EUROPA-UNIVERSITÄT FLENSBURG

DISSERTATION

Towards a sustainable energy future: Analysing existing barriers and lost benefits of energy transitions in the MENA Region with a focus on Morocco

Marina Blohm, geb. Berg

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

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Interdisziplinäres Institut für Umwelt, Sozial- und Humanwissenschaften
Abteilung Energie- und Umweltmanagement

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Abstract

The fight against climate change is one of the central challenges of our time. The Middle East and North Africa (MENA) region is inter alia characterised by an abundance of fossil as well as renewable reserves. Many countries of the region rely on fossil fuel reserves for the domestic use and export-purposes and therefore, might not set ambitious future renewable energy targets. Morocco, in contrast, is one of few MENA countries, which has only minor fossil reserves and nearly achieved its 2020 target of installing 42 % of renewable capacities.

This dissertation discusses the challenges and opportunities for different MENA countries to transform their energy systems towards a high share of renewable energies and to design these transitions based on sustainability aspects. Taking sustainability aspects into consideration ensures that future energy systems are not only built on green and carbon-neutral technologies, but also incorporate environmental and social requirements. Therefore, two global frameworks, one for sustainable energy transitions and one for sustainable green hydrogen productions, are developed and the performance of Morocco's energy transition is analysed in order to identify socially just and economically beneficial future solutions.

The content of this work is based on a mixed-method approach including energy system modelling, participatory scenario development, multi-criteria analysis, external cost modelling and expert interviews.

A number of existing barriers to the implementation of renewable energies are identified in this dissertation that affect their actual competitiveness vis-à-vis subsidised fossil fuel technologies. For example, the Moroccan case study shows that the centralised political economy of the country is reflected in the centralised way of electricity generation, which favours large scale, mostly foreign actors and prevents the creation of socio-economic benefits for small scale, domestic actors.

These results indicate that the availability of fossil resources and the countries' political structure are only two aspects, which may have significant impacts on the design and success of energy transitions. Such transitions require more than just adding renewable capacities to existing fossil energy systems or producing green hydrogen only with a focus on green electricity. In order to avoid inequalities and create new opportunities for civil society, sustainability must be a key consideration for national governments and international companies. This means that civil society in energy producing or exporting countries should not be exploited for the benefit of others.

Executive summary

Problem description

Climate change is one of the most pressing challenges for present and future generations. In a nutshell, anthropogenic climate change refers to the significant alteration of the Earth's climate patterns as a result of human activities, particularly the emissions of greenhouse gases into the atmosphere. To limit the increase of the global average temperature to a maximum of 1.5° Celsius compared to a pre-industrial level, a rapid reduction of greenhouse gas emissions is unavoidable. Therefore, our current way of living and especially global energy sectors need to be decarbonised as soon as possible, which means that only renewable and carbon-neutral resources or processes should be used and that fossil fuels, such as oil, gas and coal, must no longer be extracted. Direct electrification with renewable energies is the most cost-efficient solution for many processes to become carbon neutral. However, since electricity cannot be used in all processes, other solutions must be found to decarbonise some of the processes in the so called hard-to-abate sectors. One possibility would be the production and use of green hydrogen or its derivatives.

The overarching goal of the primarily techno-economic energy transitions should not only be to replace fossil fuels with green and carbon-neutral technologies but to incorporate environmental and social requirements, thus enabling sustainable energy transitions. Taking sustainability into consideration enables governments to respect the Earth's bio-physical thresholds and enable a safe and socially just basis for a sustainable and beneficial future for all, in which no country is risking to be exploited for the benefit of others.

The Middle East and North Africa (MENA) region is known for its abundant fossil reserves of oil and gas from which most countries generate a high share of income and which they use domestically at relatively low prices. The future demand for fossil fuels will decrease in a carbon-neutral energy future, which is why the countries of the region need to diversify their income but also need to develop strategies to support the domestic use of renewable energies to be cost-competitive compared to subsidised fossil fuels. In 2021, the majority of the MENA countries produced less than 10 % renewable electricity even though the entire region has a high renewable resource potential. This dissertation focusses on Morocco, which is part of the MENA region, but differs from the average MENA country as it has no fossil reserves, a strong reliance on imported coal for energy production and a ruling monarchy in a relatively stable political environment. Due to the lack of fossil reserves and the objective of increasing its energy independence, Morocco successfully expanded renewable energies and nearly met its target of a share of 42 % installed renewable capacities by 2020. By 2050, the country aims at using 80 % renewable energies, which is currently one of the most ambitious renewable targets in the region. Additionally, the production of green hydrogen is a much-discussed topic, which includes both opportunities and challenges for the country.

Methodology and contribution to the existing literature

This dissertation is based on a mixed-method approach including quantitative and qualitative methods, such as energy system modelling, participatory scenario development, multi-criteria analysis, external cost modelling and expert interviews.

Based on the different methods, each of the five articles contributes differently to the growing body of interdisciplinary research on climate change mitigation. The underlying objective of all articles is the need for more sustainability in energy transitions, to achieve not only carbon-neutral, but also socially acceptable and beneficial future solutions. Therefore, two analytical frameworks have been developed to support transitions towards sustainable energy systems. Both frameworks, one on the broader topic on sustainable energy transitions and one on sustainable hydrogen productions, do not have a specific regional focus and allow to systematically analysis existing barriers and lock-in factors of energy transitions and green hydrogen productions. The other three articles have a regional focus on the MENA region, especially on Morocco, and contribute to the literature on overcoming fossil lock-in factors to achieve sustainable energy solutions.

Findings

The overall results of this dissertation show that historically developed support mechanisms for fossil fuels still exist today and that renewable energies are disadvantaged with regard to a fair and cost-efficient competition of technologies. Besides the important techno-economic transition from fossil fuels to renewable energies, considering environmentally friendly and socially just criteria for decarbonising energy systems are important to stay within the planetary boundaries, to limit negative impacts on the environment and to design the energy transition based on basic social needs and intergenerational justice.

The first article of this dissertation identifies 32 criteria in 11 categories to overcome existing barriers and to support a sustainable energy transition at the national level. The criteria are clustered under the categories (1) environmental and ecological protection, (2) society, culture, and behaviour, (3) equity and justice, (4) knowledge, (5) energy markets, (6) energy policy, (7) legal requirements, (8) finance, (9) institutions, (10) infrastructure, and (11) clash of interests. The categories and criteria are interlinked and influence each other and the application of the framework would enable decision-makers to overcome barriers and create socio-economic benefits for local populations.

The second article presents four to five future electricity scenarios per country for Morocco, Jordan and Tunisia, which were developed during participatory workshops with national stakeholders. A multi-criteria analysis is used to rank the scenarios according to the preferences of workshop participants, which resulted in the highest ranking for the scenarios with the highest shares of renewable energies in all three countries. Decisive for the positive ranking were the criteria "Energy independence" (25 %), "System costs" (16 %), "System flexibility" (12 %) and "Water consumption" (12 %) in Morocco; "Safety" (27 %), "Air pollution (health)" (14 %) and "Hazardous waste" (14 %) in Jordan; and "Energy independence" (16 %), "System costs" (13 %), "Water consumption" (13 %) and "Air pollution (health)" (13 %) in Tunisia. A clear preference for renewable energies compared to fossil fuels could be observed during the workshops. However, also the future use of domestic shale oil was preferred by workshop participants in Jordan to increase the country's energy independence.

The third article presents a bottom-up approach of calculating external costs from energy generation in Morocco. The results indicate that the Moroccan fossil power plant inventory emits significant amounts of PM_{10}, $PM_{2.5}$, NO_x and SO_x, which lead to health impacts such as chronic mortality, infant mortality, respiratory diseases or restricted activity days. In total, the results show external costs of between 8.4 and 18 billion $€_{2015}$ for 2015, which equals around 18 % of the Moroccan annual GDP.

The fourth article discusses the historical developments of the Moroccan energy transition and identifies positive and negative impacts of liberalising electricity generation. Morocco is successful in constructing renewable energies but increased its coal capacities at the same time. In 2020, 4 GW of renewable energies and 4 GW of coal were installed in total in addition to 2 GW of gas and oil capacities. However, energy planning processes seem to create social injustices due to a missing participation and involvement of local communities and the local workforce. Private households, rural communities, domestic companies and rural workforce can be seen as losers of the energy transition, whereas large, mostly foreign international companies, the government and rural areas that were electrified with the help of the electrification program are winners of the energy transition.

The fifth article presents 16 sustainability criteria for the production of green hydrogen, clustered under six impact categories. Criteria under the categories (1) energy transition, (2) environment, (3) basic needs, (4) socio-economy, (5) electricity supply and (6) project planning allow to achieve a socially just and resource-saving way of producing green hydrogen. The development of such criteria is important as the trade of green hydrogen is predicted to take place between different countries as resources such a renewable energies or land are finite in many countries. Implementing such sustainability criteria could prevent an excessive resource exploitation in producing countries and can lead to the creation of socio-economic benefits also for projects that are dedicated for export-purposes.

Policy recommendations

Based on the derived findings, two sets of policy recommendations can be given. It is important to note, that these recommendations are given by a Global North researcher studying energy transitions in the Global South. This methodological limitation is important as it might be challenging to find beneficial and appropriate solutions for Global South countries, having the Global North perspective in mind.

The first set of six policy recommendations target the Moroccan energy transition with its domestic perspective of decision-making and are summarised in the following:

1. Updating the national energy strategy and developing a Moroccan roadmap with intermediate targets to achieve long-term goals
2. Involving the Moroccan society in the energy transition
3. Creating participation possibilities for small-scale domestic actors
4. Focusing on suitable renewable technologies and limiting air pollution
5. Following domestic needs instead of foreign demands
6. Increasing the overall sustainability for the energy transition

The second set of five recommendations address international actors that are active in foreign electricity sectors or in the global green hydrogen sector.

1. Asking the local population about their needs as part of energy planning processes
2. Providing access to electricity and water with energy projects, if needed
3. Creating domestic value chains and leaving economic benefits in countries of the Global South, especially for export-oriented projects
4. Implementing sustainability criteria for the production of green hydrogen at the global-level
5. Preventing neo-colonialism and resource exploitation in countries of the Global South to achieve sustainable energy transitions in the Global North

Conclusion

Morocco, a resource-poor country of the MENA region, achieved to install around 4 GW of renewable energies, which was initiated by liberalising electricity generation in the 2000s and allowing foreign investments and ownership without many limitations. Today, most of the power plants are owned by large, mostly foreign companies. Unfortunately, a positive spillover effect to Moroccan businesses is still in its infancy and there is a lack of socio-economic opportunities for small-scale Moroccan companies or the local workforce. Additionally, energy planning seems to create social injustices because the local population is not involved in most of the decision-making processes. It can be concluded that the techno-economic dimension of constructing renewable energies has been successful during the last years, but that a simultaneous and not internationally-recognised expansion of coal-fired capacities has happened during the same time. This is why one cannot speak of a sustainable energy transition but only that renewable capacities were added into the fossil system, which seem to be based on social injustices. Due to the mentioned differences between MENA countries, it is difficult to transfer the results from the Moroccan case to other countries in the MENA region. However, the results indicate that working with an enabling framework to overcome existing barriers or implementing sustainability criteria for the production of green hydrogen could result in an environmentally friendly or socially just energy transition based on a respectful use of scare resources and the possible creation of socio-economic benefits from energy transitions.

Acknowledgement

I would like to take the opportunity to thank everyone who has accompanied and supported me on the way to this dissertation. My biggest thank goes to my supervisor and mentor Prof. Dr. Olav Hohmeyer, who encouraged me in writing this dissertation and with whom the many content-related discussions during the past years were very interesting. I would also like to thank my second supervisor Prof. Dr. Pao-Yu Oei, who gave me new food for thought and always took the time to answer questions. The cooperation with the Berlin colleagues from the CoalExit research project and the foundation of our FossilExit research group have led to motivating discussions and have steadily increased my motivation to find future solutions for sustainable energy transitions for different countries around the world. I look forward to further exchange with you and thank you for the time spent so far.

Special thanks go to my former and current colleagues in the EUM department. Not only the daily coffee breaks, but also the cooperations and exchanges among each other always made for a very pleasant working atmosphere and increased my motivation to work. Especially, I would like to express my heartfelt thanks to my colleague Franziska Dettner. Without your proofreading and constant feedback, this work would not have turned out so well and I will miss in the future in particular our team work and your great ideas. I would also like to thank my best friend Christine Winkelmann, who proofread this document in a very short time and who has accompanied and supported me since we were children.

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List of Abbreviations

ANRE	National Electricity Regulatory Authority
AOC	Actors, Objectives, and Context
EUF	Europa-Universität Flensburg
FDI	Foreign Direct Investment
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Greenhouse gas
IRESEN	L'Institut de Recherche en Énergie Solaire et Énergies Nouvelles (engl. Research Institute for Solar Energy and New Energies)
IPCC	Intergovernmental Panel on Climate Change
KfW	Kreditanstalt für Wiederaufbau (engl. Development Bank)
LOHC	Liquid Organic Hydrogen Carriers
MASEN	Moroccan Agency for Sustainable Energy
MENA	Middle East and North Africa
MTF	Meta-Theoretical Framework
NDC	Nationally Determined Contribution
OCP	Office Chérifien des Phosphates
OECD	Organisation for Economic Co-operation and Development
ONEE	Office Nationale de l'Electricité et de l'Eau (engl. National Electricity and Water Office)
OPEC	Organisation of the Petroleum Exporting Countries
R&D	Research and Development
RE	Renewable energy
SDGs	Sustainable Development Goals

Part I – Introduction and Background

1 General Introduction

1.1 Author's Motivation

Simon Sinek's TED-Talk "Start with Why" on identifying the WHY behind personal and company-related successes and failures (TED, 2010) was the starting point for me to question my employment as a project developer for wind farms and to think about my intrinsic motivation to work. Being born in 1988, the construction of renewable energy generation technologies (called renewables or renewable energies in the following) was never a question but everyday life for me. This made it difficult to understand social protests against renewable energies. Unfortunately, discussions in local communities about constructing new wind farms were mostly combined with the argument *Not In My Backyard* (NIMBY) and guided by the question on how individual people can acquire as much money as possible from constructing renewables in their community. Arguments on why to replace the current mix of electricity were rarely seen. These discussions were disappointing as only a few people were not driven by a possible economic benefit, but by combating the more and more pressing challenges of climate change. This argument does not mean that I do not support the approach of benefiting from energy transitions, in contrast, a high share of this dissertation deals with how different parts of the society can benefit from energy transitions, rather than individual people profit financially while others may even have or fear disadvantages. In a country, in which most of the population can rely on a certain standard of living and that is internationally known for its *Energiewende*, the German energy transition should also be possible without claiming financial compensations only because people have to look at wind farms, as one example. At the same time, constructing wind farms in the most cost-effective way to generate the highest profits for companies – which mostly does not consider the most socially accepted and socio-economic beneficial decisions – was also not what I wanted to support. I wanted to actively shape energy transitions to influence current developments related to climate change and aimed to work in an environment that is not narrowed on purely economic decisions and that enables me to continuously expand my knowledge on how to achieve a sustainable way of living.

Working at the Europa-Universität Flensburg (EUF) allowed me to work on finding solutions for realising sustainable energy transitions, in which civil societies actively participate in designing these transitions. When I started working on a research project dealing with the energy transition in Morocco, Tunisia and Jordan, I quickly realised that there are many more important aspects associated with energy transitions than only generating carbon-neutral electricity. And that these aspects differ greatly from country to country and from continent to continent, but also influence each other. Discussions with workshop participants in Morocco, Tunisia and Jordan on their future energy systems were inspiring and have therefore aroused my interest in dealing more intensively with these countries in my dissertation. The participants pointed out the necessity for the countries to further develop – which mostly results in an increased energy demand – but mostly having in mind finding the most energy-efficient solutions. However, while we talked about using electrical vehicles in the future, some horse-drawn carriages were still on the streets in Morocco. The intrinsic motivation for countries suffering the negative consequences of climate change, such as increased water scarcity and increased average temperatures, is contrary to the behaviour of many industrialised nations, which insist on limiting future growth and which cannot imagine behavioural changes for the benefit of the climate and to enable future generations to live their lives in comfortable conditions. My work experience in other countries was very inspiring because we sometimes assume that best-practice examples of one region will be also successful in other regions, which they are mostly not. That is why I aimed to examine the energy transition of other countries and not exclusively the German one.

Climate change and the need for sustainable energy transitions

The entire topic of combating climate change and limiting the increasing global average temperature to a maximum of 1.5° Celsius (UNFCCC, 2015, p. 2) is a broad and important topic that requires social attention. In a nutshell, climate change refers to long-term changing climate and weather conditions, such as rising air and ocean temperatures, differences in precipitation levels and changing weather patterns including increased extreme weather conditions, which occur due to increasing greenhouse gas (GHG) emissions (Allen et al., 2018, p. 61). Besides a normal change in weather patterns over time, GHG emissions, primarily carbon dioxide (CO_2) and methane (CH_4), result mainly from human activities, such as from burning fossil fuels or our current way of living (see for example (IPCC, 2018, p. 7)). Preventing and minimising the amount of GHG emissions as soon as possible should be one of today's most important targets, to continuously enable life on earth in climatic conditions comparable to those of today. Mitigating and adapting to climate change and its consequences require not only technological solutions for reducing GHG emissions, but also changing social behaviours due to a more efficient or sufficient way of living (Creutzig et al., 2022, pp. 39–40). As this is a global topic, not only national actions to implement necessary policy instruments but also international efforts, such as international policy dialogues within the frames of the United Nations and the Intergovernmental Panel on Climate Change (IPCC), are required. This dissertation does not claim to present a suitable solution for every country to achieve a successful energy transition but aims at providing insights on what is unsustainable in some, currently promoted as successful, energy transitions, in which primarily large-scale companies benefit from this transition and societies do not have a say in designing the transition based on social needs. This dissertation is not focused on pure techno-economic analyses of transitions from fossil to renewable energies – many studies already exist and have proven the feasibility of fully renewable energy systems on a global (Greenpeace et al., 2015) or regional level (Bogdanov & Breyer, 2016; Child et al., 2019; Hansen et al., 2019) – but combines the identification of social needs and future visions of civil societies with designing an environmentally friendly way of using renewable energies in future energy systems. A pure techno-economic analysis would not unveil all existing problems, because the performance of an energy transition cannot simply be evaluated based on the numbers of renewable energy projects that have been built. Integrating technical solutions, adopting them to specific regional needs and studying socio-ecological impacts of these changes are at least of the same importance and correlate with the author's motivation of writing this dissertation. Therefore, this dissertation discusses challenges and opportunities for different MENA countries to transform their energy systems towards a high share of renewable energies and to design these transitions based on sustainability aspects.

1.2 Outline and Contribution of this Dissertation

1.2.1 Outline of the Dissertation

This subchapter outlines the structure of this dissertation, which is divided into three different parts. *Part I Introduction and Background* – including chapters 1 and 2 – introduces the author's motivation for writing this dissertation, discusses the state of research, and identifies the contribution of this dissertation to the existing scientific literature. *Part II Publications* – including chapters 3 to 7 – is the content-related foundation of this cumulative dissertation and presents the five scientific articles. *Part III Synthesis and Conclusion* – including chapters 8 to 10 – discusses and combines research results of the different articles, points out the limitations of this study and concludes with giving policy recommendations.

In the following, short summaries of the scientific articles *(Part II)* are outlined including the used methodology and a description of how they build on each other. Through this, the content-related red thread of the dissertation is presented.

Chapter 3, "*An Enabling Framework to Support the Sustainable Energy Transition at the National Level*" (Blohm, 2021), can be seen as the thematic foundation of this dissertation and the reason for the author to further research energy transitions. Transitioning fossil-based to renewable-based energy systems requires identifying and overcoming existing barriers that rather new renewable energy technologies, such as wind and solar energy, face compared to established fossil technologies. Analysing the national level of energy transitions, the article presents 32 criteria in 11 categories that can enable a sustainable energy transition. It identifies potential regulatory barriers that can prevent the use of renewable energies as well as interdependencies and connections of presented criteria to achieve an environmentally friendly, economically viable, and socially accepted energy production that is built on creating socio-economic benefits for civil society. The framework can be used for case studies on specific countries to identify existing barriers and enablers that either hamper or support the use of renewable energies. Even though this article was published one year after the article in Chapter 4, the other articles in chapters 5 to 7 consider individual criteria of this framework as a basis for analysis.

Chapter 4, "*Long-Term Electricity Scenarios for the MENA Region: Assessing the Preferences of Local Stakeholders Using Multi-Criteria Analyses*" (Zelt et al., 2019), is the result of the research project MENA SELECT in which the author participated. Participatory workshops together with national stakeholders were conducted in Morocco, Jordan and Tunisia to develop future electricity scenarios for the year 2050. For each country, four to five different future scenarios were developed and modelled during the workshops, so that workshop participants were directly able to see and react on consequences and benefits of using different renewable and fossil technologies in their future energy systems. The developed scenarios were used for a multi-criteria analysis to identify the most preferred future scenarios. The results show that the scenarios with the highest shares of renewables were ranked the highest in all three countries. The project aimed to enable discussions about different technological possibilities and social preferences for future electricity production of different stakeholder groups.

Besides this article, there are three grey publications available on the project results of each country (Amroune et al., 2017, 2018; Berg et al., 2016).

Chapter 5, "*External Cost of Air Pollution from Energy Generation in Morocco*" (Dettner & Blohm, 2021), presents and applies a bottom-up method for calculating the external costs of fossil electricity generation due to resulting air pollution in Morocco and addresses the missing consideration of social, especially health, effects of the current Moroccan energy system. It closes the research gap by providing a straightforward external cost calculation method as well as integrating them in an analysis of the Moroccan electricity generation. This article provides insights on the resulting air pollution of the fossil fuel based Moroccan power plants and estimates the calculated total health costs in 2015 to up to 18 billion €.

Chapter 6, "*The Hidden Costs of Morocco's Energy Transition: Investigating the Impact of Foreign Investment and the Lack of Social Participation*" (Blohm, 2023a), identifies specific challenges and injustices related to the Moroccan energy transition. It analyses the historical developments in the energy sector and unveils weaknesses and impacts of the, technologically speaking, well-progressing expansion of renewable energies. Within the article, some criteria of the enabling framework (Blohm, 2021) have been used for a detailed analysis and the data collection included the workshop results of Chapter 4 (Zelt et al., 2019) combined with a literature review and conducted interviews on the Moroccan energy transition in 2022. The results show, that the country has not only been supporting renewable energies but has also significantly expanded its coal capacities within the last years. Additionally, the role of foreign investments and foreign ownership are discussed as well as existing social injustices of energy planning.

Chapter 7, "*Green Hydrogen Production: Integrating Environmental and Social Criteria to Ensure Sustainability*" (Blohm & Dettner, 2023), describes the development of sustainability criteria for the production of green hydrogen in order to achieve a sustainable decarbonisation of other sectors than electricity. In total, 16 sustainability criteria were identified. The results indicate that an environmentally friendly and socially just production of green hydrogen can be ensured, if these sustainability criteria are considered. The term green hydrogen is not strictly defined but generally only refers to the use of renewable electricity for the production of hydrogen and does not include further criteria which shape the energy transition positively. The definition of sustainability criteria for the production of hydrogen is therefore important on a global-scale because many countries of the Global North enter into trade agreements with countries of the Global South to import green hydrogen or its derivatives. These trade relationships are not necessarily positive for exporting countries, which is why specific criteria could lead to the creation of socio-economic benefits and enable a sustainable development.

Figure 1-1 presents a graphical outline of the scientific articles included in this dissertation; including two analytical frameworks without a specific country focus (blue) and three case studies on the Moroccan energy system (green). Whereas the first four articles provide knowledge on electricity generation the last one is related to hydrogen production.

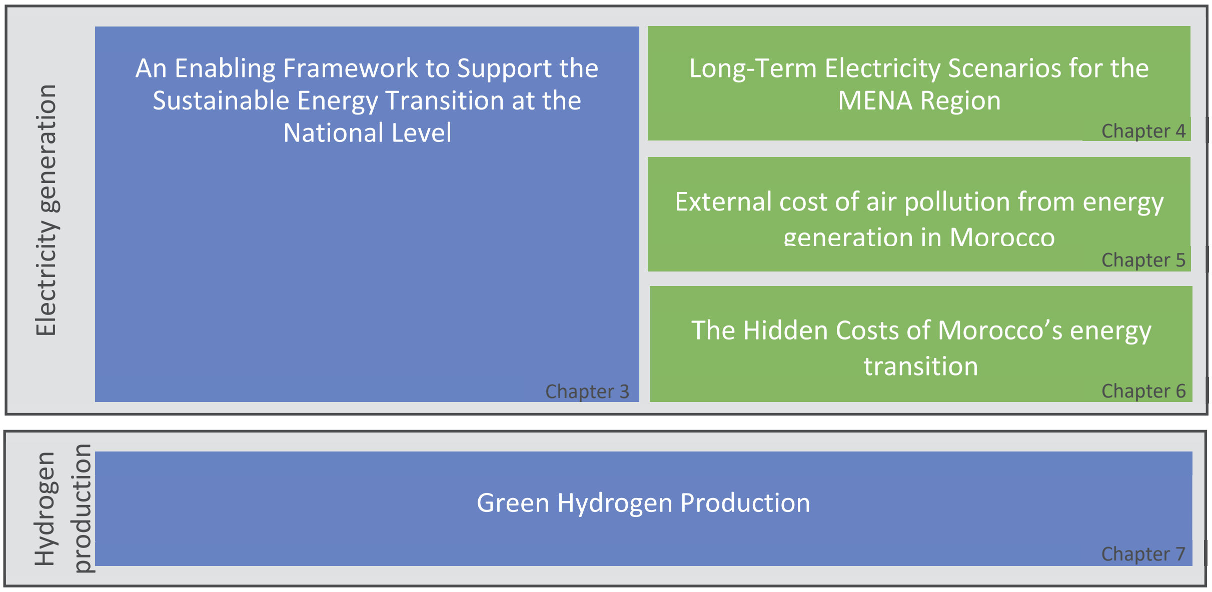

Figure 1-1 Graphical outline of the scientific articles

(blue = no specific country focus; green = country case study)

Table 1-1 summarises the author's contribution to the scientific articles.

Table 1-1 Dissertation chapters and author's contributions

Ch.	Title	Publication	Author's contribution
3	An Enabling Framework to Support the Sustainable Energy Transition at the National Level	*Sustainability* in 2021 doi:10.3390/su13073834	Single-author article (from conceptualising to writing)
4	Long-Term Electricity Scenarios for the MENA Region: Assessing the Preferences of Local Stakeholders Using Multi-Criteria Analyses	*Energies* in 2019 doi:10.3390/en12163046	Joint work with Ole Zelt, Christiane Krüger, Sönke Bohm and Shahrazad Far. All authors jointly organised and conducted the workshops, which are the basis for the article. During the workshops, Sönke Bohm and Marina Blohm were in charge of the scenario development as well as discussing different energy generation technologies with workshop participants. The author's contribution to the article was focused on topics of modelling aspects and scenario development as well as discussing the workshop results, which she wrote in cooperation with Sönke Bohm, who mainly developed the energy system model for the three countries Jordan, Morocco and Tunisia.
5	External Cost of Air Pollution from Energy Generation in Morocco	*Renewable and Sustainable Energy Transition* in 2021 doi:10.1016/j.rset.2021.1000 02	Joint work with Franziska Dettner. Marina Blohm and Franziska Dettner cooperated in writing the article. Marina Blohm was in charge of writing the subsections about the Moroccan energy system as well as the strategies and targets and contributed to the final editing of the article.
6	The Hidden Costs of Morocco's Energy Transition: Investigating the Impact of Foreign Investment and the Lack of Social Participation	Submitted to *Energy Reports* in 06/23	Single-author article (from conceptualising to writing)
7	Green Hydrogen Production: Integrating Environmental and Social Criteria to Ensure Sustainability	*Smart Energy* in 2023 doi:10.1016/j.segy.2023.100 112	Joint work with Franziska Dettner. Marina Blohm and Franziska Dettner cooperated in conceptualising the research design as well as writing the original draft. Marina Blohm conducted the interviews and processed the data.

1.2.2 Research Questions and Contribution to the Literature

Table 1-2 summarises the research questions and contributions to the scientific literature of the five scientific articles. In general, this dissertation is based on a mixed-method approach including both quantitative and qualitative approaches.

Table 1-2 Research questions and contribution to the existing literature

	Chapter 3 (Blohm, 2021)	Chapter 4 (Zelt et al., 2019)	Chapter 5 (Dettner & Blohm, 2021)	Chapter 6 (Blohm, 2023a)	Chapter 7 (Blohm & Dettner, 2023)
Methods used	Literature review	Energy system modelling, participatory scenario development, multi-criteria analysis	External cost modelling	Literature review and expert interviews	Literature review and expert interviews
Geographical scope	Global	Morocco, Jordan, Tunisia	Morocco	Morocco	Global
Research questions	(1) Which dimensions and criteria can act as barriers or enablers for sustainable and carbon-neutral technologies to support the reduction of fossil fuel technologies? (2) Which criteria of an enabling framework are most important when analysing the national level of the energy transition? In other words, which criteria seem to be more important at the regional, business, or project level? (3) Which criteria are important to strive for the decarbonisation of entire systems and thus, are important to push sector coupling? (4) Which criteria can or should be treated differently from country to country?	(1) What long-term electricity scenarios for the year 2050 do local stakeholders in Morocco, Jordan and Tunisia actually prefer? (2) And what criteria are seen as most important in such scenarios?	The hypothesis is that internalising external costs promotes the transition towards a 100% renewable energy-based electricity sector in Morocco.	(1) Which positive and negative impacts occurred from liberalising the Moroccan electricity generation? (2) What is the role of foreign investments and foreign ownership in this liberalisation? (3) Who are the winners and losers of the energy transition and how beneficial is the transition for the Moroccan society?	(1) Which sustainability aspects have to be considered for the production of green hydrogen? (2) And how can they be defined (made measurable)?

