all ships operating in SQ-2015. The pilot fuel consumption is assumed to be approximately 5% (Nagel, 2020) of the total fuel demand in the future scenarios. It is assumed that *future ships* will have the same dimensions, but the tank arrangement will be adapted to accommodate the increased fuel demand (Nagel, 2020). In the engine room, the spaces previously used for the preparation of LSMGO will be replaced 1:1 for the use of E-methanol.

CO_2, NO_x, SO_2 and $PM_{2.5}$ emissions were calculated using a life-cycle performance analysis tool (Joules, 2014; Thiem et al., 2013; Nagel, 2020). Literature-based emission factors for other pollutants under consideration in this study are not yet soundly available, so a distinction was made between two emission paths (future projections), *high* and *low*. These describe the range in which the potential emissions may lie. Table 2 summarises the assumptions made.

Ash and BC emissions were set to zero in both scenarios. It is assumed that the carbon contained in methanol is burnt cleanly and without residues, although methanol is presumably not used without additives to aid ignition, so some hydrocarbon by-products are likely to be formed. The *low* scenario sets all other emissions, which are not known, to zero. For comparison, a *high* scenario was modelled, which equates all remaining emissions to the SQ-2015 scenario. The possibility of increased emissions of, for example, carbon monoxide (CO) from methanol compared to the use of LSMGO in dual-fuel operation (Verhelst et al., 2019) is neglected. Sogaard et al. (2021) reports that the replacement of conventional fuels with methanol can result in a reduction particulate matter emissions by up to 95%. This information was taken into account in the modelling of the *high* scenario.

Particularly relevant for the analysis of methanol as an alternative fuel are not only the tank-to-propeller emissions, but in particular the life cycle emissions during the production and distribution of the fuel (well-to-tank). Table 3 shows the production emissions for LSMGO (SQ-2015) and E-methanol (FS-2030/40), as well as the share of renewable energies (RE) in the production process (Joules, 2014).

2.3. Carbon pricing

A CO_2 price, also called a carbon price, is a price that an emitter of carbon dioxide has to pay. The use of a carbon price serves to internalise external costs of carbon dioxide release, in particular the consequences of global warming. The carbon price is levied on CO_2 emissions to induce polluters to reduce the amount of emissions into the atmosphere. So-called carbon pricing is thus a market based strategy to reduce global warming. Carbon pricing programmes can be implemented at local, state or national level through legislation or regulation. One such programme is the EU-ETS, in which maritime shipping is set to be integrated from 2023 (EU, 2018). The cost assumptions for CO_2 certificate prices in the present analysis are taken from a study by the OECD, which suggests three carbon price levels (EU-ETS_low) (OECD, 2021). Higher CO_2 costs (EU-ETS_high) are taken from Pietzcker et al. (2021), which analysed two CO_2 reduction scenarios, assuming in an *ambitious* scenario that the decarbonisation in Europe is fast tracked and that total emissions in 2030 are 55% lower than the level in 1990.

In addition to carbon pricing, the environmental damage costs of CO_2 emissions were analysed. These describe the costs that arise as a direct result of the impact (consequence) of environmental pollution. The Federal Environment Agency (Umweltbundesamt, UBA) understands damage costs to be an indicator for the loss of benefits resulting from a deterioration of the state of the environment. The cost rates suggested by the UBA (2020) use a damage cost approach and therefore describe the total societal costs of CO_2 emissions (see Table 4).

2.4. Carbon budget

To reach the 1.5 °C target set by the Paris Agreement, global greenhouse gas emissions must be reduced by 50% by 2030. Global CO_2 emissions amount to about 36 billion tonnes per year, so the calculated budget of 400 billion tonnes of carbon (to meet the 1.5 °C target) will be used by 2030 if emissions remain at current levels (IPCC, 2021).

Calculating the carbon budget for the maritime shipping sectors is fraught with difficulties. One difficulty is the distinction between country-specific and area-specific emissions, as ships operate in international waters, are operated by different shipowners in different countries and sail under different flags (the state in which they are registered).

A study by the University of Manchester identifies a carbon budget for maritime shipping in 2 °C and 1.5 °C scenarios (Traut et al., 2015). Traut et al. (2015) transfer the global CO_2 budget to international maritime shipping, assuming a fair sharing of mitigation efforts, with the result that international maritime shipping reduces its emissions by the same share required for the global average value. In their 1.5 °C reference scenario, which offers a 50% chance of limiting global warming to 1.5 °C, cumulative CO_2 emissions in the period 2011–2100 amount to about 773 Gt CO_2 (Traut et al., 2015). It is noted that this figure is well above the range given in the IPCC AR5-Synthesis Report (IPCC, 2021). According to Traut et al. (2015) and the IMO (2015), CO_2 emissions from maritime shipping between 2007 and 2012 account for approximately 2.33% of global CO_2 emissions. This results in a CO_2 budget of 18 Gt for the period 2011–2100 for international maritime shipping under the 1.5 °C scenario.

Within this study of the European maritime shipping sector, a generic approach was chosen, based on Traut et al. (2015). The amount of CO_2 emissions from shipping within the North European SECA as a proportion of global shipping emissions was determined and the carbon budget was adjusted proportionally.

3. Results

The results are presented in three areas: (1) emission quantities, (2) carbon mitigation through the use of methanol and (3) carbon budget and costs.

3.1. Emission quantities

Pollutant emissions are primarily related to fuel consumption and thus the energy demand of the ship. Therefore, emissions are highest in the areas where most ships operate. The modelling results presented in Fig. 2 are a basic plausibility check for the bottom-up ship route and emission calculation, as the known main shipping routes (cf. EC, 2017) are clearly identifiable from the routes created from AIS data. It is assumed that the carbon bound in the fuel is almost completely converted to CO_2.

The results in Table 5 for SQ-2015 show that maritime shipping in the North Sea and the Baltic Sea within the SECA is responsible for the emission of 34,931 Gg CO_2. The NO_x emissions are 818 Gg, which is only slightly lower than the EU27 + UK industrial emissions in 2019 (EEA, 2021). SO_2 emissions, even after the introduction of the 0.1% sulphur directive for marine fuels in 2015, are still close to 25 Gg.

Well-to-tank emissions

The life cycle emissions (well-to-tank) for the year 2015 are shown in Table 6 for SQ-2015. Tanker, Container, MPV and RoPax contribute the highest share of total emissions, which is connected to the number of active vessels.

Relating the well-to-tank emissions to the emissions over the entire life-cycle, as shown in Table 7, it is noticeable that the well-to-tank SO_2 emissions account for just under 40% of the total SO_2 emissions. NO_x emissions account for 2% and $PM_{2.5}$ and CO_2 emissions account for 11% and 13% respectively.

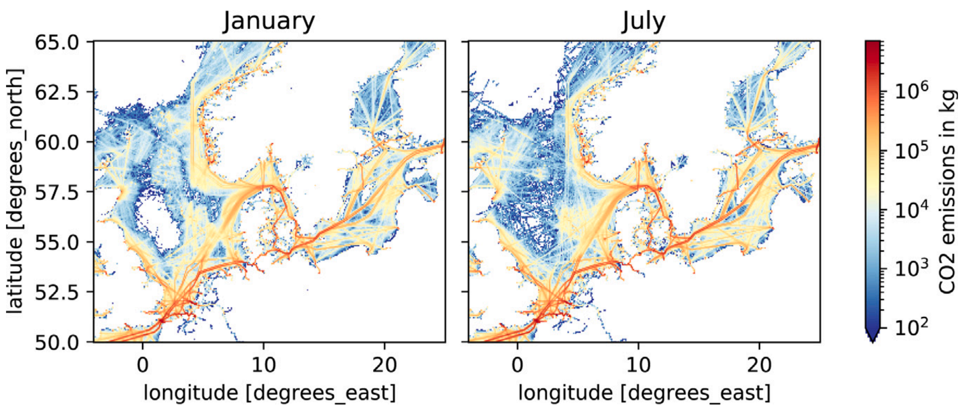


Fig. 2. CO_2 emissions in the North Sea and Baltic Sea in 2015.

Table 5
Annual tank-to-propeller emissions per ship type in Gg in SQ-2015.

Type	SO_2	NO_x	$PM_{2.5}$	CO_2	Ship count
All	24.90	818.00	13.94	34931.98	16,632
Bulker	2.00	67.27	1.19	2800.67	2,946
Car Carrier	0.82	28.18	0.46	1148.53	513
Container	4.21	140.59	2.30	5904.52	1,225
Cruise	1.42	40.01	0.79	1988.33	360
Diverse	2.47	71.43	1.39	3465.69	4,278
MPV	3.82	131.38	2.20	5351.43	3,117
RoPax	3.44	104.16	1.71	4829.57	572
RoRo	1.64	55.06	0.90	2295.89	217
Tanker	5.10	179.90	3.01	7147.35	3,404

Table 6
Annual well-to-tank emissions per ship type in Gg in SQ-2015.

Type	SO_2	NO_x	$PM_{2.5}$	CO_2	Ship count
All	16.02	17.84	1.76	5,257.46	16,632
Bulker	1.28	1.43	0.14	421.52	2,946
Car Carrier	0.53	0.59	0.06	172.86	513
Container	2.71	3.01	0.30	888.66	1,225
Cruise	0.91	1.02	0.10	299.26	360
Diverse	1.59	1.77	0.17	521.61	4,278
MPV	2.45	2.73	0.27	805.42	3,117
RoPax	2.22	2.47	0.24	726.88	572
RoRo	1.05	1.17	0.12	345.55	217
Tanker	3.28	3.65	0.36	1,075.72	3,404

Table 7
Life-cycle emissions (well-to-tank and tank-to-propeller) in Gg and share of well-to-tank (wtt) emissions of total emissions in SQ-2015 using LSMGO.

Pollutant	Well-to-tank	Tank-to-propeller	Total	Share wtt (%)
SO_2	16.02	24.90	40.92	39.15
NO_x	17.84	818.00	835.84	2.13
$PM_{2.5}$	1.76	13.94	15.70	11.21
CO_2	5,257.46	34,931.98	40,189.44	13.08

Table 8
Energy used as calculated within SQ-2015 (100% LSMGO), FS-2030 (approx. 50% LSMGO, 50% e-methanol) and FS-2040 (100% e-methanol) in GWh.

	SQ-2015	FS-2030	FS-2040
Energy (Well to tank)	51,946 GWh	264,108 GWh	468,918 GWh
Energy (Tank to propeller)	258,322 GWh	255,477 GWh	249,516 GWh

3.2. Carbon mitigation

The results are presented as a heat map, which shows the deviations of the future scenario in 2040 (FS-2040_high), utilising 100% methanol fuelled ships, compared to the SQ-2015 scenario, using 100% LSMGO fuelled ships (tank-to-propeller) (Table 1).

Clearly visible in Fig. 3 is a nearly doubled fuel demand in the FS-2040_high scenario compared to the SQ-2015 scenario, while energy consumption increases only marginally. This is due to the lower calorific value of methanol (19.613 kJ/kg) compared to LSMGO (42.675 kJ/kg). Ash, BC and SO_2 emissions are eliminated entirely. The quantities of CO, NMVOC, and POA emissions depends on the selected emission factors. While NMVOC and CO emission factors are based on fuel consumption and therefore increase proportionally to fuel usage, the POA emission factor is based on energy consumption and therefore decreases in proportion to energy expenditure. Based on the chosen assumptions, $PM_{2.5}$ emissions in the *high* dimension are reduced by 95%.

Despite the lower carbon content (20.34%) of methanol compared to LSMGO (86.3%) (Joules, 2014), the reduction in CO_2 emissions is only marginal due to the nearly doubled fuel demand in the FS-2040_high scenario compared to the SQ-2015 scenario. Consequently, CO_2 emissions remain almost the same during the combustion process (tank-to-propeller) in the future scenario. For further explanation, Table 8 summarises the energy required in the different scenarios. It can be clearly seen that the energy demand for the well-to-tank (production) in particular increases. This is due to the required renewable energy capacities that have to be additionally built.

In order to assess the carbon mitigation potential of E-methanol, the CO_2 emissions over the entire life cycle must be taken into account. Based on the scenario assumptions introduced in Section 2.2, a CO_2 reduction of approximately 45% is possible by 2030 and

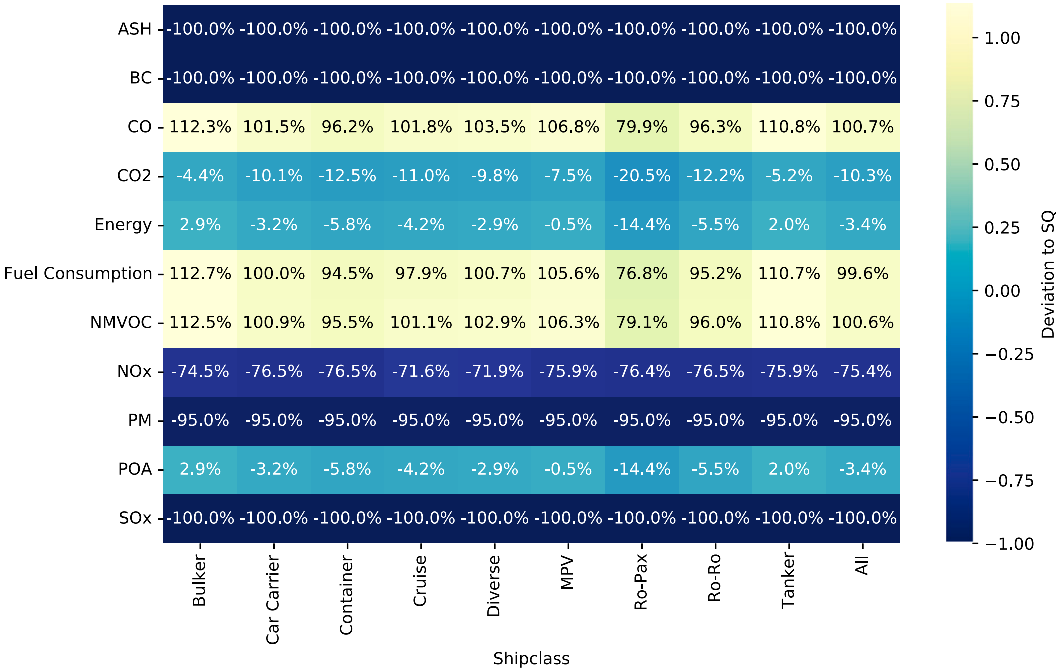


Fig. 3. Percentage deviation of emissions, energy and fuel consumption in FS-2040_high compared to the SQ-2015 scenario.

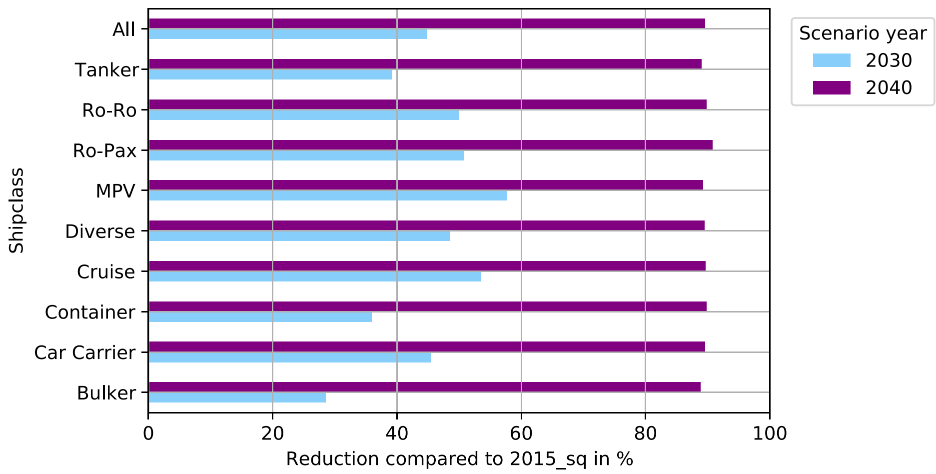


Fig. 4. CO_2 emissions within FS-2030 and FS-2040 as a percentage change to the SQ-2015 scenario.

90% can be achieved by 2040. MPV, RoPax and RoRo ships offer the largest reduction potentials of 57%, 50% and 49% respectively, which relates to the age structure of the existing fleet. Fig. 4 shows the CO_2 emission reduction potential of E-methanol in 2030 and 2040 as a percentage of the SQ-2015 value for individual ship classes, taking into account the complete life-cycle emissions (well-to-propeller).

3.3. Carbon budget

Global carbon emissions from international maritime shipping were 998,000 Gg in 2015 (average of values from IMO, 2020a and IMO, 2015). Different studies were compared to determine the emission quantities from maritime shipping in the North Sea and Baltic Sea. The total CO_2 emission quantities from Jalkanen et al. (2016) (35.740 Gg), Johansson et al. (2013) and Johansson et al. (2017) (43.121 Gg and 48.030 Gg, respectively), Schwarzkopf et al. (2021) (44.886 Gg) and our study (34.932 Gg) were set in relation to global shipping emission values. On the basis of the indicated emission quantities, the share of maritime shipping in the North Sea and Baltic Sea together corresponds to a share of 3.5% to 4.8% of global maritime CO_2 emissions. 4.1% was chosen as a central value to calculate the carbon budget, calculated from the global maritime carbon budget of 18 Gt suggested by Traut et al. (2015). This results in a budget of 0.75 Gt (745,645.16 Gg) for international maritime shipping in the North Sea and Baltic Sea.

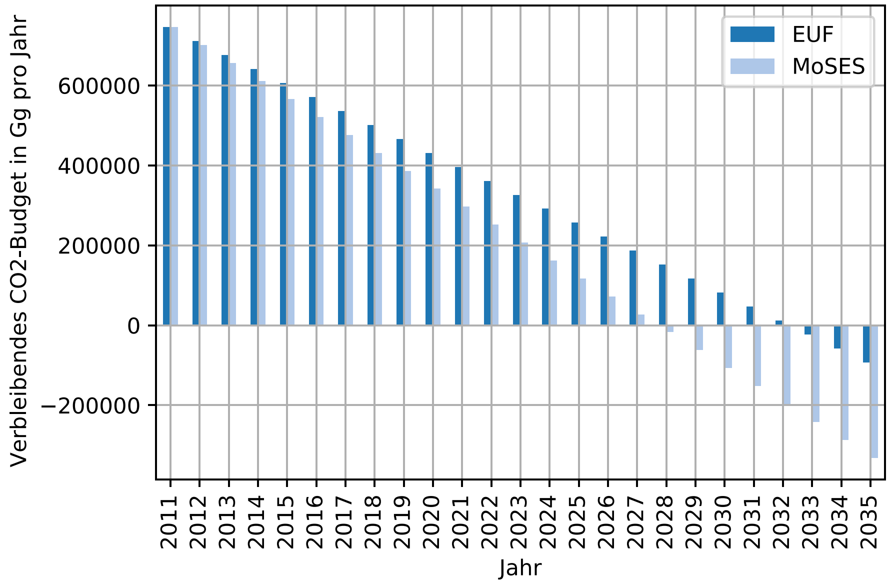


Fig. 5. CO_2 budget for the European maritime shipping sector (North Sea and Baltic Sea) 2011–2100, based on Traut et al. (2015), under the assumption of constant annual emissions as calculated in this study and MoSes (Schwarzkopf et al., 2021).

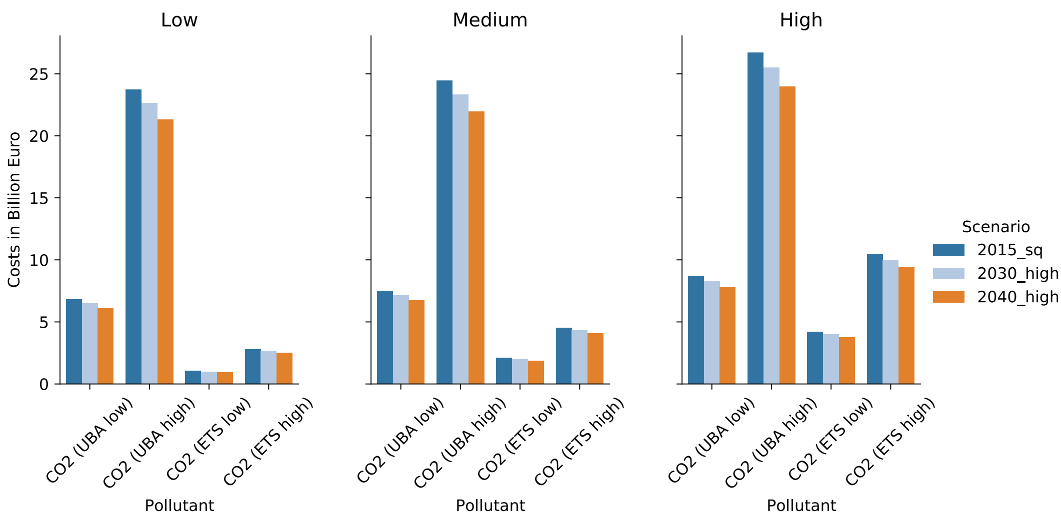


Fig. 6. Environmental damage and carbon certificate costs in EUR_{2020} per scenario.

There are different trajectories of potential CO_2 emissions over time corresponding to the same budget. Our study assumes that the CO_2 emissions in the North and Baltic Seas in 2011 include the calculated 1.5 °C budget, which then decreases linearly over time (budget 2011–2100 analogous to Traut et al., 2015). The development of the cumulative budget (Fig. 5) shows that even under conservative assumptions with an annual emission quantity of 34.932 Gg, as calculated in this study, starting in 2012, without developments in the ship sector, the CO_2 budget will already be consumed in 2033. Higher emission levels, as modelled, for example, by Schwarzkopf et al. (2021), lead to a significantly earlier exhaustion of the budget (2028).

3.4. Carbon pricing

CO_2 emissions from maritime shipping caused damages of between 1.00 and 26.73 billion EUR in SQ-2015, depending on the chosen cost rates (see Fig. 6). A distinction is made between expected economic costs, as represented through the EU-ETS, of between 1.048 and 10.480 million EUR and damage costs, which are between 6.800 and 26.700 million EUR. The high damage costs of CO_2 emissions from maritime shipping arise if the welfare of future generations is valued the same as the welfare of the current generation (compare Section 2.3). The costs are about 70% lower if the welfare of the current generation is valued higher than the welfare of future generations.

The central value for a predicted CO_2 certificate price in 2040 is between 60 and 130 EUR/t_{CO2} (cf. Table 4). The expected economic costs thus amount to between EUR 1,800 and 4,000 million for SQ-2015. Since the reduction in CO_2 emissions through the use of E-methanol is not reflected in the tank-to-propeller emissions, the costs incurred remain at a high level.

Table 9
Expected annual fuel costs in 2015, 2030 and 2040, under the given assumptions, calculated in millions EUR_{2020}.

Price expectation	All LSMGO		All Methanol	
	Central	High	Central	High
2015	10,365	10,365	n/a	n/a
2030	19,282	35,153	n/a	n/a
2040	31,063	55,453	25,380	50,760

3.5. Fuel costs

As fuel costs account for the largest share of a ships operating costs (Nagel, 2020), a comparative analysis of LSMGO and E-methanol costs is useful. LSMGO costs are expected to increase substantially by 2040, from 550 USD/t in 2015, to 1.023 USD/t in 2030 and 1.648 USD/t in 2040. Costs could reach up to 2.942 USD/t in 2040 (Joules, 2014). For renewably-produced E-methanol produced from CO_2 in the ambient air, the costs in 2040 are estimated to be 105 EUR/MWh. For the *high* cost estimates (in Table 9 in 2040, the current estimate of 210 EUR/MWh is considered (Joules, 2014). It is clear that in 2040, in both price projections, E-methanol will have economic advantages over LSMGO. It should be noted, however, that due to uncertainties in future fuel prices, which have not yet reached final market maturity, the results should be interpreted with caution.

4. Discussion

It should be noted that E-methanol reduces not only CO_2 emissions, but also emissions of particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and other pollutants (e.g. mineral ash, carbon monoxide and non-methane volatile organic compounds). Thus, external costs from air pollution are reduced and fewer precursors for the formation of harmful particulate matter are emitted. The much-discussed emission of black carbon in the maritime sector, which can increase the Albedo effect by deposition on ice caps (especially in the Arctic and Antarctic), is avoided with the use of E-methanol. However, the high cost (financial and environmental) of renewable energies for the production of E-methanol needs to be considered in an economic analysis. A comprehensive analysis of life-cycle emissions and the resources used for infrastructure and fuel production is needed to determine how sustainable E-methanol would be as a maritime shipping fuel.

It should be noted that industry decisions on cost-effective future investments are heavily based on expected fuel costs, which are estimated by Nagel (2020) to account for more than 60% of the total costs (operating and investment costs) over the lifetime of a ship. The current state of the energy system makes it more difficult than usual to estimate future fuel costs. An analysis that takes into account different impacts and associated changes in the price of E-methanol is recommended.

4.1. Carbon abatement

This study shows that when life cycle emissions are taken into account, switching the entire maritime shipping sector in the North Sea and Baltic Sea (as of 2015) to E-methanol has a carbon abatement potential of up to 90% (by 2040). However, the decisive factor here is the energy required to produce renewable methanol, which requires significant investment and the expansion of renewable energy capacities. For the potential import of E-methanol, sustainability criteria and guarantees of origin must be mandatory in order to ensure that the fuel is produced in a socially-just and environmentally-sound manner.

Shi (2016) argues that technological solutions alone are not sufficient to achieve emission reductions in the short term, and that operational measures can lead to more immediate reductions. These measures, such as slow steaming, can affect international maritime trade due to longer lead times. For a rapid and timely reduction of carbon emissions, it is therefore necessary to introduce market-based steering and control measures. Various approaches have been proposed, such as Ship Efficiency and Carbon Credit Trading (USA), the Greenhouse Gas Fund (Cyprus, Denmark and Marshall Islands), a Port State Levy (Jamaica), an Efficiency Incentive Scheme (Japan), a Global Emissions Trading Scheme (Norway, Germany, UK, France) and Trade and Development Penalties (Bahamas). In addition, it is essential to first implement operational emission reduction measures and increase the energy efficiency of ships before the reduced energy input is covered by low-GHG fuels or alternative propulsion methods.

4.2. Carbon budget & the 1.5 °C goal

This study provides a conservative estimate of emission quantities in the North Sea and Baltic Sea as only ships $\leq$ 100 GT are considered. A study by Traut et al. (2015) (based on IMO, 2015) attributes a share of 2.33% of global carbon emissions to international maritime shipping. Different studies assume a share of up to 3%, which would result in an increased CO_2 budget and thus a later achievement of the budget. In assessing the shipping sector's compliance with the Paris Agreement, it is apparent that the allocated CO_2 budget will be exhausted early if no countermeasures are taken (cf. Section 3.3).

Bullock et al. (2020) shows that the IMO's target of a 50% reduction in global CO_2 emissions from shipping by 2050 needs to be adjusted and that it is necessary to have a 34% reduction in the emission levels of 2008 by 2030, and zero emissions by 2050. It is crucial that the target is revised in the IMO Strategic Review in 2023. The long lifespan of ships and shipping infrastructure limits the speed of transition. A delay of just a few years increases the risk of the already ambitious Paris targets becoming unachievable.