	Chapter 3 (Blohm, 2021)	Chapter 4 (Zelt et al., 2019)	Chapter 5 (Dettner & Blohm, 2021)	Chapter 6 (Blohm, 2023a)	Chapter 7 (Blohm & Dettner, 2023)
Contribution to the literature	The developed enabling framework to support the sustainable energy transition at the national level provides a systematic approach of analysing existing barriers and lock-in factors of energy transitions. It combines social, environmental and economic aspects to achieve a decarbonisation of the energy system while creating socio-economic benefits.	The article fills the research gap of developing and analysing long-term electricity scenarios for the countries under study and combines energy system modelling with conducting a multi-criteria analysis.	This article closes the research gap by providing a straightforward external cost calculation method as well as integrating them in an analysis of the Moroccan electricity generation. Additionally, it provides insights on the resulting air pollution of the fossil fuel based Moroccan power plants.	In this article, a techno-economic analysis of historical developments in the energy system is combined with identifying social injustices of electricity generation. It shows the winners and loser of the energy transition so far and indicates how socio-economic benefits of it could be increased.	In this article, 16 sustainability criteria for the production of green hydrogen are presented. Respecting these criteria would ensure that civil societies will not suffer from hydrogen production and that socio-economic benefits for local populations can be created through green hydrogen projects

2 Thematic Introduction

The three countries under study in Chapter 4 – Morocco, Jordan and Tunisia – are part of the MENA region, which is characterised by its rich endowment of fossil reserves, but also for its substantial renewable energy potential (Friedrich Ebert Stiftung & Germanwatch, 2019, pp. 5–7). A transformation of current energy systems poses particular challenges for countries that are economically dependent on the use of domestic fossil fuels today, but at the same time need to find solutions for their future sustainable development (Friedrich Ebert Stiftung & Germanwatch, 2019, p. 10). Therefore, this chapter will provide a brief comparison of differences and similarities of MENA countries in order to understand regional achievements and hesitations of individual countries related to their energy transitions and to better classify the results in the following chapters. This dissertation follows the World Bank's definition of the MENA region, which includes Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, the United Arab Emirates, West Bank, Gaza and Yemen (The World Bank, n.d.). However, the lack of data on Djibouti, West Bank and Gaza led to the exclusion of these countries hereafter. On the other hand, data on the Western Sahara are partly included in this dissertation under the frame of Morocco. Morocco has claimed the territory of the Western Sahara since 1975 (Mayrhofer, 2021, p. 1) and includes some information in official data from Moroccan ministries. As these are the official data on Morocco and the author was not able to separate them from each other, they are listed together as Morocco in this dissertation. Geopolitically, this does not mean that the author supports Morocco's territorial claims, but only makes this generalisation based in the availability of data.

The following chapters do not only include information on electricity generation, but also explain the correlation between fossil resource availability and long-term renewable targets as well as the status quo and future relevance of green hydrogen in the region. This dissertation includes the topic of green hydrogen mainly for two reasons. First of all, electricity is an essential input parameter for the production of green hydrogen, which is why this sector might be in competition with targets related to the decarbonisation of the energy sector. Secondly, this chapter will show that the region has a high potential for renewable energies, which could enable the countries to produce and export high amounts of green hydrogen or its derivatives and with this, replace current export revenues from fossil fuels.

2.1 MENA Countries

Many countries of the MENA region are known for their abundant fossil reserves, which together account for around half of the global oil and gas reserves (Tagliapietra, 2019, p. 1) and which distinguish this region from many other regions in the world. Figure 2-2 shows a map of MENA countries and includes information on fossil reserves as well as which countries belong to the Organisation of the Petroleum Exporting Countries (OPEC). Additionally, countries being monarchies are illustrated in the figure.

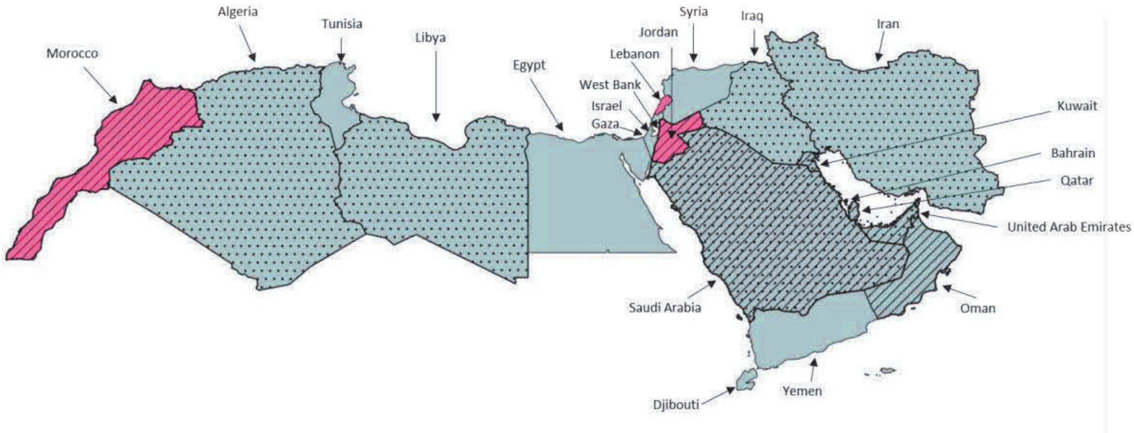

Figure 2-2 Map of MENA country's fossil reserves, OPEC memberships and monarchies
Own illustration

Legend: (= no or neglectable fossil reserves; = domestic gas and/or oil reserves; = OPEC countries; = monarchies)

The MENA region includes different sub-regions such as north African countries (Morocco, Algeria, Tunisia, Libya and Egypt), levant countries (Israel, Lebanon, Syria, West Bank, Gaza and Jordan), Gulf Cooperation Council (GCC) countries (Saudi Arabia, Kuwait, Bahrain, Qatar, the United Arab Emirates and Oman) and more surrounding countries (Iran, Iraq, Djibouti, Yemen) (Griffiths, 2017, p. 250). 17 out of 21 countries had an electrification rate of close to 100 % in 2020 and the remaining four countries had an electrification rate of between 61.8 % and 89.1 % (The World Bank, 2023). These figures show the significance of analysing grid-connected electricity generation instead of off-grid solutions.

Most countries have high amounts of gas and/or oil reserves but no country has significant coal reserves (Griffiths, 2017, p. 252). Even though Morocco possesses around 14 million tons of coal reserves (CIA, 2023) it closed its last coal mine in 2001 because coal mining was not profitable anymore due to the low quality of the coal combined with rising mining costs (Khalid, 2018). The availability of high amounts of fossil reserves influences a country's reliance on generating economic rents with extracting the resource and explains why this region is still focussed on further using fossil fuels in their energy systems. Oil and gas rents for example as a percentage of Gross Domestic Product (GDP) made up to 38 % in Libya in 2017 (Tagliapietra, 2019, p. 3). Countries without fossil reserves are much freer to switch to renewable energies because they do not have to replace fossil rents and usually have an intrinsic motivation to increase their energy independence by replacing imported fossil resources with domestic renewable resource. Seven of the 18 countries are members of the OPEC, which own and control most of the petroleum reserves on the globe (OPEC, 2023). Only three countries have no or neglectable fossil reserves, to which also two of the countries under study belong.

Besides resource availabilities, this dissertation will also analyse the role and influence of the Moroccan monarchy on the energy transition (see Chapter 6). Therefore, it is important to know that Morocco is the only north African monarchy, which makes the political economy of the country special compared to its neighbouring countries.

2.1.1 Electricity Generation

Electricity generation varies significantly between MENA countries. Countries having high shares of domestic gas or oil reserves (grey countries in Figure 2-2), such as Saudi Arabia, Qatar or the United

Arab Emirates mainly rely on the respective resource for their electricity generation. Table 2-3 summarises how the different countries produced their electricity in 2021 and indicates the share of renewable electricity. The three countries under study – Morocco, Jordan and Tunisia – are highlighted in red. For a better comparison, countries are clustered according to their proven oil and gas reserves (U.S. EIA, 2023a, 2023b) into three different categories A, B and C.

Table 2-3 Electricity generation in TWh in 2021, based on country-specific information derived from (Our World in Data, 2023)

	oil	coal	gas	nuclear	Solar (PV, CSP)	wind	hydro	Bio-energy	total	Share of RE
Category A: Proven gas and oil reserves										
Algeria	1.33	-	75.30	-	0.81	0.01	0.09	-	77.54	1.17%
Egypt	26.14	-	153.08	-	4.80	4.23	14.00	-	202.25	11.39%
Iran	46.33	0.62	274.46	3.24	0.62	0.60	15.00	0.01	340.88	4.76%
Iraq	16.42	-	75.56	-	0.38	-	4.90	-	97.26	5.43%
Kuwait	-	-	71.22	-	0.02	0.03	-	-	71.27	0.07%
Libya	1.01	-	31.00	-	0.01	-	-	-	32.02	0.03%
Oman	-	-	36.40	-	0.16	-	-	-	36.56	0.44%
Qatar	-	-	47.46	-	0.01	-	-	0.03	47.50	0.08%
Saudi Arabia	130.79	-	207.03	-	0.21	-	-	-	338.03	0.06%
Syria	5.60	0.09	10.31	-	-	-	0.75	0.01	16.76	4.53%
United Arab Emirates	-	-	127.14	1.79	6.69	-	-	0.01	135.63	4.94%
Yemen	1.91	-	1.01	-	0.60	-	-	-	3.52	17.05%
Category B: Only proven gas reserves										
Bahrain	0.03	-	31.76	-	0.01	-	-	-	31.80	0.03%
Israel	-	20.01	48.11	-	4.64	0.19	0.02	0.11	73.08	6.79%
Tunisia	**-**	**-**	**19.93**	**-**	**0.41**	**0.53**	**0.06**		**20.93**	**4.78%**
Category C: No or neglectable* proven reserves										
Jordan	**1.67**	**-**	**15.06**	**-**	**3.50**	**1.57**	**0.02**	**0.06**	**21.88**	**23.54%**
Lebanon	8.02	-	11.39	-	0.12	0.01	0.97	0.06	20.57	5.64%
Morocco	**4.36**	**23.88**	**4.88**	**-**	**1.82**	**5.11**	**1.21**	**0.04**	**41.30**	**19.81%**

*Neglectable: availability of less than 0.5 billion barrels of oil and less than 0.5 trillion cubic foot of natural gas

Category A countries possess both domestic oil and gas reserves. Some countries use both fuels in their electricity generation, some only gas. The share of renewable electricity is low to medium compared to the other countries, with several countries having a share of less than 1 % renewables. In contrast, Yemen produced 17 % renewable electricity but due to the low total generation, it only corresponded to 0.60 TWh in 2021. Countries in category B can only rely on domestic gas reserves, which is why they also use it as their primary resource for electricity generation. The share of renewables is also low to medium. Countries in category C have no or neglectable fossil reserves and therefore, have a more diverse electricity mix. Also, the share of renewables is medium to high compared to the other countries. Jordan is somewhat unique compared to the other two countries of category C, as the country started to develop local oil shale reserves some years ago, which they also aim at extracting and using for its energy generation in the future (Jordan Ministry of Energy & Mineral

Resources, 2020, p. 19). These reserves are not included in the official statistics on which the clustering of countries is based on. Furthermore, Hilpert et al. (Hilpert et al., 2020, p. 13) showed that electricity generation based on oil shale is very cost-intensive in Jordan and therefore not competitive with low-cost renewable energies. It is therefore assumed that oil shale will not play a major role in Jordan's future energy system even though this kind of resource is favoured by domestic stakeholders to increase the energy independence of the country (Komendantova et al., 2020, p. 10).

Compared to most MENA countries, Morocco and Israel are the only two countries that use coal in their electricity system, although they cannot rely on domestic coal mining. Moreover, Iran and the United Arab Emirates are until now the only two countries using nuclear in their electricity systems, but Egypt is also already constructing nuclear power plants. As of June 2023, in total 10.6 GW of nuclear power plants were operational or under construction in the three countries (World Nuclear Association, 2023a, 2023b, 2023c). The future use of nuclear has been controversially discussed in many other MENA countries for many years, but most of the plans are put on hold due to different challenges, such as limited water resources for cooling purposes or security issues related to project locations in earthquake-prone regions (Shalash, 2022).

It can be concluded that most of the countries rely on gas or oil for their electricity generation and that the share of renewables, in particular from solar power plants, is comparably low for a region that has substantial renewable potentials (Solargis s.r.o, 2023). Solar energy is the most promising renewable resource with solar radiations ranging between 4.5 kWh/m² in northern Tunisia and 6.8 kWh/m² in southern Yemen (Solargis s.r.o, 2023). Mean wind speeds vary between countries, ranging from low wind speeds of less than 3 m/s at 100 m in central Morocco, South-West Saudi Arabia and Yemen and high wind speeds of more than 10 m/s at 100 m in southern Morocco/Western Sahara, the coastal areas of the Suez Canal and the Gulf of Aqaba (Technical University of Denmark, 2023). Even though there are many hydro power plants installed (IRENA, 2016, p. 9), the future potential of hydroelectricity is limited in the MENA region (United Nations, 2023) due to increasing temperatures and a decreasing freshwater availability. The potentials of biomass/biowaste and geothermal are limited and present much more cost-intensive options for electricity generation, inter alia, because of a currently missing waste separation and collection management system in the region (Amroune et al., 2017, p. 26) and comparable high costs for geothermal energy production (IRENA, 2022g, p. 156). The high resource potential of mainly solar and wind leads to similar levelized costs of electricity (LCOE) for renewable energies across the region (Lux et al., 2021, p. 9). In fossil poor countries, such as Jordan and Morocco, renewable electricity from solar and wind are already cheaper than using natural gas or fuel oil (Benali et al., 2021, p. 6). The use of CSP in Morocco is an exemption, which will be further elaborated in Chapter 6. The cost for generating fossil electricity in resource-rich countries such as Bahrain, Qatar or Saudi Arabia is low but governmental subsidises make it even cheaper for consumers, which creates high opportunity costs for these countries (Eskandar, 2023).

A physical electrical interconnection of MENA countries' energy systems, such as it is the case with European systems, is only partly in place (Fischedick et al., 2020, p. 133) and resource trade among the countries is rare (Griffiths, 2017, p. 264). Prevailing geopolitical tensions among member countries used to prevent a full interconnection of all countries in the past, even though it would enable a more efficient use of renewables and would allow a better-balanced electrical grid. The former Desertec vision, in which interconnected Saharan countries wanted to produce renewable electricity for export-purposes to Europe failed not only due to a misguided influence from outside of the MENA region but also because of geopolitical tensions within the region (Schmitt, 2018, p. 763). However, some countries have already announced the establishment of interconnections through grids or pipelines, as they see the potential to reduce electricity surpluses and reduce the overall amount of installed capacities for power generation (Griffiths, 2017, p. 264).

2.1.2 Comparing Long-Term Electricity Targets

Available long-term renewable electricity targets are defined for many MENA countries in the Nationally Determined Contributions (NDCs) of the Paris Agreement and are mostly targeting the year 2030. In general, there are two different types of targets, one for future electricity generation from renewable energies and the other for future installed renewable energy capacities. Figure 2-3 illustrates the countries' long-term NDC targets for 2030 and compares the data with the respective status quo of either electricity generation or installed capacities of 2021, depending on the NDC target of the respective country. This comparison helps the reader to assess the feasibility of the renewable targets. Countries that are not mentioned in this figure either did not submit an NDC document or did not include any specific renewable targets.

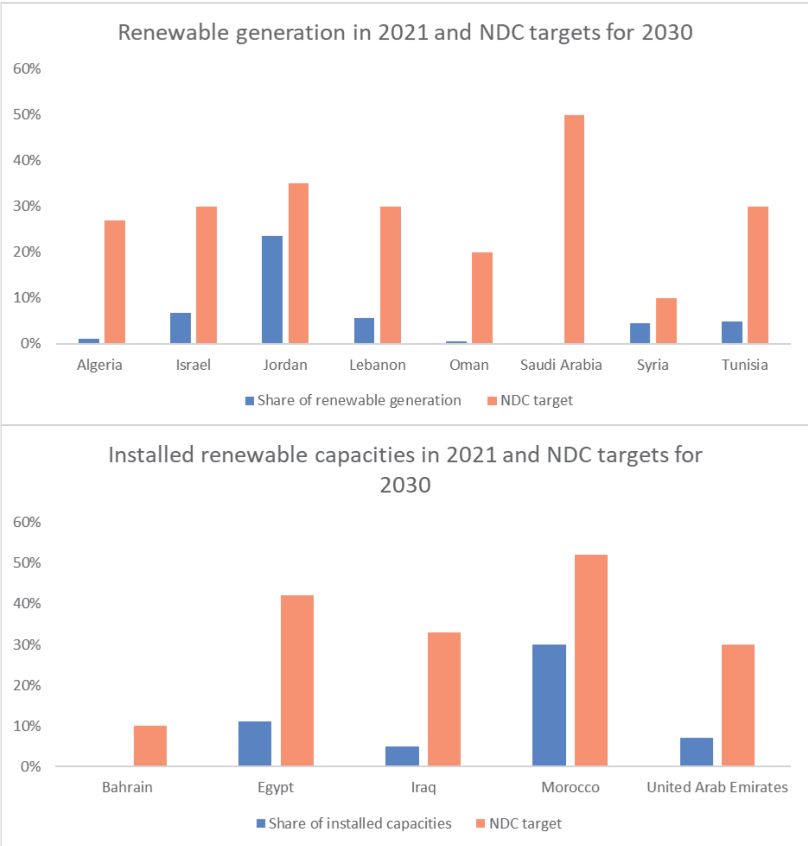

Figure 2-3 Renewable energies in 2021 versus NDC targets for 2030

Own illustration based on (IRENA, 2022a, 2022b, 2022c, 2022d, 2022e; Our World in Data, 2023; UNFCCC, n.d.)

In total, eight MENA countries published long-term renewable generation targets, which are illustrated in the upper part of the figure and are compared to the share of renewable generation in 2021 from Table 2-3. Targets range between 10 % renewable generation in Syria to around 50 % in Saudi Arabia by 2030. However, Saudi Arabia's share of renewable electricity production was less than 1 % in 2021. Jordan, in contrast, already produced 24 % renewable electricity in 2021 and aims at producing 35 % renewable electricity by 2030.

Comparing future NDC targets with installed capacities in 2021 is illustrated for five MENA countries in the lower part of the figure and shows a similar picture. The United Arab Emirates, for example, hold a share of 7 % renewable capacities in 2021 and aim at installing 30 % renewables by 2030. It is important to note that the country also includes nuclear in its renewable 2030 NDC target (United Arab Emirates Ministry of Climate Change & Environment, 2022, p. 12). The other countries using nuclear energy either excluded their future nuclear plans in their NDCs (such as Egypt) or did not mention the share of the potential contribution (such as Iran). Bahrein had no renewable capacities installed in 2021, but aims at installing 10 % renewable capacities by 2035. Morocco already achieved to construct a share of 30 %[1] renewables in 2021 and plans to increase the share to 52 % by 2030. As shown in Figure 2-3, the difference between the status quo and the stated goals is very large which is why it is questionable if the countries will be able to achieve their goals. Whether the goals can be successfully implemented is based on many factors, such as investment plans or coordination mechanisms (NDC Partnership et al., 2021, p. 3), but also on how realistically long-term goals have been chosen. Generally, it seems that targeting electricity generation instead of installed capacities shows more honestly how well the energy transition is advanced because installation does not necessarily mean that renewable capacities are running or that fossil capacities still get priority to feed electricity in the national grid.

Morocco, Jordan and Tunisia are among the countries that have realistic targets for future renewable energy generation. Morocco and Jordan are already close to achieving their targets, while Tunisia is further away.

It is important to note that many of the NDC targets are announced to be conditional, which means that the countries announced that they will only be able to achieve the specified targets with the help of international financial support. In contrast, unconditional targets are planned to be achieved with domestic financial resources but the targets are in most of the cases much lower compare to the conditional targets (UNFCCC, n.d.).

Related to the previously mentioned use of coal, Morocco will most likely be the only country in the MENA region using high amounts of coal for electricity generation after 2026 since Israel announced in its NDCs to phase out coal. New coal-fired power plants will however not be built in Morocco because the country signed the Glasgow agreement in 2021 (UK Government & United Nations Climate Change, 2021). Nevertheless, coal will continue to play an important role in Morocco's energy sector at least until the 2040s, since the government signed an agreement for an extended lifetime of the largest coal-fired power plant in 2020 (ONEE, 2021, p. 6).

2.1.3 Green Hydrogen Production

Green hydrogen can play an important role in future energy systems, which need to be decarbonised as soon as possible. Today, fossil hydrogen is mainly used in industrial and chemical processes, such as oil refining, steel production or fertilizer production (IEA, 2021, p. 20). Direct electrification is the most cost-efficient solution for many processes to become carbon neutral (Liebreich, 2021, p. 8). If an electrification is not possible, such as in the case of the fertilizer production, fossil hydrogen can be replaced with green hydrogen to achieve a full decarbonisation. Such hard-to-abate sectors might have high future demands for green hydrogen (IEA, 2021, p. 20; IRENA, 2022f, p. 39), which is why many countries around the globe are preparing themselves in taking root in this growing sector.

1 Other statistics name a share of 38% installed capacities by 2021 but they also include pumped hydro storage capacities, which are not included in these statistics. However, this statistic was chosen at this point for a better comparison of different countries.

Green hydrogen can be further processed to **green ammonia** or synthetic fuels, such as methanol, so that it can be used to decarbonise other hard-to-abate sectors (German Advisory Council on the Environment, 2021, p. 23). These derivatives require the input resource hydrogen, which is why they need to be included in the current discussion of designing the global green hydrogen market. Transporting hydrogen and its derivates would be possible via pipelines for gaseous hydrogen and via ships for liquified hydrogen, liquid organic hydrogen carriers (LOHC), ammonia and methanol (Staiß et al., 2022, p. 25). However, transportation costs of the derivatives vary strongly. Using a pipeline to transport green hydrogen being the most cost-efficient solution for distances at least up to 8,000 km (Staiß et al., 2022, p. 39). Transporting ammonia or methanol might be more cost-efficient for longer distances, but create additional costs for conversion and entail additional safety risks (Staiß et al., 2022, p. 65).

Selected colours of hydrogen and ammonia (German Advisory Council on the Environment, 2021, p. 16)

Green hydrogen is produced in an electrolyser and uses freshwater and renewable electricity as an input, which is why the production process does not generate any GHG emissions.

Blue hydrogen is produced through the reforming of natural gas combined with a carbon capture and storage process to capture the emitted CO_2 emission.

Yellow hydrogen describes the grid-connected production using the grid's electricity mix.

Pink hydrogen is produced of nuclear electricity in an electrolyser.

Grey hydrogen is produced through the reforming of natural gas without the carbon capture and storage process to prevent CO_2 emission.

Black hydrogen describes the gasification of coal.

Green ammonia can be produced in a Haber-Bosch process using green hydrogen and nitrogen (direct air capture).

Grey ammonia uses the steam reforming process with natural gas and therefore creates high amounts of GHG emissions.

The vicinity to Europe combined with high renewable potentials for solar energy (Solargis s.r.o, 2023) and wind energy (Technical University of Denmark, 2023), opens up new possibilities for MENA countries to substitute fossil export revenues with green hydrogen exports. Due to lower renewable potentials and higher predicted demands, Europe will most likely not be able to cover its green hydrogen demand of 20 Mt in 2030 on its own but will rely on hydrogen imports (European Commission, 2022, pp. 26–32). As of 1st December 2022, ten countries of the MENA region (Morocco, Algeria, Tunisia, Egypt, Israel, Jordan, Saudi Arabia, United Arab Emirates, Oman and Djibouti) either implemented official national hydrogen strategies or initiated studies on which such a strategy should be built upon (Mered, 2022). The Middle East is predicted to supply significant amounts of hydrogen and its derivatives mainly towards Europe as well as to some Asian regions (Mered, 2022). Besides national hydrogen strategies, many bilateral hydrogen agreements between different countries related to supporting or constructing green or **blue hydrogen** projects are also in place. Many GCC countries made agreements with European countries, such as Germany or the Netherlands, Asian countries, such as Japan or South Korea, or between neighbouring MENA countries, such as between Saudi Arabia and Oman (Heinemann et al., 2022, pp. 17–37). North African countries, such as Morocco, Algeria or Egypt, made mostly bilateral agreements with European countries such as Germany, Italy, Portugal or the Netherlands. As of January 2023, at least 59 hydrogen projects were under development in the MENA region. More than 85 % are planned to be green hydrogen and the rest are planned to be blue hydrogen or have not been further specified, yet (van Son, 2023). If the production of **yellow** or **pink** hydrogen will play a future role in the MENA region, is currently not predictable. However, if national restrictions are not sufficiently defined, at least the production of yellow hydrogen, using the grid's electricity mix, is very likely. The production of turquoise and black hydrogen is, on the other hand, very unlikely. As the local demand for using green hydrogen in the countries is relatively low and fossil rich countries are trying to elaborate new perspectives of replacing fossil rents with hydrogen rents, many of the projects are planned to be for export purposes or for both covering the local demand and exporting (van Son, 2023). Only a small portion of projects are planned to cover only the domestic demand in the countries. The ramp-up of the hydrogen market in the region is very fast, with an average of one new hydrogen project announced every week in the first half of 2022 (MEED, 2023). The production and use of other colours of hydrogen, such as pink, turquoise or black hydrogen (German Advisory Council on the Environment, 2021, p. 16) are currently not under discussion in the region.

Morocco's green hydrogen sector
As this dissertation has a special focus on the Moroccan energy transition, a short summary of country-specific information on the Moroccan hydrogen sector will be provided to understand the importance of this topic for the country and for this dissertation. Because Morocco, compared to other MENA countries, has no available gas reserves that could easily be used to produce blue hydrogen, the country focuses on producing green hydrogen and green ammonia and published its national hydrogen strategy in 2021 (MEME, 2021, p. 5). Accordingly, the country is following two long-term objectives. The first objective is to make its fertilizer production more sustainable and to replace currently imported **grey ammonia** – which is needed together with domestically available phosphate reserves for producing fertilizers – with its own production of green hydrogen and further processing of green ammonia. In 2021, Morocco imported more than 1.6 million tons of ammonia from different countries such as Russia, Trinidad and Tobago or Algeria with a trading volume of 770 million US dollars (World Integrated Trade Solution, 2023d). Imports increased from 1 million tons of ammonia in 2016 (World Integrated Trade Solution, 2023b) to 1.9 million tons of ammonia in 2020 (World Integrated Trade Solution, 2023c). In terms of exports, Morocco, following China, was the second largest exporter of phosphorous fertilizer in the world, a product being made of ammonia and phosphate (Fertilizers Europe, 2023), with an export trade volume of more than 1.1 billion kg in 2021 (World Integrated Trade Solution, 2023a). Thus, fertilizer production and export are extremely important for the country. The export of hydrogen and ammonia, which is the second objective of the national hydrogen strategy, would be another possibility for the country to gain export revenues (MEME, 2021, pp. 10–13). Morocco is currently focused on exporting ammonia instead of hydrogen, which might be based on the fact that the country needs this type of resource domestically and because of the existing infrastructure for the import of ammonia and a lack of hydrogen pipelines towards Europe. As of August 2023, there were at least eight large-scale green hydrogen projects with a total capacity of more than 7 million tons of ammonia annually under development, which are partly planned for the domestic use and for exports towards Europe (Blohm, 2023b; Enerdata, 2023). Many foreign stakeholders are involved in developing the projects, such as the German Kreditanstalt für Wiederaufbau (KfW), CWP global, Fusion Fuel or Total Eren. Moroccan stakeholders are mainly the Office Chérifien des Phosphates (OCP), which is the Moroccan fertilizer company, the Moroccan Agency for Sustainable Energy (MASEN), the Institut de Recherche en Énergie Solaire et Énergies Nouvelles (IRESEN) and the University Mohammed VI (UM6P).

2.2 State of Research

This dissertation can be embedded in the broad field of climate science and the research on climate change mitigation. More precisely, it discusses how countries can transform their energy sectors to achieve carbon neutrality and thus trying to limit the increasing global average temperature to a maximum of 1.5° Celsius (UNFCCC, 2015, p. 2). Each of the scientific articles include a concise state of research related to the respective focus of the article. Therefore, the here presented state of research focuses on the overall topic of energy transitions, sustainability and why we need sustainable energy transitions instead of only replacing fossil fuels with renewable energies.

A very short history of climate change and why we need energy transitions

The finding, that increased GHG emissions lead to an increasing global temperature – today known as climate change – was already discovered by the Swedish scientist Svante Arrhenius in the year 1896 (Arrhenius, 1896). Until the 1960s, a few more scientists and research groups analysed the increasing CO_2 concentrations (Franta, 2018, p. 1024) and even the American Petroleum Industry was already aware of the negative impacts on the Earth's climate using fossil fuels in the 1950s (Teller, 1960, p. 58). In 1967, the first global climate model had already been developed (Manabe & Wetherald, 1967). However, the concept and consequences of global change received public attention from the broader population with the foundation of the IPCC in 1988. The publication of the first assessment report in 1990 presented a comprehensive analysis of a changing climate in detail for the first time (IPCC, 1992). Accordingly, the human influences on rising temperatures and changing climate conditions were confirmed (working group 1), the related consequences for our current way of living were identified (working group 2) and appropriate mitigation measures were presented, one of which is the replacement of fossil fuels with renewable energies (working group 3). Historical developments to increase the use of fossil energies and to achieve higher degrees of industrialisation took many decades (Solomon & Krishna, 2011, pp. 7423–7424), which is why this renewable transition is also supposed to be time consuming (B. Sovacool, 2016, p. 1). The historically created path dependency and the amount of implemented fossil lock-in factors influence how different the new, carbon neutral, future will be compared to the current, carbon intensive, status quo and will impact how much time this transition will need to be successful (B. Sovacool, 2016, pp. 4–5). As energy plays a dominant role in all aspects of life and requires fundamental changes across all fields, one can refer to the necessary "trajectory of change" (Williams & Doyon, 2019, p. 145). The main objective of this primarily techno-economic development is to replace carbon-intensive fossil energies with renewable technologies and to find financially viable solutions for these new energy systems (Markard, 2018, p. 628).

This dissertation is based on the recognition that the shift towards renewables will mostly not happen on its own. It seems as if there is not an important techno-economic reason for such a development today, such as the former drive for an increased industrialisation, the discovery of new sources of energy or other innovations and circumstances which required a fast adaptation (Flavin & Dunn, 1999, p. 24). Even though climate scientists have proven the need for limiting GHG emissions, the human rationality of ideologies, uncertainties and perceived interventions in the current way of living, among others (Gifford, 2011, pp. 291–297), prevent to act as an urgent rationality (B. K. Sovacool et al., 2015, pp. 96–97). Therefore, supportive measures at the local, national and international level, to enable and fasten this urgently needed transition need to be developed, because governments have the power to guide this transition "in a certain direction, e.g. towards sustainability" (Kitzing & Mitchel, 2014, p. 2).

The need for a sustainable development

Technologies create many environmental and social impacts (O'Neill et al., 2018, p. 7; Raworth, 2012, p. 12), which is why interdependencies and influences between technological, environmental and social aspects need to be carefully studied. Combining these aspects to achieve an environmentally friendly and socially just energy generation, leads to the concept of *sustainability*. In 1987, sustainability was defined by the Brundtland Commission of the United Nations as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations World Commission on Environment and Development, 1987, p. 16) and that "sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs" (p.17). The Agenda 2030 of 2015 defined that a sustainable development can only be achieved, if the economic, the social and the environmental dimension of development are considered "in a balanced and integrated manner" (United Nations, 2015, p. 3). In 1992, Mitlin published a literature review on the topic of sustainable development, which already originated in the 1970s, including critics and opportunities of such a development, such as that this concept has no clear theoretical approach and does not require any specific policy interventions, but that it assigns values to ecosystems and social needs in decision-making processes (Mitlin, 1992). In a more recent publication, Klarin (2018) analyses the history of sustainable development and its importance on the international level.

In addition to the more social requirements of intergenerational sustainability, there are also pressing environmental needs that necessitate sustainable development. Rockström et al. (2009) have identified nine interconnected planetary boundaries that define a safe space for humanity and whose crossing could lead to an uncontrolled and unpredictable change in the Earth's bio-physical system. Accordingly, not only climate change, but also biodiversity loss, global freshwater use, land use change and chemical pollution, among others, are affected and threatened by humanity's current way of life (Rockström et al., 2009, p. 473). Therefore, sustainable development is required not only related to energy production, but related to all aspects that have an impact on critical ecological or environmental elements. Raworth (2012) further developed the concept of planetary boundaries and combined the bio-physical thresholds with a social foundation, including for example health, income, gender equity or education, to illustrate a safe and socially just framework for humanity. This work served inter alia for developing the Sustainable Development Goals (SDGs) to end poverty and achieve a sustainable development at a global scale (United Nations, 2015).

Sustainable energy transitions

Like the previously described content on sustainability, there is also no single definition for the term sustainable energy systems but different research approaches exist to analyse sustainability pathways and trajectories of energy transitions. Geels et al. (2016) proposed the definition of resulting "major changes in buildings, energy, and transport systems that substantially enhance energy efficiency, reduce demand, or entail a shift from fossil fuels to renewable inputs. These system transitions entail not only technical changes, but also changes in consumer behaviour, markets, institutions, infrastructure, business models and cultural discourses" (Geels et al., 2016, p. 577). Williams and Doyon (2019) wrote "that we cannot achieve a sustainability transition without justice, indeed that an unjust transition is not sustainable" (Williams & Doyon, 2019, p. 144). In recent years, different frameworks have been developed to achieve a more sustainable or just energy future, which will be presented and compared to the here presented enabling framework in Chapter 8.2.

The growing body of literature on energy and social sciences recognises that research on energy transitions should not only include the techno-economic perspective of producing renewable electricity, but "enable us to comprehend better the sources and dynamics of energy problems and develop feasible and acceptable solutions to them" (B. K. Sovacool et al., 2015, p. 95). The authors' stress the importance of conducting interdisciplinary research to incorporate all dimensions of energy transitions (B. K. Sovacool et al., 2015, pp. 97–98). While former energy systems were based on centralised fossil power plants, which seemed to be less present in our daily life, using decentralised renewable technologies seem to be more prominent, at least, in a visual manner (Price et al., 2022, p. 8). Economic-wise, producing decentralised renewable electricity can provide both positive and negative effects compared to fossil electricity, while positive effects appearing to be the strongest (Maradin et al., 2017, p. 56). Simultaneously, new economic opportunities can emerge based on changing structures of a future decentralised energy generation from renewables, especially for rural areas. Inglesi-Lotz (2016) found a correlation between increasing renewable energy productions, a growing GDP as well as increased employment possibilities and a growing share of R&D expenditures in Organisation for Economic Co-operation and Development (OECD) countries between 1990 and 2010 (Inglesi-Lotz, 2016, p. 13). However, economic opportunities for small-scale actors only result when the right policy instruments are implemented, which will be shown in this dissertation in Chapter 6.

Even though fossil energies still dominate the production of electricity in many countries of the world, the global share of renewable electricity increased to more than 28% in 2021 (Our World in Data, 2023). As different countries have progressed to different degrees, some countries are already working on the next phase of their energy transition, which includes the coupling and decarbonisation of other sectors than electricity (Markard, 2018, p. 630). Therefore, this dissertation does not only focus on decarbonising electricity production but also on the production of green hydrogen.

Green hydrogen will play an important role in decarbonising other sectors than electricity, namely hard-to-abate sectors, which cannot be electrified (IEA, 2019, p. 23; IRENA, 2022f, p. 15). The global demand of green hydrogen in a carbon neutral energy system ranges between 530 Mt (IEA, 2021, p. 151) and 614 Mt (IRENA, 2022f, p. 15) by 2050, based on different assumptions and pathways. As the production of green hydrogen requires the use of resources, such as freshwater or renewable resources (most likely wind or solar), some areas of the world are better suited to competitive large-scale production than others. It follows, that green hydrogen will most likely be traded between different countries. Due to several reasons, such as the high demand for hydrogen and the limited availability of space in the Global North, it is predicted that countries of the Global North will import significant amounts of green hydrogen from countries of the Global South (Hydrogen Council & McKinsey&Company, 2022, pp. 9–13; Van de Graaf et al., 2020, p. 3). History has shown, that the global trade of energy can result in an extractive and post-colonial relationship, in which countries of the Global South are risking to be exploited for the benefit of countries of the Global North as it has been the case for coal, oil and gas (Blondeel et al., 2021, p. 2; Van de Graaf et al., 2020, p. 4). Therefore, the topic of sustainability related to the production of green hydrogen will be of importance to prevent and reduce inequalities and burdens.

Part II – Publications

3 An Enabling Framework to Support the Sustainable Energy Transition at the National Level[2]

Marina Blohm

[2] published as: Blohm, M. An Enabling Framework to Support the Sustainable Energy Transition at the National Level. *Sustainability* 2021, 13, 3834. https://doi.org/10.3390/su13073834

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Article

An Enabling Framework to Support the Sustainable Energy Transition at the National Level

Marina Blohm

Department Energy and Environmental Management, Europa-Universität Flensburg, Auf dem Campus 1b, 24943 Flensburg, Germany; marina.blohm@uni-flensburg.de; Tel.: +49-461-8053028

Abstract: The world is fighting against the impacts of the climate crisis. Although the technical feasibility of 100% renewable energy systems was already verified by a variety of research studies, there were still more than 200 GW of unsustainable new coal power capacity under construction at a global level in 2018. To achieve the required carbon neutrality, current energy systems need to be transformed toward sustainable energy. The review of the literature has shown that several barriers for carbon-neutral technologies exist, which currently impede the sustainable transition. This paper focuses on the development of an enabling framework to overcome existing barriers to facilitate sustainable and carbon-neutral technologies at the national level. Additionally, it should support decision makers to consider all underlying criteria of this urgently needed energy transition. The criteria of such an enabling framework can be classified in 11 categories, which are (1) environmental and ecological protection; (2) society, culture, and behavior; (3) equity and justice; (4) knowledge; (5) energy markets; (6) energy policy; (7) legal requirements; (8) finance; (9) institutions; (10) infrastructure; and (11) clash of interests. Even though some criteria differ from country to country, a strong governmental support for the transition is always required to be successful.

Keywords: energy transition; enabling framework; technology transfer; knowledge transfer; sustainable development; renewable energies

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1. Introduction

The need for changes in current energy systems to achieve carbon neutrality by mid-century, as determined by the Paris Agreement, is commonly known by policymakers [1]. Increasing the share of sustainable carbon-neutral technologies as soon as possible is needed to be able to decrease the greenhouse gas (GHG) emissions and to limit the global average temperature increase at preferably 1.5 degrees Celsius above preindustrial levels. Even though this knowledge exists and the negative impacts of the climate crisis are more and more present in many countries of the world, the renewably produced share of global electricity in 2017 was just at around 26.5% [2].

A variety of research verified the technical feasibility of 100% renewable energy systems (RES) in a number of countries by the year 2050, such as Hansen et al. [3] who published a state of research paper including 180 published articles dealing with the transition toward 100% RES. According to this work, the majority of studies confirm the technical feasibility of 100% RES for electricity sectors or a multisector approach. The transformation toward renewable energy or other sustainable carbon-neutral technologies is necessary to limit GHG emissions and to reduce the negative effects of pollution. Countries, such as Portugal for example, already covered 100% of electricity production from wind and hydro energy throughout the month March in 2018 [4]. However, this is rather an exception than the rule. In 2018, 236 GW of coal power capacity were under construction globally added with 338 GW of planned capacity in preconstruction status [5]. The question why such carbon-dioxide-emitting technologies are still under construction on a large scale needs to be raised. The answer can be found in numerous existing barriers that prevent the increasing penetration of renewable energy technologies while promoting fossil fuels, which is demonstrated in this paper.

According to the special report *Global Warming of 1.5 °C* of the Intergovernmental Panel on Climate Change (IPCC) [6], total cumulative CO_2 emissions amounted to 2230 $GtCO_2$ until the end of 2017, and the remaining budget to limit the average global temperature rise to 1.5 °C until 2050 was at 420 $GtCO_2$ (January 2018). Considering the nationally determined contributions (NDCs), 95–130% of the remaining budget will be spent until 2030. At the same time, the electricity sector just contributed to approximately 44% to the total CO_2 emissions in 2018 [7]. These two aspects indicate the urgent need to foster the decarbonization of all sectors as soon as possible.

A short historical review of how and why the use of fossil fuel accelerated in the past indicates a high inertia of energy system transitions. According to Solomon and Krishna [8] scarcity of wood, technological advances in using coal as the primary energy for manufacturing, electricity generation, transportation, and urbanization were the main reasons for fossil fuels to become the most important primary energy source around the globe. However, this transition from wood to fossil fuels took up to 400 years but resulted in industrial advances to meet the increasing energy demand and enabled rising economic activities. Specific historical events such as the OPEC oil embargo in 1973/1974 forced countries to quickly replace the previously high amount of oil with another cheap energy carrier, such as coal and nuclear energy, to limit the negative effects of the following global recession. The oil embargo required a rapid response of governments to decrease the dependence of oil imports and, optimally, increase the use of domestic or widespread resources.

However, energy from fossil fuels was cumbersome to develop and respectively expansive, which is one of the reasons, why the production of fossil fuel was initially promoted and is still being promoted through political and financial measures today [9]. Nowadays, affordable energy is vital to guarantee the access to energy for all and to enable the competition among global market players. However, an implementation of new technologies, such as renewable energies, needs to be promoted as long as a fair competition with existing technologies is possible [10]. Otherwise, distortive market effects or other inequalities prevent an increased integration of new market players. Nevertheless, neither the pure transfer of technology and knowledge nor the sole design of a nondistortive policy framework indicate that a successful promotion of renewable energies on a large scale can be achieved as other criteria can prevent the transition of entire energy systems. An enabling framework that encompasses a full set of conditions and requirements (hereinafter named criteria) to overcome all existing barriers that prevent the penetration of renewable energy technologies (RETs) [11] is required. The removal of barriers should involve all potentially affected stakeholders such as policy makers, companies, or members of the public through participation and capacity building to gain a broad acceptance of the population [12]. Most of the criteria are not related to technical issues [13] but depend on reducing barriers on dissemination and transfer of technology, mobilizing financial resources, supporting capacity building in developing countries, and other approaches to assist in the implementation of behavioral changes and technological opportunities in all regions of the globe [13]. Barriers can be very individual and "may be specific to a technology, while some may be specific to a country or a region" [11] (p. 3). The entirety of framework criteria can be seen as a module kit, with which each country or region can build upon their specific framework.

This paper focuses on the development of an enabling framework to overcome existing barriers to facilitate sustainable and carbon-neutral technologies at the national level. Additionally, it should support decision makers to consider all underlying criteria of this urgently needed energy transition. The development of such an enabling framework provides structured knowledge on existing barriers as well as key enablers to support the increasing use of clean technologies. However, the presented criteria are not just focused on the construction of clean technologies but on the transformation of the entire social system including aspects such as social equity and distribution. Therefore, it is important to understand the linkages between the human social system, the environment, and the energy system, which is described in Section 3. The technical feasibility of such systems is not questioned as the analysis of 180 publications is plausible and comprehensible verified [3]. However, a detailed framework that guides decision makers through the energy transition is important, as the transition currently stagnates in many countries although the remaining carbon budget just gives little time to still limit the negative impacts of the climate crisis. The state of the research concerning existing barriers to renewable energies followed by the gaps in current research is presented in Section 2. Section 3 describes the categories and criteria of the enabling framework in detail. Section 4 focuses on a discussion about further research and recommendations. The paper ends with a conclusion in Section 5.

2. Materials and Methods

Current energy systems are dominated by the use of fossil fuel resources and the transition toward sustainable and carbon-neutral technologies seems to progress very slowly in many countries around the world. Therefore, this paper deals with the identification of barriers and enablers to facilitate the energy transition at the national level. The following research questions are answered: (1) Which dimensions and criteria can act as barriers or enablers for sustainable and carbon-neutral technologies to support the reduction of fossil fuel technologies? (2) Which criteria of an enabling framework are most important when analyzing the national level of the energy transition? In other words, which criteria seem to be more important at the regional, business, or project level? (3) Which criteria are important to strive for the decarbonization of the entire systems and thus, are important to push sector coupling? (4) Which criteria can or should be treated differently from country to country?

The enabling framework was developed through an extensive literature review and analysis. The following Section 2.1 summarizes the main findings of this analysis and includes the most important motivations transforming existing energy systems. Section 2.2 describes the gaps of current research concerning an enabling framework. Both sections combined lay the foundation for the developed enabling framework in Section 3.

2.1. State of Research

The literature review included both scientific literature and gray literature and was mainly focused on the national level of the energy transition. Enabling framework, enabling environment, renewable energy barriers, and technology transfer were relevant keywords to identify appropriate literature. The limitation of analyzing the national level of the energy transition was chosen to generate an overall approach that is not limited to the transfer of clean technologies or the implementation of policies for specific projects.

The term enabling framework is not consistently defined in existing literature. Sometimes, the term enabling environment is used instead but focuses on the same content. It is often used by addressing only one field of transformation, such as the transfer of technology or the necessary policy framework to support renewable energies, but not by including all criteria that are relevant to successfully transform entire energy systems toward sustainable and carbon-neutral systems.

One of the earliest international programs that pointed out the importance of necessary measures to support and promote environmentally friendly technologies was the Agenda 21, which was published by the United Nations in 1993 [14]. Accordingly, a successful transfer of environmentally friendly technologies to developing countries is crucial when striving for a sustainable development and reducing poverty and inequalities. That is why it is much more important than just for the sole transfer of clean technologies. It is instead related to the whole system of socioeconomic, cultural, human, environmental, and organizational aspects and emphases combined with the transfer of know-how through capacity building in all the aforementioned areas. However, as stated by one of the proposed activities (Section 34.18. d.) of the Agenda 21, the specific relation to an enabling framework is given. The Intergovernmental Panel on Climate Change (IPCC) published in their special report Methodological and Technical Issues in Technology Transfer of 2000, the chapter 4 "Enabling Environments for Technology Transfer" [12]. This publication already considers a wide range of policy tools for the successful transfer of technology and highlights the importance of different participation processes and capacity building. Participation connects different social actors and helps to find good solutions for different countries or regions among the variety of available options concerning technologies or policy tools. However, Pueyo et al. [15] criticized such enabling frameworks for the transfer of technology as they are mostly just successful on the project-by-project basis and not by transforming entire energy systems. In the year 2001, J.P. Painuly published "Barriers to Renewable Energy Penetration; A Framework for Analysis" [11]. Although it describes barriers instead of favorable framework conditions, it is fundamental for further development for this publication as important aspects are already covered.

Scientific literature that deals with the description and analysis of barriers to facilitate the use of sustainable and carbon-neutral technologies can be classified according to the scope, which can be at the international, national, regional, or city level and the business, technology, or process level. The decision to concentrate on the national level was mainly due to the number of available publications and the relationship of barriers and enablers tackling the entire system perspective, which is further described in Figure 1. The national level of the energy transition can be separated in two research areas, which are the energy system modeling perspective and the economic analysis of drivers and barriers to facilitate the use of clean technologies. Country-specific energy system modeling results can, for example, be found in [3,16–18]. These studies lay the foundation for the technical feasibility of 100% RES. The economic analysis of drivers and barriers to facility the energy transition at the national level can be seen as the next step dealing with the implementation of sustainable energy systems. The focus of this national perspective of the energy transition can either be country-specific countries (cf. [19–21]), on technology-specific (cf. [22–24]) or related to specific criteria (cf. [11,12,15,25,26] such as in this paper. The analysis of these publications has shown that topics such as equity, justice, knowledge transfer, environmental impacts besides CO_2 emissions, or the strengthening of the domestic economy are in most of the cases not mentioned at all. However, publications such as [11], [24], or [26] already draw the attention to a variety of the barriers that are also presented in this paper.

Besides scientific publications, there have been substantial contributions from NGOs or nonprofit organizations to give recommendations about a sustainable transition toward 100% RES, however, without a specific focus on an enabling framework (cf. [27]). Unfortunately, no work describes the totality of an enabling framework in one single approach.

The aforementioned examples lead to the conclusion that the best-designed enabling framework cannot work properly if two basic enablers are missing. According to Pueyo [19], initially, the resource itself (e.g., wind speed or solar radiation) needs to be sufficiently available. Second, if the resource demand is given and the relevant technology and knowledge could be transferred, a governmental support and commitment for the transition must be guaranteed. Such a support must foster the improvement of the local manufacturing and institutional sector instead of preferring the pure import of foreign equipment or workers. However, if countries dispose of high amounts of domestic fossil reserves, the government must be willing to decrease the use of these reserves and consequently stop all related fossil fuel subsidies. Otherwise, no new industry would be able to compete with such existing market players. Solomon and Krishna [8] analyzed different governmental reactions after the oil embargo in the 1970s. Accordingly, governmental decisions were responsible for the success or failure of the energy transition reducing the import of OPEC-oil in Brazil, France, and the United States. These historical developments have shown that well-managed transitions combining the three dimensions of supporting niche and novel innovations, building sociotechnical regimes of social groups and networks, andsustaining sociotechnical landscapes of the exogenous environment are the most successful [8].

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The motivation behind the transition toward high-share renewable energy systems can vary as well. The authors of [28] name five different motivations that support changes in energy systems:

- Cost minimization of the optimal power dispatch
- Least-cost access to electricity and grid expansion
- Electricity decarbonization accompanied by increased energy independence
- Climate related goals
- Or other cost-minimization objectives

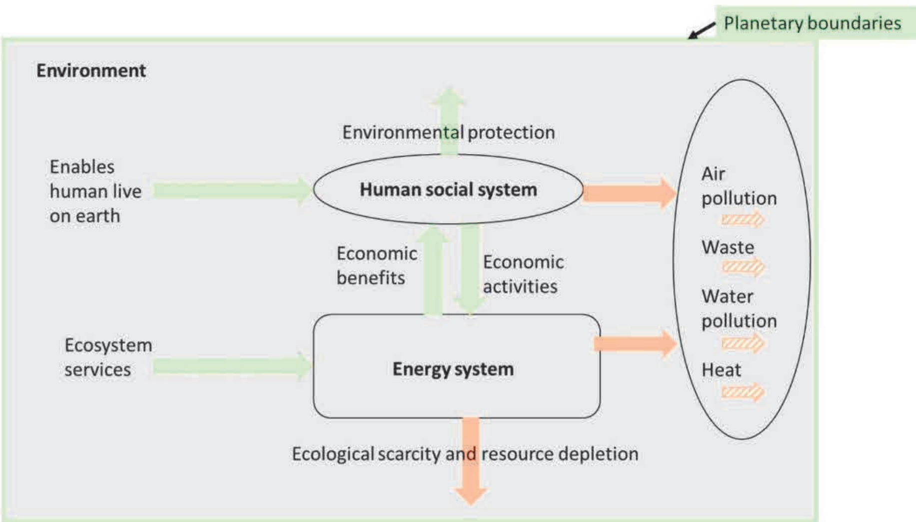

Figure 1. Human-energy–environment trade-off. Illustration based on [29,30] (dark green = positive inputs/outputs; dark orange = negative outputs; striped orange = negative outputs when critical values are crossed).

All motivation results in very different future energy system pathways but most likely achieves the common goal of carbon neutrality. By studying the transition toward 100% RES to meet the targets of the Paris Agreement, it is assumed that climate change mitigation combined with finding the least-cost solution is the most relevant motivation. In doing so, it is neglected that a number of economies are either financed by the export of fossil fuel resources or are striving for energy independence without having any domestic fossil fuel resources. No matter which motivation stands at the beginning of the transformation, the use of domestic renewable resources can help to achieve the underlying motivations.

2.2. Gaps in the Current Research

The research found several aspects that were not included in the analyzed literature but helps to understand the national level of the energy transition and thus forms a comprehensive enabling framework, which tackles the three dimensions of sustainable development: environment, society, and economy. First, the transition of entire energy systems instead of electricity sectors alone is not considered appropriate. The transition of the electricity sector is much easier to handle, as only renewable energy technologies must be supported. The production of renewable electricity has advanced considerably within the last decades, and the priority feed-in of renewable electricity was implemented in a number of countries. The transition of the transportation and heating and cooling sectors is more challenging as electricity must be converted in other sustainable and carbon-neutral fuels. Sector coupling is the term that is used to describe the elimination of all kinds of fossil fuels in the heating, cooling, and transportation sector and to use renewably produces electricity instead [18]. This is also the reason why the enabling framework is not just about increasing the share of renewables but also about decarbonizing entire energy systems.

Second, as already mentioned in the previous chapter, a lot of progress was achieved concerning the pure transfer of technology toward developing countries. However, this pure technology transfer does not provide as many benefits to the recipient country as it would be possible with the implementation of their own economic and industrial structures. Pueyo [19] analyzes different case studies in which the strengthening of a country's own economic activities leads, in most of the cases, to financial benefits and job creation. However, this publication is very much focused on special projects and not on the transformation of entire energy sectors, which is why this approach needed to be further developed and integrated in the overall approach of an enabling framework.

Third, the importance of identifying knowledge gaps and thus the strengthening of knowledge about the importance of stopping the climate crisis and the criteria of an enabling framework are not prioritized enough in existing literature. Without knowledge or the knowledge transfer, countries would not benefit from a successful transformation. The developed enabling framework includes knowledge as its own independent category and additionally connects other categories with further aspects of knowledge. Finally, most of the analyzed publications talk about existing barriers and not about criteria that need to be fulfilled (cf. [11,12,25]. Existing barriers can be specific to a situation of a country, whereas the elaboration of criteria that need to be met allows a better transferability of the entire framework toward different countries or case studies.

3. Results

The development of renewable energies has shown that many barriers in different fields exist. The following Figure 1 describes the interdependencies between the environment, the human social system, and the energy system, which is relevant for the further design of the enabling framework.

Environmental economic theories draw the attention to the human–environment relationship; according to which, there is a strong interdependence between the social and economic system and the provision of environmental assets [29]. Other environmental theories analyze the economy–environment trade-off, whereas economic benefits can just be generated while depleting resources and leading to an ecological scarcity [30]. Combining both approaches and linking them to the concept of a sustainable development can help to understand the importance of a comprehensive view on energy generation at the national level. The transformation of energy systems should include the environmental, social, and economic dimension to encompass all positive and negative aspects for the society. Human life on earth has always led to the generation of negative outputs such as air and water pollution, waste, and heat generation. However, we have nowadays reached critical values that urgently require changes in human behavior.

Table 1 names the criteria of an enabling framework for the transition toward 100% renewable energy systems, which can be summarized in 11 categories under the three dimensions: environment, society, and economy. The 11 categories are (1) environmental and ecological protection; (2) society, culture, and behavior; (3) equity and justice; (4) knowledge; (5) energy markets; (6) energy policy; (7) legal requirements; (8) finance; (9) institutions; (10) infrastructure; and (11) the clash of interests.

Table 1. Categories and criteria of the enabling framework.

Category	Criteria
Environmental and ecological protection	Planetary boundaries
Society, culture, and behavior	Consumer acceptance Social acceptance Public awareness and contributions
Equity and justice	Distributional equity Climate and resource justice
Knowledge	School education Highly skilled workers Highly skilled policy makers and decision makers Information and awareness
Energy markets	Liberalization of energy market Elimination of trade barriers Strengthening domestic economies Market infrastructure Ownership structure
Energy policy	Regulatory body to promote the use of CO_2 neutral technologies Good governance Long-term predictability
Finance	Financial co-operations Economically viable cost structures Competitive and reliable capital market Adequate energy pricing Financial participation
Legal requirements	Standards, codes, and certification Elimination of administrative barriers Legal aspects
Infrastructure	Strengthening existing local infrastructure Efficient power grid operation
Institutions	National systems of innovation Independent professional institutions Research and development
Clash of interests	Lobbyism

3.1. *Environmental Dimension of the Enabling Framework*

The transformation of energy systems must combine what is socially just with what are environmentally friendly measures. No data are available that the eradication of poverty, which is the most important social goal at the global level, increases environmental degradation [31]. However, some welfare-increasing developments in industrialized countries have significant influences on the environment. The last decades of research have shown that human activities accelerate the global heating and eventually lead to irreversible changes of environmental degradation and biodiversity loss, if no serious changes in current trends occur. Some of these changes, such as the increasing air and water pollution, the change of land use or the extinction of species, would make life and food production impossible in some areas of the world. That is why the protection of the environment is one important element for the energy transition.

In 2009, Rockström et al. [32] introduced the framework of planetary boundaries, which identified critical values of nine earth-system processes that define a "safe operating space for humanity". Accordingly, all nine processes are interlinked, and the crossing of the critical values can lead to disastrous consequences for human life on earth. Three of the nine boundaries, which are climate change, rate of biodiversity loss, and nitrogen cycle, have already crossed the proposed critical values. The necessity of a decarbonized energy sector, which is the focus of this paper, can directly be linked to the boundaries climate change and rate of biodiversity loss. The emission of carbon dioxide from fossil-fuel energy generation accelerates the increase of the global average temperature. In the long-term, this global heating causes significant impacts on the stability of ice sheets, the extinction of species, negative health effects caused by air pollution, or land-use changes, just to name a few [32].

The use of environmentally friendly technologies in the energy sector to achieve a net-zero carbon emission as soon as possible is the only way to stop current trends of GHG emissions. The economy–environment trade-off must clearly favor the careful use of natural resources as well as the emission abatement instead of receiving economic benefits from increasing economic activities. Concepts such as the "valuation of the environment" and the "internalization of external effects" must be integrated in decision-making processes [33]. Otherwise, fossil energy systems appear to be cheaper compared to renewable energy systems, which they are not necessarily [34].

The environmental dimension is highly interlinked with all other dimensions and criteria that are be presented in the following section, as all human actions have a significant influence on the environment. It is therefore not required to specify a number of separate criteria. The reduction of GHG emissions and the limitation of environmental degradation in planning processes are for example integrated in the criteria energy policy (Section 3.3.2) and legal requirements (Section 3.3.4), respectively.

3.2. Societal Dimension of the Enabling Framework

The role of the society to drive and foster sustainable development is crucial. The following sections describe the importance of knowledge, equity, justice, and behavior, as these aspects need to be considered because no one and no country should be left alone with the increasing impacts of global heating.

3.2.1. Society, Culture, and Behavior

An increased consumer and social acceptance is directly linked to social processes to implement structural changes and to adopting social consequences to support the transition. The normal consumer, who has no environmental-related background, needs information on technologies, products, and the consequences of consumption patter or on environmental-related effects to be able to make informed choices [11,14]. A mixture of product labeling and information campaigns on the advantages of environmentally friendly technologies and products enables the consumer to decide about the consequences of consuming. Energy and environmental-related behavior of people, either individually or collectively, have a great potential for advancing the society but only if governments set the right signals [35]. Furthermore, the social acceptance of the society toward decentralized energy generation must be taken into account and guided carefully. The broad society must be willing to accept changes in current energy systems due to presenting the advantages of renewable energies, for example, and involving local citizens in decision-making processes ideally at a very early stage. Through this approach, citizens have the impression that they can decide on changes and that they are not just confronted with decisions and the underlying consequences. As decentralized power plants could have aesthetic impacts on the landscape, these changes must be communicated neutrally to the local population [11]. The last years have shown that the engagement of the population through specific social movements has increased concerning climate related topics. The movement "Fridays for Future" is just one example of raising voices for a more ambitious climate policy all over the world. The influence of the civil society as well as nongovernmental organizations is important for demanding a stronger governmental focus on the transformation of energy systems. Overall, it can be summarized that the acceptance of the broad population can be very helpful to achieve behavioral changes and consumer acceptance.

3.2.2. Equity and Justice

All aspects of equity and justice need to be cautiously taken into account because the transfer of technology and knowledge can effect different issues of justice and distribution [12]. Poverty and a lack of access to electricity is much more prominent in developing countries. At the same time, those developing countries depend on co-operations and support of industrialized countries due to a lack of knowledge and economic development. That is why a successful collaboration concerning the transfer of technology and knowledge must be beneficial for developing countries to achieve a certain standard of living. Additionally, the most vulnerable countries to global heating are and were not the biggest contributors to the climate crisis, but they must deal with the environmental degradation. The transfer of technology and knowledge can be a chance for developing countries to fight against poverty and environmental degradation at the same time. Besides this co-operation between countries, the consideration of equity and justice on a country-level must be considered [12]. The allocation of newly constructed power plants, the construction of schools or capacity-building institutions, and the implementation of environmental regeneration measures require decisions that directly affect the local population. Such decisions must be transparent and consistent among a country, so that all parts of the population are able to benefit from the transition. On the other hand, the depletion or competition of natural resources must be prevented. Water, for example, that is urgently needed as drinking water or land that is needed for agricultural purposes should not be used for energy production.

3.2.3. Knowledge

In most of the publications about an enabling framework, the aspect of knowledge is not as prominent as in this paper, as it is normally just one aspect among others describing the necessity of transferring knowledge toward workers and policy makers. However, the importance of such a knowledge transfer leads to a further analysis. The creation of knowledge begins with a fundamental and appropriate school education. According to the United Nations Department of Economic and Social Affairs [36], there were still more than 260 million children that have no access to school education in 2017 and about 750 million adults remained illiterate in 2016. These numbers show that a fundamental school education is currently not available globally. However, the lack of school education leads to problems in knowledge transfer to workers as basic knowledge is missing. Different case studies in Chile have shown that human capital is crucial for a successful technology transfer to the local economy [19]. Apart from normal workers, policy makers or other decision makers, such as business leaders, need to be well informed about positive and negative impacts of current and future energy systems. Governments can only give appropriate technological signals, if decision makers emphasize the importance of climate change mitigation or other environmental-related aspects. Otherwise, decisions would be made based on aspects of economic growth without considering future generations and global heating. Sometimes, the term "capacity building" is used instead of knowledge transfer. However, this normally does not include school or fundamental education. The adequate knowledge transfer to the whole society requires several aspects. First, prevailing knowledge must be identified to know what knowledge must be trained. Second, the implementation of an institutional framework to enable the scientific, technical, and political knowledge transfer must be built. Third, if training capacities or the required knowledge is not sufficiently available, foreign experts must be involved to build up new training centers. In this way, informed decisions can be made taking into account both economic growth and environmental-related effects. The criterion information and awareness again connect the different categories of the enabling framework as neutral information must be given to the broad population through neutral agencies or institutions, and feedback of the population should be returned to decision makers.