Uncertainties in this study include the estimation of the CO_2 budget in terms of both international maritime transport demand trends and trajectories, and operational and technical carbon intensity. The volume of trade has tripled since 1980. In 2017, maritime shipping transported almost 90% of internationally-traded goods (DNV-GL, 2017). DNV-GL (2017) predicts overall maritime trade to increase by 35% from 2017 to 2030, with a further increase of 12% in all segments except petroleum and petroleum products. UNCTAD (2019) projects annual growth in maritime transport volumes of 3.5% between 2019 and 2024, with the largest relative growth expected for the gas and containerised cargo sectors, each increasing by 135%–150%. Bulk carriers are projected to increase by 40% in 2050, based on a combination of an increase in non-coal bulk trade and an eventual reduction in coal shipments (UNCTAD, 2019). Considering the future emissions from container ships, it can be assumed that these will increase, leading to an even quicker exhaustion of the CO_2 budget. Other challenges for maritime emissions and transport development include the impact of climate change and mitigation measures on the maritime shipping industry. One example of this is the impact of changes in transport costs, due to carbon mitigation policies and connected costs, on transport demand.

4.3. Carbon prices

In the maritime shipping sector, longstanding assets increase the likelihood of high levels of sequestered emissions. A carbon price that is close to the actual level of damage is necessary to create incentives to counteract this effect. As shown in Fig. 6, carbon prices in the *high* price assumption are already higher than the damage costs for the current generation, but amount to just 40% of the damage costs when the welfare of future generations is taken into account. The well-being and welfare of future generations must be taken into account because the consequences of climate change will primarily be borne by future generations. The carbon price suggested by Pietzcker et al. (2021) (between 120–300 EUR_{2020}/t_{CO2}) is a step in the right direction, as are the damage costs offered by the UBA (2020) (between 250–765 EUR_{2020}/t_{CO2}). Based on the results of our study, it is recommended that the carbon price in an emissions trading scheme be set at a minimum of 300 EUR/t_{CO2}. However, it is clear from the UBA (2020) that in order to capture all externalities, a price close to the actual damage costs of up to 765 EUR/t_{CO2}(UBA, 2020) is advisable.

The cost of fuel and associated infrastructure in the future, as well as the investment costs for new ships, must also be taken into account when determining an appropriate CO_2 price (for certificates). A further, more detailed economic assessment taking into account all costs (including external costs) is necessary to set an appropriate CO_2 certificate price. Furthermore, for the integration of emissions from maritime shipping into the EU-ETS, a mechanism needs to be developed and integrated that takes into account negative life-cycle emissions (well-to-tank), as is the case for E-methanol.

4.4. Modelling limitations

The results of this study must be viewed critically with regard to the methods and models used. One factor that can lead to uncertainty in the results is the methodology used to quantify emissions. The developed open-source model for this study offers the possibility to create ship routes from historical AIS-data, and generates well-documented results (in the form of a temporally and spatially highly-resolved emission inventory) and intermediate results (in the form of temporally and spatially highly-resolved energy and fuel consumption data), which can be used for further analysis (Hilpert et al., 2022), (Hilpert, 2022). However, the ship route calculation is influenced by the quality of the available AIS data and interpolation routines chosen.

Unlike other studies (e.g., Schwarzkopf et al., 2021), this study does not consider engine load in the calculation of fuel and energy consumption. The speed-power curves take this into account, but the auxiliary engine only partially reacts to the engine load and the energy consumption of the auxiliary engine is simplified for the modelling. Unlike in the STEAM model developed by Jalkanen et al. (2014), the influence of waves and currents is not directly considered in the model in this study. However, the speed power curves used to calculate energy consumption in this study tend to assume higher powers, so that consideration of waves and currents is not considered relevant. The loading condition is not mentioned in any of the analysed studies and is also not considered here. An analysis of the different results from STEAM, MoSES and this study shows how decisive the choice of emission factors is for the determination of emission quantities. The chosen factors for this study were based on an extensive literature analysis. Nevertheless, these uncertainties must be taken into account when interpreting the results.

It is to be noted, that the use of a single year, such as 2015, may not be sufficient to represent maritime transport volumes for all years. Maritime traffic volumes can fluctuate depending on a number of factors, including economic conditions, global trade patterns and changes in regulations or shipping routes. 2016, 2017 and 2018 were characterised by overcapacity, weak demand, rising fuel costs, increasing regulatory requirements, and geopolitical tensions (EC, 2020), (Renshaw, 2016). Years following 2018 could not be used for analysis due to the drastic changes resulting from the COVID 19 pandemic. Therefore 2015 was chosen as a representative, stable year for analysis, however deviations may occur for other years.

5. Conclusions

This study emphasises the urgent need for CO_2 mitigation action in the maritime shipping sector to meet the Paris Agreement's 1.5 °C target. The study's bottom-up approach, including life-cycle emissions modelling and scenario analysis of e-methanol demonstrates the potential to reduce CO_2 emissions by up to 50% by 2030 and approximately 90% by 2040 by utilising e-methanol instead of LSMGO. However, immediate action is required to avoid depleting the allocated carbon budget before 2030.

Furthermore, the study supports the significant impact of the onshore energy transition on overall shipping emissions, as the production of low-carbon propulsion technologies and fuels necessitates large amounts of renewable energy. Designing a carbon-neutral maritime sector for the future must take into account the interplay of shipping speed, innovation, and technology costs while avoiding carbon lock-in effects and committed emissions resulting from long-lived assets and investment decisions.

To encourage decarbonisation, a carbon price that reflects the actual harm from CO_2 emissions is crucial, and the inclusion of maritime shipping in the EU-ETS is a promising step forward. However, meaningful allowance costs for CO_2 emissions must be established to encourage investment in carbon-neutral fuels and propulsion systems and to achieve effective decarbonisation promptly.

Funding

This study is based on the results of a research project funded by the *Gesellschaft für Energie und Klimaschutz Schleswig-Holstein*, Germany.

CRediT authorship contribution statement

Franziska Dettner: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Simon Hilpert:** Software, Validation, Visualisation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The link to the related Code and available Datasets are included within the publication.

Acknowledgement

The authors would like to thank Rolf Nagel and Frank Borasch from FSG-Nobiskrug for the continuous support and expertise throughout the research period. Thanks to HELCOM for making the AIS Data for the Baltic Sea available free of charge for research purposes. Furthermore, we are grateful for the editing work of Dr. Jonathan Mole.

Appendix A. Methodology emission inventory

Table 10
Summary description of the methodology used to compile the emission inventory as the basis for the subsequent scenario analysis. Full length within Dettner and Hilpert (2022).

Ship routes	• Using the obtained AIS data (**activity data**) for all ships identified by their IMO number, ship routes were generated in the area under consideration; between 65°N, -5°W, 48.3°S and 30.7°E. • These routes consist of segments created by using two consecutive AIS data points. • The process involved sorting the data by time stamp and calculating distance, time duration, and speed between consecutive time stamps using the Haversine equation. • Two speed threshold criteria were set; the speed was set to 0 knots if the calculated speed is less than 1 knot, assuming the vessel is not manoeuvring and only the auxiliary engine is active. If the speed exceeds 29 knots the point is removed, as this is mainly due to erroneous AIS data. • The data points per IMO number were re-sampled and interpolation was used to form uniform 5 min time intervals.
Ship classification	• The determining factors for the emission output of any ship are primarily the ship type, size, age and engine configuration. Based on existing international ship sizes, statistical analyses of the Marine Data Base (MDB) (Vesselfinder, 2022) and expert interviews (Nagel, 2020), among others, nine generic ship types were classified: *CarCarrier*, *Container*, *RoRo*, *Bulker*, *RoPax*, *MPV* (Multi Purpose Vessel), *Tanker*, *Cruise* and *Diverse*. • These are further subdivided into two to four weight categories (GT or DWT) per ship type. • A ship is typically equipped with two engine sets: the main engine(s) that generate the necessary propulsion power and the auxiliary engine(s) that provide electrical power to the ship's electrical system through generators (Nagel, 2020). Both sets of engines operate at varying loads, exhibit different engine characteristics, and consequently, produce varying levels of fuel consumption and emissions. In general, diesel engines can be categorised as slow-, medium- or high-speed, with the engine speed being a determining factor for emission output (DNV-GL, 2017). This is also recognised within the model.

(*continued on next page*)

Table 10 (*continued*).

Energy & fuel consumption	• To determine the necessary **propulsion power** P_D (main engine), the energy consumption of each ship type is established as a function of speed by utilising a **speed performance curve (SPC), also speed power model,** specific to each weight category and ship type. • Based on the EEDI guidelines (IMO, 2020a), it is assumed that the auxiliary engine for all ships is a medium-speed diesel engine, and the power values are derived accordingly. • The energy and fuel consumption were calculated using a proprietary life cycle performance analysis (LCPA) tool (Thiem et al., 2013), Joules (2014). The fuel mass flow was calculated by coupling the LCPA tool and the SPC model, using the assumed engine power together with the mechanical or electrical efficiencies and the specific fuel consumption. All vessels are assumed to use low sulphur marine gas oil (LSMGO) (LHV (42.675 kJ/kg) with a sulphur content of less than 0.1% in accordance with IMO regulations in the SECA (IMO, 2017) in the SQ-2015 scenario.
Emission quantity	• The speed-dependent emissions $e(v)$ in kg are determined following $e(v) = ef \cdot E(v)$ or $e(v) = ef \cdot F(v)$ utilising selected activity based **emission factors** ef and the ship's energy (E) or fuel consumption (F), respectively. • The tank-to-propeller pollutant emissions were determined using activity-based emission factors related to the fuel or energy consumption associated with the navigation phase of the ship (EEA, 2019). A distinction is made between three navigation phases; cruising, manoeuvring and stay at berth. • The CO_2 emissions were calculated using the carbon content of the fuel used (Joules, 2014). • Information on the emission factors used for the emission quantities of SO_2, NO_x, $PM_{2.5}$, POA, NMVOC, Ash, BC, and CO, refer to Dettner and Hilpert (2022). • The used emission factors and a thorough literature review of supplementary emission factors for engine types' sensitivity analyses are available in the Zenodo repository (Hilpert et al., 2022) and Dettner and Hilpert (2022). • The well-to-tank emissions of CO_2, NO_x, SO_2 and $PM_{2.5}$ are calculated within the LCPA tool. The well-to-tank emissions consider various life stages of marine fuels, such as extraction, transportation, conversion, carriage, and bunkering, for more information please refer to Thiem et al. (2013) and Joules (2014).

Appendix B. Methanol background

Renewably-produced methanol from the hydrogenation of CO_2 (from ambient air) with electricity from wind energy (Joules, 2014) was analysed as a potential future marine fuel. Methanol is used worldwide in the chemical industry. Its availability is high due to its application in many industries (Klepsch, 2020). The global amount of methanol produced is about 55 million tonnes of oil equivalents (2016), which is about one sixth of the global energy demand of maritime shipping, according to Klepsch (Klepsch, 2020). The emission reduction potential of methanol is 60% for NO_x, 99% for SO_x and 95% for PM. The remaining SO_x and PM emissions are due to the pilot fuel and not methanol itself (Klepsch, 2020). Crucial for the reduction of greenhouse gas (GHG) emissions is the sustainable production of methanol with renewable energies.

The DNV-GL already presented a comprehensive analysis of methanol as a marine fuel in 2016 (DNV-GL, 2017). The assessment showed that the methanol fuel system largely consists of known components, and technological maturity for the maritime industry has been achieved (IMO, 2020b). However, economic competitiveness still needs to be improved. With rising heavy oil prices and the expansion of ECAs, methanol can offer economic advantages (Corbett and Winebrake, 2018). According to Smith et al. (2019), methanol will be widely available for maritime shipping from 2025. Hansson et al. (2019) analysed seven alternative fuels for the Swedish shipping sector in 2030 based on a multi-criteria analysis. While shipbuilders and industry members consider economic factors to be particularly important and thus prioritise LNG and heavy fuel oil, respondents from the Swedish government see methanol from renewable energy sources as having the second greatest potential, behind renewably produced hydrogen, due to low GHG emissions as well as social aspects such as safety and potential legislation. A study by Lloyd's Register (Lloyd's Register and UMAS, 2019) summarises the estimated production costs of non-carbon fuels for maritime applications. E-methanol (methanol from renewables) in 2030 is priced at about 80$/MWh in the study and can drop to below 50$/MWh by 2050, making it cheaper than fossil fuels. The production cost of E-methanol is likely to fall from 742$/t in 2018 to 219$/t in 2050 (Lloyd's Register and UMAS, 2019). An analysis by Svanberg et al. (2018) additionally shows that there will be no major problems with potential supply chains.

Operationally, the use of methanol is possible in 2- and 4-stroke engines (Verhelst et al., 2019). In addition, the IGF Code for methanol will be adopted shortly (IGF, International Code of Safety for Ships using Gases or other Low-flashpoint Fuels; aims to minimise risks to ships, crews and the environment given the fuels used) (IMO, 2020b) (IMO, 2017). Also, methanol in technical use is liquid at ambient temperature, which is critical for on-board storage. The toxicity of methanol in water is exclusively localised and complete dilution with water takes place, unlike heavy fuel and gas oils and their synthetic substitutes, which can cause environmental problems in the event of an accident (Nagel, 2020). One problem is the corrosiveness of methanol and the extended fuel capacity due to the lower calorific value compared to heavy fuel oil, which leads to a doubling of the necessary tank space (Klepsch, 2020),(Nagel, 2020).

The use of methanol and the associated reduction in nitrogen emissions can reduce eutrophication and the formation of summer smog. In addition, nitrogen acts as a precursor for harmful particulate matter emissions (Matthias et al., 2016). Like nitrogen, sulphate particles formed in the atmosphere from sulphur dioxide also contribute to particulate matter pollution. Sulphur dioxide can additionally damage plants and cause acidification of soils and waters after deposition in ecosystems (Thiem et al., 2013). Various studies additionally discuss the effect of Ash and BC emissions with regard to the influence on human health, but especially that of (Arctic) shipping and the associated amplification of the Albedo effect (Bond et al., 2013) (Comer et al., 2017) (Gilgen et al., 2018) (Winnes et al., 2020).

References

Anderson, K., Bows, A., 2012. Executing a Scharnow turn: reconciling shipping emissions with international commitments on climate change. Carbon Manag. 3 (6), 615–628.

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G., Zender, C.S., 2013. Bounding the role of black carbon in the climate system: A scientific assessment: BLACK CARBON IN THE CLIMATE SYSTEM. J. Geophys. Res.: Atmos. 118 (11), 5380–5552.

Bows-Larkin, A., Anderson, K., Mander, S., Traut, M., Walsh, C., 2015. Shipping charts a high carbon course. Nature Clim. Change 5 (4), 293–295.

BSH, 2015. Schwefelgrenzwerte in Schiffskraftstoffen. Anlage VI, Regel 14, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg, URL: https://www.bsh.de/DE/THEMEN/Schifffahrt/Umwelt_und_Schifffahrt/MARPOL/marpol_node.html.

Bullock, S., Mason, J., Broderick, J., Larkin, A., 2020. Shipping and the Paris climate agreement: a focus on committed emissions. BMC Energy 2 (1), 5.

Cariou, P., Lindstad, E., Jia, H., 2021. The impact of an EU maritime emissions trading system on oil trades. Transp. Res. D 99, 102992.

CCC, 2020. The Sixth Carbon Budget - Shipping. Technical Report, Climate Change Committee, London, URL: https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Shipping.pdf.

Comer, B., Olmer, N., Mao, X., Roy, B., Rutherford, D., 2017. Black Carbon Emissions and Fuel Use in Global Shipping, 2015. Technical Report, The International Council on Clean Transportation, Washington, p. 112, URL: https://www.ccacoalition.org/sites/default/files/resources/1.5-6%20Global_BC_inventory_for_CCAC.pdf.

Corbett, J.J., Winebrake, J.J., 2018. Life Cycle Analysis of the Use of Methanol for Marine Transportation. Technical Report, US Department of Transportation, Maritime Administration, Washington, p. 54.

Davis, D., Grodzinsky, G., Kasibhatla, P., Crawford, J., Chen, G., Liu, S., Bandy, A., Thornton, D., Guan, H., Sandholm, S., 2001. Impact of ship emissions on marine boundary layer NO_x and SO_2 distributions over the Pacific basin. Geophys. Res. Lett. 28 (2), 235–238.

Dettner, F., Hilpert, S., 2022. Emission inventory for maritime shipping emissions in the North and Baltic Sea (2015). mdpi data (submitted for publication). Publisher: arXiv Version Number: 1.

DNV-GL, 2017. Martime Forecast to 2050. Forecast, DNV GL, Høvig, Norway, p. 82.

Dong, Y., Kaario, O., Hassan, G., Ranta, O., Larmi, M., Johansson, B., 2020. High-pressure direct injection of methanol and pilot diesel: A non-premixed dual-fuel engine concept. Fuel 277, 117932.

EC, 2017. Baltic Sea shipping traffic intensity. URL: https://maritime-spatial-planning.ec.europa.eu/practices/baltic-sea-shipping-traffic-intensity.

EC, 2020. Statistics | eurostat. URL: https://ec.europa.eu/eurostat/databrowser/explore/all/transp?lang=en&subtheme=mar&display=list&sort=category&extractionId=MAR_TP_GO.

EC, ICF, UCL, Lloys's Register, Lloyd's List Intelligence, Sintef Ocean, 2019. A Study to Estimate the Benefits of Removing Market Barriers in the Shipping Sector: Final Report. In: Directorate General for Climate Action, European Commission. Directorate General for Climate Action, Luxembourg, URL: https://data.europa.eu/doi/10.2834/475782.

EEA, 2019. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019 - Technical Guidance to Prepare National Emission Inventories. European Environment Agency.

EEA, 2021. European Union Emission Inventory Report 1990–2019 Under the UNECE Convention on Long-Range Transboundary Air Pollution (Air Convention). EEA Report 05/2021, European Environment Agency, Luxembourg, p. 161, URL: https://www.eea.europa.eu//publications/lrtap-1990-2019.

EU, 2018. Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018. Directives 76/3, European Union, Brussels, URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0410&from=EN.

Gilgen, A., Huang, W.T.K., Ickes, L., Neubauer, D., Lohmann, U., 2018. How important are future marine and shipping aerosol emissions in a warming arctic summer and autumn? Atmos. Chem. Phys. 18 (14), 10521–10555.

Gu, Y., Wallace, S.W., Wang, X., 2019. Can an Emission Trading Scheme really reduce CO2 emissions in the short term? Evidence from a maritime fleet composition and deployment model. Transp. Res. D 74, 318–338.

Hansson, J., Månsson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173.

helcom, 2019. Emissions from Baltic Sea Shipping 2006–2018. MARITIME 19-2019 5-2, HELCOM, Lisbon, URL: https://portal.helcom.fi/meetings/MARITIME/2019-2019-582/MeetingDocuments/5-2%20Emissions%20from%20Baltic%20Sea%20shipping%20in%202006%20-%202018.pdf.

Hilpert, S., 2022. KlimaSchiff - Source Code. Europa Universität Flensburg, Flensburg, http://dx.doi.org/10.5281/zenodo.6951672, Source code, BSD 3-Clause.

Hilpert, S., Dettner, F., Nagel, R., 2022. Emission inventory of maritime shipping on the Baltic and North Sea in 2015 with scenario capabilities. http://dx.doi.org/10.5281/zenodo.6919557, Dataset.

Horvath, S., Fasihi, M., Breyer, C., 2018. Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. Energy Convers. Manage. 164, 230–241.

IMO, 2015. Third IMO Greenhouse Gas Study 2014. Technical Report, International Maritime Organization, London, p. 327, URL: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf.

IMO, 2017. Safety for Gas-Fuelled Ships – New Mandatory Code Enters into Force. International Maritime Organization, URL: https://www.imo.org/en/MediaCentre/PressBriefings/Pages/01-IGF.aspx.

IMO, 2020a. Fourth IMO Greenhouse Gas Study 2020. Technical Report, International Maritime Organization, London, p. 327, URL: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth/20IMO20GHG20Study2020-Fullreportandannexes.pdf.

IMO, 2020b. Interim Guidelines for the Saftey of Ships Using Methyl/Ethyl Alcohol as Fuel. Guideline 1621, International Maritime Organization, London, p. 38.

IMO, 2021. Status of IMO Treaties - Comprehensive Information on the Status of Multilateral Conventions and Instruments in Respect of Which the International Maritime Organization or Its Secretary-General Peforms Depositary or Other Functions. Technical Report, International Maritime Organization, p. 566, URL: https://wwwcdn.imo.org/localresources/en/About/Conventions/StatusOfConventions/Status-2021.pdf.

IPCC, 2021. Climate Change 2021 - The Physical Science Basis - Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers, Intergovernmental Panel on Climate Change, Switzerland, URL: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf.

Jalkanen, J.-P., Johansson, L., Kukkonen, J., 2014. A comprehensive inventory of the ship traffic exhaust emissions in the baltic sea from 2006 to 2009. Ambio 43 (3), 311–324.

Jalkanen, J.-P., Johansson, L., Kukkonen, J., 2016. A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011. Atmos. Chem. Phys. 16 (1), 71–84.

Johansson, L., Jalkanen, J.-P., Kalli, J., Kukkonen, J., 2013. The evolution of shipping emissions and the costs of regulation changes in the northern EU area. Atmos. Chem. Phys. 13 (22), 11375–11389.

Johansson, L., Jalkanen, J.-P., Kukkonen, J., 2017. Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. Atmos. Environ. 167, 403–415.

Joules, 2014. LCPA Tool Incl. LCPA and LCA Descripton. Confidential Report 21-1, Flensburger Schiffbau-Gesellschaft mbH & Co KG, Flensburg, p. 69.

Kasibhatla, P., Levy, H., Moxim, W.J., Pandis, S.N., Corbett, J.J., Peterson, M.C., Honrath, R.E., Frost, G.J., Knapp, K., Parrish, D.D., Ryerson, T.B., 2000. Do emissions from ships have a significant impact on concentrations of nitrogen oxides in the marine boundary layer? Geophys. Res. Lett. 27 (15), 2229–2232.
Klepsch, B., 2020. Bewertung von Technologien zur Minderung von Luftschadstoffen in der Seeschifffahrt (Master thesis). Europa Universität Flensburg, Flensburg.
Kågeson, P., 2007. Linking CO2 Emission from International Shipping to the EU Emission Trading Scheme. Technical Report (UBA-FB) 001085, Umweltbundesamt, Dessau-Roßlau, p. 44, URL:.
Kågeson, P., 2008. The Maritime Emissions Trading Scheme. Technical Report, Nature Associates, Environmental and public health research and consultancy, p. 15, URL: http://www.natureassociates.se/pdf/METSfinal.pdf.
Lindstad, E., Eskeland, G.S., Rialland, A., Valland, A., 2020. Decarbonizing maritime transport: The importance of engine technology and regulations for LNG to serve as a transition fuel. Sustainability 12 (21), 8793.
Lloyd's Register, UMAS, 2019. Fuel Production Cost Estimates and Assumptions. Technical Report, Lloyd's Register, London.
Matthias, V., Aulinger, A., Backes, A., Bieser, J., Geyer, B., Quante, M., Zeretzke, M., 2016. The impact of shipping emissions on air pollution in the greater North Sea region – Part 2: Scenarios for 2030. Atmos. Chem. Phys. 16, 759–776.
Mellin, A., Hansson, J., Zetterberg, L., Fridell, E., 2020. Including Maritime Transport in the EU Emission Trading System – Addressing Design and Impacts. IVL Svenska Miljöinstitutet, URL: http://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-69.
Nagel, R., 2020. Shipbuilding expertise.
OECD, 2021. Effective Carbon Rates 2021: Pricing Carbon Emissions Through Taxes and Emissions Trading. Technical Report, OECD, Paris, http://dx.doi.org/10.1787/0e8e24f5-en.
Pietzcker, R.C., Osorio, S., Rodrigues, R., 2021. Tightening EU ETS targets in line with the European green deal: Impacts on the decarbonization of the EU power sector. Appl. Energy 293, 116914.
Renshaw, T., 2016. 2016 Year in review: Container shipping industry's annus horribilis. URL: https://biv.com/article/2016/12/container-shipping-industrys-annus-horribilis. Section: Transportation.
Schwarzkopf, D.A., Petrik, R., Matthias, V., Quante, M., Majamäki, E., Jalkanen, J.-P., 2021. A ship emission modeling system with scenario capabilities. Atmos. Environ. X 100132.
Selin, H., Zhang, Y., Dunn, R., Selin, N.E., Lau, A.K.H., 2021. Mitigation of CO2 emissions from international shipping through national allocation. Environ. Res. Lett. 16 (4), 045009.
Shi, Y., 2016. Reducing greenhouse gas emissions from international shipping: Is it time to consider market-based measures? Mar. Policy 64, 123–134.
Shi, Y., Gullett, W., 2018. International regulation on low-carbon shipping for climate change mitigation: Development, challenges, and prospects. Ocean Dev. Int. Law 49 (2), 134–156.
Smith, T., O'Keefe, E., Hauerhof, E., Raucci, C., Bell, M., Deyes, K., Faber, J., Hoen, M., 2019. Reducing the UK Maritime Sector's Contribution to Climate Change and Air Pollution - Scenario Analysis: Take-Up of Emissions Reduction Options and Their Impacts on Emissions and Costs - Technical Annex. Report for the Department for Transport, UMAS and E4Tech and Frontier economics and CE Delft, London, p. 111, URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816019/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs-technical-annexes.pdf.
Sogaard, K., Laxekjar, L., Krantz, R., Rud, S., Maver, T., Spiegelenberg, F., Kriketerp-Moller, T., 2021. Report on Climate Commitments by Signatories to the Call to Action for Shipping Decarbonization. Technical Report 3rd Edition, Getting to Zero Coalition, p. 242, URL: https://www.globalmaritimeforum.org/content/2021/09/Report-on-Climate-Commitments-by-Signatories-to-the-Call-to-Action-for-Shipping-Decarbonization.pdf.
Svanberg, M., Ellis, J., Lundgren, J., Landälv, I., 2018. Renewable methanol as a fuel for the shipping industry. Renew. Sustain. Energy Rev. 94, 1217–1228.
Thiem, C., Liebich, A., Münter, D., 2013. Joules - Fuel Data Report, Identification, Physico-Chemical Properties and Well-to-Tank Data of Marine Fuels. Confidential Report FP7-SST-2013-RTD-1, Flensburger Schiffbau-Gesellschaft mbH & Co KG, Hamburg, p. 105.
Traut, M., Bows-Larkin, A., Anderson, K., McGlade, C., Sharmina, M., Smith, T., 2015. Emissions Budgets for Shipping in a 2°C Global Warming Scenario, and Implications for Operational Efficiency. University College London, Glasgow, URL: https://www.researchgate.net/publication/321348333_Emissions_budgets_for_shipping_in_a_2C_and_a_4C_global_warming_scenario_and_implications_for_operational_efficiency.
UBA, 2020. Methodenkonvention 3.1 zur Ermittlung von Umweltkosten Kostensätze Stand 12/2020. Technical Report, Umweltbundesamt, Dessau-Roßlau, URL: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf.
UNCTAD, 2019. Review of Maritime Transport. Technical Report, Uniterd Nations Conference on Trade and Development, New York, p. 129, URL: https://unctad.org/en/PublicationsLibrary/rmt2019_en.pdf.
UNFCCC, 2016. Shipping aviation and Paris | UNFCCC. URL: https://unfccc.int/news/shipping-aviation-and-paris.
Verhelst, S., Turner, J.W., Sileghem, L., Vancoillie, J., 2019. Methanol as a fuel for internal combustion engines. Prog. Energy Combust. Sci. 70, 43–88.
Vesselfinder, 2022. AIS ship types - AIS data. URL: https://api.vesselfinder.com/docs/response-ais.html.
Walsh, C., Mander, S., Larkin, A., 2017. Charting a low carbon future for shipping: A UK perspective. Mar. Policy 82, 32–40.
Wettestad, J., Gulbrandsen, L.H., 2022. On the process of including shipping in EU emissions trading: Multi-level reinforcement revisited. Politics Gov. 10 (1).
Winnes, H., Fridell, E., Moldanová, J., 2020. Effects of marine exhaust gas scrubbers on gas and particle emissions. J. Mar. Sci. Eng. 8 (4), 299.
Zhu, W., Erikstad, S.O., Nowark, M.P., 2014. Emission allocation problems in the maritime logistics chain. EURO J. Transp. Logist. 3 (1), 35–54.