3.3. Economic Dimension of the Enabling Framework

The third aspect of the sustainability triangle is the economy. This dimension includes all aspects of technological, financial, and political criteria that are relevant for a successful transition toward a sustainable economic system.

3.3.1. Energy Markets

All aspects tackling the liberalization and organization of the energy sector form the category of energy markets. Numerous market structures impede a free-market competition and thus form one of the greatest barriers for environmentally friendly technologies to enter into markets on a big scale. Some authors, such as John Dryzek, argue that current democracy and governance fall short in achieving emission reduction targets due to "short time-horizons induced by election cycles and the apparent inability of voters to comprehend complex issues" [37] (p. 411). These findings might be correct to achieve a higher social welfare; however, in times where not-in-my-backyard discussions are still prominent, political guidance is required to limit negative impacts of the climate crisis as much as possible.

On a project-by-project basis, these structures may not be as essential as looking at the national energy market because most individual flagship projects are based on special agreements, which suspend unfavorable market structures for these special projects.

A liberalized energy market is the opposite of a highly controlled energy market and is based on different pillars to achieve a free competition among independent market participants. Former energy sectors that were primarily based on big, central conventional power plants were characterized by state-owned utilities, which held the monopoly for the generation, transmission, and distribution of electricity and thus were able to dictate the price for electricity. The deregulation of monopoly structures allows independent power producers (IPPs) to invest in sustainable energy projects and either sell their electricity or use the electricity itself (self-generation) and consequently increase the efficiency of the entire market through market competition [11]. In this way, energy prices are no longer controlled, and big state-owned utilities must compete with the private sector. Such a commercialization of the energy sector also means the unbundling of generation, transmission, and distribution of electricity to allow a real competition price setting [25]. However, not just the deregulated energy market itself is important to increase the share of renewable energies but also the access to and availability of the technology plays an important role. New technologies are usually owned by private (sometimes foreign) companies. The market entry of such companies must not be restricted by trade barriers to allow the import or export of these technologies [19].

Strengthening domestic economies is one key aspect to avoid the pure transfer of technology but to enable an economic benefit for all. Governments must create incentives for foreign companies to build up new local markets for their own production of equipment and electricity, while at the same time training domestic workers to create new jobs [19]. The empowerment of the local economy helps foreign companies to switch to an economically suitable and environmentally friendly industry, while at the same time creating new jobs for locals. One example is the construction of a rotor blade factory in Tangier, Morocco, of the wind turbine manufacturer Siemens Gamesa Renewable Energy to meet the regional demand of wind energy technology. Even if this factory just constructs parts of a whole wind turbine, it generates 600 direct and 500 indirect jobs and is coupled with a training center to guarantee the necessary knowledge transfer toward the domestic society [38].

A well-managed energy sector and the elimination of logistical problems are just two aspects of favorable market infrastructures. The management of entire energy sectors require clear structures and persons or ministries in charge that must work closely together and follow the same goals. If such an efficient and transparent management cannot be guaranteed, ministries would then follow their individual businesses and perhaps counteract necessary developments. The creation of favorable logistical aspects includes the construction of supply channels and supply chains as well as convenient business locations and availabilities [11].

The ownership structure of centralized, big fossil power plants can substantially differ from the ownership of decentralized renewable-energy power plants. In Germany in 2004, 38.5 GW of installed coal-fired power plants were owned by five big operating companies [39]. In contrast, only 5 GW of renewable energies were owned by utilities and slightly more than 10 GW by private individuals or farmers [40]. In 2020, these numbers grew to 23 GW and 53 GW, respectively. Such a high number of private investments was possible because the renewable energy law in Germany limited the economic risk of investors due to predictable and fixed feed-in tariffs [41]. In this way, the energy transition with its underlying risks is spread over various investors, and the influence of big utilities is restricted. The advantage of private investments or small companies is a fast adjustment of business activities in relation to new innovations and the ability to achieve fundamental changes in energy systems. The administration and possibilities for fast actions is much more restricted and limited for big, mostly listed companies [42]. Advances in nice and novel technologies, which are urgently required to successfully carry out the transition of entire energy systems—apart from the electricity and transportation sector—might be easier to achieve with high numbers of flexible private investors or small companies.

3.3.2. Energy Policy

It is important to note that the implementation of a regulatory body to promote the use of CO_2 neutral technologies is one of the most crucial aspects to successfully perform the transition toward a 100% RES. At the same time, the individual design of the regulatory body can differ widely among different countries according to their underlying motivation (see Section 2). Nonetheless, no matter how the specific regulations look like, there are many criteria that are relevant for all energy systems. It is very important that renewable energies or other carbon-neutral and sustainable technologies gain priority access and feed-in to both the electricity and gas grid. In this way, carbon-neutral technologies are prioritized to conventional technologies, and investors get the guarantee that their produced electricity will be used and paid [35]. Besides this compulsory renewable feed-in, there are many different favorable regulations to promote the use of renewables. If governments would like to manage the energy supply via price-driven regulations such as fixed-payment feed-in tariffs (FITs) or via quantity-driven regulations such as quotas, they need to be decide on it individually. A detailed overview and definitions of potential policies can be found in [25,35].

To set the right political framework is probably the most discussed and developed aspect of an enabling environment. The development of the most suitable regulations to promote the use of renewable energy technologies has already lasted since the 1990s, and today, about 126 countries implemented power policies, 68 countries implemented transportation policies, and 21 countries implemented heating and cooling policies [2]. These numbers show that there needs to be much more effort to foster all aspects of sector coupling to incentivize the switch toward green fuels or green gas. This switch is much more complicated because in the transportation and heating sectors, green fuels and green gas are non-natural end-products. The production of such sustainable resources requires either the transformation of entire markets to use electricity as the main source, such as the switch from diesel cars to electrified cars, or the use of electricity to be converted into green gas. In the case of a further use of electricity, the exemption from taxes and levies for electricity end-users must be guaranteed [43]. Furthermore, sector coupling will require much higher electricity demands in the future. One possibility to use already existing additional amounts of electricity is the use of currently curtailed electricity from fluctuating sources. The feed-in management of some countries allows for the curtailment of excess electricity that cannot be injected in the electricity grid due to limited capacities. In 2018, more than 5 TWh of electricity, mostly generated by wind turbines, were curtailed in Germany [44]. Such high amounts of electricity should be used as they do not require the expansion of the electricity grid but enable the production of hydrogen as an example instead of paying compensation fees.

Even though the implementation of renewable-energy support policies increased over the last years, the removal of pervasive subsidies for conventional energy remains static. In 2015, all G20 member states paid in total about 4500 billion USD for fossil fuel related subsidies [9]. Such high amounts of investments in conventional energies prevent the transition toward carbon-neutral energy sources but lead to a market distortion. However, as the most important aspect of the transition is the reduction of GHG emissions, the decarbonization of all energy sectors must be the priority [45]. Binding CO_2 reduction targets accompanied by either a carbon tax or emission trading scheme can ensure the abatement of CO_2 emissions throughout all energy sectors. The implementation of the European Union Emission Trading Scheme (EU ETS) shows that such systems must be well designed to persuade industries to invest in mitigation and abatement instead of just buying more and more allowances whereby no emission reduction can be achieved. If such policy implications to reduce the amount of emissions are not enough, governments should decide to focus on the total phasing out of conventional energy sources like the phase out of coal. Therefore, it is necessary to analyze if countries are just focusing on the mining of coal for exportation, such as Colombia; are using solely imported coal to produce electricity, such as Morocco; or depending both on coal mining and energy production, such as Poland. Measures to compensate negative effects of a coal phase out range between the establishment of know-how and training capacities to enable new employments, the transformation of former coal mines toward areas to produce sustainable electricity, or to convert them into touristic attractions and the connection of remote areas to urban centers to enable the search for new employment possibilities [46,47]. All cases require a detailed country-related analysis of regional and national influences of socioeconomic indicators to identify the most important drivers and barriers to look at the transformation "as a window of opportunity [. . .] to transform the regions according to a more sustainable vision" [46] (p. 11).

A well-designed political framework is very crucial to switch on the one hand from a conventional electricity production toward a carbon-neutral electricity production and on the other hand, to enable the coupling of all energy sectors away from carbon intensive energy sources. There is a strong link between this category and the financial, technical, and institutional framework, as a priority feed-in of carbon-neutral energy must be tackled from grid operators and accompanied by financial decisions. Additionally, the progress of the last decades has shown that, from a political side, the transition can be already well managed but a lack in knowledge transfer or lobbyism for conventional energy harm the implementation on a large scale. The influence of lobbyism with be further discussed in Section 3.3.7.

Another very basic but extremely important criterion is a safe environment and good governance. Kaufmann et al. [48] define six dimensions of governance: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. All these aspects require transparency as well as a strong opposition to enable a strong and powerful polity. This powerful and well-developed polity guarantees the required collaboration between stakeholders and politicians in all sectors using power and water so that a sustainable development toward a decarbonized economy is possible to implement. The absence of corruption is crucial, as corruption probably does not lead to achieve the necessary goals on a just and economically feasible manner.

The importance of a long-term predictability is linked to both aforementioned criteria of good governance and a regulatory body to promote the use of decarbonized and sustainable energy. Long-term predictability includes the development of long-term goals in a transparent, and ideally participatory, manner to enable a strategic planning for all involved market participants. Such a long-term planning possibility reduces the financial risks for investors [35] because it reflects a clear signal of governments toward the expansion of technologies or the achievement of goals (e.g., to produce 100% renewable electricity in 2050) [19].

3.3.3. Finance

This category deals with criteria that affect the international, national, and local level. As many developing countries have limited possibilities to finance the reduction of their GHG emissions, international funding possibilities are a very important tool. Besides the Global Climate Fund (GCF) which "is the largest global fund dedicated to help fight climate change" [49], many other international funding opportunities exist. The NAMA Facility, Clean Development Mechanism (CDM), or Global Environment Facility (GEF) are just some of the existing funds that exist besides private investments at an international level. The problem is that a lack in knowledge transfer impedes developing countries to invest in climate-friendly technologies as they cannot finance such a transformation with the help of own financial resources. According to Painuly [11], there are several criteria that are important for the investment in sustainable energy projects at the national level. Economically viable cost structures mean that the cost of capital, labor, resources, or material needs to be competitive and at an adequate level so that it is worth it to transfer the technology or knowledge to the relevant country. The importance of a competitive and reliable capital market heads in the same direction. On the one hand, the capital market must be well developed and reliable so that a long-term planning without uncertainties and risks is possible. Such a predictability also includes stable exchange rates or adequate and stable taxes on profits. Perhaps, capital subsidies can also be a possible incentive for investors; however, they need to run only for a limited time to guarantee improvements in efficiencies. At the other hand, the access to cheap capital, like credits at low discount rates, is important for both investors and private consumers as debt capital plays an important role in costly large-scale energy projects. Finally, the absence of capital market entry restrictions enables investors to invest in the construction of, for example, new production capacities in foreign countries as a way that the foreign country can benefit most from the transfer of technology [11]. The third criterion under the category finance is the adequate energy pricing. This criterion consists of two different aspects. First, the positive as well as negative environmental externalities must be considered in all fields of energy pricing. Negative health effects of pollution caused by conventional energy production, the environmental damage of resource mining, or the damage of nuclear accidents are just some important negative externalities that are mostly not reflected in the price of electricity. Renewable energy technologies have significantly less environment-damaging negative external effects but must compete with conventional energies, which do not consider the underlying external costs (cf. [34]). All financial support mechanisms that are required to support renewable energy technologies, technological advances, or decarbonization of the energy systems were treaded in the category energy policy.

At the local level, the financial participation of local citizens in energy projects can be a very successful toolkit to increase the acceptance of the local population. It is not mandatory to implement any financial participation in renewable energy projects, but such measures should at least be offered, if the local population is directly affected by new projects like, for example, wind farms in the direct vicinity of settlements. Many studies exist, that show a direct correlation between a financial participation (e.g., reduced power price or citizen-owned wind farms) in a specific wind farm and the acceptance of the local population toward that wind farm in industrialized countries (cf. [50–52]). The participation is sometimes understood as the financial compensation for perceived negative effects, such as noise [53]. However, the implementation of a financial participation is, depending on the type of participation, sometimes accompanied by work that is required to found or manage a corporation. The author of this article herself has gained experience in a former position as a wind farm planner, where financial participation sometimes failed due to different reasons. Excessive demands or disagreement from locals or the fact that voluntary and unpaid work needs to be done can make the implementation of a financial participation difficult. However, if the local population is willing to participate in such activities, a financial participation should be offered and implemented. The question remains: is it possible for a financial participation to be implemented in developing countries, as financial resources are limited in poorer regions? One possible way of finding an answer to such an approach would be to analyze the regional challenges and opportunities together with the local population in a transparent manner.

3.3.4. Legal Requirements

The category "legal requirements" mainly consists of three important aspects: legal aspects; standards, codes, and certification; and the elimination of administrative barriers. All the following criteria are important because a proper legal framework guarantees the protection of intellectual property rights (IPR) as well as the trade of technology under certain environmental-related restrictions.

The term "legal aspects" covers a very broad field and encompasses criteria that tackle the planning of new power plants or legal questions such as the access to the power or gas grid. The construction of new power plants needs to be possible without unnecessary restrictions and under well-defined frameworks. The conduction of an environmental impact assessment (EIA) during the planning process of newly constructed power plants is one example to follow a systematic process. A variety of environmental-related information needs to be collected during the planning phase of a new power plant to enable the planning authority to consistently judge and predict whether the project effects on the environment can be compensated and thus, the project can be built [54]. Additionally, a mandatory public consultation and participation allows the local population to be a part of the planning process, which might lead one to find the most socially accepted projects [35]. Like this, the EIA allows a comparable decision-making for authorities and investors. Another application of an impact assessment would be the life-cycle impact assessment at the product level. Governments should carefully take into account how environmentally friendly new products and technologies are produced. In this way, the life cycle of constructing power plants or other products also contribute to reduce overall CO_2 emissions as well as, for example, water pollution [55]. Besides the legal basis of project planning, administrative barriers can hinder to implement the transition toward sustainable energy systems. The presence of red tape, complicated procedures or high transaction costs related to knowledge transfer, planning, and implementation can discourage investors to invest in new markets [11]. A further criterion that is mainly important when it comes to the trade of technology is a well-developed framework of standards, codes and certifications. One reason to transform an energy system toward carbon-neutral technologies lies in its sustainability and the prevention of global heating. That is why the equipment also needs to fulfil certain energy efficiency standards, which need to be secured during the trade among countries [12]. The implementation of ecolabels, Environmental management standards (EMS), or other environmental performance standards provides many opportunities "to overcome information barriers, as they allow consumers to be less knowledgeable about the equipment they are purchasing" [12].

3.3.5. Infrastructure

According to Pueyo [19], a local infrastructure must be able to deal with a new, transferred technology. By strengthening the existing local economy, as mentioned in the section "strengthening existing economies", existing industries should gain from the benefits that a successful technology transfer enables. Horizontal spillovers across different industries make it easier for investors to build up new companies as not everything, the technology and the know-how, must be imported. Additionally, a good transportation infrastructure is important to be able to build up companies in remote areas [19], where the space for big manufacturing buildings is sufficiently available. A good transportation infrastructure is also important when it comes to the transportation of newly produced big goods, such as big wind turbine blades, for example. If these blades cannot be transported to the production side due to a lack of infrastructure, a company will not build up its manufacturing building in such a remote area. However, not just the implementation of roads is important concerning a sufficient technical infrastructure; all aspects of logistics as well as internet connectivity or public services are extremely important for investors to find the right location for a new company. Furthermore, a technological or knowledge spillover can also achieve a certain cost reduction or other local improvements for further research and developments [19]. The aspects of an efficient power grid operation are not mentioned in many of the analyzed literature. Painuly [11] names two criteria concerning the energy grid such as the connectivity to the grid and other system constraints that limit the capacity of the grid. The capacity limitation due to an increased share of decentralized renewable technologies leads in many cases to a curtailment of electricity produced out of intermittent renewable energies, which was already mentioned in the previous section. There are different possibilities to use this electricity instead of curtailing it or expanding the grid substantially. A substantial expansion or improvement of the electricity grid might be necessary, if the existing energy system is very old and entirely based on big, centralized fossil power plants. In this case, the expansion of renewable energies should be accompanied by a substantial grid improvement to guarantee energy security in the future. The decentralized production of hydrogen would be just one possibility. Additionally, the increased importance of sector coupling more and more leads to an increased demand of electricity, which requires a further connection of the gas and electricity grid [56]. The expansion of or the excess to the existing gas grid is currently accompanied by different technical and legal barriers, which are not described in more detail in this section. However, the appropriate policy framework combined with the elimination of technical and legal constraints must enable an efficient use of both energy grids as well as the utilization of currently generated excess power. Furthermore, a necessary technical infrastructure either to charge electrified vehicles or to use green gas on a large scale must be implemented as soon as possible to enable an increased use of such a technology properly. Otherwise, the transition of especially the transportation sector will not be successful.

3.3.6. Institutions

The importance of a well-functioning and independent institutional framework is broadly discussed in literature. According to Agenda 21 [14], the access to know-how and the exchange of information can be strengthened by institutional capacities that enable to give informed choices. Developing countries often lack such necessary institutional frameworks, so that a sustainable access to and transfer of environmentally friendly technology is difficult. The construction of a national system of innovation to enable and push the transfer of knowledge, which is crucial for being able to disseminate information, supports the technological development and helps to manage experiences [12]. Such a system connects institutions "to create, store, and transfer the knowledge, skills, and artefacts, which define" [57] opportunities to create new "transfer channels making foreign inputs locally available" [19]. With the focus on knowledge transfer, an eye can be kept on the expansion of so-called social capital [12]. The different dimensions of knowledge were discussed in the category knowledge. It is important to note that national systems of innovation combine public policies, institutions, business, and social relationships, which is why independent nongovernmental organizations play a big role [12]. Independence from governmental views or financing sources is crucial, as unbiased feedback mechanisms are useful to observe and improve markets. It is furthermore important that different channels for the transfer of technology and knowledge are considered because there are different possibilities to make foreign technology and knowledge (inputs) locally available [19]. Besides a well-managed national system of innovation, research and development (R&D) itself must be possible and promoted in an independent manner. Even if governments are often encouraging R&D with the help of policies and governmental funding, both public research institutions and private sector R&D need to be well established, to guarantee an effective information transfer of environmentally friendly technologies [12,14]. Different analyses have shown, that strong governmental support and investment in institutional capacities can help to accelerate the transition toward sustainable energy systems [8]. Additionally, the role of local universities can help to achieve a spillover through the conduction of joint R&D projects together with local companies [19]. Overall, it can be summarized that independent institutions are crucial for enabling a successful technology and knowledge transfer while disseminating information so that they are understandable for the broad population.

3.3.7. Clash of Interests

The category clash of interest deals mainly with the effects of lobbyism. Today, every decision maker should have understood that human activities need to be changed urgently due to the impacts of global heating. Nevertheless, powerful lobbyists work against the transition toward a carbon-neutral energy sector to represent their interests of earning more money with their businesses or business partners. The link of a powerful car lobby with German policy makers is just one prominent example. Between 2009 and 2015, about 13.6 million Euros were donated from the car industry to finance political parties [58]. However, not just the transportation sector is influenced by powerful lobbyists. During the last decades, the coal industry all over the world has put a lot of effort in the consultancy of politicians and international climate negotiations. The coal atlas of 2015 detected many events in which either the coal industry itself or powerful coal lobbyists were trying to advise international politicians in the margins of international climate conferences [59]. These two examples show that the influence of every kind of lobbyism focusing on impeding the transition toward a carbon-neutral economy must be detected and prevented.

4. Discussion

This section gives an overview of the limitations of this study, identifies further research areas, and gives recommendations of how a successful transition can be managed.

4.1. Limitations of Study

There are some limitations of the presented enabling framework, which need to be mentioned. First, the criteria of different categories depend strongly on each other so that it can be difficult to identify, which of the criteria need to be fulfilled before another. Sometimes, the so-called "chicken-and-egg problem" must be ignored to enable investments in currently not highly used technologies such as the construction of electric charging stations even though the amount of registered electricity cars is still low. In this way, decisions fostering changes in behavior are much easier to realize for the entire society. Additionally, the way of how exactly the criteria can be fulfilled is not fully described in this article. Different countries need to find individual ways that best suit their existing economies. Industrialized countries, having a strong fossil industry, face other challenges compared to developing countries, lacking energy access for all. In this case, the identification and elimination of pervasive fossil subsidies are probably not necessarily important for the developing country but extremely important for the industrialized country. Second, the identification of barriers that currently hinder the transition can be difficult, or there might at least be aspects that are complicated to detect. The decision, for example, of not using available domestic fossil resources, could be difficult to be made by governments, as the use of domestic resources might increase energy independence or gains revenues in case of exportation. Some countries are not seeing the benefits of using domestic renewable resources instead of domestic fossil resources, which is why a stronger awareness needs to be drawn to the negative effects of fossil resource use.

This paper gives explicitly no specific policy suggestions, as some countries are successful with implementing, e.g., quota systems and others with implementing feed-in tariffs to increase their share of renewables. However, without the government willing to focus on carbon-neutral economies, less success might be achieved.

4.2. Further Research and Recommendations

There are mainly three areas where further research is required to guarantee an easier application and further development of the enabling framework:

1. The development of a detailed guideline or step-by-step identification of prevailing barriers and problems. This could also include the development of a comparable and measurable index.
2. The identification of knowledge gaps that currently hinder the transition toward carbon-neutral energy systems.
3. The analysis of individual or general local content requirements to successfully strengthen domestic economies or infrastructure. This includes both the transfer of technology and knowledge.

Some important recommendations can be given that help to implement the aforementioned enabling framework. On the one hand, the criteria which are implemented must guarantee a certain technological neutrality and energy efficiency. Energy efficiency must be fostered to limit the additional amount of electricity that results from sector coupling. The preservation of technological neutrality and the possibility of technological advances must be considered when designing new policy frameworks or long-term goals. In this way, new technologies can benefit from different support mechanisms. The early preselection of special technologies, such as supporting electrical transportation instead of hydrogen transportation, hampers the emergence of least-cost solutions. Furthermore, a mix of different technologies leads to a higher security of supply. On the other hand, the transferability of specific decisions among different countries might be difficult. Some countries have the possibility to invest in the production of, for example, green hydrogen for a sustainable transportation sector, while others do not. This highly depends on the amount of excess power of the entire energy system or the availability of renewable resources. However, the dissemination of best-practice solutions is very helpful and urgently needed for countries with limited possibilities of their own R&D.

5. Conclusions

This paper presents an enabling framework to overcome existing barriers to facilitate sustainable and carbon-neutral technologies at the national level. The literature analysis has shown that most of the analyzed publications are related either to barriers in the electricity sector or to only some of the criteria that are presented in Section 4. The diffusion of, for example, clean technologies is just one important aspect of a successful energy transition, as a new technology alone is not able to compete with established technologies. The transfer of knowledge and the strengthening of the domestic economies are also very important to achieve an understanding for this urgently needed transformation as well as the possibility to gain as many benefits out of the necessary changes as possible.

The enabling framework presented in this paper is at some points not as detailed as presented in other publications. However, criteria such as the protection of the environment or the importance of knowledge are not mentioned or prioritized in other publications but are important parts of the energy transition as a whole. Furthermore, different policy options to support the use of clean technologies exist. The decision on which policy should be chosen must be taken by countries individually, based on the currently installed energy technologies and on the long-term targets that should be achieved.

Science and reality have shown that the technical feasibility of 100% RES is technically feasible around the world. Even though it took more than a century until coal evolved to be the primary energy source in many countries, the transformation toward the use of carbon-neutral technologies needs to be implemented as soon as possible.

Nowadays, it is about implementing these findings to still be able to limit the impacts of the climate crisis. In recent years, great progress has been made toward the integration and expansion of renewable energies in the electricity sector. However, the transition toward a more sustainable future does not end with the construction of renewable power plants. Substantially larger effort is required to focus on the decarbonization of all sectors to achieve a carbon-neutral economy in the near future. Governmental goals must consider both an increasing share of renewables and emission reduction in all areas of the society to enable a sustainable development as well as affordable energy for all.

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Abbreviations

The following abbreviations are used in the manuscript:

CDM	Clean Development Mechanism
EIA	Environmental Impact Assessment
EMS	Environmental Management Standards
EU ETS	European Emission Trading Scheme
GCF	Global Climate Fund
GEF	Global Environment Facility
GHG	Greenhouse gas
IPR	Intellectual Property Rights
IPP	Independent Power Producer
IPCC	Intergovernmental Panel on Climate Change
NAMA	Nationally Appropriate Mitigation Action
NDC	Nationally Determined Contribution
R&D	Research and Development
RES	Renewable Energy System
RET	Renewable Energy Technology
TT	Technology Transfer

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4 Long-Term Electricity Scenarios for the MENA Region: Assessing the Preferences of Local Stakeholders Using Multi-Criteria Analyses[3]

Ole Zelt
Christine Krüger
Marina Blohm
Sönke Bohm
Sharazad Far

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Long-Term Electricity Scenarios for the MENA Region: Assessing the Preferences of Local Stakeholders Using Multi-Criteria Analyses

Ole Zelt [1,*], Christine Krüger [1], Marina Blohm [2], Sönke Bohm [3] and Shahrazad Far [4]

1 Division Future Energy and Industry Systems, Wuppertal Institute for Climate, Environment and Energy, 42103 Wuppertal, Germany
2 Center for Sustainable Energy Systems, Europa-Universität Flensburg, 24937 Flensburg, Germany
3 Institute of Geosciences, Christian-Albrechts-Universität zu Kiel, 24118 Kiel, Germany
4 Center for Development Research (ZEF), University of Bonn, 53113 Bonn, Germany
* Correspondence: ole.zelt@wupperinst.org; Tel.: +49-30-2887-45815

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Abstract: In recent years, most countries in the Middle East and North Africa (MENA), including Jordan, Morocco and Tunisia, have rolled out national policies with the goal of decarbonising their economies. Energy policy goals in these countries have been characterised by expanding the deployment of renewable energy technologies in the electricity mix in the medium term (i.e., until 2030). This tacitly signals a transformation of socio-technical systems by 2030 and beyond. Nevertheless, how these policy objectives actually translate into future scenarios that can also take into account a long-term perspective up to 2050 and correspond to local preferences remains largely understudied. This paper aims to fill this gap by identifying the most widely preferred long-term electricity scenarios for Jordan, Morocco and Tunisia. During a series of two-day workshops (one in each country), the research team, along with local stakeholders, adopted a participatory approach to develop multiple 2050 electricity scenarios, which enabled electricity pathways to be modelled using Renewable Energy Pathway Simulation System GIS (renpassG!S). We subsequently used the Analytical Hierarchy Process (AHP) within a Multi-Criteria Analysis (MCA) to capture local preferences. The empirical findings show that local stakeholders in all three countries preferred electricity scenarios mainly or even exclusively based on renewables. The findings demonstrate a clear preference for renewable energies and show that useful insights can be generated using participatory approaches to energy planning.

Keywords: MENA; electricity scenarios; MCA; multi-criteria; stakeholder participation; sustainability; Tunisia; Morocco; Jordan; energy modelling

1. Introduction

Countries of the Middle East and North Africa are at an energy crossroads. Governments in these countries will soon need to address the continued increase in energy demand for the next few decades. Energy consumption in the region is projected to almost double by 2040 [1]. This increase in demand is largely due to expected population growth well into 2050 and beyond [2]. At the same time, countries in this region also face the challenge of addressing their high vulnerability to climate change, which has a strong social dimension [3]. In the medium term (i.e., until 2030), the power sector is set to undergo the most important change in the countries' energy plans. In Morocco, awareness of this was reflected in the National Energy Strategy of 2009 and the updated version of 2015, which included the Moroccan Solar Plan (Noor). Under these plans, renewables-based installed capacity in the electricity sector is set to increase from 34% in 2015 to 52% by 2030 (20% wind, 20% solar, 12% hydro) [4]. Tunisia also put out a Solar Plan, in 2009, as well as an updated version in 2012; this was followed by the Tunisian Renewable Energy Action Plan 2030. Under these plans, renewables as part of the installed capacity for electricity generation are set to increase from2% to 30% by 2030 (15% wind, 10% Photovoltaic (PV) and 5% Concentrating Solar Power (CSP)) [5]. Jordan has also established the National Master Strategy of the Energy Sector (2007–2020) as well as the National Strategy for the Development of Renewable Resources. Under these plans, 10% of electricity generation is to be based on renewable energy technologies (solar and wind) by 2020, increasing to 20% by 2025 [6,7]. The national plans in these three countries mean that the choices made today regarding the technologies that constitute the electricity mix will reverberate for decades.

The policies in these three countries signal a transformation of energy systems and tacitly a transformation of the interaction between society and these systems. Energy planning is an intricate exercise of balancing between different priorities and effects on different segments of society. As such, the different societal segments are local stakeholders in the energy planning exercise. Short to medium-term energy policies set the stage for long-term energy scenarios. To ensure that energy planning for future electricity systems corresponds to the needs and priorities of the different local stakeholders, it is important to capture societal preferences in a systematic manner.

Electricity infrastructures are technical systems that need to go in tandem with the societal systems of the populations they serve. Decisions about electricity infrastructures are made even more complex, given the technical challenge of matching electricity demand and supply at any point in time. There has been a growing appreciation of the necessity to better understand the relationship between sources of energy and societies, particularly in the MENA region [8]. Under the concept of "Energy Humanities", such scholarship has gained ground in recent years, allowing for humanities and social sciences to investigate energy challenges against the background of anthropogenic climate change, thereby complementing natural sciences (which have long been dominant in energy scholarship) [9]. Within this academic trend, one particular strand of research has focused on transitions and has been generating a growing body of academic literature under the umbrella of Sustainability Transitions (ST). ST as a field of research has three main perspectives: socio-technical, socio-institutional and socio-ecological, which nevertheless share an understanding that transitions result from the interaction of dominant regimes with changing external landscape factors as well as emerging innovations [10]. The frameworks under ST [11–15] are designed to better understand the dynamics of what triggers a potential system reconfiguration and how such shifts may be hindered or facilitated.

This paper locates its contribution within the socio-technical perspective of the steadily growing ST literature. Nevertheless, in spite of the emergence of this field, especially in the last decade [16], its expansion into covering transitions in the Global South has been far less advanced and more recently been subject to several research caveats. These caveats have given impetus to exploring new research frontiers [17] with major relevance in the context of developing countries. However, the MENA region itself has barely been studied thus far.

Local stakeholder preferences of future electricity scenarios in particular are still understudied for this region. While renewables are "normatively" regarded as the cornerstone of decarbonisation, the degree to which reliance on renewables in future electricity systems is seen as desirable by local stakeholders is unclear. In light of this, the article attempts to answer the following research questions: what long-term electricity scenarios for the year 2050 do local stakeholders in Morocco, Jordan and Tunisia actually prefer? And what criteria are seen as most important in such scenarios? Various scholars have previously conducted studies using the core methods of this article, electricity scenario modelling and MCA. We can distinguish between two particular categories of these studies: MCA, with a view to energy (technologies) in different countries or regions or with a different time frame than the ones proposed here (1) and electricity scenarios for countries in the MENA region but without MCA (2):

1. Indeed, Brand and Missaoui [18] developed five electricity scenarios combined with a stakeholder-based MCA in Tunisia, that is, applying the same methodology as the one undertaken

here. However, their study was conducted against a horizon of 2030 instead of 2050. Several studies apply MCA methodologies for different countries but focus solely on energy production technologies, instead of electricity mix scenarios: Shaaban et al. [19] have studied Egypt, Bohanec et al. [20] Slovenia, Štreimikiene et al. [21] Lithuania and Promentilla et al. [22] the Philippines, for example. Other studies have developed scenarios displaying different electricity mixes in combination with MCA but not for the countries/region in question: Klein and Whalley [23] studied the USA, Santos et al. [24] Portugal, Strantzali et al. [25] a Greek island, Mirjat et al. [26] Pakistan, Santos et al. [27] Brazil and Atilgan and Azapagic [28] Turkey, for instance.

2. Alhamwi et al. [29] sought to quantify an optimal mix of renewable power generation in Morocco, using a mismatch energy modelling approach with the aim of minimising the need for storage capacities. Damerau et al. [30] considered three alternative pathways, looking at energy efficiency, carbon intensity and energy exports from the MENA region and studied them with a focus on water demand. However, neither study involved local stakeholders in the development of distinct electricity scenarios against a certain time horizon and did not proceed to rank them based on stakeholders' preferences with regard to different criteria. Rather, their studies evaluated the pathways against one single criterion respectively: the minimisation of storage capacities or of water use.

Based on the analysis of existing literature, we locate the novelty of our approach in the combination of selected theoretical approaches—which have so far mainly been deployed separately—within a new temporal and spatial scope. This approach contributes to an increasingly integrated research of both technical feasibility and social priorities, as a basis to develop robust transformation pathways. This article thus addresses the knowledge gap pertaining to participatory scenario development and MCA in Jordan, Morocco and Tunisia in the policy horizon of 2050 by looking more specifically at the extent to which local stakeholders in these three countries support the deployment of different electricity generating technologies and scenarios in the future, up to the year 2050.

This approach relies heavily on local stakeholders' participation as a central component of the empirical investigation. The research adopts an understanding of energy transition as a socio-technical undertaking, the course of which would benefit from insights generated by empirical and participatory methods involving a broad spectrum of local stakeholder representatives. This required to develop a multidisciplinary approach that devised methodologies that merged natural science (mainly engineering) methods of electricity modelling with social science methodologies for achieving complementarity.

To answer the research questions, the article starts by presenting the scenario development and modelling method and proceeds by describing how stakeholder preferences were captured using MCA (Section 2). It moves on to presenting the results of the selected scenarios and their rankings in Section 3, which also highlights the top-ranked scenarios per country, provides a roadmap to achieve them and compares the results of all three countries. The discussion subsequently focuses on major findings and challenges (Section 4), culminating in a number of conclusions (Section 4.5).

2. Methods and Data

During workshops held in 2016 and 2017 on-site in the countries under review [31–33], about 25 participants per country developed, discussed and evaluated various scenarios of their respective country's future power supply in 2050. To do so, an energy simulation model and an MCA were applied.

Discovering preferences of local stakeholders regarding electricity scenarios in 2050 was conceived as the exercise of the participatory building of visions and scenarios. To include different interests and perspectives, the group of stakeholders involved had to be decidedly heterogeneous, which could be ensured by involving local scientific partners in the workshop organisation. Stakeholders included representatives from academia, policymakers and private sector actors, as well as civil society representatives and Non-Governmental Organisations (NGOs). The participating organisations are listed in References [31–33].

2.1. Scenario Development and Modelling

The workshop participants developed scenarios of their respective country's future power supply with the help of a stripped-down version of renpassG!S, an open-source energy system simulation software [34–38]. The full model's main functionalities were included in this spreadsheet version. However, the utilisation order of dispatchable generation was pre-defined and its application allowed straightforward scenario inputs and an on-the-fly display of results.

During the development of the scenarios, all workshop participants were invited to state their expert judgment, their assessment about potential future developments and the view of the institutions they represented about their country's future power system. All inputs to the model were adjustable during the exercise; however, the main focus was set on adjusting the installed capacity in 2050. The workshops' intended aim was to develop technically feasible scenarios, not prognoses [39] (p. 59).

In order to reduce complexity and for methodological reasons [40] (p. 89), the countries' future power systems were conceptualised as isolated systems without transmission links abroad. In the model, each country was split into four regions. Every region was represented by an hourly-resolved load curve and hourly-resolved meteorological data (based on References [41–43]), relevant for the modelling of the power generation from wind power, solar PV and CSP. Fluctuating, non-dispatchable renewable energy technologies (wind power, solar PV) were assumed to operate any time the natural resource would be available due to their marginal cost close to zero [39] (p. 245). The residual load was calculated according to the (lack of) production of fluctuating renewables on an hourly basis. It would have to be covered by dispatchable and partly-dispatchable generation technologies (e.g., CSP) and the utilisation of storage options. A scenario was considered to be functional once it was possible to cover the load for every hour of the target year. To calculate potential additionally required transfer capacity, the model compared the residual load in the regions of a country and the existing transmission grid infrastructure between the regions.

A major outcome from the model was the production of every technology in the system as defined by the workshop participants according to their personal assessment, experience and expectations, simulated in an hourly resolution for the year of analysis. Regional values were aggregated to national totals, which again were automatically translated into direct CO_2 emissions of all energy sources and of the entire system. Additionally, the installed capacity as well as the annual production were utilised for the calculation of annuitised investment costs and operational costs. The levelised cost of electricity (LCOE) was calculated for the electricity produced. In order to take different stakeholder views and assessments into account, it was useful and indeed necessary to develop several scenarios under different storylines for the target year, focusing for example on low CO_2 emissions, use of domestic resources or high shares of renewables. This meant deriving corresponding development trajectories until 2050 for the selected scenarios that described potential system settings. All system configurations, which were passed on to the subsequent multi-criteria analysis, allowed to balance load and demand for every hour of the target year. This assured their basic technical feasibility.

2.2. Identifying Stakeholder Preferences Using Multi-Criteria Analysis

An MCA is a useful method for systematically identifying and examining the preferences of stakeholders for various alternatives. In this case, the alternatives were the scenarios that had been defined previously (see Section 2.1). The MCA was applied to consider the importance assigned by national and local stakeholders to a range of social, techno-economic and ecological implications. As a result, this process allowed the identification of those development pathways that would be expected to receive broad support from the stakeholders involved. An MCA consists of the following essential steps: Before starting the assessment, the alternatives which are to be scrutinised must be defined or identified (see Section 2.1). Then, it is necessary to define criteria (see Section 2.2.1) that are appropriate for examining the differences between the alternatives. Afterwards, these criteria are weighted according to the stakeholders' preferences (see Section 2.2.3). For each alternative and each criterion, the proper respective indicators have to be derived (see Section 2.2.2). Finally, the weighted criteria are applied to the alternatives in order to develop a ranking of alternatives (see Section 2.2.4).

There is a multitude of different methods that can be used in an MCA [44] and many of them have been applied in the context of sustainable energy [45]. Some of those methods apply to the weighting process (e.g., the Simos Method or the AHP), some to the ranking of alternatives (e.g., the Weighted Sum Model (WSM) or "outranking-relations" methods such as the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)), some can be used for both steps (e.g., the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)). This study applied the AHP for the weighting; for the ranking, both the WSM and TOPSIS ranking methods were used. The utilisation of both ranking methods allowed us to analyse the robustness of the results.

2.2.1. Criteria definition

Based on [45], the criteria need to cover all relevant aspects of the question under examination, allow representative indicators for each criterion, avoid redundancies (and thereby distorted results) and allow for clear and unambiguous categorisation. Therefore, the next step was to define criteria that would assess stakeholder preferences about the question "What are the most preferable long-term electricity scenarios for the year 2050 among the local population?" (see Table 1).

Table 1. Criteria for the acceptability of electricity scenarios.

Category	Criterion	Sub-Criterion
Techno-economic criteria	System costs	
	System flexibility	
	Energy independence	
Environmental criteria	CO_2 emissions	
	Land use	
	Water consumption	
	Hazardous waste	
Societal criteria	Contribution to local economy	On-site job creation
		Domestic value chain integration
	Safety	
	Air pollution (health)	

Each criterion is clearly defined to allow for a well-founded discussion in the weighting process. The following definitions apply:

- Techno-economic criteria: These criteria analyse the technical and economic characteristics of the electricity system. They take electricity production costs, dependency on energy imports and production volatility into consideration.
    - System costs: The costs of the electricity system include production, grid extension and storage costs.
    - System flexibility: The electricity system's capacity to react rapidly and flexibly to changes in electricity demand.
    - Energy independence: Future capacity of the scenarios to make use of local resources in order to reduce energy dependency.

- Environmental criteria: These criteria analyse the environmental characteristics of the electricity system. They take water consumption, land use, CO_2 emissions and management of hazardous waste into consideration.
  - CO_2 emissions: Direct CO_2 emissions of all power plants during the observation period.
  - Land use: Soil occupation caused by the operation of all power plants (on-site).
  - Water consumption: Direct freshwater consumption during the operation of all power plants (cooling, steam cycle, cleaning).
  - Hazardous waste: Quantity and quality of hazardous waste produced by all power plants, including radioactive waste.
- Societal criteria: These criteria analyse the socio-economic characteristics of the electricity system. They take the system's effects on public health, the risk of serious incidents and the support of the local economy into consideration.
  - Contribution to local economy: The scenarios' capacity to integrate the local economy into the electricity system.
    - On-site job creation: The scenarios' capacity to create on-site jobs during the construction and operation of power plants.
    - Domestic value chain integration: The scenarios' capacity to encourage the emergence and/or development of national industries and of indirect jobs during the entire life cycle of power plants.
  - Safety: The number of fatalities as a result of serious accidents during the operation and maintenance of power plants.
  - Air pollution (health): Air quality deterioration resulting from atmospheric pollutants that can bring about health risks.

2.2.2. Evaluation of Scenarios With Regard to the Criteria

Each alternative, that is, each scenario, needed to be evaluated with regard to the previously defined criteria. Each criterion was represented by one indicator for each scenario. The techno-economic criterion of "system costs" was represented by the indicator of "levelised costs of electricity", which directly resulted from the scenario modelling. So did the indicator "CO_2 emissions". The indicator for the criterion of "system flexibility" was calculated from the shares of intermittent, partly dispatchable and dispatchable energy generation in the scenarios with a ratio of one (intermittent) to two (partly dispatchable) to three (dispatchable).

The other eight criteria were based on surveys from [46]. Numerous indicators for the different energy technologies were collected in stakeholder workshops in the three countries. The criteria of "land use" (hectares per megawatt), "water consumption" (litres per megawatt hour), "safety" (fatalities per megawatt hour) and "air pollution" (kilograms per megawatt hour) had quantitative indicators. For these, the indicator values were scaled up and then totalled according to the installed capacities and the energy generation of the respective energy technologies in the scenarios. For the remaining criteria of "energy independence" (represented by the "possible share of domestic resources"), "hazardous waste", "on-site job creation" and "domestic value chain integration", semi-quantitative indicators on a scale from one to five were derived for each energy technology in each country. To obtain an indicator value for the scenarios, the indicator values of the energy technologies were scaled according to the corresponding generation quantities or the installed capacities and then normalised by dividing by either the total generation or the sum of the installed capacities in the scenario, respectively.

2.2.3. The Weighting Process

We employed the AHP as the weighting process, since it leads to a structured evaluation of all criteria, promoting awareness of the participants' own priorities and thus providing a basis for a well-founded discussion. It therefore enhances communication and dialogue among different stakeholders. The AHP uses a pairwise comparison of the criteria categories and of the criteria in each category. These pairwise comparisons are then automatically aggregated into a total weight using a mathematical procedure based on the eigenvalues and eigenvectors of the resulting weighting matrix. The pairwise comparison reduces the complexity of the multidimensional assessment. In addition, it allows the detection of inconsistencies in the evaluations and thereby deepens researchers' understandings of these preferences. To enable the integrated assessment of indicators with different units, the weighting process transforms these indicators into dimensionless comparable classifications on a common numeric scale. For a detailed description of the AHP, see References [44,47]. Here, this method was embedded in a three-step procedure: individual, group and overall weighting, of which the group weighting was the most relevant part.

The individual weighting, in which each stakeholder applied the AHP according to their own preferences, served as preparation for the subsequent group weighting. In the group weighting, we specified four different working groups with focus on different criteria. We then asked all participants to join one of these groups according to their individual preferences:

- a techno-economic group,
- an environmental group,
- a societal group,
- and an equal preference group.

The group weighting is the essential part of the weighting process, since it is on this level that dialogue is enhanced and a fruitful discussion becomes achievable. It results in a weighting that is representative for the individual weightings in the group. The question of how to reach consensus was left to the groups. In some groups, the participants' weightings did not differ significantly, so these groups were able to come to a group result easily. In other groups, an intensive and vivid discussion ultimately led to a consensus. Some groups calculated the arithmetic mean of the single weightings and used this as a basis for further discussion. Although the need for discussion was very different among the groups, each group ultimately reached consensus in each country workshop.

As an optional third step, the workshops also worked on an "overall weighting"—an attempt to bring together all stakeholder preferences. Finding a consensus in a larger group of heterogeneous stakeholders is a difficult task, with a likelihood of failure. The arithmetic mean of all group weightings was used as a starting point, from which the stakeholders were given the opportunity to change the weighting if it did not reflect their judgment. In Tunisia, the discussion of the arithmetic mean led to alterations in the weighting. Not all groups, however, were able to agree on the resulting weighting. But when it turned out that such alterations had no effect on the ranking of the scenarios, the participants nevertheless decided that the adjusted weighting would be the overall weighting. In Morocco, the discussion of the arithmetic mean and alterations in the weighting led to a consensus among all groups. In the Jordan country workshop, no consensus could be agreed on because the majority of participants felt that the average results did not represent their preferences.

In this case, where a consensus could not be reached, the arithmetic mean of group weightings was used for a summarising view across preference groups instead. This weighting does not reflect the actual preferences of a person or group. However, it can be a useful tool to summarise general trends and also to examine the impact of different decisions on the outcome of the MCA, in this case on the resulting scenario ranking.

2.2.4. Ranking the Identified Electricity Scenarios

In the last step of the MCA, the study applied the weighted criteria to the alternatives in order to create a ranking of the scenarios. This meant that all the indicators were combined with the weighting factors, using the WSM as well as the TOPSIS methods. In the WSM, the indicators were simply multiplied by the weighting factor of the corresponding criteria and totalled for each scenario. Each criterion therefore influences the result directly according to its assigned weighting. This procedure leads to a score for every scenario and the scenarios can be ranked. The TOPSIS ranking method computes the distance of a scenario to the best possible alternative, ranking the scenarios from best (with the shortest distance) to worst (with the longest distance to the ideal solution). A detailed description of the ranking methods can be found in Reference [45].

3. Results

This section describes and analyses the scenarios for the target year 2050 developed in the workshops for all three countries, as well as the rankings resulting from the MCA. This is followed by a more detailed description of the top-ranked scenario of each country and a short roadmap showing how to achieve the proposed installed capacities of the scenarios.

3.1. Describing the Scenarios Developed

In each country, the workshop participants successfully developed four (Morocco, Tunisia) or five (Jordan) electricity scenarios for the target year 2050. Such a variety of scenarios allowed participants to consider the diverse range of stakeholder views and to compare a broad spectrum of future energy system arrangements.

All three countries are expected to face a significant increase in their electricity demand in the long term [48,49]. Such growth requires considerable expansion of currently installed capacity, ranging between four-fold and seven-fold increases in the target countries by 2050. Having limited domestic fossil resources [46] but at the same time focusing on conventional fossil fuels in the current energy system, all three countries have the aim of shifting from their current position as net energy importers to net energy exporters in the future. Since the potential of domestic renewable resources is very high in all three countries, the installation of renewable energy capacities can reduce national-level energy dependence, though this would also create a need for additional electricity production capacities due to renewables' intermittency. Additionally, Morocco, Jordan and Tunisia are still considered "developing" economies today [50], which means that expected future economic development will further intensify their energy needs.

In general, the workshops revealed that even though the criterion of CO_2 emissions was not prioritised by stakeholders, the increase in renewable energy options in the future was supported by participants based on the criteria of "energy independence" and "low water consumption of the electricity system". This understanding is reflected in the various scenarios they developed (see Appendices A.1–A.3), where a mix of different renewable energy technologies combined with gas-fired power plants are the most frequent composition of the proposed future electricity systems.

In order to keep the diversity of the developed scenarios at an easily manageable level, the scenarios were classified into four major groups, depending on the role renewables play. Category A comprises scenarios that are fully based on renewable energy technologies. Scenarios focusing on renewables but still including a minor share of conventional technologies fall into Category B. Rather balanced shares of renewable and conventional production can be found in Category C, while in Category D, the dominant conventional technologies are supplemented by lower shares of renewables. A list of all scenarios can be found in Appendix A.

Morocco is expected to experience a significant increase in electricity demand until 2050. Installed generation capacities will have to increase from about 8000 MW in 2014 [51] to between 70,000 MW and 85,000 MW in 2050, depending on the respective scenario (see Appendix A.1). Such a development is required due to an estimated five-fold increase in electricity demand, up to 173 TWh/year in 2050 [31]; this represents the highest projected absolute electricity demand in 2050 among the three countries surveyed here. According to national targets, 52% of installed capacity should be renewable by 2030 [52], which equals about 13,000 MW. In the scenarios developed here, this number could increase to between 57,000 MW and 85,100 MW by 2050, mainly covered by high shares of wind energy and solar PV. The amount of hydropower and CSP capacities in 2050 would probably be the same as those planned for 2030 in order to limit the use of water and maintenance-intensive technologies in mainly desert regions. Conventional technologies will play a minor role in the future electricity system, as domestic resources are very limited and CO_2 intensive fossil fuel technologies are not able to meet the requirements of the Paris Agreement [53,54].

Jordan faces the highest projected percentage increase of its electricity demand by 2050; at approximately 106 TWh/year, this would be seven times higher than in 2014 [32]. Thus, the total amount of installed capacities needs to increase significantly from 4000 MW in 2014 [55] to about 20,000 MW to 78,000 MW, depending on the future composition of the electricity system in 2050 (see Appendix A.2). Although Jordan has very limited domestic natural gas reserves [56], gas-fired power plants represent the highest share of conventional power generation in the present energy system and, as Appendix A.2 shows, will presumably play a significant role in the future. There might be considerable potential for pumped hydropower storage, either between the Dead Sea and the Red Sea or as one system directly located near the Red Sea; this might even be less expensive than battery storage options. These options, however, were not pursued by the stakeholders during the scenario development due to their currently unknown potential.

In contrast to the Moroccan scenarios, there is no clear preference for one or two renewable energy technologies; wind energy, solar PV and CSP are all considered with significant shares. In total, renewable capacities range between 2300 MW and 69,000 MW in 2050 in the scenarios.

Tunisia's electricity demand is set to increase from 18 TWh/year in 2014 [57] to approximately 70 TWh/year in 2050 [33]. To cover such growth, installed capacities must increase from about 4800 MW in 2014 [57] to between 18,000 MW and 26,300 MW by 2050. The installed capacities of renewable energy technologies will probably have to increase from the currently planned 3815 MW by 2030 to at least 8400 MW, depending on which scenario is developed. 95% of currently installed capacities run on natural gas, which is also the only conventional technology that was considered by the workshop participants for the future electricity scenarios (see Appendix A.3).

Wind energy, solar PV and CSP were included in all of the scenarios, with a slight focus on solar technologies. However, the planned renewable capacities from wind and solar for the future only correspond to the lower end of the estimated total potential of 10 GW and 280 GW, respectively [58] and could therefore even be exploited to a greater extent than currently envisaged. Hydro power is limited to current installations as water is very scarce in Tunisia [59]. Another source not explicitly described in the scenario results but very important for the Tunisian population is the use of domestic rooftop PV systems to enable the cheap generation of their own electricity [60].

More detailed information about the scenarios described and the underlying workshop results are available in Reference [31] for Morocco, in Reference [32] for Jordan and in Reference [33] for Tunisia.

3.2. *Applying an MCA to the Given Scenarios*

As outlined in Section 2.2, the results of the stakeholder-based MCA can be further divided into (intermediate) weighting results and (final) ranking results. While the former give insights into the preferences of different stakeholders with regard to individual criteria, the latter represent a ranking of the identified alternatives in light of these preferences. Sections 3.2.1 and 3.2.2 give an overview of both types of results for all three countries under study.

3.2.1. Results of the Scenario Weighting

The criteria weightings resulting from the stakeholder workshops in Morocco, Jordan and Tunisia are presented in Appendix B. The figures in the respective tables represent the weight in percentage points calculated from the pairwise comparisons of criteria during the group weighting stage.

Given the fact that the stakeholder groups in the MCA process were assembled according to the general preferences of the respective participants (see Section 2.2.3), this group bias was expected to be mirrored by the weighting results of the groups, for example, resulting in high weightings assigned by the environmental group to criteria linked to aspects of environmental degradation. This effect was observed in most groups but not all.

In **Morocco**, most of the groups prioritised techno-economic criteria and weighted "energy independence" as the most important criterion by far (42–52%). The other criteria obtained a relatively low weighting compared to "energy independence". Only the environmental group developed a structurally different weighting, resulting in "water consumption" as the most important criterion (40%)—followed by "air pollution (health)" and "hazardous waste". During the subsequent plenary discussion, a consensus weighting among all workshop participants could be reached. This consensus still focused on techno-economic criteria but also acknowledged the importance of "water consumption" and "domestic value chain integration."

In **Jordan**, most group weightings reflected the respective groups' category priority as expected, that is, the techno-economic group prioritised all techno-economic criteria (15–31% each), the environmental group ranked environmental criteria higher (24% each, with the exception of "land use," which was considered less important) and the societal group gave more importance to social aspects of energy systems, especially "safety" (46%) and "air pollution" (20%). However, the equal preference group did not consider the categories to be equally significant: environmental and societal criteria, especially "air pollution" and "hazardous waste," dominated techno-economic aspects. In the arithmetic mean, "safety" stood out as the most significant criterion. Forming a consensus (considered an optional step of the process, see Section 2.2.3) could not be reached in the plenary discussion due to the strongly diverging opinions of the participants.

In **Tunisia**, the preferences of the different groups roughly represented their respective focus, that is, the techno-economic group weighted criteria from the techno-economic category higher than the other groups and the environmental group placed its focus on environmental criteria. The equal preference group displayed rather balanced weightings among the three criteria categories. However, "energy independence" also seemed to be crucial to groups other than the techno-economic one: the societal and equal preference groups still weighted this criterion as rather important. It was also the only outstanding criterion in the arithmetic mean. A consensus across the groups could be reached only after the participants were assured that their original group rankings would remain part of the final ranking and the workshop's conclusions. Using the arithmetic mean as the starting-point of the discussion, the consensus included a slight increase of the weighting assigned to "system costs" and "system flexibility" as well as "on-site job creation" at the expense of "energy independence" and "safety" but it did not differ significantly from the average weighting.

3.2.2. Results of the Scenario Ranking

In **Morocco**, the different group weightings all resulted in the same scenario ranking (Table 2). The Category A scenario featuring 100% renewables ranked first, followed by the "Mix 2" and "Mix 1" scenarios, while the "PV" scenario was least preferred across all scenarios. Only the consensus weighting showed minor deviations in the ranking—with an inverted order of "Mix 2" and "Mix 1." All scenarios in positions 2 to 4 focused on selected renewables, which were supplemented by different different compositions of fossil fuels (Category B). For a definition of scenario categories, see Section 3.1.

The fact that structurally different weightings led to an identical ranking can be considered a coincidence in Morocco: for most groups (those which considered "energy independence" crucial), the top position of the "100% renewables" scenario was mainly determined by the superior performance of the scenario with regard to this criterion. However, the scenario also features the lowest "water consumption," "air pollution" and "generation of hazardous waste," which were considered most important by the environmental group. This scenario therefore also ranked first on the basis of this group's weighting.

As a result, the scenario ranking that the participants obtained turned out to be robust with regard to the preferences of all stakeholder groups involved in the workshop. Achieving the outlines of the Category A scenario, "100% renewables" in 2050 would result in an energy system solely based on renewable energy technologies, mainly from wind and solar power.

Table 2. Resulting rankings in the Morocco country workshop.

Scenario Name (Category)	Techno-Economic Group	Environ-mental Group	Societal Group	Equal Preference Group	Group Average	Consensus
100% renewable (Category A)	1	1	1	1	1	1
Mix 2 (Category B)	2	2	2	2	2	3
Mix 1 (Category B)	3	3	3	3	3	2
PV (Category B)	4	4	4	4	4	4

Also in **Jordan**, the different weightings resulted in similar scenario priorities (Table 3). In all stakeholder groups, the "No imports" scenario, which would solely rely on domestic power sources, ranked first. In addition to renewable sources, this scenario also considers small amounts of fossil shale oil and gas. The techno-economic, environmental and societal groups' preferences all displayed the same ranking of scenarios, which was also reflected by the arithmetic mean across all groups. However, the equal preference group revealed a different prioritisation: here, the "Mix including nuclear" scenario, which is the only one containing nuclear power and coal, ranked second instead of last.

On the one hand, the "Mix including nuclear" scenario can be considered a moderate scenario that would not result in extreme values as compared to the other scenarios concerning most criteria. For example, with regard to "energy independence," "air pollution" and—due to the relatively low share of nuclear power–even "hazardous waste," this scenario ranges between "No imports" at one end of the scale and the other fossil-based scenarios at the other end. The "Mix including nuclear" scenario therefore appears to correspond better to the rather balanced category preference of the equal preference group. The other groups, on the other hand, placed stronger emphasis on their own individual criteria groups and especially those criteria in which the gas-focused and renewables-exempt scenarios ("Current plans + gas," "RE + gas" and "medium RE + gas") outperformed "Mix including nuclear" (e.g., in "system costs," "water consumption" or "safety"); this is consequently reflected in their ranking results.

The scenario ranking generated by the MCA turned out to be in accordance with the criteria weightings and preferences of the various stakeholders. Even though the stakeholders could not agree on a single set of common weighting results, they could, however, still relate to the final averaged scenario rankings. As a final result of the MCA, the "No imports" scenario proved to dovetail best with the preferences of the workshop participants. This scenario features a future electricity system that would rely mainly on renewable energy sources that are minimally supplemented by fossil fuels derived from domestic shale oil reserves (Category B).

Table 3. Resulting rankings in the Jordan country workshop.

Scenario Name (Category)	Techno-Economic Group	Environ-Mental Group	Societal Group	Equal Preference Group	Group Average
No imports (Category B)	1	1	1	1	1
Medium RE + gas (Category D)	2	2	2	3	2
RE + gas (Category D)	3	3	3	4	3
Current plan + gas (Category D)	4	4	4	5	4
Mix including nuclear (Category C)	5	5	5	2	5

In **Tunisia**, in contrast to the other two countries, the different weightings led to structurally different scenario priorities, with the exception of the societal and equal preference groups, which displayed the exact same scenario ranking (Table 4).

In line with its strong focus on "system costs," the techno-economic group's ranking basically sorted the scenarios in ascending order with regard to this criterion. As a result, the "Mix" scenario, with large amounts of natural gas and relatively little new installation of renewables, ranked first for this group, while participants' lowest preference was for the most cost-intensive scenarios "Mix + solar" and "5 GW mix." However, the "5 GW mix" scenario at the same time ranks first for all other groups, which dedicated more attention to aspects other than cost. The resulting scenario ranking turned out to be in accordance with most stakeholders' criteria weightings and preferences. Nevertheless, there were significant differences among the four stakeholder groups, especially between the techno-economic on the one hand and the remaining groups on the other. The arithmetic mean as well as the consensus ranking resulted in the "5 GW mix" (Category A) scenario corresponding most closely with the preferences of the workshop participants. This scenario was characterised by a future electricity system relying exclusively on a balanced set of renewable energy sources.

Table 4. Resulting rankings in the Tunisia country workshop.

Scenario Name (Category)	Techno-Economic Group	Environ-Mental Group	Societal Group	Equal Preference Group	Group Average	Consensus
5 GW mix (Category A)	4	1	1	1	1	1
Mix (Category B)	1	2	3	3	2	2
Mix + solar (Category B)	3	3	2	2	3	3
Solar + gas (Category C)	2	4	4	4	4	4

3.3. Comparing the Top-Ranked Scenarios From the Three Study Regions

For each country case, the top-ranked scenario for the year 2050 was selected for further analysis of future options and needs to increase the installed capacity over time, according to the preference rankings developed during the workshops. In addition to the system description for 2050, the next step was to develop possible pathways to bring the electricity systems in those scenarios to fruition.

3.3.1. Top-Ranked Scenarios

According to the weighting results from Section 3.2.1, the top-ranked scenarios relied heavily on renewable energy technologies and thus were from Categories A and B. Their rankings were based on participants' consensus in the case of Tunisia and Morocco and on the group average in the case of Jordan, where no consensus could be achieved (see Section 3.2.2). This section describes these scenarios as well as the most important underlying discussion results from the workshops in more detail.

Table 5 summarises the main characteristics of the top-ranked scenarios of each country. These scenarios can be seen as one possibility of a future electricity system, featuring a high share of renewables.

Today, the power systems in all three countries differ significantly, relying on different mixes of electricity generation techniques as well as meeting different electricity demand curves; this makes a direct comparison difficult. Different expectations regarding future electricity demand as well as varying electricity storage options also lead to different future energy system requirements. However, all countries could rely on sufficient renewable resources, which could be combined in a mix of different technologies to achieve energy independence in the future, as this criterion was very important for the stakeholders involved (see Section 3.2.1).

Morocco's excellent wind resources, resulting from both high wind speeds and high wind availability [61], contribute to a slight focus on wind power (onshore) followed by a high share of solar PV in the top-ranked scenario. These intermittent technologies would be combined with a diverse mix of variable technologies to produce electricity in times when the intermittent technologies of wind and solar would not be able to meet electricity demand. Since hydropower resources are limited, workshop participants considered the utilisation of gaseous biomass (biogas) as another flexible electricity production technology besides CSP. Although there are currently no large-scale biogas plants in Morocco and no exact resource assessment is available, the use of biogas would reduce the increasing amount of agricultural and organic waste, which was also seen as important by the workshop participants.