8

Green Hydrogen Production: Integrating Environmental and Social Criteria to ensure Sustainability[1]

Marina Blohm
Franziska Dettner

[1]published as: M. Blohm, F. Dettner (2023): Green hydrogen production: Integrating environmental and social criteria to ensure sustainability, *Smart Energy*, 11, 100112

Smart Energy 11 (2023) 100112

Contents lists available at ScienceDirect

Smart Energy

journal homepage: www.journals.elsevier.com/smart-energy

Green hydrogen production: Integrating environmental and social criteria to ensure sustainability

Marina Blohm [a,b,*], Franziska Dettner [a,b]

[a] Department of Energy and Environmental Management, Europa-Universität Flensburg, Auf dem Campus 1, 24943 Flensburg, Germany
[b] Centre for Sustainable Energy Systems (ZNES), Flensburg, Germany

ARTICLE INFO

Keywords:
Green hydrogen
Just transition
Measurable criteria
Social sustainability
Sustainability criteria

ABSTRACT

Hydrogen is experiencing an unprecedented global hype. Hydrogen is globally discussed as a possible future energy carrier and regarded as the urgently needed building block for the much needed carbon-neutral energy transition of hard-to-abate sectors to mitigate the effects of global warming. This article provides synthesised, measurable sustainability criteria for analysing green hydrogen production proposals and strategies. Drawn from expert interviews and an extensive literature review this article proposes that a sustainable hydrogen production should consider six impact categories; *Energy transition, Environment, Basic needs, Socio-economy, Electricity supply,* and *Project planning.* The categories are broken down into sixteen measurable sustainability criteria, which are determined with related indicators. The article concludes that low economic costs can never be the only decisive criterion for the hydrogen production; social aspects must be integrated along the entire value chain. The compliance with the criteria may avoid social and ecological injustices in the planning of green hydrogen projects and increases inter alia the social welfare of the affected population.

1. Introduction

Hydrogen is experiencing an unprecedented global hype. Hydrogen (H_2) is globally discussed as a possible future energy carrier and regarded as the urgently needed building block for the much needed carbon-neutral energy transition to mitigate the effects of global warming. The life-cycle emissions of hydrogen are solely determined by the energy carrier used for production. Currently, nearly the total global supply of hydrogen is produced from fossil fuels, especially natural gas. Hydrogen is proving to be attractive for the energy transition as it can be produced carbon neutral from renewable energy sources as well as store electricity from volatile renewable energy sources.

Many countries in the Global South have high renewable resources and due to low electricity generation costs a high potential for electricity from renewable energies and therefore for a cost-optimal green hydrogen production. As large (energy) projects have shown in the past, strict sustainability and social standards are necessary to ensure a climate just future for all.

We understand sustainability as a combination of the five pillars; *people, planet, prosperity, peace*, and *partnership*, which form the basis for the Sustainable Development Goals (SDG)[1] in the Agenda 2030 [1]. The pillars are of equal value and serve to eradicate global poverty. This includes advocating for universal access to a violence-free, healthy life, equal opportunities, mindful resource utilisation for the benefit of future generations, and global solidarity in supporting the most vulnerable. These conditions, as well as the increasing number of hydrogen partnerships and agreements between countries of the Global North and Global South, must be considered in the production of green hydrogen, necessitating the development of sustainability criteria.

Some countries with high potential for renewable energies, e.g. Morocco, are willing to produce high amounts of green hydrogen [2], with a number of projects under development to produce for export only [3]. On the one hand, the production of green hydrogen must not be at the

* Corresponding author at: Department of Energy and Environmental Management, Europa-Universität Flensburg, Auf dem Campus 1, 24943 Flensburg, Germany.
E-mail addresses: marina.blohm@uni-flensburg.de (M. Blohm), franziska.dettner@uni-flensburg.de (F. Dettner).
URLs: https://www.uni-flensburg.de/?id=22169 (M. Blohm), https://www.uni-flensburg.de/?id=27190 (F. Dettner).

[1] Abbreviations used in this article: Concentrated Solar Power (CSP), Environmental Impact Assessment (EIA), Power Purchase Agreements (PPA), Power-to-X (PtX), Photovoltaic (PV), Sustainable Development Goals (SDG), World Health Organisation (WHO) and kilo-, mega- and terrwatt hour (kWh, MWh, TWh), megatonne (Mt), carbon dioxide (CO_2), cubic meter (m^3), decibel (dB) and A-weighted decibel (dB(A)).

https://doi.org/10.1016/j.segy.2023.100112
Received 15 December 2022; Received in revised form 22 June 2023; Accepted 2 July 2023
Available online 13 July 2023

expense of the local population or use scarce resources, but can on the other hand enable countries to expand their industrial development. Therefore, not only the export of green hydrogen requires the implementation of sustainability criteria, but also the domestic use of green hydrogen [4,5]. Furthermore, social injustices play a major role in the expansion of renewable capacities, which is why it is crucial that the production of green hydrogen is not built upon the same structures and inequalities as the energy transition that is taking place [6,4].

The aim of this article is to develop sustainability criteria for the production of green hydrogen and to strengthen the social science perspective in hydrogen research. These criteria can be used by decision-makers for planning and implementing hydrogen projects as well as for analysing national hydrogen strategies, to determine whether the planned hydrogen project meets set sustainability standards. The sustainability criteria not only take into account techno-economic and ecological aspects, but also address the social dimension of project planning. The proposed criteria are made measurable, which in this context does not mean that explicit thresholds are set for each criterion, but that the fulfilment or non-fulfilment of the criteria can be assessed.

The identified findings need to be contextualised within the framework of a smart energy system transformation. In order to achieve a 100% renewable energy system, the integration of various smart energy solutions is imperative. By adopting a smart energy system approach, it becomes feasible to effectively tackle the challenges associated with the integration of fluctuating renewable energy sources into both present and future 100% renewable energy systems [7].

1.1. Hydrogen background

Green hydrogen can be produced using different processes [8]. This article focuses on the analysis of green hydrogen produced within an electrolyser, which uses from renewable energy sources generated electricity to decompose water into oxygen (O) and hydrogen (H_2). The process electrolysis has a high efficiency and zero or near-zero emissions during operation.

The production of 1 TWh hydrogen requires approximately 1.4 TWh of green electricity due to an electrolysis efficiency of approximately 70% [8]. In total, around 50 kWh electricity are needed to produce 1 kg of hydrogen [9]. The current global hydrogen demand of 90 Mt [10] is expected to grow significantly in a net-zero emissions scenario by 2050 varies between 530 Mt [10] and 614 Mt [11]. This is driven by growth in the industrial and transport sectors. However, the use of green hydrogen is not always the most cost-effective solution, as it requires large amounts of (renewable) capacity, high investments and has a lower efficiency compared to direct electrification [8]. Today, hydrogen is mainly used in the refinery and chemical sector, while the transport sector as well as the production of synthetic fuels and ammonia are emerging markets [10]. The International Renewable Energy Agency IRENA [11] as well as the International Energy Agency [10] suggest a prioritisation of hydrogen applications across the energy systems, stating that hydrogen is only feasible and has a high priority in so-called hard-to-abate, emission intensive sectors, especially the chemical and refining industry, steel production, international shipping and long-haul aviation. A significant diffusion of hydrogen and hydrogen-based fuels for new applications in heavy industry, heavy-duty transport, shipping and aviation is also possible [10]. Especially for applications such as low- and medium-temperature heating or road transport, electrification is not only more efficient but also more cost-effective [12].

1.2. Literature review

While research on hydrogen production is currently a much-discussed topic, social aspects such as measurable sustainability criteria for the production of green hydrogen have not yet been sufficiently researched. A comprehensive literature search using the *Web of Science* database, employing the search string “sustainability criteria green hydrogen” was conducted and as of 07/2022 no related scientific article have been published. However, three relevant publications ([13], [14], [15]) were identified, that utilised sustainability criteria for an assessment of different hydrogen production processes. However, they did not contribute to the development of the criteria themselves; rather, they used pre-existing criteria which were chosen for the respective studies. Additionally, sustainability in connection with hydrogen based energy systems [16], waste-to-hydrogen [17] or the use of hydrogen for different transportation applications [18,19] was studied. Life-cycle analyses related to the generation of electricity [20], electrolyser technologies [21], and different case studies such as a wind energy based hydrogen production in the Netherlands [22], a waste-to-hydrogen bus system in Scotland [23], impacts associated with different colours of hydrogen production in Colombia [24] or related to an isolated system of hydrogen production and consumption [25] were published and include different impact categories of the production or use of hydrogen. Most of the studies include a specific case study that was analysed and discussed. None of the publication captures a total life-cycle analysis or impact assessment along the entire value chain of a hydrogen production.

Within the grey literature, five publications were identified and chosen for further analysis, which include the proposition of sustainability criteria for the production of green hydrogen. The studies are focused on the proposition of sustainability criteria for countries that focus on the export of green hydrogen and give recommendations regarding the trade of green hydrogen between countries of the Global South and of the Global North. Table 1 shows the identified sustainability criteria for the production of green hydrogen and shows, which of the proposed criteria are detailed (green), mentioned (yellow) and which are not mentioned at all (red) in the respective publications. Sustainability criteria are mostly mentioned in qualitative terms.

The “avoidance of negative impacts on the local population of the producing countries with regard to drinking water supply” German Advisory Council on the Environment [8] suggest a qualitative criterion, but there is a lack of measurable and precise guidelines on how to achieve this statement. All studies agree on more or less detailed specifications regarding the use of CO_2 neutral technologies and that an impact assessment has to be carried out prior to the electrolyser construction. Guidelines for construction and power generation capacity requirements are also included. This literature review has shown that the involvement and participation of the population is not measurable and no tangible examples can be given as a guideline [27,8,26,28]. The authors of the above-mentioned studies emphasise the importance of consultation or participation of the local population, without, however, mentioning an indicator. PtX Hub [29] offers information on how a socially acceptable expansion of green hydrogen can be achieved.

A literature analysis by the Öko-Institut e.V. and adelphi [30] focuses on the occurrence of sustainability criteria in the literature, but does not analyse the measurability of the criteria. In some of the five analysed publications in Table 1, further criteria such as *governance* or *international cooperation* were also listed. These criteria were not considered, as this article only refers to the production of green hydrogen. PtX Hub [29] explicitly writes that “this scoping paper does not yet define a PtX sustainability standard with measurable indicators and thresholds”, but “aims at providing a conceptual basis for later translation of sustainability concerns into criteria for certification”. The sole naming of non-quantifiable and purely qualitative criteria is not suitable to support the development of a sustainable green hydrogen production.

Table 1
Measurability of proposed sustainability criteria for the production of green hydrogen Legend: Green = detailed, measurable criterion; Yellow = mentioned criterion, lacking measurable specification; Red = criterion is not mentioned at all. German National Hydrogen Council [26], Heinemann and Mendelevitch [27], German Advisory Council on the Environment [8], Morgen et al. [28], PtX Hub [29].

	[26]	[27]	[8]	[28]	[29]
Water use	Yellow	Yellow	Yellow	Yellow	Yellow
Land use	Yellow	Yellow	Yellow	Yellow	Yellow
Resource use	Red	Red	Yellow	Red	Yellow
Emissions	Red	Red	Red	Red	Red
Waste and by-products	Red	Red	Red	Red	Red
Impact assessment	Green	Green	Yellow	Green	Green
Water for basic needs	Yellow	Yellow	Yellow	Yellow	Yellow
Energy for basic needs	Yellow	Yellow	Red	Yellow	Yellow
Health	Red	Red	Yellow	Red	Yellow
Human rights	Yellow	Yellow	Yellow	Yellow	Yellow
Employment and Added value	Yellow	Yellow	Red	Yellow	Yellow
Financial participation	Yellow	Yellow	Red	Red	Red
Technology and Knowledge transfer	Yellow	Yellow	Red	Yellow	Yellow
Electricity generation	Yellow	Yellow	Yellow	Yellow	Yellow
CO_2 neutrality	Green	Green	Green	Green	Green
Participatory processes	Yellow	Yellow	Red	Yellow	Yellow
Use of hydrogen	Red	Red	Red	Red	Red

1.3. Contribution and research question

The literature review shows the lack of measurability, completeness and quantification opportunities of sustainability criteria for the production of green hydrogen. This study draws on the qualitative results of the literature review and proposes criteria that also provide a clear guideline for meeting the set criteria. The developed criteria can be used for the evaluation of green hydrogen projects and hydrogen strategies. The underlying research questions are;

(1) Which sustainability aspects have to be considered for the production of green hydrogen? and
(2) How can they be defined (made measurable)?

2. Methods

The development of measurable sustainability criteria for the production of green hydrogen is carried out with the help of a mix-method approach consisting of a literature review and expert interviews. The following list summarises the methodological steps.

1. **Literature review** Identification of relevant literature.
2. **Criteria development** Identification of criteria interrelations and dependencies to develop criteria clusters.
3. **Criteria evaluation** Interviews with stakeholders in the hydrogen sector (Germany and Morocco).
4. **Criteria quantification** Establish measurability of criteria using inter alia Sustainable Development Goal benchmarks.

The literature review is necessary to identify existing research on sustainability criteria for the production of green hydrogen and to determine corresponding quantitative and qualitative indicators. Sixteen relevant criteria were identified. For more clarity, the defined criteria were assigned to super-ordinate impact categories that shape the production and use of green hydrogen as shown in Fig. 1.

The pre-developed, clustered sustainability criteria form the basis for semi-structured expert interviews, which were conducted with relevant stakeholders of the hydrogen sector in Germany and Morocco. The focus was placed on German and Moroccan interviewees, as both countries have agreed on a hydrogen partnership in 2020 [31] with the long-term goal of producing green hydrogen in Morocco and exporting it to inter alia Germany. Additionally, Germany published its hydrogen strategy in 2020 aiming at importing up to 96 TWh by 2030, while the domestic production is planned to be at 14 TWh by 2030 [32]. Morocco is an internationally much-discussed hydrogen producer that aims to become export-oriented due to its high potential for renewable electricity generation [2]. Both regions are pursuing different goals in the implementation of their hydrogen strategies and are currently experiencing difficulties in connection with the ecological and social dimension of the energy transition. A recently published study by Sens et al. [33] shows that the costs for the production of green hydrogen in (North) Germany and Morocco are almost the same due to the high potential of renewable energies. It is assumed that taking into account the findings and insights of actors from both regions makes is useful for the present analysis, as they can be representative of other trade relations and trade agreements between countries of the Global South and countries of the Global North.

A total of 15 interviews were conducted between February and July 2022 with stakeholders from the industrial sector, the energy industry, politics and civil society. Participation details and results were anonymised for data protection at the request of the interviewees. Table 8 summarises the abbreviation for each interview used as a reference in the following text, e.g. [p1] for an interview partner from the policy sector. All answers of the interview partners were evaluated neutrally and set in relation to the results of the conducted literature review. Therefore, no subjective individual opinions are presented in the developed sustainability criteria, the development is based on provable and comprehensible facts.

The pre-developed criteria in combination with the findings of the interviews were compiled into a first set of sustainability criteria. In order to make all identified and developed criteria measurable, laws, regulations, global sustainability indicators as well as other legal requirements – either already applied or under development – were considered and analysed. In addition, the 17 SDGs published by the United Nations in 2015 within

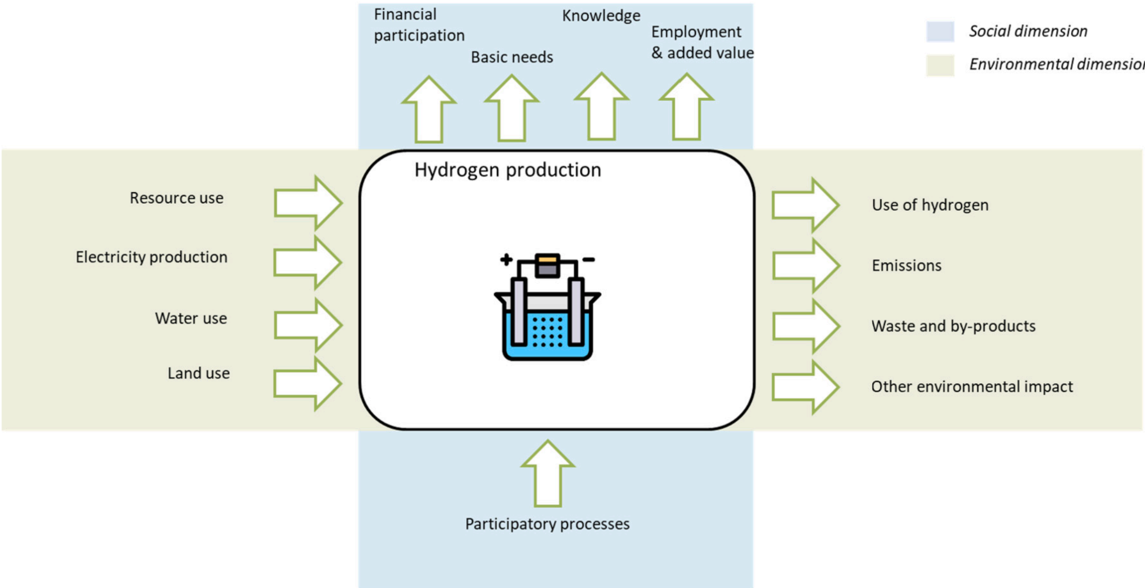


Fig. 1. Inputs and outputs of a sustainable production of green hydrogen, based on the Table 1 and conclusions drawn from section 2, *environmental dimension* depicted in green, *social dimension* depicted in blue.

the Agenda 2030 [1] were applied as a benchmark for criteria. The SDGs can be used for the assessment of regions where a hydrogen project is to be built.

An analysis of input and output parameters related to environmental and social impacts and effects of the electrolysis was carried out to capture all relevant criteria that should be included in the sustainability assessment. The strict economics of the green hydrogen production were not considered, as an economic feasible production will be a prerequisite to produce green hydrogen and sell it at competitive prices on the global market. Fig. 1 summarises the inputs and outputs that are relevant for a sustainable production of green hydrogen.

The environmental dimension considers the impact on the environment and resources, the social dimension considers the impact on the local population. Input and output variables are defined for both dimension that influence hydrogen projects and production. The input variables define the necessary criteria for the successful implementation of a hydrogen project. The output criteria describe the direct impacts that a hydrogen project can have. The inputs and outputs – hereafter referred to as *sustainability criteria* – were clustered to focus on criteria that affect similar areas. Five areas of impact – hereinafter referred to as *impact categories* – were identified: *Environment, Basic needs, Socio-economy, Electricity supply, Project planning* and *Energy transition*.

3. Results

Sustainability criteria can be applied at different stages of the value chain of green hydrogen production or be used to develop national hydrogen strategies. Fig. 2 gives a graphical overview on the impact categories and the developed sustainability criteria.

The following subsections explain the underlying criteria and indicators for each impact category.

3.1. Environment

Three criteria relate to the impact category *Environment* (Table 2). The criterion **Land use** indicates which type of land is or is not eligible as a possible construction site for the electrolyser and the associated electricity generation. In order to ensure the conservation of nature reserves and the protection of endangered species, all types of naturally protected areas, such as nature reserves, national parks, water protection areas, landscape conservation areas, forests, biodiversity-rich ecosystems, areas with rare, threatened or endangered species or ecosystems, should not be used as a building site. The EU Directive 2018/2001, RED II, includes some land-related criteria in §29 [34]. In countries with more informal land use rights, special attention must be paid to the respect of these use rights. No person or community should be forced to sell land for the energy production if cultural or traditional land use is applied. Furthermore, no productive agricultural land should be used as a production site to ensure stable agricultural production [c1]. The least interference with nature would be the use of already sealed land in e.g. classified industrial areas, where infrastructure and possible off-takers already exist. In this way, a food-energy-nexus and also the alteration of the landscape can be avoided.

The interviewees [e1, e3] argued that in the case of grid bottlenecks and to avoid renewable electricity curtailments, electrolysers should be built in the immediate vicinity of wind farms, solar parks or substations. In areas with a high share of renewable electricity curtailments, a decentralised hydrogen production would make sense under the previously given conditions. If the development of new production areas is indispensable, a possible benchmark could be the use of land with a soil quality of less than 20 points, which would be an indication of low agricultural productivity, as applied for the construction of PV parks in Mecklenburg-Vorpommern in Germany [35].

Water use (fresh water) is a necessary input for electrolysis. However, freshwater is a scarce resource in many regions worldwide. Surface and groundwater should only be used for the electrolysis in areas, where the amount of available freshwater is sufficient for human and agricultural purposes, causing no water stress [e1]. A moderate to high water stress level with less than 1,700 m^3 of water supply per year per person can be considered a general guideline after which additional regional water demand analyses need to be carried out [36]. The SDG 6 *Clean water and sanitation* provides an initial orientation for the availability and withdrawal rate of water in each country.

Fig. 2. Sustainability criteria (outer circle) and related *impact categories* (inner circle).

Table 2
Sustainability criteria with associated indicators in the impact category *Environment*.

Criteria	Indicator	
Land use	1	Exclusion of protected areas.
	2	Avoidance of land use with respect to informal land use rights and culturally used land.
	3	No conversion or sealing of agricultural land in productive use.
	4	Construction of electrolysers primarily in industrial areas.
Water use	1	Exclusion of surface and ground water usage for H_2 production in areas with water stress (water supply less than 1700 m^3/year per person).
	2	No existing desalination plants are to be used for electrolysis, but new ones that are operated with additional renewable capacities.
	3	Desalination must not have any harmful effects on the environment.
Emissions	1	National noise emission limits in residential areas must not be exceeded; a maximum value of 40 dB during night time is recommended.

The water footprint of the electrolytic hydrogen is mainly influenced by the source of electricity used. To consider is that with an electrolysis efficiency of e.g. 70%, the water footprint using wind energy is about 0.51 t_{Water}/MWh, compared to 4.1 t_{Water}/MWh when using nuclear energy [9]. The construction of wind energy capacities requires about 0.00379 t_{Water}/MWh, whereas solar energy has a slightly higher water footprint of 0.0151 t_{Water}/MWh (construction and cleaning) [37].

In areas where desalination of seawater is required to supply water to the population, additional desalination capacities for hydrogen production must be installed. Considering reverse osmosis with a relatively low energy requirement of 0.003 MWh/t_{Water}, an electrolyser consuming e.g. 17 kg_{Water}/kg_{H2} will have a 0.1% higher energy requirement relative to producing green hydrogen from freshwater when using desalination [9], needing an additional 0.05 kWh/kg_{H2}. The degree of sustainability can increase if saline seawater, brine water or well water could be directly used in electrolysis, which is however not yet state of the art [i1, i2, e2].

The production of hydrogen causes **Noise emissions** mainly through ventilation and cooling during the electrolysis with up to 90.6 dB(A) at the production site [38]. In countries where power plants are located in close proximity to residential areas, the setting of and compliance with noise emission limits are extremely important to avoid negative health effects related to environmental noise [39]. There are no consistent limit values for noise emissions of electrolysers implemented yet. However, the World Health Organisation published guidelines on the exposure of noise, which should be limited in residential areas during night times to a maximum of 40 dB [40]. This value can be taken as a benchmark in countries, where no noise limit value is implemented.

3.2. Basic needs

The four criteria and related indicators for the impact category *Basic needs* are summarised in Table 3. The construction of electrolysers is planned in many countries around the world where **Energy poverty** is a major issue. In some countries access to electricity in rural areas is not 100% guaranteed and people suffer from energy poverty [41]. It has to be ensured, that additional power generation capacities that are dedicated

Table 3
Sustainability criteria with associated indicators in the impact category *Basic needs*.

Criteria	Indicator	
Energy poverty	1	Construction of additional power generation capacity in areas where the electrification rate of the local population is below 100%. Financing is to be provided by the investing project partners
Water supply	1	Additional desalination plants in areas with water stress (see *Water use*) must first meet the needs of the affected population before water can be used for hydrogen production. Financing is to be provided by the investing project partners
Health	1	Negative effects on human health are to be prevented by introducing emission limits.
	2	Negative effects on food security are to be prevented by securing local agricultural production.
Human rights	1	Fundamental human and labour rights must be respected throughout the project phase; fundamental rights shall include, at a minimum, the prohibition of all forms of forced labour, slavery, child labour, discrimination and inequality. Compliance with these rights must be monitored regularly.

for the local population in countries where the access to electricity rate is below 100% are built, prior to the construction of electrolyseurs. For countries like Namibia or Nigeria, which are planning to produce green hydrogen, this can create a benefit for the population, where the access to electricity is currently under 60% [42]. A benchmark for deciding whether this criterion needs to be met can be the SDG 7 with the indicator *Population with Access to Electricity*, which needs to be verified regionally. The additional renewable capacities made available to the population should be borne or supported by the international project partners to improve the economic sustainability of the countries [26,28]. In this way, the local population can benefit from these projects to a certain extent, even if the hydrogen is produced purely for export [p1, e1, e2, e3, c1]. As the additional financial investments are unlikely to be made voluntarily, international laws or bilateral agreements could be used as a guideline [c1].

In addition to addressing energy poverty, sustainable green hydrogen production can improve the **Water supply** for the local population, if there is a lack of freshwater to meet basic needs. In the event that water scarcity requires the construction of desalination plants for the production of hydrogen, additional desalination capacities are to be built than those needed for the population's needs [26–29]. It can be assumed, that in this case, additional desalination capacities may also be needed for the local population. The development and financing of these capacities must be supported by international project partners if national governments cannot provide these investments. This criterion must also be translated into internationally applicable laws.

The avoidance of negative health impacts should be self-evident in the development of a green hydrogen market, but is insufficiently defined in the published literature (cf. 1.2). The criterion **Health** is linked to the criteria *Emissions* and *Land use*. SDG 3 *Good Health and Well-being* can provide a first country-specific analysis of the relevance of air pollution, which can be used as an indicator for further analysis. In addition, land conversion should not lead to food insecurity, which can also cause health problems.

Respect for human rights is a cornerstone of every society and must therefore be considered as a social dimension of sustainability and included in projects.