Table 5. Top-ranked scenarios.

Countries	**Morocco**		**Jordan**		**Tunisia**	
Scenario	100% renewable		No imports		5 GW mix	
	Capacity (MW)	Energy (TWh/year)	Capacity (MW)	Energy (TWh/year)	Capacity (MW)	Energy (TWh/year)
Wind power	45,000	126.6	15,000	30.4	5000	12.6
PV	30,000	43.6	25,000	44.1	5000	8.7
Geothermal	0	0	3500	19.3	5000	27.5
Hydro power	3100	1.0	500	0.0	63	0.1
Biomass	5000	20.0	5000	16.7	5000	21.4
CSP	2000	2.4	20,000	6.5	5000	0.2
Coal	0	0	0	0	0	0
Oil	0	0	5000	0.3	0	0
Gas	0	0	4000	0.0	0	0
Total	*85,100*	*193.7*	*74,000*	*117.4*	*25,063*	*70.5*
LCOE (Euro cts/kWh)	9.73		28.19		16.46	

In contrast to Morocco, **Jordan**'s top-ranked scenario envisions a future based mainly on three different pillars—wind power, PV and CSP—with 15 GW to 25 GW each. Even though CSP is currently much more expensive and therefore not favoured by decision-makers, the workshop participants saw a clear benefit in it as an energy storage option compared to PV. However, using CSP mainly for covering the residual load during times when wind power and solar PV would not be capable of producing cheap electricity, it contributes only to small shares to the electricity production due to relatively high production costs. Since the possible exploitation of domestic shale oil and shale gas is currently under study [62], the scenario includes small shares of these conventional fossil fuels, contributing slightly to the total electricity production in times of a positive residual load. Another regional restriction of the Jordanian energy system is the assumed limited potential of relatively cheap pumped hydro power already mentioned above. Since no reliable estimates or research studies on the potential for this technology have been conducted, it was initially excluded and batteries were considered instead.

The top-ranked scenario for **Tunisia**'s future electricity system differs from the other countries because equal shares of wind power, PV, geothermal, biomass and CSP were all considered. In general, the workshop participants preferred PV most, being beneficial both as rooftop home systems and large-scale power plants. Under the assumptions made, geothermal and CSP were considered to be more expensive than other renewables. Although geothermal power is still cost-intensive and its potential is currently unknown, the participating stakeholders included this technology in future scenarios.

Looking at all the scenarios in Appendices A.1–A.3, differences in the specific costs (in Eurocents(cts)/kWh) are noticeable between the scenarios that have high generation shares of renewable technologies and scenarios that have higher shares of conventional technologies. All three renewable-focused scenarios are the most expensive ones per country according to the presented results. However, this is not necessarily due to the renewables themselves. Assumed storage capacities as well as supplementary fossil plants operating with low capacity factors to compensate for fluctuating generation also contribute to high specific costs of electricity. The assessment of costs also changes when the external costs, mainly arising from conventional fossil energy, are internalised. According to Reference [63], externalities arise when a market transaction affects a third party that is not involved in the actual transaction. Internalising externalities is one approach to incorporating such impacts back into the market transaction. The most prominent negative environmental externality is pollution caused by conventional fossil fuel technologies. Pollution causes health problems but the underlying costs of such problems are not for the most part incorporated into electricity prices but are paid by the suffering party directly. The Moroccan case shows that when considering system costs and external costs, the 100% renewable scenario is by far the cheapest–with externalities exceeding system costs by three to four times [64]. This point makes it clear that external costs, energy independence and sustainability all play an important role with regard to cheap and environmentally friendly future electricity systems.

3.3.2. A Roadmap to Achieving High Shares of Renewables

The next step was to generate technology roadmaps for the top-ranked scenarios for each country that describe development towards the 2050 goals on an annual basis, using a back-casting approach [65]. This was achieved by linearly interpolating existing installations and capacities, intermediate targets and the 2050 scenario data (based on References [31–33,48,51,55,57,60]). The annual numbers that emerged represent the approximated development path required to reach the envisaged 2050 system. Although there might be room for manoeuvre over time in the actual implementation, intermediate goals should be in agreement with the calculated figures.

Since Morocco's wind power installation is expected to be 5 GW in 2030 [4] (p. 29), a target of 45 GW in 2050 requires substantial capacity additions. This also holds for solar PV, albeit at a lower capacity level, reaching 16.7 GW in 2040 and 30 GW in 2050. Only an increase in installed CSP capacity can flatten out somewhat after 2030 due to the fact that CSP capacity is already expected to reach a substantial level (1.3 GW) by 2030. In the top-ranked scenario, conventional capacities would no longer be required in 2050 and therefore they can be or must be taken out of operation in the years before.

Similar to the Moroccan case, the installed capacity of renewables in Jordan under the top-ranked scenario significantly increases until 2050. While the Moroccan case anticipated total power demand to multiply by a factor of five between the intermediate year of 2020 and the target year of 2050, the corresponding factor of 10 in Jordan translates into an even more dramatic increase in installed capacity. In 2020, both wind power and solar PV will remain far below 2 GW of installed capacity [66] and they are forecast to reach 15 GW and 25 GW, respectively, in the scenario for 2050, meaning more than a tenfold increase. In contrast to the Moroccan scenario, in Jordan's 2050 power system, there would still be conventional installations, which, however, would only be required to cover a few peaks in demand.

In Tunisia, power demand was forecast to more than double between 2020 and 2050, which nevertheless would result in a smaller necessary increase in installed capacity compared to the other two country cases. With multiple renewable technologies, each contributing 5 GW in the scenario for 2050, however, substantially increased development of all technologies would still be required.

For all three country cases, it is apparent that reaching a fully or substantially renewables-based power system by 2050 will require a major expansion of renewable capacities as well as a reduction in conventional capacity. The conventional capacity installed today or in use as part of the intermediate targets can or should be taken out of operation in the years before 2050. The role of this conventional capacity should be subject to further in-depth analyses. For all countries, it is clear that conventional capacity should not be expanded beyond current intermediate goals. At least for Morocco and Tunisia, it may even be advisable to reconsider intermediate targets. Figure 1 illustrates the calculated installed capacity in selected years. It becomes obvious that the increases among the countries differ, depending on hypothesised electricity demand in 2050 and national intermediate installation targets. These roadmaps should therefore be seen as a sound basis for further discussion about what steps are necessary in terms of a required legal framework, incentives, or the prevention of stranded investment.

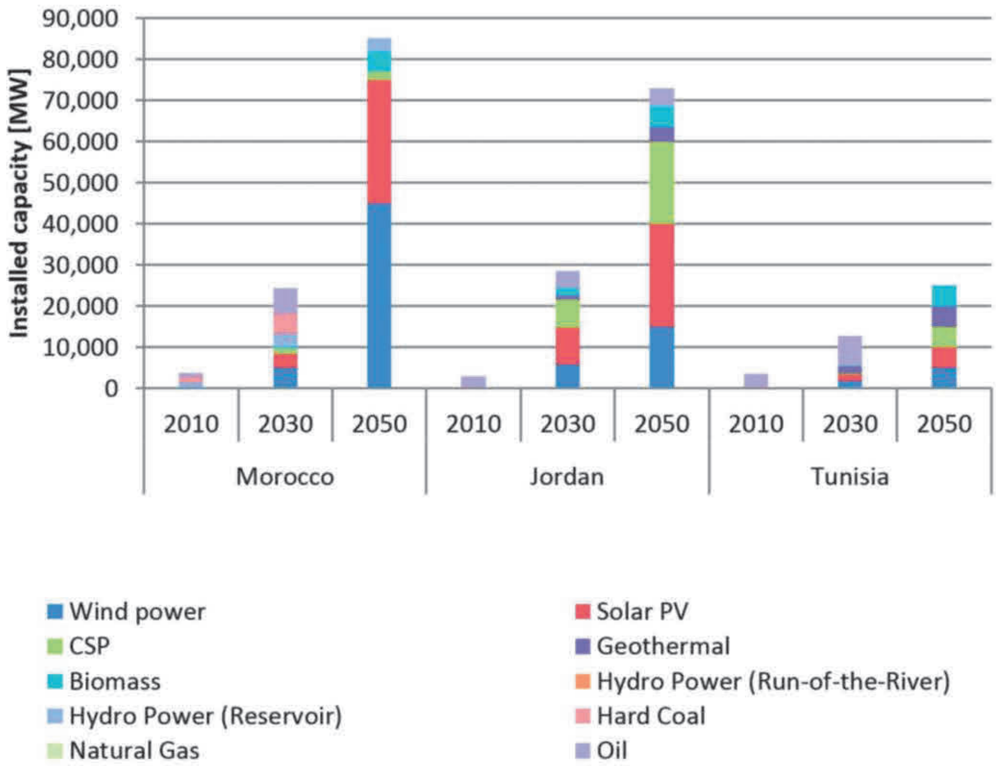

Figure 1. Capacity expansion trajectories in the top-ranked scenarios for Morocco, Jordan and Tunisia. Based on [31–33,48,51,55,57,60].

3.4. Comparison of Country Results

The individual workshops focused on one country each and intentionally provided an arena for discussions about country-specific issues such as national targets and plans, and potential challenges and opportunities. The additional juxtaposition of the country results and country-specific discussions further reveals similarities and differences between the country cases. Such a comparison could be utilised by a country's stakeholders to learn from other country cases. Moreover, stakeholders from third countries might be inspired by the differing aspects of the three country cases, which could be translated into the development of targets and plans in their own countries.

Analysing all country weightings as a whole reveals repeating patterns of criteria, with similar weighting results in different countries: while high weightings are assigned to all techno-economical criteria as well as "water consumption", "hazardous waste" and "air pollution" by different groups in all countries, "land use", "CO_2 emissions" and aspects of job creation are considered less important in all countries. Some of these patterns are rather obvious, such as a far higher importance assigned to "water consumption" as compared to "land use", with all three countries characterised by an arid climate and a low population density, especially in vast rural areas. Other patterns appear to contrast with political focal points at the global level as well as local characteristics of the countries. Especially in the light of the "Paris Agreement" [53], the subordinate weighting of the "CO_2 emissions" criterion in all countries is a noticeable result. Only the environmental workshop group in Jordan gave this criterion a two-digit weighting (24%); in many other groups, it even turned out to be considered the least important criterion. It therefore appears that, in the perception of most stakeholders, the long-term global goal of climate protection is still outweighed by urgent short-term challenges, mainly socio-economic ones. Furthermore, although unemployment rates are high in all three countries [67], none of the countries prioritised one of the two job-related criteria of "on-site job-creation" or "domestic value chain integration" by assigning larger weights.

When comparing the MCA stakeholder process in all countries, similar rankings across multiple groups could be observed even after vigorous discussions and widely diverging opinions during the weighting stage of the process. However, this does not allow us to conclude that different criteria weightings only have limited influence on the scenario rankings. It rather shows that different scenarios developed in the workshops simultaneously demonstrate similar characteristics concerning different criteria that are regarded as important by different groups. For example, a scenario contributing both to "energy independence" as well as lower air pollution may by highly ranked by two different groups, which nevertheless assigned specific importance to the one or the other criterion. As a result, although consensus-finding on the importance of different aspects of future electricity systems may be difficult, it would still be possible for heterogeneous groups of stakeholders to ultimately agree on particular transformation pathways for the electricity system.

With regard to the calculated ranking results in the respective countries, it appears that most stakeholder groups across all three countries had similar preferences for similar types of scenarios. With the due caution with regard to the relatively small sample of countries, scenarios and stakeholder groups, we observe the following:

- The highest preferences were calculated for scenarios from Categories A and B, characterised by high shares of renewable power, especially for 100% renewable scenarios (if available from the respective range of scenarios).
- Lower preference values were calculated for Categories C and D scenarios, which assumed that conventional fossil-based power would continue to play an important role in the decades to come.
- In most cases, nuclear power had already been excluded during the stage of scenario definition. The only scenario that discussed nuclear power ("Mix including nuclear", in Jordan) ended up receiving the lowest preference results.
- With regard to renewables, most scenarios (especially the top-ranked ones) feature a diverse mix of different renewable power sources instead of deploying single technologies such as only wind power or only CSP.

However, in addition to some recurring patterns, it was also possible to notice differences between the three countries under study: the Moroccan stakeholders initially refrained from considering Category C and D scenarios including nuclear power as well as relevant future shares of fossil fuels. As a consequence, while the first-ranked scenario is based on renewables only (Category A), all other—rather similar—scenarios (ranked second to fourth) still focus on renewable technologies that are only supported by fossil fuels to a limited extent (Category B). Although the Moroccan scenarios also showed an aforementioned tendency towards a diversified electricity mix, compared to the other countries, they nevertheless had a stronger focus on single technologies, especially wind and PV power.

In principle, the Tunisian stakeholders developed a similar range and ranking of scenarios as the Moroccans did but they additionally also defined a Category C scenario with a rather balanced share of renewables and fossil-based power. However, this scenario was least preferred according to the calculated rankings.

In contrast to the two other countries, in Jordan, three out of five scenarios the stakeholders defined could be assigned to Category D, because they still focused on selected fossil technologies (mainly gas) even in 2050. These were ranked from second to fourth, while the only Category B scenario with a focus on diverse renewables ranked first. The only scenario with relatively balanced shares of renewables and fossils as well as supplementary nuclear power (Category C) received the lowest ranking.

This comparison of the three country cases shows that a large variety of arrangements of these countries' future power systems is possible. Not only do the scenarios differ substantially in the future mix of technologies but also in the resulting costs and the amount of direct CO_2 emissions (see Appendix A). Such differences, again, can be found not only within one country but also in the comparison of one country with another. However, the three country cases have shown that high shares of renewable energy sources in these countries' future power systems were gladly included in most of the scenarios developed or vice versa, high shares of conventional power generation in the countries' future power systems were regarded to be rather unpopular. Results from all three countries demonstrated that an electricity supply based solely or to a large extent on renewables is technically possible and economically feasible in the countries of analysis. This depends to a limited extent on the amount of local resources, while the main driver in these countries' future power system concerns the question of available storage potential and the anticipated load level.

4. Discussion

The following paragraphs take a look at the results with respect not only to content but also to the methodology surrounding group MCA.

4.1. MCA Methodology

The workshops highlighted procedural challenges linked to the application of an AHP-based multi-criteria assessment in groups. The lessons learned include the following aspects:

To check pairwise weightings of criteria for consistency is as fundamentally important as it is difficult. In our workshops, we relied on printed questionnaires that were subsequently transferred to an Excel-based MCA tool that included a mathematical consistency check. Although participants were asked to check their results for consistency before handing them in, some inconsistencies could only be pointed out by the Excel tool. This created needs for another iteration of the weighting process, which was partly seen as an attempt to influence the formation of opinion. This process could be improved by applying a less strict consistency check (e.g., as described in Reference [68]) than the check based on Reference [47] which was used here.

The successful application of the AHP relies on the definition of structurally different alternatives that are fed into the weighting and ranking stage. However, in a group process that starts with the definition of alternatives, individual preferences are already included in the definition stage, which may result in the exclusion of unpopular alternatives at the outset. The process owner of the MCA needs to make sure that alternatives defined in the process demonstrate fundamental differences.

Applying an MCA in a process with groups of heterogeneous stakeholders is expected to result in a wide range of different weightings. However, a range of diverse weightings may even result in similar rankings.

Based on our observations, participants in the process may have a tendency to assign inferior weightings to criteria which they generally rate as important but which are currently not considered as a problem (e.g., presently good air quality in a specific country).

4.2. High Electricity and Capacity Demand

As described in Section 3.3, the scenarios in all countries are based on a major increase in future demand for electricity production as well as for the installation of corresponding additional generation capacities. On the one hand, our calculations show that the resulting systems might be technically viable. They are also in line with the high level of technology optimism among the workshop participants, which became apparent during the workshops. On the other hand, large power systems, even those relying mainly on renewable resources, cause severe side effects such as high investment cost, high demand for mineral resources (including critical minerals) [69], increased water consumption and ecosystem degradation. The threats from these adverse effects might even be exacerbated as soon as a transformation of the entire energy system is seriously considered by national policymakers or in case the countries under study decide to harvest their export potential for electricity-based products such as solar fuels and chemicals. However, several strategies exist to reduce the amount of future construction required and the usage needs of additional plant capacities:

first, energy sufficiency and efficiency policies can lead to lower long-term electricity demand. Second, there are balancing effects in connected energy systems, in contrast to the isolated systems assumed in this study. This reduces the necessary peak generation capacity. And third, additional measures not considered in this study, such as demand-side management and sector-coupling technologies, can also reduce the need for electricity generation capacity.

4.3. Stakeholder Preferences

In all three countries, there was a very high commitment for high shares of renewable energy in the future energy system. That is especially because these contribute to energy independence, which stakeholders considered very important. In this context, cost effectiveness and the availability of local resources were the important features of the most widely preferred energy generation technologies. A mix of different renewable energy systems with a focus on solar sources (as well as wind in Morocco) emerged as the most popular option. The use of biogas plants on a large scale was seen as an option to reduce waste in the three countries. Coal and nuclear power were regarded as unpopular technology options in all three countries because of their high costs, the lack of international funding and their non-sustainable characteristics. Energy storage is a key question, especially for Jordan, since pumped hydro power was not considered to be an option due to water scarcity, and batteries would be necessary instead.

The stakeholder preferences outlined above correspond to recent scenario literature describing global and regional 100% renewables scenarios in the electricity as well as the entire energy sector [70–74]. Already in 2011, the Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) of the Intergovernmental Panel on Climate Change (IPCC) pointed out that "a significant increase in the deployment of RE by 2030, 2050 and beyond is indicated in the majority of the 164 scenarios reviewed in this Special Report" [75], referring to an analysis of Reference [76]. In terms of renewable energy shares, many of the scenarios discussed in our work (those of category B, C and D) even lag behind the scenario studies from the literature mentioned above.

Apart from being socially preferred or accepted, future electricity scenarios must also be plausible from an electrical engineering perspective. Aspects of electrotechnical feasibility of preferred scenarios beyond a balancing of supply and demand on an hourly basis are not covered by our analysis. However, these aspects, such as the consideration of sub-hourly time resolutions, the provision of reserve power or other ancillary services, are subject of numerous publications. For example, Reference [74] concludes that "there are solutions using today's technology for all the feasibility issues raised" in the discussion about scenarios featuring 100% renewable electricity. However, even with the required technologies available, the comprehensive transformation of the electricity sector of a country from mainly fossil to renewable sources remains a challenging task, which needs to be accomplished in a cost- and resource-efficient manner.

4.4. Strategic Decisions

In all three countries under study, the approach using participatory workshops to identify priorities for future electricity systems proved to be an appropriate method to enable constructive discussions and receive valuable contributions from a wide range of stakeholder groups. The workshops created awareness about the necessity of adopting national long-term goals up to the year 2050, because the currently adopted targets for 2020 or 2030 will not be sufficient to cover the expected increase of future electricity demands. In the discussions, participants saw the dissemination of knowledge related to the long term (i.e., until 2050) as a basis to facilitate informed planning and investment decisions that need to be made today. The workshops also pointed out the potential need to revise existing 2030 development plans for the respective countries: according to the workshop discussions and modelling results, many scenarios featured a decommissioning of most fossil power plants before 2050. As a result of the usually high technical lifetime of such types of plants, any construction of additional fossil-fuel plants in the decades to come would therefore likely be linked to a high risk of stranded investments. The same logic not only also applies for nuclear power plants but is further bolstered by larger environment-related challenges and problems. Due to infrastructural and geographical concerns, plans to build two nuclear power units in Jordan by 2025 were cancelled in 2018. However, the Jordan Atomic Energy Commission (JAEC) is still planning the construction of small modular nuclear reactors to deploy the country's domestic uranium reserves [77]. According to the workshop participants in Tunisia and Morocco, plans for nuclear energy in both countries have been put on hold as no potential sites could be identified and the technology's deployment was perceived to be too closely linked to a host of techno–economic, ecological and societal risks [31,33]. In light of the respective domestic levels of renewable resources from solar and wind as well as the modelling results obtained from renpassG!S, this study found nuclear power to be unnecessary in the future with respect to covering the rising electricity demand of the three countries under study. The results of the study therefore entail a recommendation of reviewing and possibly abandoning remaining plans to build nuclear power plants, thus facilitating a focus on the implementation of more widely accepted renewable technologies.

4.5. Conclusions

To achieve a high level of energy independence, all three countries should focus on their abundant renewable energy sources such as solar and wind power for their future power supply. Provided that sufficient residual material flows are available, sustainable biomass technologies should also be considered in long-term national goals; conventional generation should play a minor role.

Opportunities to establish electricity systems based on high shares of renewable energy should be investigated while simultaneously working to reduce the required capacities for electricity generation and storage. These opportunities may include a combination of renewable technologies with different feed-in profiles or balancing supply and demand by means of various flexibility options. Even though the scenarios take thermal storage through CSP plants into account, the need to further reduce storage demand is especially important with regard to the limited availability of other storage options such as pumped hydro power in Jordan and Tunisia. In the case of Morocco, researchers should work to identify the potential application of additional storage technologies (other than pumped hydro power) in an effort to reduce the country's dependency on the availability of its water resources.

Researchers and policymakers should define long-term goals and intermediate steps towards these goals; existing intermediate goals might need to be revised in order to avoid stranded investments, since today's decisions will have a significant influence on the future system. There is a need for new policies to support these goals and to enable new business models.

It will be necessary to disseminate knowledge to the general public about long-term goals and improve participation processes, while concurrently further analysing and discussing available options to produce electricity, with all their advantages and disadvantages in economic, ecological and social terms. Representatives of the population need to be included in the discussion on the countries' future electricity supply to increase public support for national targets. There should be a strategy to assure that all societal groups are empowered to participate in this process. Finally, action needs to be taken to ensure that the local population has its fair share of benefits from the increase in renewable energy technologies, such as new green jobs or financial participation in decentralised projects.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytical Hierarchy Process
CO_2	carbon dioxide
CSP	Concentrating Solar Power
cts	Euro cents
IPCC	Intergovernmental Panel on Climate Change
JAEC	Jordan Atomic Energy Commission
LCOE	levelised cost of electricity
MCA	Multi-Criteria Analysis
MENA SELECT	Middle East North Africa Sustainable ELECtricity Trajectories
MENA	Middle East and North Africa
NDC	Nationally Determined Contribution
NGO	Non-Governmental Organisation
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PV	Photovoltaic
renpassG!S	Renewable Energy Pathway Simulation System GIS
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation
ST	Sustainability Transitions
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WI	Wuppertal Institute for Climate, Environment and Energy
WSM	Weighted Sum Model

Appendix A. Installed Capacity, CO_2 Emissions and LCOE in the Developed Scenarios

Appendix A.1. Morocco, 2050

Table A1. Selected characteristics of scenarios (Morocco, 2050).

Ranking Result		**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**
Technology	**Unit**	**100% Renewable Category A**	**Mix 1 Category B**	**Mix 2 Category B**	**PV Category B**
Renewable					
Wind power	MW	45,000	35,000	40,000	10,000
PV	MW	30,000	15,000	10,000	50,000
Hydro power	MW	3100	3100	3100	3100
Biomass	MW	5000	3000	3000	0
CSP	MW	2000	2000	1500	1300
Conventional					
Coal	MW	0	5000	6000	4937
Oil	MW	0	741	741	741
Gas	MW	0	500	6172	6172
Total	*MW*	*85,100*	*69,341*	*70,513*	*76,250*
PHS (pump)	MW	10,000	9000	10,000	23,906
PHS (turbine)	MW	17,926	9635	7511	14,283
CO_2	Mt/a	0.0	18.5	19.1	29.3
LCOE	cts/kWh	9.73	8.56	8.61	9.44

Appendix A.2. Jordan, 2050

Table A2. Selected characteristics of scenarios (Jordan, 2050).

Ranking Result		Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
Technology	**Unit**	**No Imports Category B**	**Medium RE + gas Category D**	**RE + gas Category D**	**Current Plans + gas Category D**	**Mix Incl. Nuclear Category C**
Renewable						
Wind power	MW	15,000	3000	4000	1200	8000
PV	MW	25,000	3500	4000	1000	9000
Geothermal	MW	3500	0	0	0	750
Hydro power	MW	500	12	12	12	250
Biomass	MW	5000	1500	90	90	700
CSP	MW	20,000	2000	2000	0	5000
Conventional						
Nuclear	MW	0	0	0	0	2000
Coal	MW	0	0	0	0	1000
Oil	MW	5000	470	470	470	1500
Gas	MW	4000	16,000	17,500	18,000	12,000
Total	*MW*	*78,000*	*26,482*	*28,072*	*20,772*	*40,200*
Batteries (energy)	GWh	40.0	2.0	2.0	0	9.0
Batteries (power)	MW	18,000	900	900	0	5,187
CO_2	Mt/a	0.3	18.4	20.6	26.7	15.2
LCOE	cts/kWh	28.19	9.99	10.08	9.52	13.68

Appendix A.3. Tunisia, 2050

Table A3. Selected characteristics of scenarios (Tunisia, 2050).

Ranking Result		Rank 1	Rank 2	Rank 3	Rank 4
Technology	**Unit**	**5 GW mix Category A**	**Mix Category B**	**Mix + solar Category B**	**Solar + gas Category C**
Renewable					
Wind power	MW	5000	7000	1755	1755
PV	MW	5000	6000	10,000	5000
Geothermal	MW	5000	500	500	0
Hydro power	MW	63	63	63	63
Biomass	MW	5000	1000	1000	100
CSP	MW	5000	1500	5000	1500
Conventional					
Coal	MW	0	0	0	0
Oil	MW	0	0	0	0
Gas	MW	0	8000	8000	9500
Total	*MW*	*25,063*	*24,063*	*26,318*	*17,918*
PHS (pump)	MW	400	400	400	400
PHS (turbine)	MW	400	400	400	400
CO_2	Mt/a	0.0	7.24	6.90	14.01
LCOE	cts/kWh	16.46	8.96	11.76	9.47

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Appendix B. Resulting Weightings in the Country Workshops

Appendix B.1. Morocco

Table A4. Resulting weightings in the Morocco country workshop.

	Techno-Economic Group	Environ-Mental Group	Societal Group	Equal Preference Group	Consensus
System costs	16	1	14	20	16
System flexibility	5	2	6	10	12
Energy independence	51	8	52	42	25
CO_2 emissions	1	6	1	1	4
Land use	1	3	1	1	1
Water consumption	6	40	6	9	12
Hazardous waste	6	16	6	3	4
On-site job creation	3	1	1	2	6
Local value chain integration	8	6	3	8	11
Safety	2	3	3	2	3
Air pollution (health)	2	17	8	3	6

Appendix B.2. Jordan

Table A5. Resulting weightings in the Jordan country workshop.

	Techno-Economic Group	Environ-Mental Group	Societal Group	Equal Preference Group	Arithmetic Mean
System costs	15	2	1	3	4
System flexibility	21	2	4	1	5
Energy independence	31	2	9	10	12
CO_2 emissions	1	24	1	4	4
Land use	0	3	1	3	2
Water consumption	4	24	1	4	4
Hazardous waste	4	24	5	24	14
On-site job creation	1	0	4	1	1
Local value chain integration	4	1	1	3	3
Safety	15	15	46	13	27
Air pollution (health)	5	4	20	26	14

Appendix B.3. Tunisia

Table A6. Resulting weightings in the Tunisia country workshop.

	Techno-Economic Group	Environ-Mental Group	Societal Group	Equal Preference Group	Consensus
System costs	49	2	2	3	13
System flexibility	8	2	8	9	11
Energy independence	20	6	18	21	16
CO_2 emissions	2	9	5	4	6
Land use	1	3	2	2	2
Water consumption	5	35	5	8	13
Hazardous waste	10	16	2	18	12
On-site job creation	0	3	2	2	5
Local value chain integration	1	3	5	8	5
Safety	4	3	37	5	4
Air pollution (health)	1	16	15	19	13

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5 External Cost of Air Pollution from Energy Generation in Morocco[4]

Franziska Dettner
Marina Blohm

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External cost of air pollution from energy generation in Morocco

F. Dettner[a,b,*], M. Blohm[a,b]

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

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ABSTRACT

Morocco's electricity demand is increasing and the country is struggling to improve its energy independence. Also, air quality levels in Morocco are considered moderately unsafe, as its $PM_{2.5}$ annual mean concentration of 33 $\mu g/m^3$ exceeds the recommended maximum of 10 $\mu g/m^3$. Renewable energy could be the solution to reduce the country's harmful air pollution levels, mitigate climate change and decrease energy dependence. Incorporating external cost of air pollution from electricity generation into energy decision making-processes could lead to a shift from the use of fossil fuels to more sustainable and less polluting renewable energy sources. For this to happen, a detailed quantification of external costs is necessary. This paper presents a first bottom-up calculation of the costs of damage to human health from air pollution resulting from energy generation, following the Impact Pathway Approach without atmospheric chemistry modelling for the Moroccan energy system of 2015, to give a first estimate and guideline on the order of magnitude of costs. The overall external costs for 2015 were calculated to be between 8.4 and 18 billion € $_{2015}$, equating to 18% of the Moroccan GDP.

1. Introduction

The speed at which global warming is progressing makes it one of the most pressing challenges facing the earth. Urgent action is required to combat the cause of global warming, as its consequences are far-reaching. One of the main drivers of global warming is the burning of fossil fuels, which adds significant amounts of greenhouse gases to the atmosphere. Fossil fuel burning also produces non-GHGs, including the so-called criteria air-pollutants, NO_X, SO_2, PM, O_3 and NH_3, which cause considerable damage to human health and have an effect on the natural and built environment [28]. Effective mitigation measures could include the reduction in energy demand or the use of renewable energy sources to meet increasing demand. However, a shift to renewable energies comes with high investment costs and increased levelised costs of electricity (LCOE). Decision makers often prefer to use existing fossil fuel technologies to keep system costs low, but in doing so ignore external costs, which include the health impacts of non-GHG emissions and the social cost of GHG emissions without market costs of such (in case CO_2 emissions are considered within a carbon tax or trading scheme).

External costs are the uncompensated effects of producing or consuming a good on an uninvolved third party [37]. A classic example of external costs are the impacts from air pollutant emissions resulting from the burning of fossil fuels. The polluter, in this case the power plant operator, is not obliged to reduce emissions or compensate for the damages [28,29] caused to a third party, e.g. the health of the public [26], which might lead to unsustainable decisions for the energy sector. The external costs of energy generation consist of three main components: climate change damage costs associated with GHG emissions; the cost of treating health conditions, the damage to the natural and built environment resulting from criteria air pollutants and non-environmental social costs for non-fossil electricity-generation technologies. The largest share of external costs of energy generation (approximately 95%) are reflected in the effects of air pollution on human health according to inter alia Hidden Costs of Energy [9], ExternE [28], Hohmeyer [37] and Samadi [73], which is why this paper solely focuses on this area.

Countries in the Middle East and North Africa are particularly vulnerable to the consequences of global warming. Some of these countries, such as Morocco, are also at an energy crossroad. Although Morocco has

Abbreviations: CB, Chronic Bronchitis; CCGT, Combined Cycle Gas Turbine; CHA, Cardiac Hospital Admissions; CRF, Concentration Response Function; CO_2, Carbon dioxide; DE, Diesel Engine; EPA, Environmental Protection Agency; ERF, Exposure Response Function; GDP, Gross Domestic Product; GHG, Green house gas; GT, Gas Turbine; HA, Hospital Admissions; LCOE, Levelised Cost of Electricity; LRS, Lower Respiratory Symptoms; MENA, Middle East and Northern Africa; MRAD, Minor Restricted Activity Days; NH_3, Ammonia; NO_X, Nitrogen Oxide; O_3, Ozone; ONEE, Moroccan National Agency for Electricity and Water; PM, Particulate Matter; PHS, Pumped Hydro Storage; PV, Photovoltaic; RAD, Restricted Activity Days; RHA, Respiratory Hospital Admissions; SO_X, Sulphur Oxide; SO_2, Sulphur dioxide; ST, Steam Turbine; UBA, Umweltbundesamt (German Federal Environment Agency); VOLY, Value of a Life Year; VSL, Value of a statistical Life; VPF, Value of a prevented fatality; WLD, Work Loss days; YOLL, Years of life lost.

* Corresponding author.
E-mail addresses: franziska.dettner@uni-flensburg.de (F. Dettner), marina.blohm@uni-flensburg.de (M. Blohm).

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Nomenclature

Variables

A_f	activity rate
B_p	adjusted policy site benefit
B_s	original benefit estimate at study site
c_p	pollution concentration
e	income elasticity
E	emission quantity
EF	emission factor
ER	emission reduction
h	health endpoint
h_e	plume centreline height
$I\ (s_{CRF,c})$	total health impact
$I_{h,p}$	impact per pollutant and health endpoint
k	summation limit for multiple reflections of the plume off of the ground and elevated inversion
P	population number
P_t	share of population affected
P_a	share of population in age group affected
P_r	share of population at risk
q_f	energy content of fuel
Q_n	produced electricity per power plant
Q	emission rate
s_{CRF}	slope of concentration response function
u_s	wind speed at stack height
x_h	cost factor per health endpoint
X	total external costs from air pollution
z_r	receptor height above ground
z_i	mixing height
η	efficiency factor
σ_y	lateral dispersion parameter
σ_z	vertical dispersion parameter

made undeniable economic progress and has improved the population's average standard of living, the country faces considerable challenges to meet the expected increased electricity demand in the coming years. The current fossil fuel based system emits high levels of CO_2 as well as other harmful air pollutants, causing stress on the global environment through increased global warming, and stress on the health of the local population. Rather than relying on fossil fuels for electricity generation [42], renewable energies could be considered in Morocco to reduce pollution levels and increase energy security and independence.

The aim of this study is to provide a first, rather conservative, analysis of the external costs of air pollution from energy production in Morocco in order to estimate the magnitude of the costs and thus improve the understanding of the far-reaching consequences of fossil fuel combustion. The analysis of Morocco's current energy system and the presented simplified IPA methodology can be applied, extended and adapted by policy makers and researchers in Morocco as well as other countries. Particular emphasis is placed on the ease of application of the model, which atmospheric chemistry models often lack, to ensure transparency, traceability and reproducibility of results. The lack of atmospheric chemistry modelling and concentration-response-functions (CRF) tailored to Morocco and the MENA region is the main uncertainty factor of this study. Nevertheless, it provides a significantly robust guide for policy makers to assess future energy systems. The data presented underlines the necessity of renewable energy sources for climate change mitigation and air pollution reduction. This study is particularly important for Morocco as the country's government is determined to continue investing in coal even though this is potentially counterproductive for climate change mitigation and air quality improvement.

1.1. Energy system

In 2015, 84% of Morocco's total electricity production was derived from fossil fuels, resulting in the emission of substantial amounts of GHGs and non-GHGs. Table 1 shows the development of installed capacities of energy sources between 2005 and 2019.

Coal-fired power plants constitute the largest share of installed capacities at just over 4,100 MW in 2019. According to the Moroccan National Agency for Electricity and Water (ONEE), 2,370 MW of new coal-fired power plants were installed between 2014 and 2018 [60,63], [64]. Concurrently, 165 MW of older coal capacity was decommissioned in 2019 [66]. The latest annual report of ONEE [65] shows that coal provided approximately 39% of the total installed capacity at the end of 2019. In terms of electricity production, the newly constructed power plants increased the overall amount of coal-fired electricity to approximately 27,000 GWh in 2019, which is an increase of almost 10,000 GWh from 2015. The coal-fired power plant Jorf Lasfar alone, generated approximately 15,000 GWh of electricity in both 2015 and 2019, which is approximately 40% of the total generated electricity [65]. There are plans to construct a new coal-fired power plant in Nador by 2023, which will have a capacity of 1,320 MW. An extension of the plant in Jerada providing 350 MW is planned by 2022 [43]. The natural gas-fired power plants utilise combined cycle gas turbines (CCGT) and had a capacity of approximately 834 MW in 2019, whereas gas turbines (GT) and steam turbines (ST) are running on fuel oil.

Although there has been an increase in the coal capacity in Morocco, the country invested substantially between 2015 and 2019 to increase the share of renewable capacities. Renewable energy accounted for 38% of the total installed capacity in 2019. The expansion in wind power has been rapid; between 2010 and 2019 the wind power capacity increased by 1 GW. In contrast, the development of solar power plants was slower as Morocco focused on the construction of large solar thermal power plants, which require a long planning and construction period. In terms of generated electricity, renewable energy had a share of 21% with a production of approximately 8,300 GWh in 2019 [66]. The amount of imported electricity was reduced from approximately 5 TWh in 2015 to 500 GWh in 2019, which has increased Morocco's energy independence, according to ONEE [62,66].

The electricity demand has increased from 34.4 TWh/a in 2015 to 38.8 TWh/a in 2019 [62,66]. Projections from different studies indicate that this level of increase is unlikely to continue until 2050. Both Trieb et al. [82] and Zelt et al. [91] calculated the electricity demand to be approximately 50 TWh by 2020 and 173 TWh by 2050. Current data for 2020 shows that the actual future increase might be slightly lower, nonetheless a substantial increase is certain as the standard of living is likely to increase and electricity imports will need to be further reduced to meet the aim of energy independence.

1.2. Energy strategies & targets

Current developments and future strategies for the Moroccan energy sector are based on two requirements: 1) the need to meet the increased future energy demand while 2) reducing the fuel import dependency. The targets to meet the increasing energy demand are primarily based on the national energy strategy *Stratégie Energétique Nationale – Horizon 2030*, published by the Moroccan Energy Ministry MEMEE in 2009 [48]. According to this strategy, Morocco's aim is to rely on robust and established technologies to guarantee both energy security and low cost electricity. The strategy underlines that coal-fired power plants meet both requirements, which is why the country is continuing to rely heavily on coal. Underlying reasons for the preference for coal over natural gas could be the high number of coal suppliers around the world, the possibility of entering into short term contracts, a relatively stable coal price compared to the high price volatility of gas, and the low operation cost of coal power plants. In addition to this coal-based fossil energy path, Morocco plans to further increase the share of renewable energies. By 2020,

Table 1
Development of installed capacities in Morocco, in [MW], after [58,59,61,65] (CC: combined cycle gas turbine, GT: gas turbine, DE: diesel engine, ST: Steam turbine, PHS: pumped hydro storage, PV: photovoltaics, CSP: concentrated solar power)

	CCGT	DE	ST [a]	Coal	GT [a]	Hydro (incl. PHS)	PV	CSP	Wind
2005	400	69	600	1,785	615	1,729	0	0	54
2010	850	203	600	1,785	915	1,770	0	0	221
2015	854	202	600	2,545	1,230	1,770	0	161	796.5
2019	834	316	600	4,116	1,110	1,770	170	541	1,220

[a] running on fuel oil

the installed capacities of hydropower (including pumped storage), solar power (PV and CSP) and wind power should reach 2 GW each, so that 42% of the installed capacity comes from renewable sources. These targets will, under current assumptions, most likely be reached by 2022 for solar, by 2023 for hydro and by 2024 for wind, taking into account all power plants currently under development. By 2030, the share of installed renewable capacities should reach 52% consisting of 20% solar, 20% wind and 12% hydro power [16]. Additionally, Morocco is striving to increase the share of gas-fired power plants to 2,400 MW by 2025 [33].

Within the Paris Agreement, Morocco's aim is to reduce GHG emissions by 42% below the business as usual projections by 2030 [56]. However, according to World Bank data [80], per capita emissions increased significantly between 1960 and 2012 from 0.295 tCO_2 to 1.783 tCO_2 per year. In order to achieve the emission reduction targets, Morocco is working on the implementation of a carbon market. It is planned to combine an emissions trading system with a carbon tax that would include the sectors of electricity generation and cement and phosphate production [57]. Currently, the consumption of natural gas and coal for electricity generation is exempt from Morocco's fuel tax [69]. To regulate air pollution, Law No. 13-03 exists in conjunction with Decree No. 2-09-631, which sets maximum levels per pollutant, enacted by the Moroccan Energy Ministry (see [53]).

2. State of research

The following section provides a review of the most relevant literature concerning the external costs of energy generation methodology, studies concerning health effects of air pollution in Morocco, and 100% renewable energy system research for Morocco. The Section 2.4 identifies gaps in the key literature and underlines the importance of the presented research to the area of interest, namely air pollution from energy generation and linked health effects in Morocco.

2.1. External cost of energy generation

Research on the external cost of energy generation peaked in the 1990s and early 2000s. The most prominently cited research in this context is from ExternE, an EU-funded project series [28]. The Impact Pathway Approach (IPA) was developed within this EU funded project series from the early 1990s to 2005. The IPA is used to calculate external costs and has been used in a number of prominent studies, such as NEEDS [55], Hope [19,39], as well as in the drafting of EU strategies to combat acidification and the setting of air quality limits for PAHs (Polycyclic Aromatic Hydrocarbons) and other pollutants [18]. The IPA uses a bottom-up methodology to determine environmental damage costs, which are considered the most accurate indication of external costs. The four steps of the IPA are followed in the present study, namely : 1) **emission**, with specification in regards to technology and site, resulting in the quantity of the emitted pollutants per year; 2) **dispersion**, using an atmospheric dispersion model to determine the increase in the concentration of pollutants at the receptor site; 3) **dose-response function**, connecting the pollutant concentration at a specific site with that at the receptor itself, resulting in health endpoints per receptor site resulting from emissions from the source; and 4) **monetary valuation**, applying literature values or pre-determined values to each health endpoint to determine economic costs of activity.

Table 2
Overview of methodology with main inputs.

Result	Input
Annual emission quantity per power plant	fuel quantity per power plant efficiency factor of each power plant emission factor respective to used fuel and firing technology gross calorific value of used fuel
Pollutant concentration per power plant site	dispersion model (e.g. Gaussian Plume) meteorological data per site emission quantity per power plant stack data per power plant (i.a. diameter, height, exit velocity)
health endpoints of affected population	pollution concentration per site total population number share of population affected by health endpoint share of population at risk exposure-response function per pollutant and health endpoint
Cost of air pollution	health endpoints per pollutant and site monetary value of each health endpoint GDP ratio between study site and literature values

In 1990, a comprehensive study led by Richard Ottinger [68] followed a similar approach to determine the economic value of environmental effects from pollution sources. He used standardised emission factors for various power plant types. These were also used in the study presented here. In 2010, the American Committee on Health and Environment published an extensive study [9], on electricity related damage cost assessment, largely following the IPA methodology. The book *How much is clear air worth?* by Ari Rabl and Joseph Spadaro from 2014 [70], includes updated CRF and calculation examples, as well as methodology advice for uncertainty analysis, which are used in the present study. Other relevant work includes the HRAPIE (Health risks of air pollution in Europe) project by the WHO of 2013 [38,40,86] including recommendations for CRF for cost-benefit analysis, which were included here for possible further sensitivity analysis (see Tables 8 and 9), and the REVIHAAP Project, a review of evidence on health aspects of air pollution [87].

2.2. Health effects from air pollution in Morocco

Based on World Health Organisation (WHO) guidelines, the air quality in Morocco is considered moderately unsafe. The most recent data indicates that the country's annual mean concentration of $PM_{2.5}$ is 33 $\mu g/m^3$, which exceeds the recommended maximum of 10 $\mu g/m^3$ [41]. An update of the WHO guidelines is expected to be published in June 2021 [89]. IAMAT [41] suggests high air pollution levels in Meknes and Kenitra. A recent study by the University in Agadir and the French meteorologic institute indicated that the level of air quality is a major concern for decision makers and that the lack of monitoring systems hinders the improvement of air quality [1].

A limited number of studies have analysed the impact of air pollution on the health of the Moroccan population. A joint study by the

University of Casablanca and the General Directorate of Meteorology in Morocco, analysed air quality and health in Casablanca and Marrakesh [45]. The study attributes an average of 13,000 deaths per year in Morocco to air pollution. This is 7% of all deaths, making it the 8th largest mortality factor in the country. According to a recent Greenpeace study, between 3,300 and 7,300 (central value 5,100) premature deaths in Morocco in 2018 were linked to fossil fuel-related air pollution [27]. These air pollution related deaths have an estimated associated cost of between 670 and 1,600 million USD (central value 110 million USD), equivalent to 0.6% to 1.4% of the Moroccan GDP. The most comprehensive study of health impacts from air pollution in Morocco is by the World Bank Group [13]. They analysed ambient and indoor long-term exposure to $PM_{2.5}$ air pollutants in 8 major Moroccan cities and the corresponding premature deaths. The study used emission measurements of $PM_{2.5}$, using the value of a statistical life year (VSL) in Morocco of US$ 191,500 to determine the damage costs and obtained a figure of between 420 million and 1.14 billion US$, equivalent to 0.79% of the 2014 Moroccan GDP. Croiture et al.[13] reported that there were between 2,200 and 6,000 premature deaths resulting from air pollution in Morocco in 2014, 50% of which were in Casablanca. They also derived that 70% of the health impacts of pollution in Morocco are related to ischemic heart disease and strokes. A more generic study of air quality and health impacts in Africa by Marais et al. [49] forecasts between 1,000 and 9,999 deaths to air pollution from fossil fuel use in electricity generation and transport in Morocco in 2030, using GEOS-Chem using gridded power plant emission, based however, on a number of assumptions. The study also stated that SO_2 and NO_X emissions, as precursors of fine particles ($PM_{2.5}$), will approximately double in Africa between 2012 by 2030. Marais et al. [50] calculated that there will be 48,000 avoidable deaths in Africa in 2030, and that the mortality rate resulting from power plants will be three times that from transport.

Other air pollutant damages such as impacts on building material, visibility and transmission lines are negligible, according to ExternE [28]. Additionally, damages caused by renewable energy generation are also deemed to be insignificant, as they do not induce air pollution at the power plant site, but rather at the manufacturing facility and during transport. Life-Cycle and Supply-chain emissions are not considered for fossil and renewable technologies as the research here focuses on pollutants emitted during the electricity generation phase.

2.3. Renewable energy transition Morocco

The Moroccan energy system and 100% renewable energy options for it have been analysed in much detail inter alia within Zelt et al. [91], Schinko et al. [76], Schinke and Klawitter [74,75], Kousksou et al.[47], Khalid Raouz [71], de Arce et al. [15] and Choukri et al.[12]. All of these studies agree on the technical feasibility of a 100% renewable energy system, as well as on the high renewable energy potential of Morocco. A 100% renewable energy system would provide the Moroccan energy sector with favourable CO_2 emission mitigation options as well as the opportunity to reduce its high fuel import dependency (96%, as of 2015) [71]. Most of the studies listed above identified a lack of coherent energy generation targets aimed at providing energy independence and CO_2 and GHG mitigation.

2.4. Contribution & research question

A number of studies examining a 100% renewable energy based system for Morocco used energy system modelling. To our knowledge, no studies have determined the external cost of energy generation for Morocco nor are there any studies which have analysed the specific impact of energy related health costs on energy decision making processes. The here presented methodology can be used to provide an educated estimation of the external cost of energy generation for any other country beside Morocco. Therefore, the presented work does contribute to the scientific discussion of decarbonisation of the electricity sector for climate change mitigation and reduced air pollution in Morocco, but also builds an important bridge between a strictly economic cost energy system perspective to a more socially just and interdisciplinary approach towards energy system modelling, when external costs are internalised. The research aim is the calculation of the external cost of air pollution arising from energy generation in Morocco for 2015. The hypothesis is that internalising these costs promotes the transition towards a 100% renewable energy based electricity sector in Morocco. The hypothesis results from two observations: 1) that the transition from a fossil fuel based to a 100% renewable energy based electricity sector may come with high costs and 2) that the burning of fossil fuels not only produces GHG emissions, but also criteria air pollutants, which are harmful to human health. Additionally, this study aims at opening the research field for a more complex and in depth analysis of external cost including atmospheric chemistry modelling, a quantification of CRF for the MENA region and the global south and cost figures assessed within the studied countries itself.

3. Methodology

The main steps of the IPA are applied for the energy generation plants in Morocco. The intermediate results and inputs needed for each step are summarised in Table 2.

3.1. Emission

The four criteria air pollutants, SO_2, NO_X and Particulate Matter (PM_{10} and $PM_{2.5}$), as the most harmful to human health, according to the WHO [86], as well as CO_2 as the largest contributor to global warming, were chosen for analysis. Emission data for Moroccan power plants is unavailable, so the emission factor approach used by the United States Environmental Protection Agency [22] was adopted. This approach has previously been used by Ottinger et al. [68], Fu et al.[30], Ding et al. [17] and in the GHG protocol initiative [32]. Emission factors can be equally as meaningful as parametric source tests or continuous emission monitoring [8,23]. The emission factor is a representative value used to relate the amount of a pollutant released into the atmosphere to an activity associated with the release, namely the activity rate A_f. In the case of energy generation, this activity is the quantity of burnt fuel. The quantity of the emitted pollutant, E, per power plant for the analysed year of 2015 is calculated from Eq. (1).

$$E = A_f \cdot EF \cdot \frac{1 - ER}{100} \tag{1}$$

The emission factor EF in t/a is specific to the type and age of plant, fuel type and firing technology, see EPA [22,24,25]. ER is the potential emission reduction, if, for example, emission reduction equipment is applied.

$$A_f = \frac{Q_n}{\eta \cdot q_f} \tag{2}$$

As data is not available for the quantity of used fuel per power plant in Morocco, the value was derived using Eq. (2), where Q_n in GWh/a is the produced electricity per power plant, η is the respective efficiency factor and q_f is the energy content of the respective fuel in MJ/kg or m^3.

3.2. Dispersion modelling

Pollutants can cause damage to human health and the environment far away from the point of their release [14]. According to i.a. Bluett et. al [8], the dispersion of criteria air pollutants is significant up to 1,000 km from the source. For ease of application, local dispersion modelling was preferred over long-distance dispersion for an initial estimate of the damage costs of air pollutants from power generation in Morocco. Tahri et al. [78] show in their air mass trajectory modelling for the city of Kenitra, 50 % of the air masses are produced locally and remain local.

An additional 21 % of the emissions in Kenitra stem from Northern Morocco. This underlines the validity of using local dispersion modelling.

The SCREEN3 model [84], developed by the EPA in 1995, was used for the analysis of ground level pollutant concentrations. SCREEN3 is a screening version of the more advanced ISC3 model and does not incorporate atmospheric chemistry, as only local (< 50km) dispersion is considered. It includes an option for shoreline fumigation and uses a steady-state Gaussian plume simulation. SCREEN3 estimates the maximum ground-level concentrations for point, area, flare and volume sources [84]. The model also incorporates meteorological and source-related factors to estimate the pollutant concentration. The ground level concentration X in g/m^3 under the plume centre line is calculated using Eq. (3) [84]. The emission rate Q in g/s is determined through lateral and vertical dispersion parameters (σ_y respective σ_z) and the wind speed at stack height u_s, receptor height above ground z_r, plume centreline height h_e, mixing height z_i and k the summation limit for multiple reflections of the plume from the ground and elevated inversion, usually ≤ 4.

$$X = \frac{Q}{(2\pi\, u_s\, \sigma_y\, \sigma_z)} \quad \{exp[-0.5((z_r - h_e)/\sigma_z)^2] + exp[-0.5((z_r + h_e)/\sigma_z)^2] + \sum_{n=1}^{k} [exp[-0.5((z_r - h_e - 2nz_i)/\sigma_z)^2] + exp[-0.5((z_r + h_e - 2nz_i)/\sigma_z)^2] + exp[-0.5((z_r - h_e + 2nz_i)/\sigma_z)^2] + exp[-0.5((z_r + h_e + 2nz_i)/\sigma_z)^2]]\} \tag{3}$$

Stack parameters play an important role in dispersion modelling as they significantly influence the ground-level concentration of pollutants. These parameters are especially important for local dispersion, as they determine the effective release height. The input stack parameters needed for SCREEN3 are stack height, diameter, exit velocity, exit temperature and ambient air temperature [24,84]. Thomas et al. [81] regard stack height as the key factor in air pollution control. As actual stack data for Morocco is unavailable, generic stack data was used. An extensive power plant operation database provided by the US Energy Information Administration (EIA) was used to create reference stack data figures [20]. The respective plant capacity, primary fuel as well as age and firing technology were considered to determine a representative power plant and connect the named values to the Moroccan power plants. Using meteorological wind data from Meteoblue [52] for each power plant site, the direct maximum ground level pollutant concentration per power plant was calculated at distances from 0 to 50 km from the plant. It is important to note, that cross pollution was not taken into account.

3.3. Concentration-response-function

An impact can only be quantified if the corresponding exposure-response function (ERF) is known; therefore, the ERF is a central ingredient for the IPA and it merits special attention [70]. For inhaled harmful pollutants, the ERF is usually stated in the terms of ambient concentration as a concentration-response function (CRF) [77]. For the present assessment, the CRFs introduced within ExternE [28] and by Rabl et al. [70] are adapted for use in the Moroccan context (see Table 10). There are two different approaches to assess the total number of health endpoints. If the slope of the CRF is given, provided that the function is linear, no background concentration is required and only the delta contributed by the local emission source is vital. If the function, however, is not linear, the background concentration must be considered. In this paper, in accordance with ExternE [28], Rabl and Spadaro [77] and the WHO [86], all CRFs are assumed to be linear. For this study, reference is made to the functions of ExternE [28], Holland et al. [38] and Spadaro et al. [77] to ensure consistency within the IPA. There are a number of established CRFs for particulate matter emissions. For SO_X and NO_X, there are three main approaches in the analysed external cost literature (see right-hand column in Table 3 for source). For cohesion with the IPA, the CRFs provided by Spadaro et al. [77] were chosen chosen for this study, although sensitivity analysis with more recent CRFs, as shown in Table 8 and 9, is recommended. This will be discussed again in Section 5.

Table 3
Concentration-Response Functions commonly used for NO_X and SO_X emissions.

NO_X	SO_X	Source
$CRF_{NOX} = CRF_{PM10}$	$CRF_{SOX} = CRF_{PM10}$	Holland [38]
$CRF_{NOX} = CRF_{PM10}$	$CRF_{SOX} = 1.67 \times CRF_{PM10}$	Spadaro et al. [77], [70]
$CRF_{NOX} = CRF_{PM10}$	$CRF_{SOX} = CRF_{PM2.5}$	ExternE [28], [29]

The impact I (s_{CRF}, c), derived from Eq. (4), depends on the slope of the CRF (s_{CRF}) respective a certain health endpoint h, the ground-level concentration c in μg/m^3 of the respective pollutant p, and population parameters P. The impact is expressed for morbidity in cases of a health endpoint per year and for mortality in years of life lost (YOLL) per person per μg pollutant per m^3. The slope s_{CRF} is calculated by multiplying the relative risk (RR) of illness (Holland et al. [38]) with the underlying health condition ß specific to Morocco and if data was available the Western Sahara (WHO Global Health Observatory [85,88]).

$$I\,(s_{CRF}, c) = c_p \cdot s_{CRF}(h, p) \cdot P \tag{4}$$

The population parameter P, is derived from Eq. (5) as the product of the total number of people affected P_t, the age group affected by a certain health endpoint P_a, and the fraction of the population at risk within the considered age group P_r.

$$P = P_t \cdot P_a \cdot P_r \tag{5}$$

The analysed health endpoints can be split into two categories, connected to mortality and morbidity. Morbidity values include Work Loss Day (WLD), Hospitalisation, Chronic bronchitis (CB), Minor restricted activity days (MRAD), new cases of asthma, restricted activity days (RAD) and medication use. Mortality on the other hand values premature mortality, acute mortality and infant mortality.

3.4. Monetary valuation

The aim of monetary valuation is to assess the total economic value of health impacts from air pollution, including the value of goods and non-marketed goods. Monetary values for market goods are determined using, inter alia, the revealed preference method or behavioural method, direct revealed preference or the travel cost method. Non-marketed goods are determined using stated-preference methods, contingent valuation or choice experiments. Both valuation methods are therefore closely linked to income levels and the economic situation of a country. A number of studies have used eurocentric values referenced to income levels and living standards to analyse values for health endpoints resulting from the inhalation of air pollutants [28,70]. In order to apply these values to the Moroccan context, a benefit transfer is applied, considering the different GDP per capita level of each country, using Eq. (6). B_p is the adjusted policy site benefit, in this case Morocco, B_s the original benefit estimate at study site, here, European based literature values. The income elasticity, e, is set at 1.

$$B_p = B_s \cdot \left(\frac{GDP_{\text{per capita p}}}{GDP_{\text{per capita s}}}\right)^e \tag{6}$$

Most studies ([9,28,55,70]) use GDP per capita as an approximation for income in international benefit transfers, however these assumptions might not necessarily hold. For further reading please see Navrud et al. [54].

The total external cost of air pollution, X, was calculated using Eq. (7), with the Impact I and cost factor x depending on the pollutant p and health-endpoint h.

$$X = \sum_h \sum_p I_{h,p} \cdot x_h \tag{7}$$

The two main health endpoint groups mortality and morbidity introduced within 3.3 are valued differently. Morbidity related values are

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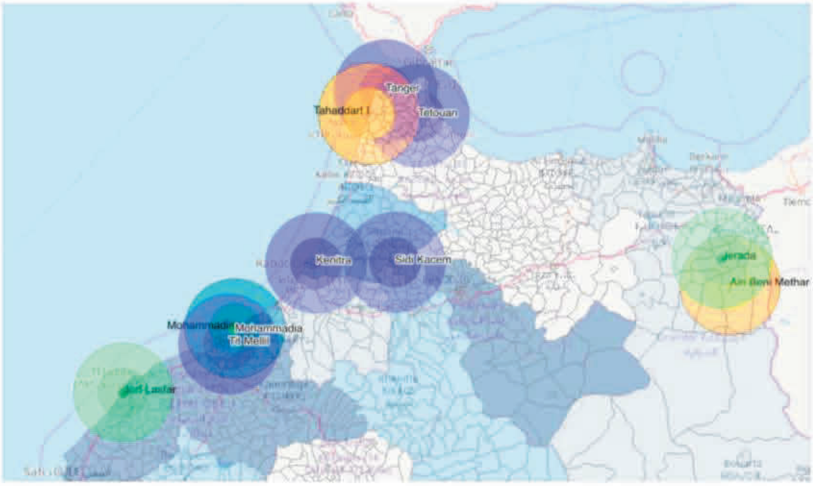

Fig. 1. GIS analysis of Moroccan population within 50 km vicinity of power plants.

Table 4
Main health impacts in 2015 using Moroccan monetary values, central and low cost value approach, rounded.

Health endpoint	Impact [per year]	central cost [million€ $_{2015}$]	low cost [million€ $_{2015}$]
Chronic mortality	771,503 YOLL	6,630.32	3,315.16
Infant mortality	30,279 YOLL	8,401.85	3,622.92
new cases of CB	28,220 cases	1,262.51	643.53
HA respiratory	18,716 cases	7.34	4.49
HA cardiac	11,575 cases	4.53	2.77
RAD_{Net}	11,457,002 cases	1,654.43	108.66

using direct costs, which occur within the health service plus any other personal cost by an individual or family member. The valuation of mortality is a rather complex issue by itself. Along with ExternE [28], Rabl, Spadaro and Holland [70], NEEDS [55] and others, the analysis chooses to analyse chronic mortality using VOLY and infant mortality using two times the determined VPF. The complete list of monetary values and adapted Moroccan values are shown in Table 11.

4. Results

The population affected by each power plant's emissions was determined using a GIS-based analysis, with population data from the Moroccan Planning Commission [34] and openAfrica [67], as depicted in Fig. 1.

86 % of the Moroccan population, which equates to 34,377,510 inhabitants in 2015, are accounted for in this analysis. Most power plants are sited no more than 50 km from large dwellings, the electricity consumers and a cooling water supply.

4.1. Air pollution costs

Table 4 summarises the health endpoints of pollution from the fuel power plants within the 50 km radius. To avoid double counting, chronic mortality was used rather than acute mortality to analyse long term effects of air pollution. The health endpoint RAD_{Net}, consisting of Restricted Activity Days (RAD) minus Work Loss days (WLD) minus Minor Restricted Activity Days (MRAD), has the highest occurrence with 11.5 million cases per year. Considering infant mortality, only those below the age of 5 are affected, resulting in a relative low number of years of life lost. However, underlining the implication behind this figure, 30,000 life years of infants are lost due to the high air pollution level.

The slope of the CRF was, when possible, adjusted to Moroccan standards. For example, the slope of the CRF for infant mortality is, according to Rabl et al. [70], $s_{CRF} = 1.0635E - 4\,YOLL/(a \cdot \mu g_{PM10}/m^3)$, using 76.95 years average Life Expectancy for Morocco and an infant death rate of 22.7 per 1,000 births. In comparison, the death rate in Western Sahara is slightly higher at 53.3 deaths per 1,000 births, which is reflected in the slope of the CRF $s_{CRF} = 2.04445 - 4\,YOLL/(a \cdot \mu g_{PM10}/m^3)$. The underlying valuation of infant mortality is the VPF. Assuming a full life in Morocco to be approximately 76 years, it is appropriate to take 2 times the VPF for infant mortality as a single VPF accounts for 35-40 years. Therefore, the health endpoint is valued much higher than, for example, chronic mortality (279,000 to 120,250 € $_{2015}$) with 646,000 and 161,500 € $_{2015}$. The total health damage in monetary terms using the adjusted figures for Morocco amounts to approximately 18 billion € $_{2015}$ (18,024,988,168 € $_{2015}$) with a lower bound of 8.4 billion € $_{2015}$, reflecting about 18 % of the Moroccan GDP for 2015. When expressed in European values, prior to equity weighting, the damage accounts for 197,414,844,711€ $_{2015}$ with a lower bound of 92 billion € $_{2015}$.