Respect for **Human rights** is a fundamental pillar of every society and must therefore be considered as a social dimension of sustainability and included in projects. The publications analysed emphasise the need to secure human rights, but only two publications give implementation possibilities [29,28]. Human rights in the context of hydrogen projects affects the entire value chain of projects. The Universal Declaration of Human Rights that was adopted in the year 1948 by the United Nations must be the basis for all involved stakeholders [43]. There are also various national and international conventions or guiding principles that cover basic human rights, workers' rights as well as all kinds of equality. In countries, where compliance with or even violation of human and labour rights is known, special attention must be paid to the implementation of this criterion. The country-specific analyses of the SDGs provide different aspects of human rights. It is not only important that those directly involved in the project comply with the regulations, but also that the local population, which is directly or indirectly affected by the production of green hydrogen, is respected. SDG 3 *Universal health coverage*, SDG 8 *Victims of modern slavery* and *Fatal work-related accidents embodied in import* and SDG 16 *Property rights* and *Corruption Perception Index* can provide important input for further analysis of the state of human rights in a country.

3.3. Socio-economy

The studies analysed do not provide specific guidelines for **Financial participation**, except that it should be facilitated at the local level [27,26]. For example, landowners must be adequately compensated for the use of their land for hydrogen production in order to create acceptance for hydrogen projects. The amount of compensation must be based on the actual value of the land, so that landowners do not suffer any loss of income due to the conversion of land use [e1]. The financial participation of regional companies or private individuals should be offered and the necessary legal framework for this should be created, if this is possible and desired by the population. A leading example are citizens-owned energy projects, which are implemented regularly in e.g. Germany or Denmark [44]. Some smaller green hydrogen projects with private individuals or regional companies as shareholders are planned and have already been implemented in Northern Germany [e1, e2, e3]. The financial entry barrier for participation must be selected in such a way that private individuals can also afford to participate.

To support the sustainable development of a country, **Employment and added value** have to be considered. SDG 8 *Unemployment rate in % of total labour force* can be a leading indicator to show how much effort needs to be made to create jobs locally. As mentioned above, many countries of the Global South are planning to build a market for green hydrogen, but in some cases have high unemployment rates, unequal wages and limited employment opportunities at the same time. Therefore, it will be extremely important that hydrogen projects create local jobs at all levels of the value chain. After a possible foreign initial introduction phase of the technology, the majority of employees should be local [e1], [26]. To increase local value creation, local companies must be given the chance to offer their participation in the development, construction and operation and maintenance. There are two possible participation options. On the one hand, depending on national regulations, local content requirements can be set with a fixed share of local companies involved. On the other hand, local companies can be invited to submit a bid for their participation. The contract is then not automatically awarded to the most cost-effective bidder, but to the so-called most sustainable variant (e.g. proximity to location, improvement of local value creation) [e1]. In order to support the creation of new local enterprises, the value of the region where the enterprises can locate (proximity to the production side) must be increased. This value can be in the living and working conditions, such as investing in new schools or kindergartens commercial and residential areas [c1].

Table 4
Sustainability criteria with associated indicators in the impact category *Socio-Economy*.

Criteria	Indicator	
Financial participation	1	Landowners must be adequately compensated for the use of their land.
	2	Regional actors must be given the chance to financially participate in the planned projects.
Employment and added value	1	Jobs must be created for the local population. Once the technology is introduced, the majority of employees should be local workers.
	2	Regional companies must be involved in the economic activities of development, construction and operation & maintenance.
	3	The hydrogen should be processed as close as possible to the production site or within the region, if hydrogen derivatives are needed.
Technology & knowledge transfer	1	Business models and adequate training (practical and academic) of the civil society for emerging jobs must be provided by involved project partners.
	2	Capacity building and training for new skill requirements must be integrated in the technology transfer.
	3	Capacity building for decision-makers must be offered by international project partners, if needed.

Table 5
Sustainability criteria with associated indicators in the impact category *Electricity supply*.

Criteria	Indicator	
CO_2-neutrality	1	Electricity must be produced by using the following renewable technologies: wind energy (onshore and offshore), solar Photovoltaic or solar Concentrated Solar Power
Electricity generation	1	If needed, additional new renewable electricity capacities for electrolysis have to be built, compared to an already defined future expansion path (long-term targets).
	a	Wind turbines whose service life and thus financial support has expired and are not being repowered could be connected to electrolysis plants.
	2	The geographical and temporal correlation between electricity generation and hydrogen production must be considered.
	3	Electricity may only be used from the grid if the electricity is generated entirely from renewable energy sources or if only surplus electricity is used at times when grid congestion would force the curtailment of electricity from renewable energy sources.

The criterion **Technology and knowledge transfer** is only important and needs to be considered in countries which lack the necessary knowledge in the field of planning, construction or operation & maintenance of renewable technologies or hydrogen production facilities. It is not possible to quantify the needed amount of capacity building in general. An analysis of the region can analyse the education and employment opportunities based on the existing skills required for the various jobs needed in the hydrogen sector. Various job levels are required throughout the value chain of hydrogen production, distribution, processing and use [c1]. The aim of capacity building measures should be to prepare the local work force for employment and development of the sector. One way to fulfil the proposed criterion is that if the potential investors of the hydrogen production plant are not able to implement an adequate training concept, a fixed share of the profit from the producer should be used for the creation of training centres and paid to the respective community. If necessary, capacity building for decision makers should be offered to ensure that the energy transition can be managed in the most sustainable and beneficial way (Table 4).

3.4. Electricity supply

The technology of electricity generation determines the carbon footprint of the hydrogen produced. Since green hydrogen is defined as being produced by electrolysis with renewable electricity, this criterion determines which type of generation technology should be considered from a sustainability perspective. The reviewed literature agreed upon the use of on-shore and off-shore wind energy, as well as solar PV and solar CSP. The most suitable technology in case of the life-cycle carbon footprint is wind energy, as less CO_2 emissions are generated during the production of the components compared to e.g. solar PV and solar CSP [8]. The use of CSP is only advisable, if additional storage capacity is required otherwise, PV would be much more cost competitive [45]. The use of biomass and nuclear are not recommended under sustainability aspects. The carbon footprint of the production of nuclear electricity is low, but since nuclear energy carries high accident risks, this technology cannot be considered as being green and sustainable [26]. Biomass, either from wood or residuals, creates a carbon footprint related to land cultivation, processing and transport, which is why it is not fully carbon neutral and therefore not feasible to use [26]. Geothermal energy could theoretically also be considered as being suitable, but the production of green hydrogen using geothermal electricity would significantly increase the production costs compared to wind or solar energy [46] and geothermal power plants are probably more suitable to provide base load electricity to the national grid [47].

There are additional requirements that need to be specified in relation to **Electricity generation**. In the context of green hydrogen production, the concept of *Additionality* plays an important role (discussed in [34]). This means that the production of green hydrogen should normally be powered by renewable capacities with a direct connection to the electrolyser, which are not part of the decarbonisation strategy of the electricity sector of the respective country [29]. Also relevant could be the use of wind turbines that have extended their lifetime and are unlikely to be repowered [e2, e3]. They are still fit to operate, which is why they should be further used.

The geographical and temporal correlation between electricity that is taken from the grid and the hydrogen production should be considered. This could be done either by entering a Power Purchase Agreement with an energy generation facility that is newly constructed or by using excess electricity from the grid. If no new renewable power plants can be built in the immediate vicinity of an electrolyser, electricity can be taken from the national grid. In this case, two possibilities exist to classify the produced hydrogen as sustainable. Either the electricity taken from the grid must be fully renewable (100% renewable electricity in the national grid) or exclusively excess electricity must be used, which would otherwise be curtailed due to grid bottlenecks or a reduced electricity demand. This option could lead to a more decentralised expansion of electrolyser capacities, which would reduce investments in grid expansion. However, if the grid will be extended, the amount of excess electricity for the production of green hydrogen might be reduced (Table 5).

3.5. Project planning

The criterion **Participatory processes** contains aspects related to the social involvement of the population and is the least researched and studied topic in relation to sustainability criteria. Almost all interview partners emphasised the need to invest in communication with the local population.

Table 6
Sustainability criteria with associated indicators in the impact category *Project planning*.

Criteria	Indicator	
Participatory process	1	Local people must be involved in all phases of the project development at an early stage, so that changes are still possible.
	2	Creation of transparent and neutral complaint mechanisms and specific contact persons for the local population.
	3	Municipalities or individual land owners should not be allowed to sell land use rights to investors without the participation of the civil society.
Impact Assessment	1	An environmental impact assessment for electrolysers with a capacity of more than 10 MW needs to be conducted before the construction of the plant, including at least impacts on humans, air, climate, land, water, biodiversity, flora, fauna, landscape and cultural heritage, if no legal regulations are in place.

Table 7
Sustainability criteria with associated indicators in the impact category *Energy transition*.

Criteria	Indicator	
Use of hydrogen	1	Hydrogen and its derivatives should only be used in hard-to-abate sectors as a no-regret-application, for which there are no alternative decarbonisation pathways.
	2	The use of hydrogen and its derivatives must be included and considered in hydrogen trade partnerships and agreements.
By-products	1	Mandatory use and further processing of all by-products that are generated during the hydrogen production process (e.g. oxygen, heat).

In general, the local population need to be involved in the early stages of the project development and be aware of the opportunities and risks of the project. A social impact assessment, similar to Environmental Impact Assessment should be conducted to evaluate the local capacity building potential; this may include holding public meetings, organising workshops and establishing lines of communication to understand the communities concerns, aspirations and expectations. Early involvement means at a stage when adjustments to the project are still possible [p7]. A mixed approach of face-to-face meetings, media campaigns and larger information events seems to be suitable to successfully involve the population [c1]. Via a stakeholder identification, involving stakeholders other than the project planner in the communication dialogue, e.g. regional ministries, electricity or gas grid operators, business, landowners, environmental groups and the local residents can be beneficial to increase trust and approval of the project [p3, p7]. Parallel, before and after construction, permanent, transparent and neutral complaint mechanisms must be established, and contact persons must be available for the local population. During the entire process information dissemination channels must be established to keep the local residents informed about the project's construction and operational phase. Regular monitoring of the project's performance and impacts while engaging with the community to gather feedback, addressing concerns and implementing necessary adjustments to improve the project's outcome during the entire process is vital for its successful implementation. In addition, landowners, municipalities or private individuals should not sell their land rights to investors without informing the civil society, if the transaction has a major impact on the region. Ideally, all informed people should accept and agree to the construction of the hydrogen plant.

The criterion **Impact assessment** defines further conditions under which the permit to construct and operate a facility can be granted. To keep the environmental impact of green hydrogen production as low as possible, a comprehensive EIA must be carried out prior to the construction of an electrolyser. From a size of 10 MW, an EIA is required. Under the with this capacity associated maximum production of 4,500 kg_{H2}/day, the plant does not fall under the regulations of an accident ordinance (in Germany) [e3]. An EIA determines the potential environmental, social, and health effects of a proposed development [48]. The assessment must include impacts on the human health, air quality, climate, land, water, biodiversity, flora, fauna, landscape and cultural heritage, if no legal regulations are already implemented in the country. In many countries, an EIA is a required part of the project application process that follows a standardised regulation (Table 6).

3.6. Energy transition

The **Use of hydrogen** can lead to a decarbonisation of carbon-intensive energy systems and thus avoid the emissions of greenhouse gases [8]. However, hydrogen and its derivatives should only be used in hard-to-abate sectors, for which there are no alternative technologies to reduce GHG emissions. The electrolysis requires the construction of additional renewable capacities and creates efficiency losses of at least 30% (depending on the processing), which is why a direct electrification would be the most suitable transformation pathway that lead to the lowest economic costs and environmental impacts [8]. Liebreich [49] developed a *Clean Hydrogen Ladder*, which prioritises the use of hydrogen for different sectors, implying which applications are better suitable for direct electrification or the use of biomass. A regional analysis of application possibilities and alternatives must be carried out. The hydrogen prioritisation proposed by Liebreich [49] as well as other studies must be taken into account when determining hydrogen consumers. Integrating the use of hydrogen into trade agreements can increase the sustainability of hydrogen production and use.

In addition to hydrogen, the electrolysis also produces oxygen and heat as so-called **By-products**, e.g. 8 kg_{O2}/1 kg_{H2}[2]. No by-products should be wasted, even though it might be difficult for power plant operators to find customers for both products [e1, e2, e3, p1] and further compression of the oxygen [e3] is necessary. The oxygen can be used in the steel industry or for wastewater treatment, which creates synergies and additional financial opportunities to make the overall hydrogen production more competitive [9]. Efforts should be made to optimally use the by-products in the vicinity of the production site to reduce transport costs and losses (Table 7).

4. Discussion

Hydrogen has the potential to help solve several critical energy problems. It offers opportunities to decarbonise a number of sectors, where emissions reductions are proving difficult. Moreover, hydrogen is versatile and can help improve air quality and energy security [50]. However, the increasing demand needs to be met by sustainably and socially just produced hydrogen. The literature review (subsection 1.2) found that a complete set of criteria to support a sustainability assessment of a hydrogen production is missing. Measurable sustainability criteria can enable decision makers and project planners to establish environmentally friendly and socially just green hydrogen production. However, when defining sustainability criteria, it should be noted that a quantitative sustainability assessment is critical, because, according to [51], a classification of sustainability contains an element of subjectivity and can be strongly influenced by value judgements of decision makers. For this reason, this article focuses exclusively on the development of quantifiable criteria that are met or not met. Therefore, the question of *how* sustainable a project is cannot be answered on the basis of this study.

There have been extensive discussions at the European level on how to define green hydrogen, beside the use of renewable electricity. The EU Directive 2018/2001 on the promotion of the use of energy from renewable sources in combination with an accompanying Delegated Act specifies rules regarding the production of green hydrogen for the transport sector [34]. These rules are likely to be applied for the use of green hydrogen in other sectors, which is why they can act as a robust benchmark for further political discussions. However, some of the discussions, such as the time lag between the construction of the electrolyser and the renewable capacities used for it, may not lead to a more sustainable production of green hydrogen. Rather, what is important is the need to built new generation capacity that is additional to the intended pathway of decarbonisation of the power sector. If such additionality is given, the time period between the two construction periods does not matter.

The establishment and global implementation of sustainability criteria for green hydrogen production are imperative to ensure fair competition between different countries. Intercontinental trade relationships are likely to be limited to destinations that are not too far apart as transportation costs have an important impact on end-user costs [52,33]. However, trade of green hydrogen between European and African countries is already under discussion. Morocco, for example, announced the construction of a green hydrogen production facility, which is only dedicated for the export to Europe [3].

The results of this study on social participation should be seen as a first attempt to identify measurable sustainability criteria. There are few best practise examples of how to engage the civil society in a way that they not only feel informed but also derive maximum benefit from the project. According to [53] “there is rarely any inter- and transdisciplinary sustainability research on hydrogen that reflects on societal development”. This lack was also noted in this study, but would be crucial to achieve sustainable production of green hydrogen.

Limitations

The results of the study must be viewed critically against the background of the methods and materials used. The previous sections have shown that the social dimension of green hydrogen production has not yet been sufficiently researched and considered. This study establishes a first set of sustainability criteria that integrate social participation in green hydrogen plans, projects and strategies. However, it is imperative to conduct further research, especially on the socio-economic and ecologic impacts of the green hydrogen economy. In particular, to capture the social dimension of hydrogen use, surveys and participatory workshops can provide detailed insights. In addition, the presented criteria need to be assessed and adapted depending on the country studied, since for example different land use rights and social habits prevail that might alter some of the given criteria.

Besides the established sustainability criteria and the sensible use of hydrogen in applications (following e.g. Liebreich [49]), there are two main issues that need to be considered when analysing green hydrogen (applications and use). Before assessing the demand and source of green hydrogen (locally produced or imported), measures need to be taken to reduce the demand for electricity and green hydrogen (or any other energy carrier); efficiency and sufficiency measures. In this context, some stakeholders argue that the consideration of green hydrogen plans and partnerships by e.g. Europe (countries of the Global North) and e.g. Africa (countries of the Global South) is a form of neo-colonialism. However, well-executed knowledge and technology transfer can contribute to increased industrialisation of countries and support the overall decarbonisation using green hydrogen. The aforementioned social impact assessment and participation patterns, as well as socio-economic impact criteria, may help to analyse and consider this. In order to achieve a fully sustainable consideration of green hydrogen in the energy transition, sustainability criteria need to be developed along the entire value chain, including the way electricity is generated.

Furthermore, it can be argued that prioritising the criteria is advisable. We believe that a ladder of criteria, indicating which criterion builds on which, would be useful to serve as a checklist for hydrogen projects. However, we think that the issue of prioritising is more of a socio-philosophical nature and cannot be answered within the scope of this study. Sustainability is a complex and interconnected concept, and it’s often best to pursue a balanced approach that considers multiple aspects simultaneously. Additionally, the compliance with the indicators set for each sustainability criterion must be monitored and measured. There is no legal framework for this until now.

5. Conclusion

The adoption of sustainable criteria for green hydrogen is crucial for promoting a responsible and sustainable approach to hydrogen production. It instills confidence in the technology, encourages investments in renewable energy infrastructure and green hydrogen projects, while avoiding social injustices and balancing the interests of all parties involved. As green hydrogen experiences significant political and economic momentum worldwide, this research highlights the need to consider socio-ecological factors in its production to prevent potential market failures and ensures a just energy transition.

The study presents 16 sustainability criteria in six impact categories, that can serve as a guideline for decision-makers and hydrogen stakeholders in evaluating green hydrogen projects and strategies. The research findings suggest that making decisions about hydrogen production based solely on economic costs is insufficient. The study emphasises the importance of integrating social aspects across the entire value chain.

This research has furthermore contributed to the existing knowledge on the sustainability dimensions of green hydrogen, particularly in the context of renewable and smart energy systems. Sustainability criteria for green hydrogen production are linked to smart energy systems through their alignment with renewable energy integration, energy efficiency, grid integration, techno-economic modelling, and policy frameworks. By considering these criteria, smart energy systems can optimise renewable energy utilisation, enhance efficiency, integrate hydrogen production into the grid, assess economic viability, and develop supportive policies.

Moreover, the adoption of sustainability criteria and their practical application through a project checklist can prove advantageous rather than hinder for the production of green hydrogen in the long-run. This approach promotes increased acceptance and transparency among all stakeholders involved, thereby fostering a more favourable environment for its implementation. The findings of this study contribute to the ongoing efforts to advance the adoption of green hydrogen and pave the way for a more sustainable and equitable energy system.

Funding

This work was supported by the Schleswig-Holstein Ministry of Education and Training, Science, Research and Culture (MBWFK) and the Gesellschaft für Energie und Klimaschutz Schleswig-Holstein (EKSH).

CRediT authorship contribution statement

Marina Blohm: Conceptualisation, Methodology, Data curation, Interviews, Investigation, Visualisation, Writing – original draft. **Franziska Dettner:** Conceptualisation, Writing – original draft, review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgement

We would like to thank all interview partners for their time and valuable input to our research.

Appendix A

A.1. Interview data

Table 8
Interviewees, sector of employment, position of interviewees in respective institution as well as date and time of the conducted interview. All interviews were carried out via Webex, Zoom or Microsoft Teams and conducted after a semi-structured interview scheme by Marina Blohm.

Abb.	Sector	Position of interview partner	Interviewees no.	Date of interview year 2022	Length (minutes)
p1	Private sector	CEO	1	16. February	60
e1	Energy management	Deputy head of department and engineer	2	05. & 12. April	90
p1	Interview	Head of department and project manager	2	28. April	90
i1	Industry	Project manager	1	29. April	90
e2	Energy management	Team lead and project manager	2	03. May	90
b1	Public sector	Project manager	1	06. May	60
e3	Energy management	Head of department	1	12. May	65
c1	Civil society	Network coordinator	1	16. May	60
p2	Policy sector	Member of the Parliament	1	24. May	60
p3	Policy sector	Consultant	1	25. May	60
p7	Policy sector	Consultant	1	01. June	30
p4	Policy sector	Member of the Parliament	1	02. June	45
p5	Policy sector	Former member of the Parliament	1	03. June	45
p6	Policy sector	Deputy head of department	1	21. June	60
i2	Industry	–	n/a	22. June	*written feedback*
p2	Private sector	General Manager and Development Director	2	08. July	60
b2	Public sector	Project manager	1	27. & 28. July	80

References

[1] U. Nations. Transforming our world: the 2030 agenda for sustainable development. https://wedocs.unep.org/20.500.11822/9814, 2015.
[2] MEME. Feuille de Route Hydrogène vert – Vecteur de Transition Énergétique et de Croissance Durable. Technical Report. Ministère de l'Énergie des Mines et de l'Environnement; 2021. https://www.mem.gov.ma/Lists/Lst_rapports/.
[3] Atchison J. 183,000 tonnes per year green ammonia in Morocco. https://www.ammoniaenergy.org/articles/183000-tonnes-per-year-green-ammonia-in-morocco/, 2021.
[4] Blohm M. The hidden costs of Morocco's energy transition: investigating the impact of foreign investment and the lack of social participation; 2023.
[5] Moustakbal J. The Moroccan energy sector: a permanent dependence. https://longreads.tni.org/the-moroccan-energy-sector, 2021.
[6] Kalt T, Tunn J. Shipping the sunshine? A critical research agenda on the global hydrogen transition. GAIA Ecol Perspect Sci Soc 2022;31:72–6.
[7] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart energy systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54.
[8] German Advisory Council on the Environment. Wasserstoff im Klimaschutz: Klasse statt Masse, Stellungnahme. German Advisory Council on the Environment. https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.html;jsessionid=1636EB94526F226209A1D5E335ED4926.intranet222?nn=393504, 2021.
[9] Newbotough M, Cooley G. Green hydrogen: water use implications and opportunities. Fuel Cells Bull 2021:12–5.
[10] International Energy Acengy. Global hydrogen review 2021. https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf, 2021.
[11] IRENA. Global hydrogen trade to meet the 1.5 °C climate goal: part I – trade outlook for 2050 and way forward. Technical Report. Abu Dhabi: International Renewable Energy Agency; 2022. https://www.irena.org/publications/2022/Jul/Global-Hydrogen-Trade-Outlook.
[12] Knobloch F, Hanssen S, Lam A, Pollitt H, Salas P, Chewpreecha U, et al. Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat Sustain 2020;3.
[13] Li W, Ren X, Ding S, Dong L. A multi-criterion decision making for sustainability assessment of hydrogen production technologies based on objective grey relational analysis. Int J Hydrog Energy 2020;45:34385–95.
[14] Xu D, Lv L, Ren X, Ren J, Dong L. Route selection for low-carbon ammonia production: a sustainability prioritization framework based-on the combined weights and projection ranking by similarity to referencing vector method. J Clean Prod 2018;193:263–76.

[15] Ren X, Li W, Ding S, Dong L. Sustainability assessment and decision making of hydrogen production technologies: a novel two-stage multi-criteria decision making method. Int J Hydrog Energy 2020;45:34371–84.
[16] Afgan N, Carvalho M. Sustainability assessment of hydrogen energy systems. Int J Hydrog Energy 2004;29:1327–42.
[17] Wijayasekera SC, Hewage K, Siddiqui O, Hettiaratchi P, Sadiq R. Waste-to-hydrogen technologies: a critical review of techno-economic and socio-environmental sustainability. Int J Hydrog Energy 2022;47:5842–70.
[18] Balli O, Caliskan H. Energy, exergy, environmental and sustainability assessments of jet and hydrogen fueled military turbojet engine. Int J Hydrog Energy 2022:S0360319922017529.
[19] Elvira K, Marisol R, Susanne H, Leif-Magnus J, Sandoval-Pineda J, de G G-HR. Hydrogen technology for supply chain sustainability: the Mexican transportation impacts on society. Int J Hydrog Energy 2022:S0360319922011168.
[20] Lassio JG, Magrini A, Castelo Branco D. Life cycle-based sustainability indicators for electricity generation: a systematic review and a proposal for assessments in Brazil. J Clean Prod 2021;311:127568.
[21] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis – a review. J Clean Prod 2014;85:151–63.
[22] Delpierre M, Quist J, Mertens J, Prieur-Vernat A, Cucurachi S. Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. J Clean Prod 2021;299:126866.
[23] Lui J, Sloan W, Paul MC, Flynn D, You S. Life cycle assessment of waste-to-hydrogen systems for fuel cell electric buses in Glasgow, Scotland. Bioresour Technol 2022;359:127464.
[24] Ullman AN, Kittner N. Environmental impacts associated with hydrogen production in La Guajira, Colombia. Environ Res Commun 2022;4:055003.
[25] Zhao G, Pedersen AS. Life cycle assessment of hydrogen production and consumption in an isolated territory. Proc CIRP 2018;69:529–33.
[26] German National Hydrogen Council. Nachhaltigkeitskriterien für Importprojekte von erneuerbarem Wasserstoff und PtX-Produkten. https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/2021-10-29_NWR-Stellungnahme_Nachhaltigkeitskriterien.pdf, 2021.
[27] Heinemann C, Mendelevitch DR. Sustainability dimensions of imported hydrogen. Working Paper. Öko-Institut e.V.; 2021. https://www.oeko.de/fileadmin/oekodoc/WP-imported-hydrogen.pdf.
[28] Morgen S, Schmidt M, Steppe J, Wörlen DC. Fair green hydrogen – chance or chimera in Morocco, Niger and Senegal? Technical Report. Berlin: Arepo GmbH; 2022. https://arepoconsult.com/wp-content/uploads/2022/04/Studie_Fair_Hydrogen.pdf.
[29] PtX Hub. PtX.Sustainability dimensions and concerns. https://ptx-hub.org/wp-content/uploads/2022/05/PtX-Hub-PtX.Sustainability-Dimensions-and-Concerns-Scoping-Paper.pdf, 2022.
[30] Öko-Institut e.V., adelphi. Comparing sustainability of RES- and methane-based hydrogen – sustainability dimensions, blind spots in current regulation and certification, and potential solutions for hydrogen imports to Europe. Technical Report. Freiburg, Berlin: Öko-Institut e.V.; 2022. https://www.adelphi.de/en/system/files/mediathek/bilder/oeko-institute and adelphi (2022) Comparing sustainability of RES and methane-based hydrogen.pdf.
[31] Guessous H. Morocco first to partner with Germany to develop green hydrogen sector. https://www.moroccoworldnews.com/2020/06/305441/morocco-first-to-partner-with-germany-to-develop-green-hydrogen-sector, 2020.
[32] BMWK. Die Nationale Wasserstoffstrategie. https://www.bmbf.de/bmbf/de/forschung/energiewende-und-nachhaltiges-wirtschaften/nationale-wasserstoffstrategie/nationale-wasserstoffstrategie_node.html, 2020.
[33] Sens L, Piguel Y, Neuling U, Timmerberg S, Wilbrand K, Kaltschmitt M. Cost minimized hydrogen from solar and wind – production and supply in the European catchment area. Energy Convers Manag 2022;265:115742.
[34] European Commission. Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. http://data.europa.eu/eli/dir/2018/2001/oj/eng, 2018.
[35] Enkhardt S. Mecklenburg-Vorpommern will 5000 Hektar Ackerland für Photovoltaik-Freiflächenanlagen freigeben. https://www.pv-magazine.de/2021/06/14, 2021.
[36] Kummu M, Guillaume JHA, de Moel H, Eisner S, Flörke M, Porkka M, et al. The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Sci Rep 2016;6:38495.
[37] Jacobson MZ. Review of solutions to global warming, air pollution, and energy security. Energy Environ Sci 2009;2:148–73.
[38] H-TEC Systems. Unterstützung des Betreibers mit Informationen, Zahlen und Fakten für eine BImSch-Genehmigung; 2019.
[39] European Environment Agency. Health risks caused by environmental noise in Europe. https://www.eea.europa.eu/publications/health-risks-caused-by-environmental, 2021.
[40] World Health Organization. Night noise guidelines for Europe. Technical Report. Copenhagen: World Health Organization; 2009. https://www.euro.who.int/_data/assets/pdf_file/0017/43316/E92845.pdf.
[41] United Nations. SDG 7 – population with access to electricity. https://dashboards.sdgindex.org/map/indicators/population-with-access-to-electricity, 2022.
[42] World Bank. Access to electricity (% of population) – sub-Saharan Africa. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZG, 2020.
[43] United Nations General Assembly. Universal declaration of human rights (UDHR); 1948.
[44] Walker G. What are the barriers and incentives for community-owned means of energy production and use? Energy Policy 2008;36:4401–5.
[45] Kost C, Shammugam S, Fluri V, Peper D, Memar AD, Schlegl T. Stromgestehungskosten Erneuerbare Energien. Technical Report. Freiburg: Frauenhofer ISI (Hrsg.); 2021. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2021_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf.
[46] Awaleh M, Adan A-B, Assowe Dabar O, Jalludin M, mahdi ahmed M, Guirreh I. Economic feasibility of green hydrogen production by water electrolysis using wind and geothermal energy resources in Asal-Ghoubbet rift (Republic of Djibouti): a comparative evaluation. Energies 2022;15.
[47] Thomann J, Edenhofer L, Hank C, Lorych L, Marscheider-Weidemann F, Stamm A, et al. Background paper on sustainable green hydrogen and synthesis products. HYPAT Working Paper 01/2022. Karlsruhe: Frauenhofer ISI (Hrsg.); 2022. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2022/HYPAT_Working_Paper_01-2022_Hintergrundpapier_zu_nachhaltigem_gruenen_Wasserstoff_und_Syntheseprodukten.pdf.
[48] University of London. Unit 1 introduction to environmental impact assessment (EIA). https://www.soas.ac.uk/cedep-demos/000_P507_EA_K3736-Demo/unit1/page_08.htm, 2022.
[49] Liebreich M. The clean hydrogen ladder: an introduction. https://drive.google.com/file/d/1X-oH04NH1477eig_BmYjtD9mHyTcoiVc/view, 2021.
[50] IEA. The future of hydrogen – seizing today's opportunities. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf, 2019.
[51] Morse S, McNamara N, Acholo M, Okwoli B. Sustainability indicators: the problem of integration. Sustain Dev 2001;9:1–15.
[52] Staiß F, Adolf J, Ausfelder F, Erdmann C, Hebling C, Jordan T, et al. Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030: Transportwege - Länderbewertungen - Realisierungserfordernisse. Technical Report. München: Schriftenreihe Energiesysteme der Zukunft; 2022.
[53] Hanusch F, Schad M. Hydrogen research: technology first, society second? GAIA Ecol Perspect Sci Soc; 2021. p. 82–6.

Part III - Connecting the Dots

9

Synthesis

This synthesis focuses on **sustainable energy system transitions** by summarising and critically assessing the key findings from the publications presented in Part II in light of the foundational concepts outlined in Part I. By examining the results and limitations of the energy and emission models used in the publications, this part of the thesis also identifies gaps in current research and addresses the research question:*How can collaborative, open-source energy system models and emission modelling be leveraged to optimise policy-making and investment decisions to achieve sustainable energy transitions and emission reduction goals?*

9.1 What makes an Energy System sustainable?

A sustainable energy system is one that ensures long-term energy security and fosters economic and social development while minimising environmental impact. In the context of climate change, sustainable energy systems go beyond simply reducing GHG emissions by addressing the **environmental pillar** of sustainability; it requires an integrated, multi-sector approach that encompasses technological innovation, economic viability and social inclusiveness. The publications within this thesis explore how the **techno-economic pillar** of sustainability can facilitate carbon neutrality across various sectors, with a specific focus on power generation (Chapter 4), sector-coupling of mobility, energy generation and cruise ships (Chapter 5) and the entire shipping sector on one of the most trafficked areas in the world (Chapter 7). Additionally, the publications delve into the **social pillar** of sustainability through the use of multi-criteria decision analysis within co-creative participatory energy scenario development (Chapter 3) and the use of social criteria in the context of environmental justice for green hydrogen (Chapter 8). A key aspect of all publications and of a sustainable energy transition is the role of **open science and open modelling** approaches, which emphasise transparency, collaboration and adaptability as part of the sustainability paradigm (all, but especially Chapter 6). Lastly, Chapter 7 address necessary **policy frameworks** to support sustainable energy transitions, demonstrating how carbon budgets within the maritime sector are necessary for sustainable energy system transitions.

Techno-Economic Pillar

Techno-economic factors are crucial in the development and implementation of sustainable energy systems. As IRENA (2022) highlights, electrification and efficiency are pivotal drivers in achieving the 1.5°C Paris Agreement target, particularly by facilitating the integration of renewable energy sources. Furthermore, techno-economic optimisations form the backbone of various energy system analyses and energy system modelling methodologies.

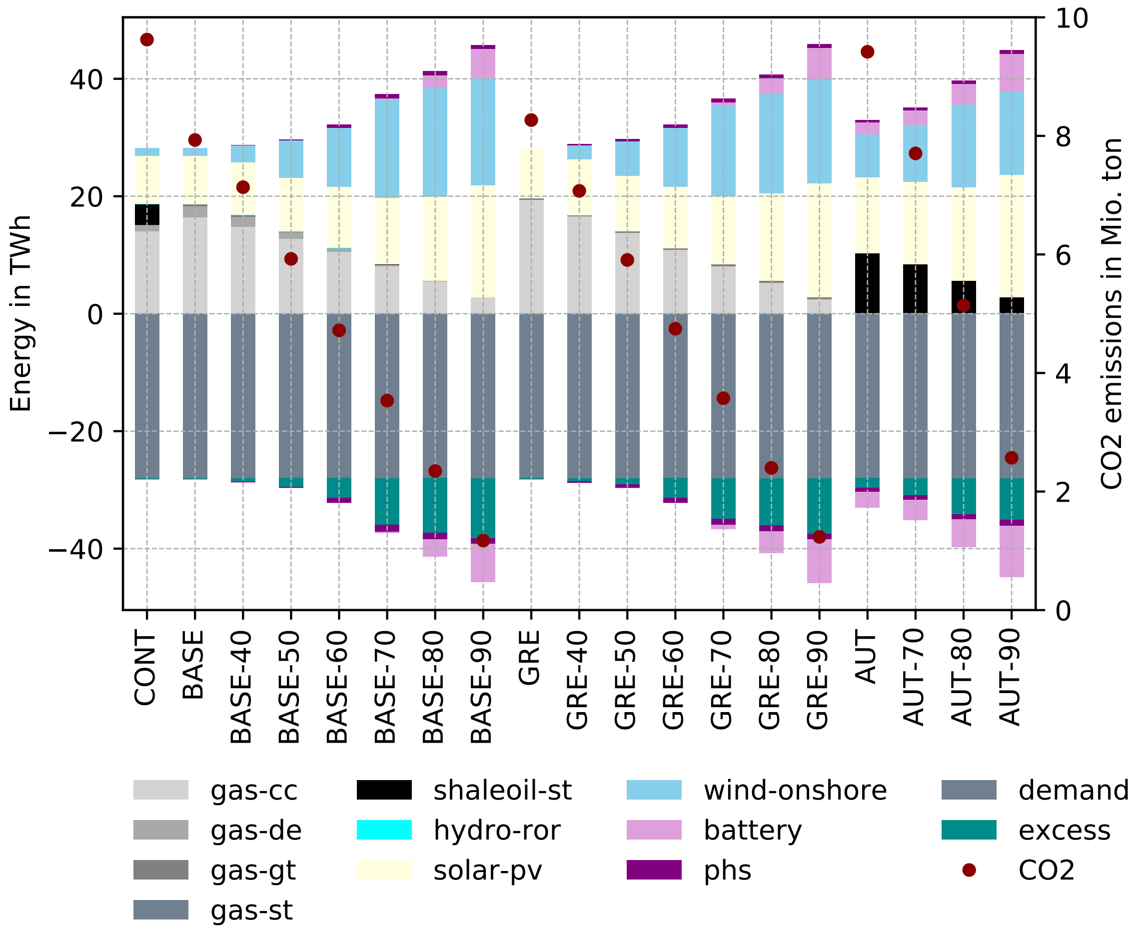


Figure 9.1: Scenario results from an energy system analysis for the Jordanian energy system. This figure compares the supply and demand dynamics (shown on the left axis) alongside CO_2 emissions (represented on the right axis) across all scenarios discussed in Chapter 4 (Hilpert et al. 2020a).

The publication in Chapter 4 *Analysis of cost-optimal renewable energy expansion for the near-term Jordanian electricity system* (Hilpert et al. 2020a) highlights the cost-effective potential for reducing CO_2 emissions in Jordan by emphasising storage modelling and the optimisation of investments in renewable energy expansion within different scenarios. Jordan faces numerous challenges resulting from climate change, water scarcity, political instability, a rapidly growing economy and socio-economic pressures. Jordan's electricity sector is particularly impacted by rising energy demand, a heavy reliance on fossil fuel imports, a low level of foreign investment and the need for effective management of both local fossil fuels and renewable resources. The publication in Chapter 4 used an open-source optimisation model based on oemof to identify the cost-optimal pathways for the expansion of Jordan's electricity system in 2030 as well as scenarios for varying shares of RE. The findings underscore the significant potential of renewable energy to drive sustainable growth in Jordan's electricity sector at minimum cost and without reliance on energy imports. A renewable energy share of up to 50 % can be achieved with only a slight increase in the levelised cost of electricity (LCOE) from \$ 54.42 to \$ 57.04 per MWh. The analysis reveals that a combination of PV and PHS offers a better solution than expanding the use of domestic shale oil due to its higher cost and CO_2 emissions (see Figure 9.1). Achieving a renewable energy share above 50 % will require substantial wind energy deployment, with wind energy providing 45 % of demand in a system with a 90 % renewable energy share.

The choice of scenarios often depends on more than just technical and economic considerations. As Jordan has to deal with political instability and difficulties in importing fossil fuel due to its geographical location, a self-sufficiency scenario (AUT) is required, in which local resources are used, especially shale oil. However, the LCOE is the highest within this scenario at just under 100 \$/MWh for an RE share of 40-70 % and around 110 \$/MWh for an RE share of 90 %. The BASE scenario (considering the existing national energy generation capacity in 2023 as the basis for capacity expansion) and the GRE scenario (greenfield planning approach, considering an unconstrained electricity mix optimisation) are more cost-effective. Results of the GRE scenario highlight that a combination of combined cycle gas turbines (CCGTs) and RE is more cost-effective than shale oil. The LCOE of the BASE and GRE scenarios do not differ significantly. However, in both scenarios, an RE share of 90 % results in an LCOE which is almost twice as high as that for the cost-optimal case (in which the RE share is around 30 %). This might be due to higher storage requirements resulting in additional investment costs and high excess electricity with curtailment.

Barbados faces a similar problem to Jordan, although it has an even greater dependence on imported fossil fuels. There are, however, opportunities in Barbados for climate change mitigation and economic diversification, which makes it ideal for energy system analysis. The publication in Chapter 5 *Open source modelling of scenarios for a 100 % renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles* (Harewood et al. 2022) used an open-source energy system model applying oemof to explore different scenarios within cost-optimal and 100 % renewable energy configurations using a greenfield planning approach. The model includes the electrification of private passenger vehicles and shore-to-ship power for cruise ships to assess their impact on Barbados' energy system. Several scenarios were analysed using wind, solar, biomass (bagasse), waste and low and medium speed diesel generators powered with heavy fuel oil on the supply side. The demand remains consistent across all scenarios, except for the Status-Quo (SQ) scenario, which excludes the 58 MW additional capacity required for electric vehicles (EVs) and cruise ships. In contrast, the High-Demand (HD) scenario assumes a higher baseline demand, which increases by 1.2 % annually. The demand pattern is consistent in all scenarios, assuming controlled charging for EVs, except within the electric vehicle uncontrolled charging (EVUC) scenario.

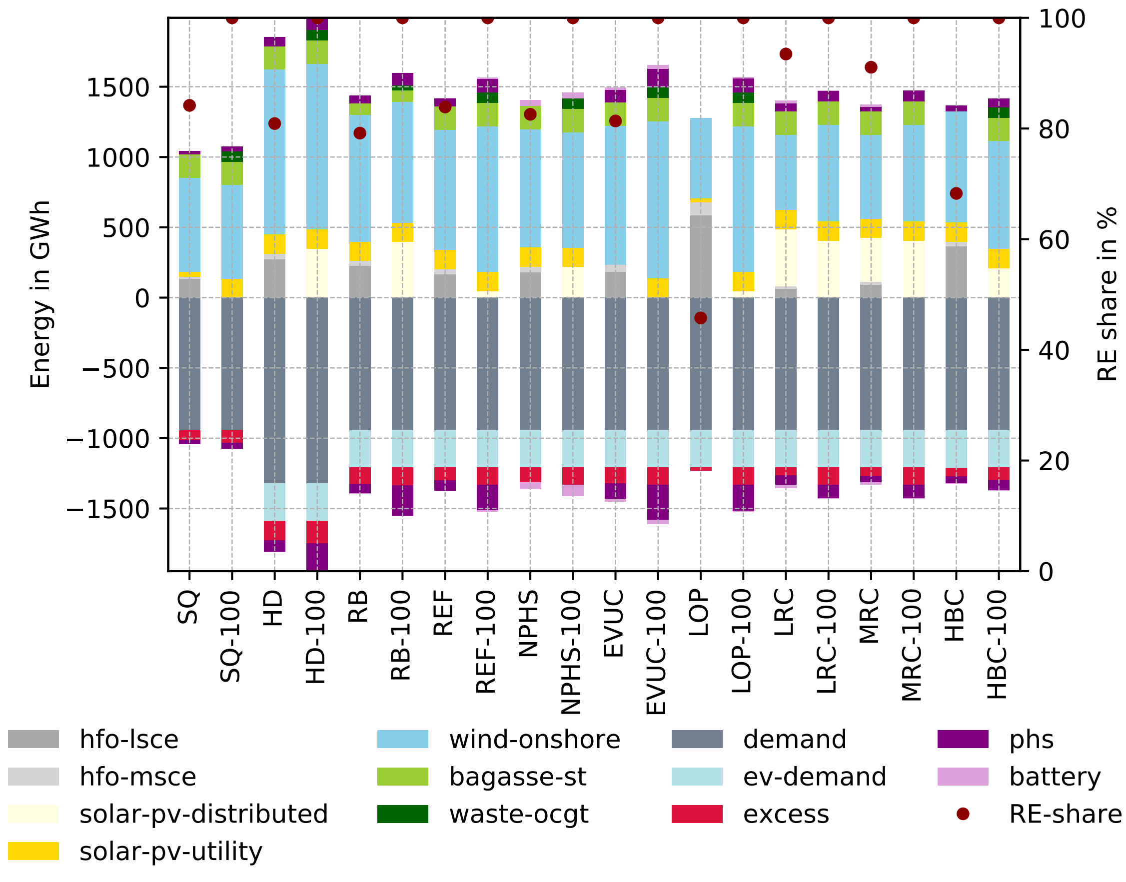


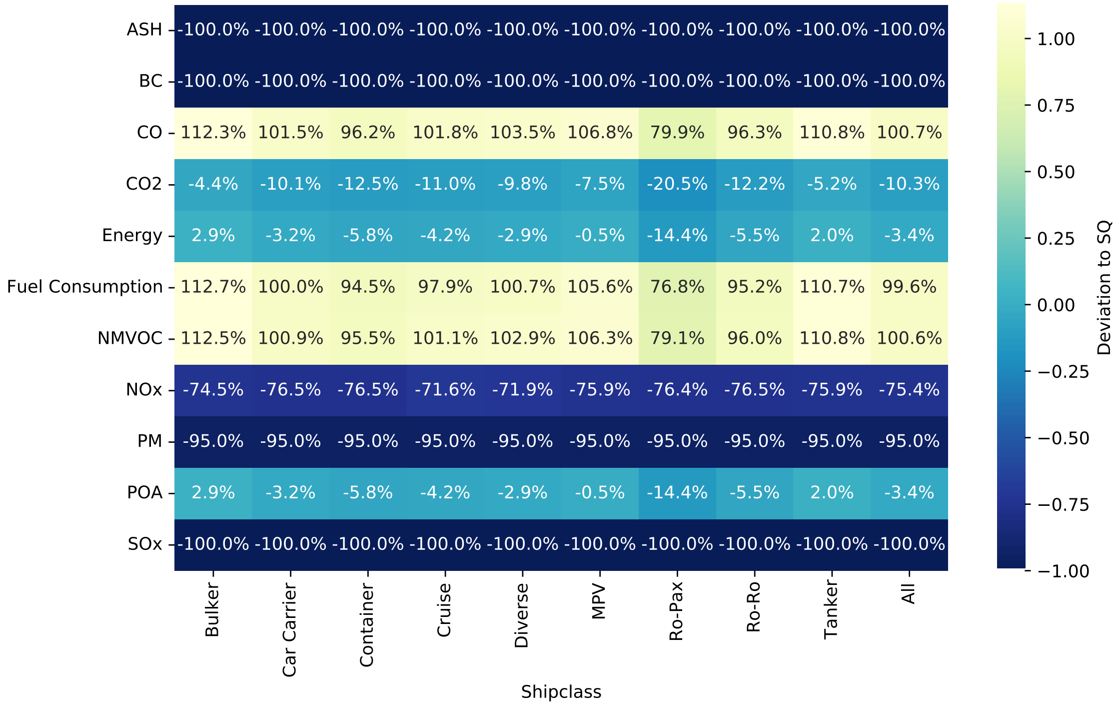
Figure 9.2: Scenario results from an energy system analysis for the Barbadian energy system. This figure compares the supply and demand dynamics (shown on the left axis) alongside the renewable energy share (represented on the right axis) across all scenarios discussed in Chapter 5 (Harewood et al. 2022).

Results show that by 2030 most scenarios achieve over 80 % renewable energy in cost-optimal cases despite the predicted increasing demand (see Figure 9.2). The system is mainly supplied with wind energy, with capacities ranging from 168 MW to 371 MW, depending on the scenario. With a maximum of 80 MW, PV-utility capacity is required across all scenarios, except for the SQ and SQ-100 configurations. Despite higher upfront costs, bagasse consistently appears in all cost-optimal scenarios due to its lower cost compared to heavy fuel oil (HFO), which, while offering lower investment costs, incurs significantly higher operational costs. This supports the argument for higher initial investment, which contributes to the long-term sustainability of the Barbadian energy system. Energy storage requirements, particularly pumped PHS, critically depend on scenario restrictions. In scenarios where bagasse use is limited, higher PHS capacities are necessary. This is also the case in all 100 % RE scenarios. Waste-to-energy technology appears exclusively in the 100 % RE scenarios due to its high investment costs. The LCOE ranges from 0.17 to 0.36 BBD/kWh, with only moderate increases observed in 100 % renewable systems. If PV costs decrease in the future, a fully renewable system could become more cost-effective than current options. PHS emerges as a no-regret solution, reinforcing the technical and economic feasibility of a 100 % RE system for Barbados.

The case studies of Jordan and Barbados focus on the combination of the technological and economic feasibility of sustainable energy systems, and highlight how both elements must work in tandem to create energy systems that are not only environmentally friendly but also technologically feasible and scalable (cost-optimal and 100 % RE). Renewable energy technologies, in combination with energy storage and sector coupling, are essential for reducing GHG emissions, improving system efficiency and promoting economic diversification in countries heavily reliant on energy imports. However, these efforts need to be supported by a robust economic framework that ensures affordability, financial sustainability and market competitiveness, without transferring costs to the consumer. The pillar of economic sustainability is particularly crucial in this context, as it aligns with the principle of inter-generational justice, ensuring that current energy solutions do not compromise the ability of future generations to meet their own needs while maintaining economic viability and environmental responsibility.

Building on advancements in energy system modelling and techno-economic solutions for carbon emission mitigation, attention must be directed toward strategies in specific sectors such as shipping, which is pivotal in achieving broader climate goals. The Northern European shipping sector, for instance, holds significant potential for carbon mitigation. The publication in Chapter 7 *Modelling CO_2 Emissions and Mitigation Potential of Northern European Shipping* (Dettner and Hilpert 2023b) used advanced open maritime emissions modelling to quantify CO_2 and air pollutant emissions in the North Sea and Baltic Sea. This study provides a comprehensive analysis of the entire CO_2 pathway in Northern European shipping as well as an analysis of other air pollutants, such as Black Carbon, Ash, NO_x and particulate matter. The emission quantities were calculated by analysing ship movement data, calculating the energy consumption for each ship type, and assessing the air pollutant and CO_2 mitigation potential within a scenario analysis. Focusing on the highly trafficked North and Baltic Seas, the study places CO_2 emissions (34,932 tons in 2015) within the context of a European CO_2 emission budget aimed at meeting the 1.5°C climate target. The publicly available dataset (Hilpert 2022b) used in the scenario analysis allows for customisation of the analysis, even by non-experts as it is available in a csv format. The dataset was applied to evaluate the carbon reduction potential of E-methanol, considering full life-cycle emissions. Renewably produced methanol, derived from CO_2 hydrogenation using wind energy (Joules 2014), shows promise as a marine fuel due to its mature technology (IMO 2020b), lower emissions (up to 99% for SO_x and 95% for PM) (Klepsch 2020), and environmental benefits. Though currently less economically competitive, costs are expected to decrease significantly by 2050, making it a viable alternative to fossil fuels (Register 2019). Methanol is compatible with existing engine technology (Verhelst et al. 2019), safe for storage, and environmentally less harmful in case of spills. Challenges include its corrosiveness, lower energy density that requires larger storage, and the need for sustainable production (Klepsch 2020) as well as the potentially extensive DAC costs as introduced within Section 2.4.1.

Life-cycle emission analysis is key in the estimation of an emission mitigation potential, as indicated in Figure 9.3. The publication in Chapter 7 compared future maritime scenarios in 2040 (FS-2040_high) with all ships fuelled with E-methanol to a 2015 scenario (SQ-2015) with ships powered by low-sulphur marine gas oil (LSMGO). The lower calorific value of methanol leads to a fuel demand that is almost twice as high in FS-2040_high. Despite methanol's lower carbon content compared to LSMGO, CO_2 emissions remain similar due to the increased fuel consumption in FS-2040_high (tank-to-propeller). Energy demand in the future scenarios, especially for production (well-to-tank), increases significantly due to the need for renewable energy infrastructure. The full life-cycle assessment indicates that E-methanol could reduce CO_2 emissions by approximately 45 % by 2030 and up to 90 % by 2040 (see Figure 9.4). The greatest reduction potential is found in MPV (Multi-Purpose Vessel), RoPax (roll-on/roll-off passenger) and RoRo (Roll-on/roll-off) ships, with reductions of 57 %, 50 %, and 49 % respectively, mainly due to the age of the existing fleet.



	Bulker	Car Carrier	Container	Cruise	Diverse	MPV	Ro-Pax	Ro-Ro	Tanker	All
ASH	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%
BC	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%
CO	112.3%	101.5%	96.2%	101.8%	103.5%	106.8%	79.9%	96.3%	110.8%	100.7%
CO2	-4.4%	-10.1%	-12.5%	-11.0%	-9.8%	-7.5%	-20.5%	-12.2%	-5.2%	-10.3%
Energy	2.9%	-3.2%	-5.8%	-4.2%	-2.9%	-0.5%	-14.4%	-5.5%	2.0%	-3.4%
Fuel Consumption	112.7%	100.0%	94.5%	97.9%	100.7%	105.6%	76.8%	95.2%	110.7%	99.6%
NMVOC	112.5%	100.9%	95.5%	101.1%	102.9%	106.3%	79.1%	96.0%	110.8%	100.6%
NOx	-74.5%	-76.5%	-76.5%	-71.6%	-71.9%	-75.9%	-76.4%	-76.5%	-75.9%	-75.4%
PM	-95.0%	-95.0%	-95.0%	-95.0%	-95.0%	-95.0%	-95.0%	-95.0%	-95.0%	-95.0%
POA	2.9%	-3.2%	-5.8%	-4.2%	-2.9%	-0.5%	-14.4%	-5.5%	2.0%	-3.4%
SOx	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%	-100.0%

Figure 9.3: Heatmap for E-methanol application for the shipping sector on the North and Baltic Seas. This figure shows the percentage deviation in emissions, energy, and fuel consumption between the future scenario (FS-2040_high) and the status quo (SQ-2015) scenario for tank-to-propeller operation, as discussed in Chapter 7 (Dettner and Hilpert 2023b)

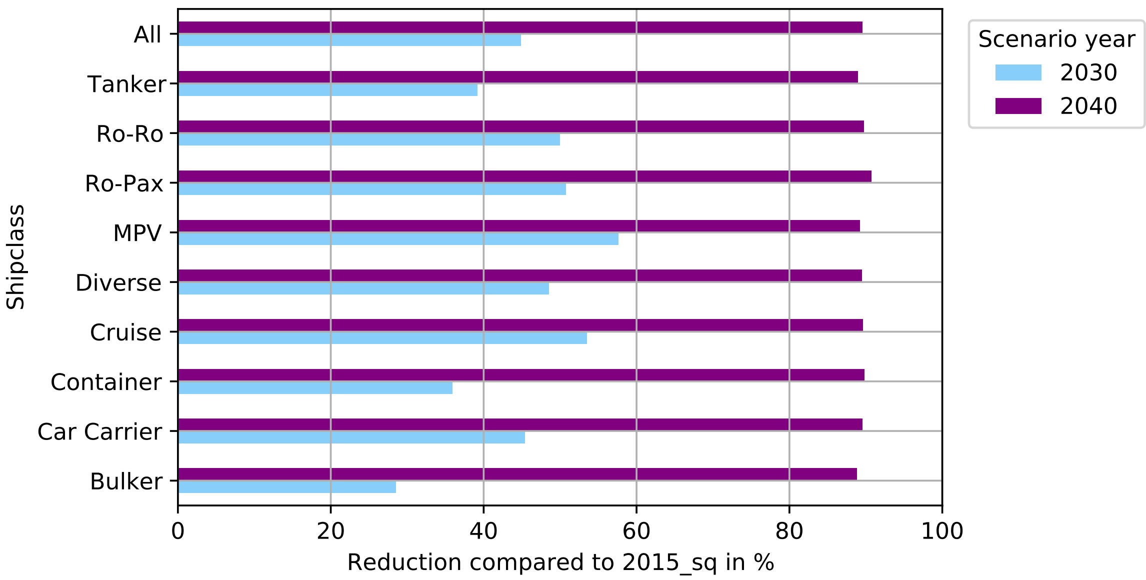


Figure 9.4: CO_2 mitigation potential for the application of E-methanol for the shipping sector on the North and Baltic Seas. This figure presents the percentage change in CO_2 emissions for the FS-2030 and FS-2040 scenarios relative to the SQ-2015 baseline, considering well-to-wake emissions, from Chapter 7 (Dettner and Hilpert 2023b).

The long lifespan of ships and shipping infrastructure slows the transition to low-carbon alternatives. Chapter 7 highlights the crucial role of the onshore energy transition in reducing shipping emissions, as low-carbon propulsion technologies and fuels require substantial renewable energy. In the SQ-2015 scenario, the energy required (well-to-tank) is approximately 52,000 GWh, whereas in the FS-2040 scenario for a fleet completely powered by E-methanol, it has increased almost nine-fold to 469,000 GWh. Achieving a carbon-neutral maritime sector will require careful consideration of the techno-economic pillar of sustainability, inter alia shipping speed, technological innovation, and costs, while avoiding carbon lock-in and committed emissions from long-lasting assets and investment decisions.

Social Pillar

The incorporation of the social pillar of sustainability in energy system analysis ensures equitable benefits from energy transitions, by addressing issues such as access, affordability, job creation, and public acceptance. Neglecting these aspects risks social inequality and hinders the success of sustainable energy initiatives as inter alia a lack of acceptance can prevent transition processes (Seidl et al. 2019; Spandagos et al. 2022). While many techno-economic and environmental criteria in energy system analysis can be measured with established metrics such as LCOE (EUR/kWh), investment costs (EUR), installed capacity (MW) and water consumption (m^3), social sustainability frequently lacks quantifiable indicators. According to Afshari et al. (2022), this is a key reason why it is often omitted from energy system analysis. Within this thesis, Chapter 3 and Chapter 8 specifically focus on the social pillar of sustainability within energy system transition processes. In addition, open science approaches are vital for ensuring social sustainability and are used in all publications. The aspects of open science is analysed further in the section Open Science & Modelling.

The publication in Chapter 3 *Water–Energy Nexus: Addressing Stakeholder Preferences in Jordan* (Komendantova et al. 2020) addresses the challenges of the closely interconnected sectors of water and energy through a co-creative approach to address differing viewpoints. Using a computer-supported co-creative method, the study evaluated stakeholder opinions of socio-ecological and techno-economic criteria and analysed future scenarios for the water and energy sector in Jordan. The study demonstrates that a participatory, multi-criteria framework can foster mutual understanding and support joint policy development, aiding national and international negotiations to resolve complex issues in both sectors. The applied multi-criteria decision analysis (MCDA) approach allows techno-economic and socio-ecological concerns to be valued and ranked within complex energy system settings. According to Khan (2021), MCDA is the most commonly used and approved method for evaluating sustainability within energy systems. Discussing conflicting opinions within the MCDA method can enhance acceptance of the selected future energy scenario by fostering a more balanced and conflict-resilient outcome. Komendantova et al. (2020) addressed the social dimension of sustainability by analysing participatory governance through the use of MCDA. The results show that economic and security factors dominated all ranking rounds, with *average annual system costs per kWh* ranked as the highest (most important) criteria. *Resource availability* and *energy/water security* followed, while *environmental impacts* were ranked the lowest (least important) by all participating groups[1]. The local environmental impacts, however, were ranked higher than *global impacts*. The most preferred energy scenario was SO_IGS (Smart Operation - Interconnected Gulf System), while the least preferred was SO_NI (Smart Operation - No Imports), despite its focus on domestic renewable energy. Overall, the interconnected Gulf system (IGS) was preferred across all groups, highlighting a priority for economic and security considerations over environmental ones.

The publication in Chapter 8 *Green hydrogen production: Integrating environmental and social criteria to ensure sustainability* (Blohm and Dettner 2023) also deals with the social pillar of sustainability of energy systems, particularly in regards to the energy supply chain. Hydrogen is gaining significant global attention as a potential energy carrier crucial for achieving carbon-neutral transitions in hard-to-abate sectors. The publication in Chapter 8 determined measurable sustainability criteria for the analysis of green hydrogen production proposals, based on expert interviews and a literature review. Six key impact categories were identified: energy transition, environment, basic needs, socio-economy, electricity supply and project planning, with 16 associated sustainability criteria. With regard to the social pillar of sustainability, the category *basic needs* addresses the following sustainability criteria: energy poverty, water supply, health and human rights. The category *socio-economy* connects the social pillar of sustainability with the economic pillar and addresses the three economic criteria of financial participation, employment and added value, as well as technology and knowledge transfer. Another perspective on social sustainability is addressed within the *project planning* category, which deals with participatory processes along the entire value chain of energy projects and planning proposals. The study highlights that economic costs should not be the only focus of energy system analysis; it advocates for the integration of social aspects throughout the value chain of energy system projects. This approach can be transferred to any energy system project, such as power plant and grid deployments, to promote social welfare and avoid social and environmental injustice.

[1]Stakeholders interacted at a workshop in Amman, Jordan, in October 2019, involving key parties from the Jordanian water and energy sectors, including the Water Authority of Jordan, National Electric Power Company, Energy & Minerals Regulatory Commission, Aqaba Water Company, Ministry of Energy and Mineral Resources, Ministry of Water and Irrigation, and Yarmouk Water Company.

Environmental Pillar

The techno-economic and socio-economic analysis of energy systems within the publications in Part II all address the fundamental environmental pillar of sustainability, namely climate change mitigation. This includes the focus on achieving a high share or even 100 % renewable energy for electricity generation (Chapter 4), for coupled sectors (Chapter 5) and specific sectors (Chapter 7).

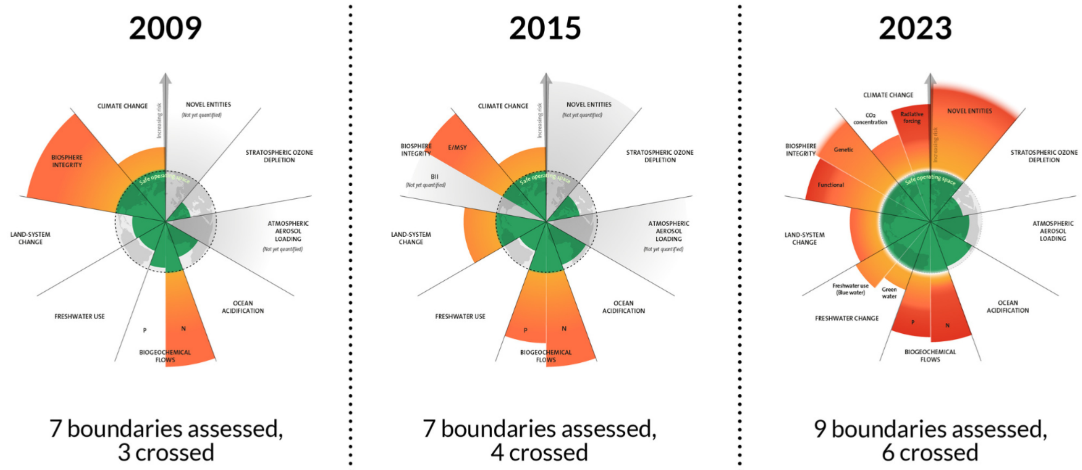


Figure 9.5: The evolution of the planetary boundaries framework. This figure illustrates the status of the seven planetary boundaries in 2009, 2015, and 2023, showing how more and more boundaries have been surpassed over time (Rockström et al. 2009; Steffen et al. 2015).

The environmental pillar of sustainability is intrinsically linked to the *planetary boundaries* framework, which defines the safe operating limits within which humanity can thrive without causing irreversible environmental damage (Rockström et al. 2009). The framework defines nine critical Earth system processes that have boundaries, which, if crossed, could lead to environmental instability and irreversible damage. Staying within these boundaries ensures that natural resources and ecosystems can regenerate, which is key to environmental sustainability. Climate change and its mitigation is one of the nine boundaries, as depicted in Figure 9.5. To fully address humanity's environmental impact, all nine critical environmental boundaries that define the Earth's stability and resilience must be analysed. As of 2023, the Earth was beyond six of the nine planetary boundaries (Richardson et al. 2023).

The publication within Chapter 3 of this thesis, establishes sustainability criteria addressing environmental concerns, particularly focusing on local and global impacts. The criterion of environmental impact, in particular, was found to target climate change and CO_2 emissions. Resources such as land, air, water and soil, which are affected by the extraction, generation, transmission and distribution of energy and water services, were analysed on both local and global scales. Similar criteria were further explored in the publication in Chapter 8, where land use, water use, and emissions were identified as critical factors for assessing energy projects. Both publications directly relate to the planetary boundaries of land system change, freshwater change, and biogeochemical cycles, while indirectly addressing atmospheric aerosol loading, ocean acidification, and biosphere integrity.

The publication in Chapter 7 quantified and analysed CO_2 and air pollutant emissions, which are known to negatively impact the (maritime) environment. Using E-methanol instead of low-sulphur marine fuel oil (LSMFO) in the Northern European shipping sector eliminates emissions of ash, black carbon and SO_2 entirely, and reduces NO_x emissions by 75 %. However, emissions of CO, NMVOC and primary organic aerosols (POA) vary depending on the emission factors applied in the calculations, with NMVOC and CO emissions increasing proportionally with fuel consumption, while POA decreases relative to energy use. Emission of $PM_{2.5}$, which are a leading health and environmental concern are reduced by 95 % with the use of E-methanol.

The publication in Chapter 4 focused on storage modelling and the optimisation of investments for renewable energy expansion, and emphasises the cost-effective potential for CO_2 emission reduction in Jordan. The findings demonstrate that achieving high energy import independence through a mix of PV, wind, batteries and natural gas imports is both economically and environmentally superior to reliance on domestic shale oil, which poses significant environmental and ecological challenges (Brittingham et al. 2014). The chosen approach therefore effectively integrates the pillars of economic and environmental sustainability.

Open Science & Modelling

Open science is the key to meeting all seventeen of the UN's SDGs (Camkin et al. 2022). Open science will make science more effective, robust and responsive to societal demands and challenges (Burgelman et al. 2019).

The publication in Chapter 4 used a bottom-up optimisation approach applying oemof-tabular (Hilpert et al. 2020b) to assess renewable energy expansion in Jordan under economic and environmental criteria. The publication in Chapter 5 applied a similar bottom-up optimisation approach using the model generator oemof-solph (Krien et al. 2020) and the oemof-tabular interface. In the context of Jordan's and Barbados' political and economic volatility, open modelling approaches offer greater adaptability and reusability than proprietary model-based approaches, which can quickly become outdated. Furthermore, most closed-source models work with data packages, which are uncommon for many modellers and challenging for non-experts. For these reasons, an adaptable spreadsheet interface was developed and used for the publication in Chapter

3 and 4. Open models, which can be easily adapted are crucial for countries that would otherwise rely on external expertise and closed or poorly documented models.

The publication in Chapter 6 *Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea* (Dettner and Hilpert 2023a) provides another example of open science and open modelling. A high-resolution emission inventory for the North Sea and Baltic Sea was developed using current emission factors and ship activity data. The bottom-up approach provides detailed emission data for pollutants such as CO_2, NO_x, SO_2, $PM_{2.5}$, alongside speed-dependent fuel and energy consumption. Data includes emissions from both main and auxiliary engines, with a five-minute temporal resolution. The open-access dataset can be used to evaluate the health impacts of maritime emissions, the social costs of shipping, the effects of alternative fuel scenarios, and shore-to-ship power solutions. Similar to oemof tabular, the emissions inventory developed in the publication in Chapter 6 is also provided in a spreadsheet format, enabling non-modelling experts to perform independent analyses, such as applying updated emission factors. Additionally, all intermediate outputs, including energy production, emission grid data or code to generate shipping routes, have been made publicly accessible. A life-cycle performance analysis offers comprehensive results on life cycle emissions for nine leading pollutants, covering both well-to-tank and tank-to-propeller emissions and energy consumption, thereby facilitating a thorough comparison of various fuel types.

Additionally, all publications presented in this thesis were published open source to promote transparency and reproducibility, except for the one in Chapter 5, which was deliberately published in a closed-source journal. Care must be taken when publishing a paper to ensure that the selected journal is read in the region studied in the paper. In the case of Barbados, the journal *Energy for Sustainable Development* is a recognised journal in the region and thus offered the opportunity to disseminate the research results appropriately.

Climate Change Policy

As highlighted in Part I, a sustainable energy transition needs all three pillars of sustainability working under the principles of open science. Additionally, achieving this transition at scale requires a carefully designed policy framework covering policies, schemes, regulations and legislation that foster innovation, encourage investment and align market incentives with sustainable objectives.

As introduced in Sections 2.3.4 and 2.4.3, the EU-ETS plays a pivotal role in the regulation of GHG emissions and in guiding economies towards decarbonisation. The publication in Chapter 7 calculated a carbon budget within the EU-ETS framework for shipping, using the method of Traut et al. (2015). A carbon budget of 0.75 Gg was calculated for the Northern European shipping sector for 2011–2050, aligned with the Paris Agreement's 1.5°C target. Furthermore, the publication in Chapter 7 demonstrated that without mitigation measures this budget will be depleted by 2030. The analysis suggests that effective implementation within the EU-ETS requires a market-based approach to drive carbon-neutral innovations, with distinct policies for the shipping sector. Unlike stationary sources, shipping receives no free allowances and depends heavily on land-based infrastructure. If refuelling facilities for low-carbon fuels are unavailable, emissions reductions cannot be achieved. By 2023, the EU ETS had contributed to a reduction of approximately 47 % in emissions from European power and industrial plants compared to 2005 levels (EC 2023).

Given the very recent nature of the IMO's GHG pricing mechanism proposal (*Draft revised MARPOL Annex VI* 2025), no thorough analysis has yet been conducted. However, for completeness and exploration, it can be acknowledged that the implementation of the new IMO legislation within the existing EU ETS framework may present several challenges. The alignment of the IMO's global emissions targets with the EU's more ambitious climate goals could be problematic, as the IMO's regulations might not fully meet the EU's stringent standards. Additionally, the integration of the IMO's pricing mechanism with the EU ETS could lead to market volatility or regulatory complexities, especially considering the sector's operational characteristics. The adoption process remains uncertain, with ratification by a two-thirds majority of Marpol Annex VI parties required in October 2025, which could introduce delays or necessitate adjustments. Furthermore, the review clauses in both the IMO and EU regulations suggest that further modifications may be needed, potentially complicating the timeline for achieving meaningful emissions reductions in the maritime sector.

9.2 Key Findings of the Dissertation

Altogether, the publications in Part II demonstrate that integrating technological advancements, transparent data, collaborative analysis and policymaking can foster the development of effective, equitable and sustainable energy system transitions. Given the significant costs and the pivotal role of energy systems in the global economy, accurate modelling is crucial to prevent stranded investments, mitigate carbon lock-in effects and ensure a reliable energy supply, all while promoting intergenerational justice. This section summarises the key findings from the publications included in Part II of this thesis, highlighting their collective contributions and overarching implications.

- **Renewable Energy and Decarbonisation Potential** The thesis demonstrates that renewable energy, particularly wind and solar in combination with storage options, can feasibly replace fossil fuels in electricity generation. If PV costs decrease in the future, a fully renewable energy system could become more cost-effective than current options. The emergence of PHS as a reliable solution reinforces the feasibility of a 100 % renewable energy system (for Barbados). In the context of maritime emissions, substituting conventional fuels with renewable alternatives such as E-methanol could reduce emissions by up to 90 % by 2040. However, the scalability of these solutions depends on substantial investments in infrastructure and renewable capacity.

- **Diversifying energy generation offers both environmental and economic benefits** Shifting towards a diverse range of energy sources could bring environmental and economic advantages, particularly in contrast to continued reliance on fossil fuels. Renewable energy not only supports climate change mitigation but also enhances energy independence and fosters economic diversification. By reducing reliance on energy imports, renewables can shield countries from dependency on politically unstable regions. Additionally, transitioning to renewable and carbon-neutral fuels helps reduce air pollutants, thereby decreasing the external health costs associated with pollution.

- **Economic and Policy Implications** The publications in Part II underscore the importance of establishing appropriate carbon pricing mechanisms and regulatory frameworks. For instance, the integration of maritime emissions into the EU Emissions Trading System (EU ETS) incentivises the adoption of low-carbon fuels by internalising the external costs of CO_2 emissions. An ambitious carbon price in the EU ETS is needed to reflect the true damage costs and create strong economic incentives for emission reduction.

- **Economic and security considerations often dominate decision-making** In many cases, decision-making across stakeholder groups is primarily influenced by economic and security factors, often overshadowing environmental considerations. This may be particularly the case in politically unstable regions, where domestically available fossil fuels, like oil shale in Jordan, are preferred due to their perceived supply security. This reliance on fossil resources can lead to significant economic, environmental and social costs. The tension between prioritising cost-efficiency, supply reliability and environmental sustainability underscores the complexity of balancing priorities in energy transition planning. To address this, policymakers must integrate environmental and social sustainability into economic and security frameworks and engage transparently with stakeholders to align interests and foster consensus.

- **Importance of Scenario Modelling** Scenario modelling highlights the advantages of transparent, open-source approaches, as these allow real-time adjustments based on emerging data and stakeholder input. Co-creative scenario modelling can foster greater public engagement and ensure that modelled outcomes align more closely with community and industry needs. A co-creative approach supports the goal of a just and inclusive energy transition, as it provides multiple stakeholders a platform to shape scenarios and understand the trade-offs involved.

- **Greenfield planning can avoid carbon lock-in effects** By adopting greenfield planning approaches in modelling, it may be possible to avoid carbon lock-in effects through the creation of energy systems that prioritise renewable integration, efficiency, and minimal carbon intensity. Advanced energy system modelling supports this process by simulating scenarios to identify the most sustainable and resilient configurations for new developments.

- **Open Science and Data Transparency** The thesis advocates for open data practices to increase scientific rigor, transparency, and public trust. Open-source models such as oemof provide a flexible foundation for continuous improvement and democratise access to essential tools for energy planning, particularly in regions with limited resources. Making both the models and data publicly accessible supports equitable participation in the development of climate solutions and ensures comprehensibility of results. Open source tools provide significant flexibility for future analyses, especially in dynamic political and economic contexts where input data and assumptions are subject to rapid change.

- **Technological solutions and mitigation measures alone may not be sufficient to meet the 1.5°C target** Demonstrated by the shipping sector, this thesis illustrates that, despite technological advancements, additional efforts may be necessary to fully meet the objectives of the Paris Agreement. Prompt action is crucial to ensure that these measures make a meaningful contribution to achieving climate goals.

- **The three pillars of sustainability** Truly sustainable energy systems require the integration of all three pillars of sustainability; environmental, economic and social. While techno-economic factors are central to most energy system modelling approaches, social criteria, if not integrated directly into the optimisation process, can still be considered in post-analysis to assess their impact. Interdisciplinary research approaches are also necessary to address the complex and interconnected issues of energy transitions, ensuring that all aspects of sustainability are thoroughly explored and integrated into the solutions.

Coming back to the Research Question

> *How can co-creative approaches, technological innovations and policy frameworks be integrated to develop cost-effective, sustainable and widely accepted solutions for a 100 % renewable energy system, while ensuring sectoral compliance with global climate targets?*

Part I outlined the need for a sustainable energy transition in the context of climate change. Achieving a 100 % renewable energy system that is both cost-effective and socially acceptable - a sustainable energy system - requires a comprehensive, multi-faceted approach. Co-creative scenario modelling has proven to increase stakeholder engagement and acceptance by incorporating diverse perspectives into decision-making processes, as demonstrated within Chapter 3. The cost-optimal mix of energy sources, as seen in Chapters 4 and 5, relies on a tailored balance of technologies such as solar and wind, or wind and bagasse (as biomass), including PHS and battery storage to meet future (increased) electricity demands. Open-source emission inventories, as applied in the shipping sector (see Chapter 6), provide critical data transparency to ensure compliance with climate targets such as the Paris Agreement's 1.5°C goal (see Chapter 7). Furthermore, the sustainable production of future energy carriers, such as green hydrogen must also account for environmental, social and economic factors along the entire value chain, highlighting the need for integrated policy frameworks that prioritise long-term sustainability while promoting innovation, as discussed in Chapter 8.

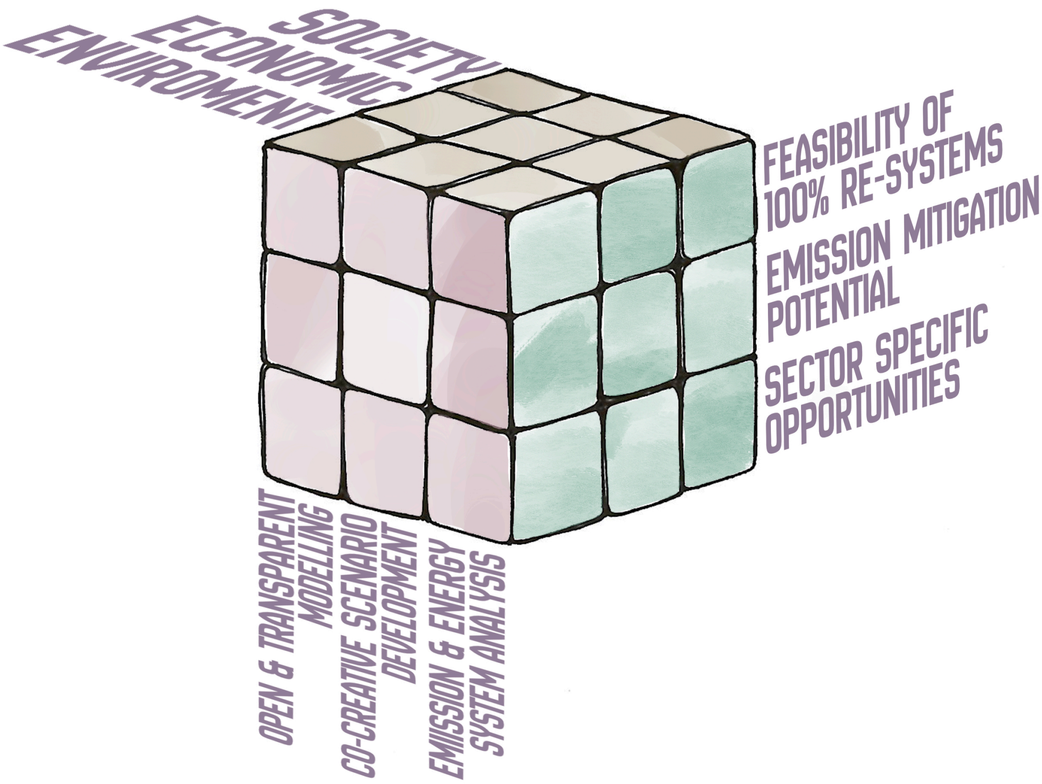


Figure 9.6: Solving the energy puzzle – Aligning sustainability, method and insight for a just energy transition. This conceptual figure illustrates the core structure of the dissertation, framing the energy system as a multidimensional challenge. The three axes represent: (1) the three pillars essential for a comprehensive sustainability assessment, (2) the necessary applied methodological approaches and (3) the key transformative insights derived from the research, highlight the feasibility of 100 % renewable energy systems, the recognition of multiple benefits (inter alia the reduction of carbon as well as air pollutant emissions) and the importance of sector specific opportunities.

9.3 Limitations & Further Research

The results of the publications in Part II must be considered against the background of the research methods used for them. Due to the diversity of research foci in this thesis, the following section summarises overarching limitations for the publications in Part II. For a detailed explanation of the specific limitations of the individual publications, please refer to the respective chapters in Part II.

Generally, efficiency and sufficiency measures were not adequately considered in the publications in Part II. It is crucial to prioritise efficiency measures, particularly demand-side management, as the foundational step before any transition or implementation of new systems. Additionally, sufficiency - adjusting the level of consumption to meet actual needs rather than exceeding them - should be integrated. By addressing both efficiency and sufficiency, energy consumption is minimised from the outset, fostering a more sustainable and cost-effective shift to alternative technologies or solutions. Without first addressing these two aspects, the potential benefits of subsequent transitions may be undermined, leading to higher resource consumption and greater environmental impact in the long term. Furthermore, all models in the publications in Part II, especially those with a techno-economic focus, lack the consideration of external costs of energy. These are vital for analysing the true costs of energy systems. Finally, all of the publications in Part II indicate that there are still challenges in resource-limited, long-term operational planning of a 100 % renewable system.

Energy System Modelling

Energy systems are complex, involving numerous actors and interactions that lead to emergent properties, adaptation, and learning processes. Emerging topics in energy research, such as transport, energy behaviour and energy justice, highlight this complexity (Bale et al. 2015). Models, which are simplified representations of real-world systems, are essential for testing mental models and developing intuition for complex systems (Sterman 2002). However, models have inherent limitations, as they are always idealised and imperfect. The aphorism *"All models are wrong, but some are useful"* attributed to Box (1976) emphasises that while models can never fully represent reality, they can still offer valuable insights. Within this context, the energy system models used in Chapters 4 and 5 apply a perfect foresight approach, optimising over the year, which particularly matters within the context of the specific Barbadian weather pattern, where a drop in wind is combined with restricted biomass in the autumn. The result of this is that more accurate planning may be required. Additionally, due to a lack of supporting studies, wind and solar capacities were capped within real-live conditions within Chapter 5. The publication in Chapter 4, analysing Jordan, used the perfect foresight approach and omits the existing power producers' contracts, which can limit RE expansion. It should be noted, however, that although increased model complexity may often improve accuracy, it may not always lead to better results, and a balance with computational resources is necessary (Priesmann et al. 2019).

For the case study in Barbados (see Chapter 5), further analysis of the potential of utility-scale photovoltaic is needed, as it is the most cost-effective option; however, the current cap is set at 80 MW. While the costs of grid expansion and backup capacities must be considered, integration costs are highly context-dependent, with literature suggesting these costs can range from 35 to 50 % (Hirth et al. 2015). Additionally, the cost of renewable energy is expected to decline significantly, potentially allowing for a renewable energy share of over 90 % in systems with LCOEs below 0.20 BBD/kWh. Flexibility will remain essential, especially as demand increases, with resources such as biomass, bagasse and waste identified as being key for balancing energy supply. In general, further research is needed to determine the viable share of flexible generation and to address operational challenges in high-renewable energy systems. Similarly, in Chapter 4, the accuracy of modelling results could be improved by having more accurate RE profiles. Within both applications of oemof, Jordan and Barbados, not all costs are fully captured, as grid constraints and spinning reserve requirements are omitted. In the case of the Jordan study (see Chapter 4), transmission lines with neighbouring countries were not analysed. The use of them would reduce system costs significantly, due to reduced excess and reduced storage requirements (Aghahosseini et al. 2020). The storage requirements can actually counteract these effects; curtailment and storage dispatch can be higher to keep the system within the country balanced in terms of distribution and transmission grid levels.

Maritime Energy Transition

According to Chen and Yang (2024), the AIS-based bottom-up approach, as used in Chapters 6 and 7 is widely used for estimating ship emissions but carries uncertainties due to the complexity of factors involved. Three key areas of uncertainty are: the acquisition and processing of AIS data, the accuracy of ship characteristic information, and engine load calculations. Unlike other models, engine load is not directly considered in Chapters 6' fuel and energy calculations. While speed-power curves are applied to the main engine, the auxiliary engines are simplified, and the results could be refined with adjustments. Additionally, influences such as waves, currents and loading conditions are not directly considered, potentially affecting energy consumption estimates, even if the effects are probably negligible. Emission factors also pose another significant limitation and source of uncertainty in determining emissions. The emission factors in Chapter 6 were chosen based on an extensive literature review, but they introduce some level of uncertainty, especially when considering new or less mature fuels.

Climate change may introduce new variables into shipping emission models, as shifting ocean currents and rising sea levels could alter shipping routes and port infrastructure. Looking ahead, the global maritime fleet is expected to expand, with seaborne trade predicted to rise by 35 % by 2030 and 12 % by 2040 (DNV-GL 2017). Container and gas cargoes are expected to grow most rapidly, while bulk carrier emissions are likely to increase as coal shipments decline but non-coal bulk trade rises (UNCTAD 2019). Future emissions may grow disproportionately as container ship capacity expands, underscoring the importance of adapting emission models to account for evolving fleet compositions and their environmental impacts.

Infrastructure plays a pivotal role in facilitating the transition to the use of alternative fuels (not only) in the shipping sector. A key component of this transition is the linking of shipping research with the bunkering, storage and production of alternative fuels such as E-methanol, which is essential for future feasibility analyses. In addition to infrastructure, demand-side management is crucial for emission mitigation within the shipping sector. Senol and Seyhan (2024) identified a significant correlation between emissions and pilot demographics and experience, suggesting that targeted improvements in operational practices could reduce emissions. Furthermore, many maritime engineers argue that enhancing ship design could improve operational efficiency, contributing to even greater emission reductions. Together, these approaches highlight the multifaceted strategies required to reduce emissions and facilitate a more sustainable shipping industry.

In maritime shipping, long-lived assets increase the potential for significant sequestered emissions. To address this, a carbon price reflecting true environmental damage is necessary to encourage mitigation. While current carbon prices under the *high* price assumption (UBA 2020) exceed damage costs for the present generation, they cover only 40 % of the costs for future generations. Since climate change impacts will mainly affect future generations, their well-being must be factored into pricing. The carbon price proposed by Pietzcker et al. (2021) of 120-300 EUR_{2020}/t_{CO2} and the damage costs outlined by UBA (2020) of 250-765 EUR_{2020}/t_{CO2} are steps in the right direction. Based on the publication in Chapter 7, a minimum carbon price of 300 EUR/t_{CO2} is recommended, though a price closer to 765 EUR/t_{CO2} is advisable to fully reflect externalities.

Social Sustainability and Transition Challenges

The integration of social sustainability into techno-economic analyses remains largely absent in the literature. While renewable energy systems contribute to social sustainability in some aspects, further research is required to substantiate this hypothesis. The publications contained in Part II of this thesis, particularly in Chapters 3 and 8, address and highlight the gap in the quantification of social factors. Current literature lacks comprehensive, measurable criteria to properly address the social dimensions of renewable energy transitions. This limitation hinders a full understanding of the social implications involved. There is growing consensus that technological advancements alone will not achieve the targets set by the Paris Agreement, and that profound societal transformation is needed (IPCC 2018). In this context, sufficiency plays a crucial role in reducing energy demand and emissions, yet it is often overlooked in European national energy and climate plans. Achieving the necessary conditions for sustainable energy transitions goes beyond the capabilities of software; it involves broader, complex social processes within the scientific community.

9.4 Concluding Reflections

> *Energy transitions are dynamic processes driven by innovation, unfolding over time and influenced by historical developments.*
>
> – Caragliu and Graziano (2022, p.1)

This thesis commenced with a historical examination of climate change research and climate science. The problem of climate change and global warming has been recognised by humanity for more than 120 years. Numerous technological solutions have been explored through models, case studies and prototypes aimed at mitigating climate change. Emission limits for GHG and air pollutants have been implemented and new policies continue to be developed.

There is growing recognition of the extensive challenges posed by a warming planet. The consequences of climate change are undeniable and increasingly tangible. The environmental and ecological impacts have been clearly quantified. The publications presented in Part II of this thesis, alongside the referenced literature, demonstrate that solutions to mitigate climate change are not only feasible but within reach. The modelling results in all chapters reveal the significant economic, environmental and social justice potential of a sustainable energy system. However, despite these promising findings, CO_2 emissions continue to rise (even though per capita emissions have stagnated), and the short-term reduction targets set by countries for the 2020-2030 period are insufficient to meet the 1.5°C Paris Agreement target.

A dynamic of energy transition processes, not strictly connected to this thesis, but highly relevant with regard to current events, is the age of post-normal science and the role of the media. Funtowicz and Ravetz (1993) states that "science is shaped around its leading problems" (p. 754). With regard to energy system analysis and policy advice, climate change is clearly one of these leading problems making the study of future energy systems part of *post-normal* science. This can be understood as issue-driven science where "facts are uncertain, values in dispute, stakes high and decisions urgent" (p. 744). Linked to this is the changing or increasing role of the media in shaping public perception and the discourse on climate protection, which is becoming increasingly important in the global fight against climate change. As the primary means of communication with the public, media outlets have significant power to influence narratives, to frame the urgency of climate action and to shape policy debates. Understanding the media's impact on climate protection is vital, as it can either mobilise public support for environmental initiatives or contribute to misinformation and apathy. As Fraune and Knodt (2018) highlighted, the rise of right-wing populist parties, the emergence of post-truth politics and local resistance present major challenges to policies and politics aimed at sustainable energy transitions. Populism, particularly from right-wing factions, signals growing political polarisation regarding climate and energy policies, while local resistance underscores the inherently political nature of sustainable energy transformations. Further research is needed to investigate the causes, characteristics and effects of the rise of extreme positions. In the context of recent political developments, Donald Trump's election as the 47th President of the United States and his drastic alteration of the Environmental Protection Agency signifies a direct challenge to climate protection efforts. Similarly, following the collapse of the German "Ampel" government, the former financial minister's call to shut down the UBA (German Environment Agency) reflects a broader trend of resistance to institutional climate action. These events exemplify the political tensions that can shape and even hinder progress in sustainable energy transitions.

This raises critical questions that are central to the ongoing debate about the existential threat of climate change: Why are we so reluctant to implement the necessary changes? Why are we failing to transition from current unsustainable systems to ones that could benefit everyone? How do media narratives and the prevailing Zeitgeist influence our actions? Is it merely a question of money? And what role does science play in a world increasingly driven by populism and fleeting trends?

References

Afshari, H., S. Agnihotri, C. Searcy and M.Y. Jaber (2022). "Social sustainability indicators: A comprehensive review with application in the energy sector". In: *Sustainable Production and Consumption* 31. Publisher: Elsevier, pp. 263–286. ISSN: 2352-5509. DOI: 10.1016/j.spc.2022.02.018.

Aghahosseini, Arman, Dmitrii Bogdanov and Christian Breyer (2020). "Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030". In: *Energy Strategy Reviews* 28, p. 100466. ISSN: 2211467X. DOI: 10.1016/j.esr.2020.100466.

Åhman, Henrik (2013). "Social sustainability – society at the intersection of development and maintenance". In: *Local Environment* 18.10, pp. 1153–1166. ISSN: 1354-9839, 1469-6711. DOI: 10.1080/13549839.2013.788480.

Aigner-Walder, Birgit and Thomas Döring (2022). "The Limits to Growth – 50 Years Ago and Today". In: 2022.3, pp. 187–191.

Ansell, Thomas and Steve Cayzer (2018). "Limits to growth redux: A system dynamics model for assessing energy and climate change constraints to global growth". en. In: *Energy Policy* 120, pp. 514–525. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2018.05.053.

Arndt, H. W. (1981). "Economic Development: A Semantic History". In: *Economic Development and Cultural Change*. Publisher: University of Chicago Press. ISSN: 0013-0079. DOI: 10.1086/451266.

Arrhenius, Svante (1896). "On the Influence of Carbonic Acid in the Air upon Temperature of the Ground". In: *Philosophical Magazine and Journal of Science* 5.41, pp. 237–276.

Aulinger, A, V Matthias, M Zeretzke, J Bieser, M Quante and A Backes (2016). "The impact of shipping emissions on air pollution in the greater North Sea region – Part 1: Current emissions and concentrations". en. In: *Atmos. Chem. Phys.*, p. 20.

Bale, Catherine S. E., Liz Varga and Timothy J. Foxon (2015). "Energy and complexity: New ways forward". In: *Applied Energy* 138, pp. 150–159. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2014.10.057.

Barbier, Edward B. (1987). "The Concept of Sustainable Economic Development". In: *Environmental Conservation* 14.2. Publisher: Cambridge University Press, pp. 101–110. ISSN: 1469-4387, 0376-8929. DOI: 10.1017/S0376892900011449.

Behrendt, Siegfried, Edgar Göll and Friederike Korte (2018). *Effizienz, Konsistenz, Suffizienz - Strategieanalytische Betrachtung für eine Green Economy.* IZT-Text 1-2018. Berlin: Institut für Zukunftsstudien und Technologiebewertung.

Bertalanffy, Ludwig von (1969). *General System Theory: Foundations, Development, Applications.* New York: G. Braziller, p. 289.

Blohm, Marina and Franziska Dettner (2023). "Green hydrogen production: Integrating environmental and social criteria to ensure sustainability". In: *Smart Energy* 11. Publisher: Elsevier, p. 100112. ISSN: 2666-9552. DOI: 10.1016/j.segy.2023.100112.

BMWK (2019). *Verordnung über Netzentgelte bei der Landstromversorgung und zur redaktionellen Anpassung von Vorschriften im Regulierungsrecht*. Verordnung 52. Bonn: Bundesministerium für Wirtschaft und Energie.

Boehm, Sophie and Clea Schumer (2023). *10 Big Findings from the 2023 IPCC Report on Climate Change*. World Resources Institute.

Borkowski, T. and D. Tarnapowicz (2012). "„Shore to ship" system - an alternative electric power supply in port". In: *Journal of KONES* Vol. 19, No. 3, pp. 49–58. ISSN: 1231-4005.

Boström, Magnus (2012). "A missing pillar? Challenges in theorizing and practicing social sustainability: introduction to the special issue". In: *Sustainability: Science, Practice and Policy* 8.1, pp. 3–14. ISSN: 1548-7733. DOI: 10.1080/15487733.2012.11908080.

Box, George E. P. (1976). "Science and Statistics". In: *Journal of the American Statistical Association* 71.356, pp. 791–799. ISSN: 0162-1459, 1537-274X. DOI: 10.1080/01621459.1976.10480949.

Boyer, Robert, Nicole Peterson, Poonam Arora and Kevin Caldwell (2016). "Five Approaches to Social Sustainability and an Integrated Way Forward". In: *Sustainability* 8.9, p. 878. ISSN: 2071-1050. DOI: 10.3390/su8090878.

Brittingham, Margaret C., Kelly O. Maloney, Aïda M. Farag, David D. Harper and Zachary H. Bowen (2014). "Ecological Risks of Shale Oil and Gas Development to Wildlife, Aquatic Resources and their Habitats". In: *Environmental Science & Technology* 48.19, pp. 11034–11047. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/es5020482.

Brown, Marilyn A. and Benjamin K. Sovacool (2007). "Developing an 'energy sustainability index' to evaluate energy policy". In: *Interdisciplinary Science Reviews*. Publisher: Taylor & Francis. DOI: 10.1179/030801807X211793.

Brown, Tom (2022). "Open Energy Modelling: Discussion & Examples from PyPSA Modelling for Europe". Workshop. Workshop. South Africa Open Energy Modelling Workshop. Berlin.

Bruckner, Thomas, I. A. Bashmakov, H. Chum, A. Navarro, J. Edmonds, A. Faaij, B. Fungtammasan, A. Garg, E. Hertwich, D. Honnery, D. Infield, M. Kainuma, S. Khennas, S. Kim, H. B. Nimir, K. Riahi, N. Strachan, R. Wiser and X. Zhang (2014). "Energy Systems". In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Brundtland, Gro Harlem (1987). *Our Common Future: Report of the World Commission on Environment and Development*. UN-Dokument A/42/427. Geneva: United Nations.

Bundestag (1998). *Konzept Nachhaltigkeit - Vom Leitbild zur Umsetzung*. Drucksache 13/11200. Berlin: Enquete-Kommission "Schutz des Menschen und der Umwelt-Ziele und Rahmenbedingungen einer nachhaltig zukunftsverträglichen Entwicklung", pp. 1–252.

Burgelman, Jean-Claude, Corina Pascu, Katarzyna Szkuta, Rene Von Schomberg, Athanasios Karalopoulos, Konstantinos Repanas and Michel Schouppe (2019). "Open Science, Open Data, and Open Scholarship: European Policies to Make Science Fit for the Twenty-First Century". In: *Frontiers in Big Data* 2. Publisher: Frontiers, p. 469872. ISSN: 2624-909X. DOI: 10.3389/fdata.2019.00043.

Callendar, George S. (1949). "Can Carbon Dioxide Influence Climate?" In: *Weather* 4.10, 310ff. DOI: https://doi.org/10.1002/j.1477-8696.1949.tb00952.x.

Camkin, Jeff, Susana Neto, Basundhara Bhattarai, Hemant Ojha, Shahbaz Khan, Ai Sugiura, Jiaying Lin, Fitrie Atviana Nurritasari and Joseph Muiruri Karanja (2022). "Open Science for Accelerating the Sustainable Development Goals: Status and Prospects in Asia and the Pacific". In: *Frontiers in Political Science* 4. Publisher: Frontiers, p. 878761. ISSN: 2673-3145. DOI: 10.3389/fpos.2022.878761.

Cao, Karl-Kiên, Felix Cebulla, Jonatan J. Gómez Vilchez, Babak Mousavi and Sigrid Prehofer (2016). "Raising awareness in model-based energy scenario studies—a transparency checklist". en. In: *Energy, Sustainability and Society* 6.1, p. 28. DOI: 10.1186/s13705-016-0090-z.

Caragliu, Andrea and Marcello Graziano (2022). "The spatial dimension of energy transition policies, practices and technologies". In: *Energy Policy* 168, p. 113154. ISSN: 03014215. DOI: 10.1016/j.enpol.2022.113154.

Carlowitz, Hans Carl von (1732). *Sylvicultura oeconomica*. Google-Books-ID: bHJDAAAAcAAJ. Braun. 326 pp.

Chen, Xiaoyan and Jiaxuan Yang (2024). "Analysis of the uncertainty of the AIS-based bottom-up approach for estimating ship emissions". In: *Marine Pollution Bulletin* 199. Publisher: Pergamon, p. 115968. ISSN: 0025-326X. DOI: 10.1016/j.marpolbul.2023.115968.

Chen, Zhong Shuo, Jasmine Siu Lee Lam and Zengqi Xiao (2023). "Prediction of harbour vessel fuel consumption based on machine learning approach". In: *Ocean Engineering* 278, p. 114483. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2023.114483.

Child, Michael and Christian Breyer (2017). "Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems". In: *Energy Policy* 107, pp. 11–26. ISSN: 03014215. DOI: 10.1016/j.enpol.2017.04.022.

Christodoulou, Anastasia and Kevin Cullinane (2022). "Potential alternative fuel pathways for compliance with the 'FuelEU Maritime Initiative'". In: *Transportation Research Part D: Transport and Environment* 112, p. 103492. ISSN: 13619209. DOI: 10.1016/j.trd.2022.103492.

Chu-Van, Thuy, Zoran Ristovski, Ali Mohammad Pourkhesalian, Thomas Rainey, Vikram Garaniya, Rouzbeh Abbassi, Sanaz Jahangiri, Hossein Enshaei, U-Shen Kam, Richard Kimball, Liping Yang, Ali Zare, Harry Bartlett and Richard J. Brown (2018). "On-board measurements of particle and gaseous emissions from a large cargo vessel at different operating conditions". In: *Environmental Pollution* 237, pp. 832–841. ISSN: 02697491. DOI: 10.1016/j.envpol.2017.11.008.

Connolly, D., H. Lund, B. V. Mathiesen and M. Leahy (2010). "A review of computer tools for analysing the integration of renewable energy into various energy systems". en. In: *Applied Energy* 87.4, pp. 1059–1082. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2009.09.026.

Corbett, James J, Paul S Fischbeck and Spyros N Pandis (1999). "Global nitrogen and sulfur inventories for oceangoing ships". en. In: *Journal of Geophysical Research* 104.D3, pp. 3457–3470.

Corbett, James J. and Paul Fischbeck (1997). "Emissions from Ships". In: *Science* 278, pp. 823–824. DOI: DOI:10.1126/science.278.5339.823.

Dagoumas, Athanasios S. and T. S. Barker (2010). "Pathways to a low-carbon economy for the UK with the macro-econometric E3MG model". en. In: *Energy Policy*. The Role of Trust in Managing Uncertainties in the Transition to a Sustainable Energy Economy, Special Section with Regular Papers 38.6, pp. 3067–3077. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2010.01.047.

Daly, Herman (1973). *Toward a Steady-state Economy*. San Francisco: W.H. Freeman.

Dettner, Franziska and Simon Hilpert (2023a). "Emission Inventory for Maritime Shipping Emissions in the North and Baltic Sea". In: *Data* 8.5. Number: 5 Publisher: Multidisciplinary Digital Publishing Institute, p. 85. ISSN: 2306-5729. DOI: 10.3390/data8050085.

— (2023b). "Modelling CO2 emissions and mitigation potential of Northern European shipping". In: *Transportation Research Part D: Transport and Environment* 119. Publisher: Pergamon, p. 103745. ISSN: 1361-9209. DOI: 10.1016/j.trd.2023.103745.

Dieckhoff, Christian (2015). *Modellierte Zukunft. Energieszenarien in der wissenschaftlichen Politikberatung*. Science Studies ISBN 978-3-8376-3097-8. Bielefeld: transcript Verlag.

Dieckhoff, Christian and Armin Grunwald (2016). *Consulting with energy scenarios : Requirements for scientific policy advice, Position Paper [of the Academies' Project "Energy Systems of the Future"]*. Ed. by Ralf Behn and Selina Byfield. Series on Science-Based Policy Advice. acatech. ISBN: 978-3-8047-3550-7.

Dietz, Simon, James Rising, Thomas Stoerk and Gernot Wagner (2021). "Economic impacts of tipping points in the climate system". In: *Proceedings of the National Academy of Sciences* 118.34. Company: National Academy of Sciences Distributor: National Academy of Sciences Institution: National Academy of Sciences Label: National Academy of Sciences Publisher: Proceedings of the National Academy of Sciences, e2103081118. DOI: 10.1073/pnas.2103081118.

DNV-GL (2017). *Martime Forecast to 2050.* Forecast. Høvig, Norway: DNV GL, p. 82.

Doane, Deborah and Alex MacGillivray (2001). "Economic Sustainability - The business of staying in business". In: *The Sigma Project.* The Sigma Project, pp. 1–52.

Draft revised MARPOL Annex VI (2025). In collab. with IMO.

EC (2020). *Communication from the commison to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.* Tech. rep. COM(2020) 562 final. Brussels: European Commision.

— (2023). *What is the EU ETS?* Accessed: 2024-12-28.

— (2024). *Scope of the EU ETS - European Commission.* Climate Action.

Eizenberg, Efrat and Yosef Jabareen (2017). "Social Sustainability: A New Conceptual Framework". In: *Sustainability* 9.1, p. 68. ISSN: 2071-1050. DOI: 10.3390/su9010068.

European Parliament (2024). *Interactive timeline: a guide to climate change negotiations.* European Parliament.

European Union (2024). *Regulation (EU)2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of greenhouse gas emissions from maritime transport, and amending Directive2009/16/EC (Text with EEA relevance)Text with EEA relevance.* Legislative Body: OP_DATPRO.

Eyring, V. (2005). "Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050". en. In: *Journal of Geophysical Research* 110.D17, p. D17306. ISSN: 0148-0227. DOI: 10.1029/2004JD005620.

Feola, Giuseppe (2015). "Societal transformation in response to global environmental change: A review of emerging concepts". In: *Ambio* 44.5. Company: Springer Distributor: Springer Institution: Springer Label: Springer Number: 5 Publisher: Springer Netherlands, pp. 376–390. ISSN: 1654-7209. DOI: 10.1007/s13280-014-0582-z.

Fraune, Cornelia and Michèle Knodt (2018). "Sustainable energy transformations in an age of populism, post-truth politics, and local resistance". In: *Energy Research & Social Science.* Sustainable energy transformations in an age of populism, post-truth politics, and local resistance 43, pp. 1–7. ISSN: 2214-6296. DOI: 10.1016/j.erss.2018.05.029.

Friedrich, Rainer and Alfred Voss (1993). "External costs of electricity generation". In: *Energy Policy* 21.2, pp. 114–122. ISSN: 03014215. DOI: 10.1016/0301-4215(93)90133-Z.

Funtowicz, Silvio O. and Jerome R. Ravetz (1993). "Science for the post-normal age". en. In: *Futures* 25.7, pp. 739–755. ISSN: 0016-3287. DOI: 10.1016/0016-3287(93)90022-L.

Gon, Hugo Denier van der and Jan Hulskotte (2010). *Methodologies for estimating shipping emissions in the Netherlands - A documentation of currently used emission factors and related activity data.* Tech. rep. 500099012. Bilthoven: Netherlands Environmental Assessment Agency.

Gong, Ke (2022). "Open science: The science paradigm of the new era". In: *Cultures of Science.* Publisher: SAGE Publications UK: London, England. DOI: 10.1177/20966083221091867.

Goodland, Robert (1995). "THE CONCEPT OF ENVIRONMENTAL SUSTAINABILITY". In: *Annual Review of Ecology, Evolution, and Systematics* 26 (Volume 26,). Publisher: Annual Reviews, pp. 1–24. ISSN: 1543-592X, 1545-2069. DOI: 10.1146/annurev.es.26.110195.000245.

Graebig, Markus, Georg Erdmann, Niko Rogler and Ingo Uhlig (2023). *Ein Atlas unserer Stromwelt und ihres Wandels – STROM, NETZ, FLUSS.* Berlin: Ellery Studio.

Groscurth, H. -M., Th. Bruckner and R. Kümmel (1995). "Modeling of energy-services supply systems". en. In: *Energy* 20.9, pp. 941–958. DOI: 10.1016/0360-5442(95)00067-Q.

Harewood, Andre, Franziska Dettner and Simon Hilpert (2022). “Open source modelling of scenarios for a 100% renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles”. In: *Energy for Sustainable Development* 68. Publisher: Elsevier, pp. 120–130. ISSN: 0973-0826. DOI: `10.1016/j.esd.2022.03.004`.

Hedenus, Fredrik, Daniel Johansson and Kristian Lindgren (2013). “A Critical Assessment of Energy-economy-climate Models for Policy Analysis”. en. In: *Journal of Applied Economics and Business Research* 3.2, pp. 118–13.

Herbst, Andrea, Felipe Toro, Felix Reitze and Eberhard Jochem (2012). “Introduction to Energy Systems Modelling”. en. In: *Swiss Journal of Economics and Statistics* 148.2, pp. 111–135. ISSN: 2235-6282. DOI: `10.1007/BF03399363`.

Hilpert, S., C. Kaldemeyer, U. Krien, S. Günther, C. Wingenbach and G. Plessmann (2018). “The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling”. en. In: *Energy Strategy Reviews* 22, pp. 16–25. ISSN: 2211-467X. DOI: `10.1016/j.esr.2018.07.001`.

Hilpert, Simon (2022a). “Development, Appication and Limitations of Open Energy System Analysis Approaches for Sustainable Energy Transformations”. Publisher: Zentrale Hochschulbibliothek. Kumulativ. Flensburg: Europa Universität Flensburg. 165 pp.

— (2022b). *KlimaSchiff - Source Code*. Source code, BSD 3-Clause. Flensburg. DOI: `https://doi.org/10.5281/zenodo.6951672`.

Hilpert, Simon, Franziska Dettner and Ahmed Al-Salaymeh (2020a). “Analysis of Cost-Optimal Renewable Energy Expansion for the Near-Term Jordanian Electricity System”. en. In: *Sustainability* 12.22, p. 9339. DOI: `10.3390/su12229339`.

Hilpert, Simon, Stephan Günther and Martin Söthe (2020b). *oemof/oemof-tabular*. original-date: 2018-11-20T16:05:32Z. URL: `https://github.com/oemof/oemof-tabular` (visited on 14/07/2020).

Hirth, Lion, Falko Ueckerdt and Ottmar Edenhofer (2015). “Integration costs revisited – An economic framework for wind and solar variability”. en. In: *Renewable Energy* 74, pp. 925–939. ISSN: 0960-1481. DOI: `10.1016/j.renene.2014.08.065`.

Hoffman, Kenneth C. and David O. Wood (1976). “Energy System Modeling and Forecasting”. In: *Annual Review of Environment and Resources* 1 (Volume 1, 1976). Publisher: Annual Reviews, pp. 423–453. ISSN: 1543-5938, 1545-2050. DOI: `10.1146/annurev.eg.01.110176.002231`.

Hölscher, Katharina, Julia M. Wittmayer and Derk Loorbach (2018). “Transition versus transformation: What’s the difference?” In: *Environmental Innovation and Societal Transitions* 27, pp. 1–3. ISSN: 22104224. DOI: `10.1016/j.eist.2017.10.007`.

Howarth, Richard B. (1997). “Sustainability as Opportunity”. In: *Land Economics* 73.4, pp. 569–569. DOI: `https://doi.org/10.2307/3147246`.

IEA (2016). *Energy and Air Pollution - World Energy Outlook 2016 Special Report*. Special Report. Paris: International Energy Agency/OECD, p. 266.

— (2023). *International shipping - CO2 emissions and energy consumption*. Accessed: 2024-08-05.

— (2024). *Renewables 2023 - Analysis and forecast to 2028*. Paris: International Energy Agency.

IMO (2020a). *Fourth IMO Greenhouse Gas Study 2020*. London: International Maritime Organization.

— (2020b). *Interim Guidelines for the saftey of ships using Methyl/Ethyl Alcohol as fuel*. Guideline 1621. London: International Maritime Organization, p. 38.

— (2023). *Revised GHG Reduction Strategy for Global Shipping Adopted*.

Ingwersen, Anna, Alvaro J. Hahn Menacho, Stephan Pfister, Jonathan N. Peel, Romain Sacchi and Christian Moretti (2025). “Prospective life cycle assessment of cost-effective pathways for achieving the FuelEU Maritime Regulation targets”. In: *Science of The Total Environment* 958, p. 177880. ISSN: 00489697. DOI: `10.1016/j.scitotenv.2024.177880`.

IPCC (1990). *Climate Change: The IPCC Scientific Assessment. Report Prepared for Intergovernmental Panel on Climate Change by Working Group I.* https://www.ipcc.ch/report/ar1/. Geneva, Switzerland. DOI: 10.59327/IPCC/AR1.

— (1995). *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar2/. Geneva, Switzerland. DOI: 10.59327/IPCC/AR2.

— (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar3/. Geneva, Switzerland. DOI: 10.59327/IPCC/AR3.

— (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar4/. Geneva, Switzerland. DOI: 10.59327/IPCC/AR4.

— (2018). *Global Warming of 1.5 ºC - Special Report 15.* Tech. rep. https://www.ipcc.ch/sr15/. Intergovermental Panel on Climate Change (IPCC).

— (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar6/. Geneva, Switzerland. DOI: 10.59327/IPCC/AR6-9789291691647.

— (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Ed. by H. Lee and J. Romero. Geneva, Switzerland: IPCC, p. 184. DOI: 10.59327/IPCC/AR6-9789291691647.

IRENA (2022). *World Energy Transitions Outlook 2022.* World Energy Transition. Masdar: International Renewable Energy Agency.

Jaccard, Mark (2006). *Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy.* Englisch. Cambridge, UK ; New York: Cambridge University Press. ISBN: 978-0-521-86179-3.

Jalkanen, J.-P., L. Johansson and J. Kukkonen (2016). "A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011". en. In: *Atmospheric Chemistry and Physics* 16.1, pp. 71–84. ISSN: 1680-7324. DOI: 10.5194/acp-16-71-2016.

Jalkanen, J.-P., L. Johansson, J. Kukkonen, A. Brink, J. Kalli and T. Stipa (2012). "Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide". en. In: *Atmospheric Chemistry and Physics* 12.5, pp. 2641–2659. ISSN: 1680-7324. DOI: 10.5194/acp-12-2641-2012.

Jalkanen, Jukka-Pekka, Lasse Johansson and Jaakko Kukkonen (2014). "A Comprehensive Inventory of the Ship Traffic Exhaust Emissions in the Baltic Sea from 2006 to 2009". en. In: *AMBIO* 43.3, pp. 311–324. ISSN: 0044-7447, 1654-7209. DOI: 10.1007/s13280-013-0389-3.

Jeronen, Eila (2023). "Economic Sustainability". In: *Encyclopedia of Sustainable Management.* Ed. by Samuel O. Idowu, René Schmidpeter, Nicholas Capaldi, Liangrong Zu, Mara Del Baldo and Rute Abreu. Cham: Springer International Publishing, pp. 1257–1263. ISBN: 978-3-031-25983-8. DOI: 10.1007/978-3-031-25984-5_197.

Johansson, L., J.-P. Jalkanen, J. Kalli and J. Kukkonen (2013). *The evolution of shipping emissions and the costs of recent and forthcoming emission regulations in the northern European emission control area.* preprint. Aerosols/Atmospheric Modelling/Troposphere/Chemistry (chemical composition and reactions). DOI: 10.5194/acpd-13-16113-2013.

Johansson, Lasse, Jukka-Pekka Jalkanen and Jaakko Kukkonen (2017). "Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution". en. In: *Atmospheric Environment* 167, pp. 403–415. ISSN: 13522310. DOI: 10.1016/j.atmosenv.2017.08.042.

Joules (2014). *LCPA Tool incl. LCPA and LCA descripton.* Eng. Confidential Report 21-1. Flensburg: Flensburger Schiffbau-Gesellschaft mbH & Co KG, p. 69.

Karl, Matthias, Jan Eiof Jonson, Andreas Uppstu, Armin Aulinger, Marje Prank, Mikhail Sofiev, Jukka-Pekka Jalkanen, Lasse Johansson, Markus Quante and Volker Matthias (2019). "Effects of ship emissions on air quality in the Baltic Sea region simulated with three different chemistry transport models". en. In: *Atmospheric Chemistry and Physics* 19.10, pp. 7019–7053. ISSN: 1680-7324. DOI: 10.5194/acp-19-7019-2019.

Khan, Imran (2021). "Sustainability assessment of energy systems: Indicators, methods, and applications". In: *Methods in Sustainability Science*. Elsevier, pp. 47–70. ISBN: 978-0-12-823987-2. DOI: 10.1016/B978-0-12-823987-2.00016-7.

Klepsch, Benjamin (2020). "Bewertung von Technologien zur Minderung von Luftschadstoffen in der Seeschifffahrt". Deutsch. Master-Thesis. Flensburg: Europa Universität Flensburg.

Köhler, Jonathan, Frank W. Geels, Florian Kern, Jochen Markard, Elsie Onsongo, Anna Wieczorek, Floortje Alkemade, Flor Avelino, Anna Bergek, Frank Boons, Lea Fünfschilling, David Hess, Georg Holtz, Sampsa Hyysalo, Kirsten Jenkins, Paula Kivimaa, Mari Martiskainen, Andrew McMeekin, Marie Susan Mühlemeier, Bjorn Nykvist, Bonno Pel, Rob Raven, Harald Rohracher, Björn Sandén, Johan Schot, Benjamin Sovacool, Bruno Turnheim, Dan Welch and Peter Wells (2019). "An agenda for sustainability transitions research: State of the art and future directions". In: *Environmental Innovation and Societal Transitions* 31, pp. 1–32. ISSN: 22104224. DOI: 10.1016/j.eist.2019.01.004.

Komendantova, Nadejda, Leena Marashdeh, Love Ekenberg, Mats Danielson, Franziska Dettner, Simon Hilpert, Clemens Wingenbach, Kholoud Hassouneh and Ahmed Al-Salaymeh (2020). "Water–Energy Nexus: Addressing Stakeholder Preferences in Jordan". In: *Sustainability* 12.15. Number: 15 Publisher: Multidisciplinary Digital Publishing Institute, p. 6168. ISSN: 2071-1050. DOI: 10.3390/su12156168.

Kotz, Maximilian, Anders Levermann and Leonie Wenz (2024). "The economic commitment of climate change". In: *Nature* 628.8008. Publisher: Nature Publishing Group, pp. 551–557. ISSN: 1476-4687. DOI: 10.1038/s41586-024-07219-0.

Kramel, Diogo, Helene Muri, YoungRong Kim, Radek Lonka, Jørgen B. Nielsen, Anna L. Ringvold, Evert A. Bouman, Sverre Steen and Anders H. Strømman (2021). "Global Shipping Emissions from a Well-to-Wake Perspective: The MariTEAM Model". In: *Environmental Science & Technology* 55.22, pp. 15040–15050. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.1c03937.

Krien, Uwe, Patrik Schönfeldt, Jann Launer, Simon Hilpert, Cord Kaldemeyer and Guido Pleßmann (2020). "oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems". en. In: *Software Impacts* 6, p. 100028. ISSN: 2665-9638. DOI: 10.1016/j.simpa.2020.100028.

Kuhn, Thomas S. (1962). *The Structure of Scientific Revolutions*. 1st ed. University of Chicago Press. ISBN: 978-0-226-45811-3.

Leemans, Rik and William Solecki (2013). "Redefining environmental sustainability". In: *Current Opinion in Environmental Sustainability* 5.3, pp. 272–277. ISSN: 18773435. DOI: 10.1016/j.cosust.2013.07.006.

Lelieveld, Jos, Andrea Pozzer, Ulrich Pöschl, Mohammed Fnais, Andy Haines and Thomas Münzel (2020). "Loss of life expectancy from air pollution compared to other risk factors: a worldwide perspective". In: *Cardiovascular Research* 116.11, pp. 1910–1917. ISSN: 0008-6363, 1755-3245. DOI: 10.1093/cvr/cvaa025.

Lenton, Timothy M., David I. Armstrong McKay, Sina Loriani, Jesse F. Abrams, Steven J. Lade, Jonathan F. Donges, Manjana Milkoreit, Tom Powell, Steven R. Smith, Caroline Zimm, Emma Bailey, Joshua E. Buxton, James G. Dyke, Ashish Ghadiali and Laurie Laybourne (2023). *Global Tipping Points Report 2023*. Exeter, UK: University of Exeter.

Levermann, Anders (2023). *Die Faltung der Welt. wie die Wissenschaft helfen kann, dem Wachstumsdilemma und der Klimakrise zu entkommen.* ger. Literaturverzeichnis: Seite 269-272 ; Hier auch später erschienene, unveränderte Nachdrucke. Berlin: Ullstein, 271 Seiten. ISBN: 978-3-550-20212-4 and 3-550-20212-1.

Li, Peiyang, Jin Lin, Zhipeng Yu, Yingtian Chi and Kai Zhao (2024). "Feasibility study of renewable e-methanol production: A substitution pathway from blue to green". In: *iEnergy* 3.2, pp. 108–114. ISSN: 2771-9197. DOI: 10.23919/IEN.2024.0013.

Lindstad, Elizabeth, Benjamin Lagemann, Agathe Rialland, Gunnar M. Gamlem and Anders Valland (2021). "Reduction of maritime GHG emissions and the potential role of E-fuels". In: *Transportation Research Part D: Transport and Environment* 101. Publisher: Pergamon, p. 103075. ISSN: 1361-9209. DOI: 10.1016/j.trd.2021.103075.

Liu, Lirong, Guohe Huang, Brian Baetz, Charley Z. Huang and Kaiqiang Zhang (2019). "Integrated GHG emissions and emission relationships analysis through a disaggregated ecologically-extended input-output model; A case study for Saskatchewan, Canada". en. In: *Renewable and Sustainable Energy Reviews* 106, pp. 97–109. ISSN: 1364-0321. DOI: 10.1016/j.rser.2019.03.001.

Lloyd, Philip J. (2017). "The role of energy in development". In: *Journal of Energy in Southern Africa* 28.1. Publisher: University of Cape Town, pp. 54–62. ISSN: 1021-447X. DOI: 10.17159/2413-3051/2017/v28i1a1498.

Lu, Jiaqi and Gregory F. Nemet (2020). "Evidence map: topics, trends, and policy in the energy transitions literature". In: *Environmental Research Letters* 15.12. Publisher: IOP Publishing, p. 123003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/abc195.

Ly, Anh M. and Michael R. Cope (2023). "New Conceptual Model of Social Sustainability: Review from Past Concepts and Ideas". In: *International Journal of Environmental Research and Public Health* 20.7, p. 5350. ISSN: 1660-4601. DOI: 10.3390/ijerph20075350.

Manabe, Syukuro and Richard T. Wetherald (1967). "Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity". In: *Journal of the Atmospheric Sciences* 24.3. Publisher: American Meteorological Society Section: Journal of the Atmospheric Sciences, pp. 241–259. ISSN: 0022-4928, 1520-0469. DOI: 10.1175/1520-0469(1967)024<0241:TEOTAW>2.0.CO;2.

McGookin, Connor, Brian Ò Gallachóir and Edmond Byrne (2021). "Participatory methods in energy system modelling and planning – A review". In: *Renewable and Sustainable Energy Reviews* 151. Publisher: Pergamon, p. 111504. ISSN: 1364-0321. DOI: 10.1016/j.rser.2021.111504.

Meadows, Donella, Dennis L. Meadows, Jørgen Randers and William W. Behrens III (1972). *The Limits to growth; a report for the Club of Rome's project on the predicament of mankind*. eng. New York, Universe Books. ISBN: 978-0-87663-165-2.

Mercator Research Institute on Global Commons and Climate Change (MCC) (2023). *CO_2 Budget*. Accessed: 2025-04-21.

Mercer, John H. (1968). "Antarctic Ice and Sangamon Sea Level". In: *Institute of Polar Studies* 139, pp. 217–225.

Monroe, Robert (2024). *The Keeling Curve*. The Keeling Curve.

Morelli, John (2011). "Environmental Sustainability: A Definition for Environmental Professionals". In: *Journal of Environmental Sustainability* 1.1. DOI: 10.14448/jes.01.0002.

Morris, Craig and Arne Jungjohann (2016). *Energy Democracy*. 1st ed. Vol. 1. 1 vols. Heidelberg: Springer.

Morrison, Robbie (2018). "Energy system modeling: Public transparency, scientific reproducibility, and open development". In: *Energy Strategy Reviews* 20, pp. 49–63. ISSN: 2211467X. DOI: 10.1016/j.esr.2017.12.010.

Mueller, Natalie, Marie Westerby and Mark Nieuwenhuijsen (2023). "Health impact assessments of shipping and port-sourced air pollution on a global scale: A scoping literature review". In: *Environmental Research* 216. Publisher: Academic Press, p. 114460. ISSN: 0013-9351. DOI: 10.1016/j.envres.2022.114460.

Murphy, Kevin (2012). “The social pillar of sustainable development: a literature review and framework for policy analysis”. In: *Sustainability: Science, Practice and Policy* 8.1, pp. 15–29. ISSN: 1548-7733. DOI: 10.1080/15487733.2012.11908081.

Nakata, Toshihiko, Diego Silva and Mikhail Rodionov (2011). “Application of energy system models for designing a low-carbon society”. In: *Progress in Energy and Combustion Science* 37.4. Publisher: Pergamon, pp. 462–502. ISSN: 0360-1285. DOI: 10.1016/j.pecs.2010.08.001.

NOAA (2024). *Climate at a Glance Global Time Series - Global Time Series*. National Centers for Environmental Information.

Nordhaus, William D. (2017). “Revisiting the Social Cost of Carbon”. In: *Proceedings of the National Academy of Sciences (PNAS)* 114.7. Contributed by William D. Nordhaus, November 21, 2016 (sent for review June 8, 2016; reviewed by James K. Hammitt, Al McGartland, and Gary W. Yohe), pp. 1518–1523. DOI: 10.1073/pnas.1609244114.

Owusu, Phebe Asantewaa and Samuel Asumadu-Sarkodie (2016). “A review of renewable energy sources, sustainability issues and climate change mitigation”. In: *Cogent Engineering* 3.1. Ed. by Shashi Dubey. Publisher: Cogent OA _eprint: https://doi.org/10.1080/23311916.2016.1167990, p. 1167990. ISSN: null. DOI: 10.1080/23311916.2016.1167990.

Pachauri, Rajendra (2008). “Climate change and sustainability science”. In: *Sustainability Science* 3.1. Company: Springer Distributor: Springer Institution: Springer Label: Springer Number: 1 Publisher: Springer Japan, pp. 1–3. ISSN: 1862-4057. DOI: 10.1007/s11625-008-0047-z.

Partanen, A. I., A. Laakso, A. Schmidt, H. Kokkola, T. Kuokkanen, J.-P. Pietikäinen, V.-M. Kerminen, K. E. J. Lehtinen, L. Laakso and H. Korhonen (2013). “Climate and air quality trade-offs in altering ship fuel sulfur content”. In: *Atmospheric Chemistry and Physics* 13.23, pp. 12059–12071. ISSN: 1680-7324. DOI: 10.5194/acp-13-12059-2013.

Pearce, D., C. Bann and S. Georgiou (1992). “The social cost of fuel cycles”. In.

Pearce, David and Edward B. Barbier (2000). *For a Sustainable Economy*. 1st ed. Politics & International Relations 6. London: Routledge. ISBN: 978-1-84977-423-9. DOI: 10.4324/9781849774239.

Peng, Roger D. (2011). “Reproducible Research in Computational Science”. In: *Science*. Publisher: American Association for the Advancement of Science. DOI: 10.1126/science.1213847.

Pfenninger, Stefan (2017). “Energy scientists must show their workings”. en. In: *Nature* 542.7642, pp. 393–393. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/542393a.

Pfenninger, Stefan, Lion Hirth, Ingmar Schlecht, Eva Schmid, Frauke Wiese, Tom Brown, Chris Davis, Matthew Gidden, Heidi Heinrichs, Clara Heuberger, Simon Hilpert, Uwe Krien, Carsten Matke, Arjuna Nebel, Robbie Morrison, Berit Müller, Guido Pleßmann, Matthias Reeg, Jörn C. Richstein, Abhishek Shivakumar, Iain Staffell, Tim Tröndle and Clemens Wingenbach (2018). “Opening the black box of energy modelling: Strategies and lessons learned”. In: *Energy Strategy Reviews* 19, pp. 63–71. ISSN: 2211-467X. DOI: 10.1016/j.esr.2017.12.002.

Pietzcker, Robert C., Sebastian Osorio and Renato Rodrigues (2021). “Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector”. en. In: *Applied Energy* 293, p. 116914. ISSN: 03062619. DOI: 10.1016/j.apenergy.2021.116914.

Pretis, Felix (2020). “Econometric modelling of climate systems: The equivalence of energy balance models and cointegrated vector autoregressions”. en. In: *Journal of Econometrics*. Annals Issue: Econometric Models of Climate Change 214.1, pp. 256–273. ISSN: 0304-4076. DOI: 10.1016/j.jeconom.2019.05.013.

Priesmann, Jan, Lars Nolting and Aaron Praktiknjo (2019). “Are complex energy system models more accurate? An intra-model comparison of power system optimization models”. In: *Applied Energy* 255. Publisher: Elsevier, p. 113783. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2019.113783.

Purvis, Ben, Yong Mao and Darren Robinson (2019). “Three pillars of sustainability: in search of conceptual origins”. In: *Sustainability Science* 14.3. Company: Springer Distributor: Springer Institution: Springer Label: Springer Number: 3 Publisher: Springer Japan, pp. 681–695. ISSN: 1862-4057. DOI: 10.1007/s11625-018-0627-5.

Raworth, Kate (2017). *Doughnut economics : seven ways to think like a 21st-century economist.* 1st ed. Vol. 1. Publication Title: Published in **2017** in London by Random House. London: Random House. ISBN: 978-1-84794-137-4.

Register, UMAS; Lloyd's (2019). *Fuel Production Cost Estimates and Assumptions: Technical Report.* Tech. rep. London: Lloyd's Register.

Richardson, Katherine, Will Steffen, Wolfgang Lucht, Jørgen Bendtsen, Sarah E. Cornell, Jonathan F. Donges, Markus Drüke, Ingo Fetzer, Govindasamy Bala, Werner von Bloh, Georg Feulner, Stephanie Fiedler, Dieter Gerten, Tom Gleeson, Matthias Hofmann, Willem Huiskamp, Matti Kummu, Chinchu Mohan, David Nogués-Bravo, Stefan Petri, Miina Porkka, Stefan Rahmstorf, Sibyll Schaphoff, Kirsten Thonicke, Arne Tobian, Vili Virkki, Lan Wang-Erlandsson, Lisa Weber and Johan Rockström (2023). "Earth beyond six of nine planetary boundaries". In: *Science Advances.* Publisher: American Association for the Advancement of Science. DOI: 10.1126/sciadv.adh2458.

Rifkin, Jeremy (2014). *The Zero Marginal Cost Society: The Internet of Things, the Collaborative Commons, and the Eclipse of Capitalism.* 1st ed. Vol. 1. Publisher: St. Martin's Publishing Group. New York: Blackstone. ISBN: 978-1-4830-0642-0.

Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, Björn Nykvist, Cynthia A. de Wit, Terry Hughes, Sander van der Leeuw, Henning Rodhe, Sverker Sörlin, Peter K. Snyder, Robert Costanza, Uno Svedin, Malin Falkenmark, Louise Karlberg, Robert W. Corell, Victoria J. Fabry, James Hansen, Brian Walker, Diana Liverman, Katherine Richardson, Paul Crutzen and Jonathan A. Foley (2009). "A safe operating space for humanity". In: *Nature* 461.7263. Number: 7263 Publisher: Nature Publishing Group, pp. 472–475. ISSN: 1476-4687. DOI: 10.1038/461472a.

Schleussner, Carl-Friedrich, Joeri Rogelj, Michiel Schaeffer, Tabea Lissner, Rachel Licker, Erich M. Fischer, Reto Knutti, Anders Levermann, Katja Frieler and William Hare (2016). "Science and policy characteristics of the Paris Agreement temperature goal". In: *Nature Climate Change* 6.9. Number: 9 Publisher: Nature Publishing Group, pp. 827–835. ISSN: 1758-6798. DOI: 10.1038/nclimate3096.

Schwarzkopf, Daniel A., Ronny Petrik, Volker Matthias, Markus Quante, Elisa Majamäki and Jukka-Pekka Jalkanen (2021). "A ship emission modeling system with scenario capabilities". en. In: *Atmospheric Environment: X*, p. 100132. ISSN: 25901621. DOI: 10.1016/j.aeaoa.2021.100132.

Schwarzkopf, Daniel A., Ronny Petrik, Volker Matthias, Markus Quante, Guangyuan Yu and Yan Zhang (2022). "Comparison of the Impact of Ship Emissions in Northern Europe and Eastern China". In: *Atmosphere* 13.6, p. 894. ISSN: 2073-4433. DOI: 10.3390/atmos13060894.

Seidl, R., T. Von Wirth and P. Krütli (2019). "Social acceptance of distributed energy systems in Swiss, German, and Austrian energy transitions". In: *Energy Research & Social Science* 54, pp. 117–128. ISSN: 22146296. DOI: 10.1016/j.erss.2019.04.006.

Senol, Yunus Emre and Alper Seyhan (2024). "A novel machine-learning based prediction model for ship manoeuvring emissions by using bridge simulator". In: *Ocean Engineering* 291, p. 116411. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2023.116411.

Shabecoff, Philip and James Hansen (1988). "Global Warming Has Begun, Expert Tells Senate". In: ISSN: 0362-4331.

Shi, Zongbo, Sonja Endres, Anna Rutgersson, Shams Al-Hajjaji, Selma Brynolf, Dennis Booge, Ida-Maja Hassellöv, Christos Kontovas, Rohan Kumar, Huan Liu, Christa Marandino, Volker Matthias, Jana Moldanová, Kent Salo, Maxim Sebe, Wen Yi, Mingxi Yang and Chao Zhang (2023). "Perspectives on shipping emissions and their impacts on the surface ocean and lower atmosphere:

An environmental-social-economic dimension". In: *Elementa: Science of the Anthropocene* 11.1. Publisher: University of California Press. DOI: 10.1525/elementa.2023.00052.

Sovacool, Benjamin K., David J. Hess and Roberto Cantoni (2021a). "Energy transitions from the cradle to the grave: A meta-theoretical framework integrating responsible innovation, social practices, and energy justice". In: *Energy Research & Social Science* 75, p. 102027. ISSN: 22146296. DOI: 10.1016/j.erss.2021.102027.

Sovacool, Benjamin K., Jinsoo Kim and Minyoung Yang (2021b). "The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities". In: *Energy Research & Social Science* 72. Publisher: Elsevier, p. 101885. ISSN: 2214-6296. DOI: 10.1016/j.erss.2020.101885.

Spandagos, Constantine, Miguel Angel Tovar Reaños and Muireann Á. Lynch (2022). "Public acceptance of sustainable energy innovations in the European Union: A multidimensional comparative framework for national policy". In: *Journal of Cleaner Production* 340, p. 130721. ISSN: 09596526. DOI: 10.1016/j.jclepro.2022.130721.

Spangenberg, Joachim H. (2005). "Economic sustainability of the economy: concepts and indicators". In: *International Journal of Sustainable Development* 8.1. Publisher: Inderscience Publishers, pp. 47–64. DOI: https://doi.org/10.1504/IJSD.2005.007374.

Spangenberg, Joachim H. and Sylvia Lorek (2019). "Sufficiency and consumer behaviour: From theory to policy". en. In: *Energy Policy* 129, pp. 1070–1079. ISSN: 03014215. DOI: 10.1016/j.enpol.2019.03.013.

Spaniol, Matthew J. and Nicholas J. Rowland (2019). "Defining scenario". en. In: *Futures & Foresight Science* 1.1. ISSN: 2573-5152. DOI: https://doi.org/10.1002/ffo2.3.

Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries, Cynthia A. de Wit, Carl Folke, Dieter Gerten, Jens Heinke, Georgina M. Mace, Linn M. Persson, Veerabhadran Ramanathan, Belinda Reyers and Sverker Sörlin (2015). "Planetary boundaries: Guiding human development on a changing planet". In: *Science*. Publisher: American Association for the Advancement of Science. DOI: 10.1126/science.1259855.

Sterman, John D. (2002). "All models are wrong: reflections on becoming a systems scientist". In: *System Dynamics Review* 18.4, pp. 501–531. ISSN: 0883-7066, 1099-1727. DOI: 10.1002/sdr.261.

Strachan, Neil, Steve Pye and Ramachandran Kannan (2009). "The iterative contribution and relevance of modelling to UK energy policy". en. In: *Energy Policy* 37.3, pp. 850–860. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2008.09.096.

Transport & Environment (2021). *Climate impact of shipping.* Transport & Environment.

Traut, M., A. Bows-Larkin, K. Anderson, C. McGlade, M. Sharmina and T. Smith (2015). "Emissions budgets for shipping in a 2°C global warming scenario, and implications for operational efficiency". In: Glasgow: University College London.

UBA (2020). *Methodenkonvention 3.1 zur Ermittlung von Umweltkosten Kostensätze Stand 12/2020.* Tech. rep. Dessau-Roßlau: Umweltbundesamt.

Uiterkamp, Anton J. M. Schoot and Charles Vlek (2007). "Practice and Outcomes of Multidisciplinary Research for Environmental Sustainability". In: *Journal of Social Issues* 63.1. Publisher: John Wiley & Sons, Ltd, pp. 175–197. ISSN: 1540-4560. DOI: 10.1111/j.1540-4560.2007.00502.x.

UN (2024). *Causes and Effects of Climate Change.* United Nations. Publisher: United Nations.

UNCTAD (2019). *Review of Maritime Transport.* Tech. rep. New York: Uniterd Nations Conference on Trade and Development, p. 129.

United Nations (1993). *Agenda 21: Programme of Action for Sustainable Development; Rio Declaration on Environment and Development; Statement of Forest Principles. The final text of agreements negotiated by governments at the United Nations Conference on Environment and Development*

(UNCED), 3-14 June 1992, Rio de Janeiro, Brazil. Rio de Janeiro, Brazil: United Nations Dept. of Public Information.

United Nations (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. United Nations.

United Nations Framework Convention on Climate Change (UNFCCC) (2025). *COP29 - 29th Conference of the Parties*.

Vallance, Suzanne, Harvey C. Perkins and Jennifer E. Dixon (2011). "What is social sustainability? A clarification of concepts". In: *Geoforum* 42.3, pp. 342–348. ISSN: 00167185. DOI: 10.1016/j.geoforum.2011.01.002.

Verhelst, Sebastian, James WG Turner, Louis Sileghem and Jeroen Vancoillie (2019). "Methanol as a fuel for internal combustion engines". en. In: *Progress in Energy and Combustion Science* 70, pp. 43–88. ISSN: 03601285. DOI: 10.1016/j.pecs.2018.10.001.

Wiese, Frauke, Gesine Bökenkamp, Clemens Wingenbach and Olav Hohmeyer (2014). "An open source energy system simulation model as an instrument for public participation in the development of strategies for a sustainable future". In: *WIREs Energy Environ* 3, pp. 490–504. DOI: doi:10.1002/wene.109.

Wilkins, E.T. (1954). "Air Pollution and the London Fog of December, 1952". In: *Journal of the Royal Sanitary Institute* 74.1, pp. 1–21. ISSN: 0370-7334. DOI: 10.1177/146642405407400101.

Willner, Sven N., Nicole Glanemann and Anders Levermann (2021). "Investment incentive reduced by climate damages can be restored by optimal policy". In: *Nature Communications* 12.1. Number: 1 Publisher: Nature Publishing Group, pp. 1–9. ISSN: 2041-1723. DOI: 10.1038/s41467-021-23547-5.

Yi, Wen, Xiaotong Wang, Tingkun He, Huan Liu, Zhenyu Luo, Zhaofeng Lv and Kebin He (2025). "The high-resolution global shipping emission inventory by the Shipping Emission Inventory Model (SEIM)". In: *Earth System Science Data* 17.1, pp. 277–292. ISSN: 1866-3516. DOI: 10.5194/essd-17-277-2025.

Zhang, Hongxia, Geoffrey J. D. Hewings and Xinye Zheng (2019). "The effects of carbon taxation in China: An analysis based on energy input-output model in hybrid units". en. In: *Energy Policy* 128, pp. 223–234. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2018.12.045.