The overall external cost of air pollution from energy generation is dependent on five main factors: 1) location, as this determines the number of people affected, 2) capacity and output of the power plant, 3) efficiency factor, 4) stack parameters and 5) meteorological factors, such as wind speed, direction and deposition.

Fig. 2 shows the external cost of different pollutants and power plants on the left-hand axis and the population affected per plant on the right-hand axis. The highest share of costs relate to SO_2 emissions, followed by NO_X emissions. For the three coal fired power plants Mohammadia, Jorf Lasfar and Jerada, a substantial share of external costs results from particulate matter emissions; more from PM_{10} than $PM_{2.5}$. The two natural gas fired power plants, Ain Beni Mathar and Tahaddart, have comparably low external costs, due to low emission levels. Here, the highest damage is caused by NO_X emissions, which is due to the nature of the fuel. Approximately 73 million € of damage is caused by NO_X emissions from Tahaddart (respective 84 million € in total) and 5.22 million € in total from Ain Beni Mathar. Ain Beni Mathar is a 500 MW power plant, which was built in 2010 and is one of the newest in Morocco. Similar to the Tahaddart plant from 2005, Ain Beni Mather has a low NO_X burner, which is reflected in the Emission Factor and its overall lower emission level. When analysing the electricity generated from the three power plants in Mohammadia in 2015 (Mohammadia (coal, 1,500 GWh), Mohammadia Oil (fuel oil, 1,100 GWh) and Mohammadia II (fuel oil, 110 GWh)), the dependency of the output of the power plants becomes apparent. These three power plants are located in close proximity to each other and their emissions affect the same population (approx. 5,000,000 people). It is clear that the emissions are highly linked to fuel and firing technology and that coal power plants PM emissions are much more defining as for fuel oil power plants.

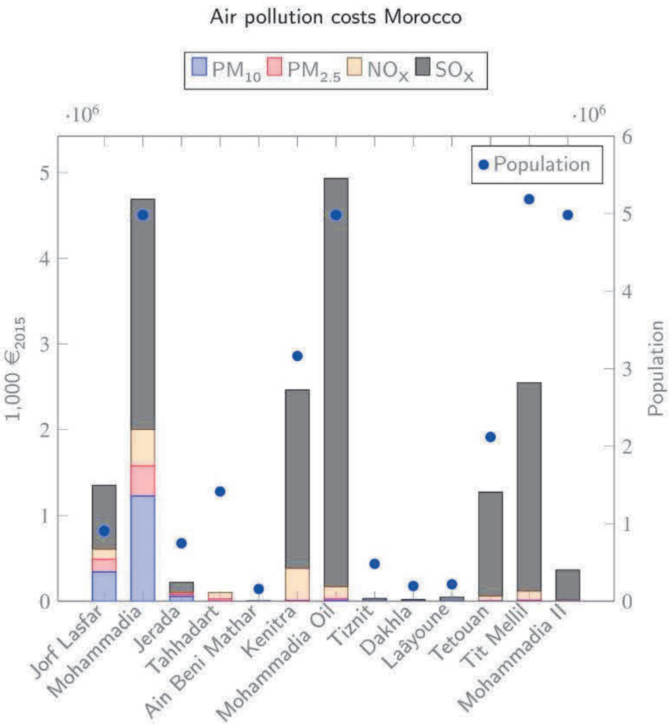

Fig. 2. External Costs of air pollution resulting from energy generation of all fossil fuel Moroccan power plants, split by pollutant and affected population per plant within 50 km radius.

Jorf Lasfar has the highest external costs per affected person at 1,491.37 € per year, assuming that the costs incurred are distributed equally among all affected people. Ain Beni Mathar, which is more creates 33.04 € /a per person. This is due to the low number of people (150,000) affected. Ain Beni Mathar has also the lowest external cost of 1.59 € /TWh, as it is a relatively new natural gas fired power plant. Jorf Lasfar has higher costs with 90.5 € /TWh. Kenitra, an oil fired power plant built in 1979 with a capacity of 300 MW, has an even higher cost of 5,827 € /TWh. Here the low capacity, correlates with the age and high emission of the power plant and the relatively high number of people (3,164,000) affected (778 € per person in 2015).

4.2. Climate costs

To compare the order of magnitude of health costs resulting from air pollution, it is vital to analyse the CO_2 emissions from all fossil fuel Moroccan power plants, which were derived using the EPA Emission Factors [24,25]. Table 5 summarises the derived CO_2 emissions per plant for 2015 together with CO_2 valuation approaches in € /t from the German Federal Environmental Agency (UBA) [83] as well as ExternE [28].

While the estimate based on ExternE costs [28] would add another 580 million € $_{2015}$ to the total external costs, the higher estimate of almost 130 € would result in an additional 3 billion € $_{2015}$ for CO_2 emissions alone. Using an average external cost damage of 9 billion € and the UBA central value, the climate costs resulting from CO_2 emissions account for approximately 22% of the external costs from air pollution. This has to be interpreted carefully, as the external costs are valued using GDP adjusted Moroccan figures, whereas the climate costs are valued using European valuation.

5. Discussion

5.1. Comparison with other studies

As there are no previous studies analysing the external costs of air pollution from energy generation in Morocco, only a few deductions can be made when comparing studies concerning air pollution and health effects in the country. Table 6 compares the main results of the studies mentioned in Section 2 with those from this study.

Croitoru et al. [13] use the value of a statistical life (VSL), also referred to as value of prevented fatality (VPF), as the determining factor, valuing it at 191,500 US$ in Morocco on application of equity weighting. The study here uses the value of a life year (VOLY) for the estimation of premature mortality, while the underlying cost of VPF is between 120,259 and 278,891 € $_{2015}$, which is in the range of Croitoru et al. [13]. It is difficult to compare the absolute figures for premature mortality, as Croitoru et al. [13] has possibly used different exposure response functions (ERFs). According to Chiabai et al. [10] and Chilton et al. [11], the underlying difference in the VOLY and VSL approaches tends to have a significant influence on the result obtained. The study by Farrow et al. [27] assumes ambient air pollution levels are related to fossil fuels but does not provide the actual values for their determination. Khmosi et al. [45] used actual measurement data, whereas Farrow et al. [27] and Croitoru et al. [13] use ambient air pollution levels, [13] utilising a conversion factor of 0.4 to derive $PM_{2.5}$ emission from measured PM_{10} emission. Marais et al. [50] analyse premature mortality attributable to fossil fuel energy generation and transport, using generic capacity values for Moroccan power plants in 2030, which explains the variation in the overall results. The Moroccan environmental ministry estimates the cost of poor air quality at approximately 9 billion € in 2014 [72].

As most studies employ ambient air pollution levels rather than measurements or a calculation of air pollution resulting from energy generation, the results from these studies tend to be higher than those presented in this paper.

According to the German Federal Environmental Agency, 67% of the Moroccan GHG emissions are linked to the energy sector [79] and air pollutants are also highly dependent on transport emissions. The share of damage costs reached within this study, solely analysing air pollution from energy generation, is between 32 to 50 % of values provided in other studies.

Table 5

CO_2 emissions from Moroccan fossil fuel power plants in 2015 calculated using EF by the EPA [24], [25] and respective monetary values from UBA [83] and ExternE [28] in [€ $_{2015}$].

Power plant	Quantity	ExternE	UBA low	UBA central	UBA high
	tCO_2/2015	*25€ /t*	*43€ /t*	*86€ /t*	*129€ /t*
Jorf Lasfar	16,249,449	406,236,232	698,726,319	1,397,452,637	2,096,178,956
Mohammadia	1,863,068	46,576,712	80,111,944	160,223,888	240,335,833
Jerada	769,601	19,240,044	33,092,876	66,185,751	99,278,627
Tahaddart I	1,018,009	25,450,238	43,774,409	87,548,819	131,323,228
Ain Beni Mathar	1,252,882	31,322,070	53,873,961	107,747,922	161,621,882
Kenitra	516,760	12,919,014	22,220,705	44,441,409	66,662,114
Mohammadia Oil	1,108,953	27,723,844	47,685,012	95,370,024	143,055,036
Tiznit	71,659	1,791,477	3,081,340	6,162,681	9,244,021
Dakhla	20,113	502,831	864,869	1,729,738	2,594,607
Laâyoune	37,731	943,285	1,622,451	3,244,901	4,867,352
Tetouan	73,221	1,830,537	3,148,524	6,297,048	9,445,572
Tit Mellil	180,941	4,523,548	7,780,520	15,561,003	23,341,505
Mohammadia II	99,284	2,482,114	4,269,236	8,538,472	12,807,708
Total (rounded)		0.58 billion	1 billion	2 billion	3 billion

Table 6

Comparison of results with studies introduced in Section 2.

Study	Health endpoint	Pollutant	Cases	Value
Croitoru et al. [13]	premature mortality	$PM_{2.5}$	2,200-6,000	420 million - 1.14 billion US$
Croitoru et al.[13]	morbidity	$PM_{2.5}$	n/a	42-114 million US$
Khomsi et al. [45]	deaths	$PM_{2.5}$ & NO_2	13,000	n/a
Farrow et al. [27]	premature deaths	ambient air pollution	3300-7300	670 million - 1.6 billion US$
Marais et al. [49]	premature mortality	$PM_{2.5}$	1,000–9,999	n/a
Dettner, Blohm	premature mortality	$PM_{2.5}$	24,295	209-104 million € $_{2015}$
Dettner, Blohm	morbidity	$PM_{2.5}$	314,788	91-44 million € $_{2015}$

Although Morocco has a limited number of measurement stations managed by the Moroccan Weather Service, the data is not publicly available. Furthermore, emission measurement data for each power plant is not publicly available. The Moroccan Department of Environment has developed a National Air Program, 2018-2030, which aims reduce air emissions [72]; however, the goals and transformation paths are not specified.

5.2. Limitations

The following section addresses the main limitations and uncertainties of this study in respect to data, atmospheric chemistry and health impact assessment. This study applied a simple excel-based modelling approach and the obtained results must be viewed against the background of the modelling limitations.

Data

A number of assumptions had to be made in the calculation of the fuel quantity, such as the firing technology, which has an influence on emission quantity, as no data from power plants are publicly available in Morocco. Also, unless explicitly stated otherwise, it was assumed that the power plants do not use state-of-the-art air filter technologies due to their age. Assumptions were also made for the stack data inputted into the SCREEN3 model. An approximation using reference power plants was used as no actual data was available. Future research could validate the obtained figures through actual on-site measured stack data. The calculation of emission quantities was carried out using established emission factors; however, as no emission measurement data could be obtained on site, the calculated data could not be validated.

Atmospheric chemistry

Atmospheric chemistry modelling analyses in the MENA region are scarce, which marks the second key factor for uncertainty in this study. The strongest argument for the local model used here is the ease of application. Within the literature, solely Marais et al. [50] apply a GEOS-Chem Model for the entire African continent, using gridded power plant emissions, based on a number of generic assumptions and calculated emissions rather than on-site measurements. Marais [21] additionally discusses the role of satellite observations for air quality monitoring in Africa, underlining the discrepancy in emission estimates from various studies, which complicates analysis and the application of atmospheric chemistry models. The underlying difficulty is the need for improved estimates of natural emissions, especially due to seasonal open fires and desert dust in Africa. Marais and Wiedinmyer [51] apply the DICE (Dynamic integrated climate-economy) model to Africa and highlight in particular that sources are missing, outdated, or misrepresented in emission inventories according to the state of the science. The interdisciplinary research team ASAP [6] establishes a systems approach to air pollution in East Africa towards air quality monitoring and sets up an agenda for action to improve air quality. Alvarez et al. [3] discuss air quality monitoring in West African cities, not including Morocco, however stating that most countries have insufficient legislation in place as well as only two out of 15 analysed countries have monitoring systems with additional difficulties in regard to largely unavailable health data in relation to air quality, which supports the findings from this study, strongly suggesting further research in the area of atmospheric chemistry and dispersion modelling Africa, and Morocco as well as health impacts from air pollution. Ajdour et al. [2] describe the difficulty of the WRF-CHIMERE model especially focusing on particulate emissions due to the vicinity to the desert for the city of Agadir.

Health impact assessment

Within the literature on external costs of air pollution, the studies presented in section 2 are of central relevance for the development of results within this study. This study followed the IPA [28] and therefore the CRFs proposed within ExternE [28], Holland et al. [38] and Spadaro et al. [77]. The use of other CRFs for SO_2 and NO_X yields substantially different results. Table 7 shows the range of CRFs, adjusted to Morocco, as well as the source of the original relative risk function and the fraction of population effected f_{pop}. The values for Western Sahara differ slightly, due to a divergent life expectancy, and are not depicted here.

CRF values for SO_2 provided by Xing et al. [90] are typical of studies in China, where CRF values tend to be estimated more conservatively than in European studies. Also, the results obtained with CRFs of Hèroux

Table 7
Summary of derived CRF for SO_2 and NO_X.

Pollutant	f_{pop}	Health-endpoint	s_{ERF}	Source
NO_X	15 +	Chronic mortality	3.91E-4	[28,77]
NO_X	All	Respiratory HA	7.03E-06	[29,77]
NO_X	30 +	All-cause mortality	0.0232	[40]
NO_X	All	Respiratory HA	0.0139	[40]
SO_2	All	All-cause mortality	5.545E-4	[90]
SO_2	All	Cardiovascular HA	7.94E-4	[90]
SO_2	All	Respiratory HA	0.791E-4	[90]

et al. [40] tend to be approximately 35 orders of magnitudes higher than those from CRFs of Friedrich and Bickel [28] or Spadaro et al. [77]. In an analysis of respiratory hospital admissions, the costs obtained using the CRF proposed by Hèroux et al. [40] result in a value of 11,700 Million € $_{2015}$ whereas the results using the CRFs after Spadaro [77] in this study results in 9.4 Million € $_{2015}$. More recent CRFs for further sensitivity analyses are provided by Hoek et al. [36], Beelen et al. [7] and Khreis et al. [46]. A wide range of risk assessments, which can be applied to validate results, are provided by the Global Burden of Disease [31] and within the APHEKOM project [4,5].

The CRFs used in this study as well as the CRFs suggested for further sensitivity analysis are applied in a number of studies; however, mostly against a European or Eurocentric background. In general, CRFs need to be determined for the global south, especially Africa, as it is very likely that especially in countries where indoor air pollution tends to be a major health problem and ambient air pollution is much higher, people are likely to be much more sensitive and susceptible to diseases when overall health is not good, compared to those in more industrialised countries.

5.3. Implications to decision makers

The excel-based calculation used in this study utilises a transparent and consistent step-by-step approach. Although it is somewhat labour-intensive, it can nonetheless be easily applied to small systems with only a few electricity power plants to estimate localised effects of air pollution.

In a number of countries, especially those with developing and emerging economies, such as Morocco, energy related decisions do not always follow the most sustainable solution, but rather the cheapest, relying on e.g. coal powered energy generation. The discussion indicates that the significant potential of renewable energy in Morocco can be used to improve air quality levels, reduce energy dependency and lower the costs to the health care system. When applying the presented methodology to future energy system settings, e.g. a 100% renewable energy system as proposed within the MENA Select project by Zelt et al. [91], it becomes apparent, assuming the external cost of renewable energy sources to be zero, that the levelised cost of electricity in a mixed fuel scenario is approximately four times higher than a 100% renewable energy scenario.

From a comparison of avoidance costs with the calculated damage costs, it is apparent that an emission reduction of up to 90% (for PM almost 100%) is possible when state-of-the-art filter technologies are used. For the Jorf Lasfar (coal) power plant, the avoidance costs were estimated to be between 3.5 - 21 % of the damage costs. For Ain Beni Mathar (natural gas) this was 44 - 70 % and for Mohammadia (fuel oil), 0.23 - 0.5 %. Clearly, investing in emission reduction technologies is not only economically feasible, it also has the potential to drastically improve air quality levels and thereby reduce health effects from air pollution.

Since 1992, Morocco has been engaged in international climate negotiations and it hosted the Conference of Parties in 2011 and 2016. Even though there seems to be a fundamental understanding of environmental issues, the country remains heavily reliant on fossil fuels for energy generation. This contradiction is difficult to understand. Reducing energy dependency utilising domestic resources, such as oil shale, is not only contradictory to GHG reduction targets, but might also not be economically feasible, as determined for the case of Jordan within Hilpert et al. [35].

In order to reduce the total amount of harmful air pollutants, these impacts must be made clear and included in energy decision-making processes. The first step would be to update the national energy strategy with; (1) energy generation targets are more efficient than targets for installed capacities and (2) coal-based electricity generation is not the cheapest technology, because negative health effects are currently not internalised in energy pricing.

6. Conclusion

The analysis provided in this paper bridges the gap between a strictly techno-economic assessment of energy generation and a more just and holistic approach to cost-optimal energy system transformation, as well as integrating air pollution in energy-related decision-making processes. This paper presents a bottom-up method for calculating the external costs of energy generation, which focuses on air pollution and its impacts on human health for the Moroccan electricity system in 2015. Results highlight and confirm that health impacts from air pollutant exposure from energy generation are a pressing challenge in Morocco, costing the society up to 18 billion € annually, which is equivalent to almost 18 % of the country's GDP in 2015. Ignoring external costs of energy generation can lead to market failure, as investment and policy decisions in energy generation are made without considering this significant cost factor. Including the cost of air pollution in decision making processes might lead to consistent energy policies. External costs of air pollution can be part of the answer to the question of how much we need to spend on environmental protection and carbon reduction.

In an environment characterised by global warming, fast economic progress and growing energy demand, such as Morocco, an assessment of health costs resulting from air pollution from energy generation can be used as an argument to convince decision makers to invest in renewable energy. This can lead to increased energy security, energy independence and reduced costs to the health care system as well as an overall improvement to living standards due to reduced air pollution levels.

Data availability:

All files and calculations can be acquired on request, please contact the author (franziska.dettner@uni-flensburg.de).

Declaration of Competing Interest

The authors declare no known conflict of interest, financial or otherwise.

CRediT authorship contribution statement

F. Dettner: Conceptualization, Resources, Data curation, Methodology, Validation, Formal analysis, Investigation, Software, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **M. Blohm:** Investigation, Writing – original draft, Writing – review & editing.

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Appendix A

Concentration-Response Functions

Table 8
Values of NO_2 CRFs for sensitivity analysis based on RR from HRAPIE [86] and ß from WHO Global Health Observatory, Morocco [85], using $s_{CRF}= RR\ x\ ß$ after [77]. - can not be determined, as no clear connection between deaths rates [85] and health outcome possible Respiratory HA, first value derived using death rate of respiratory disease, second value derived using death rate of respiratory infection Values in () for Western Sahara with slightly different underlying health conditions, than Morocco (before ()).

Pollutant metric	f_{Pop} Age group	Health end-point	RR % increase per $\mu\ g_p/m^3$	ß Annual cases per receptor ('000)	s_{CRF} Annual cases per receptor per $\mu\ g_p/m^3$
NO_2 annual mean concentration	30+	Mortality, all (natural) causes	1.055 [36]	45.86 (44.27)	0.0232 (0.0224)
NO_2 annual mean	5-14	Prevalence of bronchial symptoms	1.021	-	-
NO_2 daily max 1-h mean	all	Mortality, all (natural) causes	1.0027[44]	41.8 (38.99)	0.0139 (0.013)
NO_2 daily max 1-h mean	all	Respiratory HA	1.0015	1.50 (1.21) 1.59 (1.94)	4.982E-4 (4.019E-4) 5.2181E-4 (6.444E-4)
NO_2 24-h-mean	all	Respiratory HA	1.018	1.50 (1.21)	5.065E-4 (4.085E-4) 5.368E-4 (6.55E-4)

Table 9
Values of SO_2 CRFs for sensitivity analysis based on RR from HRAPIE [86] and Spadaro et al. [77] and ß from WHO Global Health Observatory, Morocco [85], using $s_{CRF}= RR\ x\ ß$ after [77]. - can not be determined, as no clear connection between deaths rates [85] and health outcome possible Cardiovascular HA, first value derived using rate of cardiovascular disease, second value derived using rate of ischaemic heart disease. Respiratory HA, first value derived using death rate of respiratory disease, second value derived using death rate of respiratory infection Values in () for Western Sahara with slightly different underlying health conditions, than Morocco (before ()).

Health end-point	f_{Pop} Age group	RR % increase per $\mu\ g_p/m^3$	ß Annual cases per receptor ('000)	s_{CRF} Annual cases per receptor per $\mu\ g_p/m^3$
All-cause mortality	all	0.04%	41.8 (38.99)	
Cardiovascular deaths	all	0.04%	-	-
Respiratory deaths	all	0.1%	-	-
Cardiovascular HA	all	0.19%	12.16 (9.59) 6.38 (5.02)	7.94E-4 (6.043E-4) 4.02E-4 (3.163E-4)
Respiratory HA	all	0.15%	1.50 (1.21) 1.59 (1.94)	0.746E-4 (0.602E-4) 0.791E-4 (0.965E-4)

Table 10
CRFs based on RR from HRAPIE [86] and Spadaro et al. [77] and ß from WHO Global Health Observatory, Morocco [85], using $s_{CRF}= RR\ x\ ß$ after [77], if possible distinction between Morocco (M) and Western Sahara (WS) CB - Chronic bronchitis, RHA - Respiratory hospital admissions, CHA – cardiovascular hospital admissions, RAD - restricted activity days, WLD - work loss days, MRAD - minor restricted activity days, LRS - lower respiratory symptoms.

Health endpoint	Pollutant	Receptor	P_a	P_r	RR	s_{CRF}	CRF unit per year per $\mu\ g_p/m^3$
Chronic mortality	$PM_{2.5}$	Adults 15+	M: 74,23%, WS: 62.76%	100%	1.06 for 10 $\mu g/m^3$	6.51E-4	YOLL
Acute mortality	PM_{10}	Adults 15+	M: 74,23%, WS: 62.76%	100%	0.06% per μg	M: 1.47E-06, WS: 2.43E-06	YOLL
Infant mortality	PM_{10}	Children 0-5 years	10,67%	100%	0.39% per μg	M: 1.064E-04, WS: 2.044E-04	YOLL
New cases of CB	PM_{10}	Adults 25+	M:57.19%, WS: 43.23%	70%	26.5 per 10 $\mu g/m^3$ per 100,000 Adults 25+	1.855E-05	Cases
RHA	PM_{10}	All	100%	100%	7.03 per 10 $\mu g/m^3$ per 100,000	7,03E-06	Cases
CHA	PM_{10}	All	100%	100%	4,34E per 10 $\mu g/m^3$ per 100,000	4,34E-06	Cases
RAD	$PM_{2.5}$	Adults 15-64	M: 67.49%, WS: 58.89%	67.2%	902 per 10 $\mu g/m^3$ per 100,000 aged 15-64	6.061E-02	Cases
RAD	$PM_{2.5}$	Adults 65+	M: 6.74%, WS: 3.87%	67.2%	902 per 10 $\mu g/m^3$ per 100,000 aged 65+	6.0614E-02	Cases

(continued on next page)

Table 10 (*continued*)

Health endpoint	Pollutant	Receptor	P_a	P_r	RR	s_{CRF}	CRF unit per year per μ g_p/m^3
WLD	$PM_{2.5}$	Adults 15-64	M: 67.49%, WS: 58.89%	100%	207 per 10 $\mu g/m^3$ per 1,000 aged 15-64	1.39E-02	Cases
MRAD	$PM_{2.5}$	Adults 15-64	M: 67.49%, WS: 58.89%	100%	577 per 10 $\mu g/m^3$ per 1,000 aged 15-64	3.69E-02	Cases
LRS	PM_{10}	Children 5-14	M: 15.10%, WS: 26.57%	11%		2.05E-02	Cases
Medication use	PM_{10}	Children 5-14, meeting PEACE study criteria	M: 15.10%, WS: 26.57%	22%		3.96E-04	Cases
LRS	PM_{10}	Adults 15+	74,23%	62,76%		3.25E-02	Cases
Medication use	PM_{10}	Adults with asthma 15+	74,23%	62,76%		3.28E-03	Cases

Appendix B

Monetary values

Table 11
Monetary values, European and Moroccan after applying equity weighting using Eq. (6).

Measurement unit	EU central costs [€ $_{2015}$]	EU low costs [€ $_{2015}$]	Morocco central costs [€ $_{2015}$]	Morocco low costs [€ $_{2015}$]
VPF	3,054,490	1,317,144	278,891	120,259
VOLY	94,340	47,170	8,614	4,307
Infant mortality	7,075,487	1,768,872	646,028	161,507
WLD	322	108	29	10
Hospitalisation	4,305	2,634	393	241
ER visit	1,945	882	178	81
New cases of CB	490,567	250,252	44,791	22,849
doctors visits	99	99	9	9
RAD	382	171	45	16
MRAD	50	30	5	3
Medication	1.2	0.7	0.1	0.06

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6 The Hidden Costs of Morocco's Energy Transition: Investigating the Impacts of Foreign Investment and the Lack of Social Participation[5]

Marina Blohm

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The Hidden Costs of Morocco's Energy Transition: Investigating the Impact of Foreign Investment and the Lack of Social Participation

Marina Blohm
Department Energy and Environmental Management, Europa-Universität Flensburg, Auf dem Campus 1, 24943 Flensburg, Germany; marina.blohm@uni-flensburg.de

Abstract

Morocco is a pioneer in energy transition on the African Continent and is pursuing the goal of installing 80% renewables by 2050. By 2020 the country had already 38% renewable capacities installed. At the same time, electricity production from coal more than doubled between 2010 and 2020, reaching more than 65% by 2020. These opposing developments as well as underlying and influencing factors are currently not sufficiently researched.

This paper discusses the historical developments of the Moroccan energy transition and identifies positive and negative impacts of liberalising electricity generation in the 1990s. Analysing the regulatory achievements and barriers that have shaped Morocco's path towards a more sustainable and financially viable energy system, it also unveils the existing social injustices resulting from a missing participation of local communities in planning processes of large-scale power plants and the unequal distribution of economic benefits among the population. As the study shows, the fossil and renewable expansion was influenced by international financial institutions and most of the companies involved in the Moroccan energy sector correspond to foreign investments or are related to the royal family. This centralisation impedes a larger socialisation of benefits.

The lack of participation of local communities and domestic companies prevents them from benefiting from electricity generation and taking an active role in designing a socially just energy transition. Private households, rural communities, domestic companies and rural workforce can be therefore seen as losers of the energy transition, whereas large-scale, mostly foreign international companies, the government and rural areas that were electrified with the help of the electrification program are winners of the energy transition.

Keywords:

Renewable energies, Just energy transition, Social justice, Morocco, Sustainable Development, Liberalisation

1 Background

During a speech in 2018, the Moroccan King Mohammed VI said:

> "In building the Africa of tomorrow, environmental conservation is the basis for Africa's co-emergence, the foundation on which the continent's inclusive economic growth will be built. We must work together to address global warming, its risks, and transform our economies on the basis of sustainable development." [1]

This speech illustrates Morocco's desire to build its economic growth in line with a sustainable development and its willingness to begin an economic transformation that incorporates elements of sustainability. The country has ambitious targets in this regard. Revising the National Determined Contributions (NDCs) in 2021, Morocco announced its new goal of reaching 80% renewable electricity generation capacities by 2050 [2]. This target is a pioneering step, one that distinguishes Morocco from other countries in the MENA region [3]. In addition to installing renewable capacities and reducing CO_2 emissions, the country's energy transition strategy also considers how technology and knowledge transfer can be used to support its domestic industrial development. The 2014-2020 Industrial Development Plan, published in 2014, called for a strengthening of the entire industry sector through the use of renewable energies and the target of an industrial integration of 32% [4]. As part of this plan, the German-Spanish wind energy company Siemens Gamesa constructed and opened its first rotor blade factory in 2017 in Tangiers, which produced wind turbine rotor blades for the domestic and international market and included a training centre for local employees [5]. Unfortunately, the factory was closed in early 2023 due to changing market conditions and financial losses [6].

Morocco's vulnerability to increasing water scarcity, decreased precipitation, rising average temperatures [7] and other negative consequences of global warming have prompted it to take an active role in global efforts to combat climate change. On the positive side, Morocco is well suited to the development of renewable energies, thanks to natural conditions like strong solar radiation (GNI between 1.8 and 2.2 kWh/m² [8]), high wind speeds (up to 11 m/s at 100m height [9]), energy storage capacities and areas of underpopulation [10]. The country's absence of domestic fossil resources and steadily growing electricity demand has also created a strong drive towards renewable energy as a way to reduce its dependence on energy imports (which accounted for 92% of the total energy supply in 2019 [10]). In contrast to the expansion of renewable energies, Morocco produced more than 65% of its electricity from coal-fired power plants by 2020 [11] and is not willing to phase-out coal as soon as possible [12]. At the international level, this development does not seem to be taken into consideration, as the country is only celebrated for its efforts to expand renewable energies.

This paper analyses Morocco's energy pathway from the French protectorate in 1912 until 2020, presenting achievements and challenges of the energy transition and identifying positive and negative impacts of liberalising electricity generation in the 1990s. The identified impacts are inter alia related to foreign investments and the ownership structure of the power plant inventory. Sections 1.1 and 1.2 describe the historical background of the country's developments related to the use of resources and electricity generation. Section 2 reviews existing research on the Moroccan energy transition and describes how this paper contributes to this scholarship. Section 3 presents the author's chosen methodology. The result Section 4 analyses why Morocco supported both fossils and renewables and identifies existing social injustices, followed by a discussion on the winners and losers of the country's energy transition as well as the distribution of benefits among the society in Section 5. Section 6 concludes the study.

1.1 Historical Development of Resource Use In Morocco

At the start of the French protectorate in 1912, Morocco still lacked large-scale electricity generation facilities. The discovery of large amounts of mineral resources in the eastern and southern areas of the country caused the protectorate to set its priority: building an electric railway system to transport the minerals (mainly phosphate) from the mining areas to the coastline, to be shipped abroad [13]. Historically speaking, the goal of the French protectorate was to electrify "the useful Morocco" – that is, the productive part of the country [14]. Until the 1950s, this electrification effort focused on constructing large-scale hydropower plants and small-scale gas engines fuelled by domestic charcoal [15]. The choice to prioritise hydroelectricity in combination with coal was the best option for ramping up electricity production due to the promising geographical and climatic conditions in the Atlas Mountains. Both coal and hydroelectricity presented specific problems, however. With respect to coal, Morocco discovered and mined a small amount from domestic mines in its north-eastern region. However, the low quality and difficult location of the coal resources meant that Morocco remained dependent on coal imports [16] from France, Germany, and England, among others [15]. While hydroelectricity offered a domestic source of energy the sector declined continuously since the 1960s as precipitation levels dropped significantly, giving coal renewed importance for electricity generation [17]. Oil-fired power plants also gained salience at this time, but rising and volatile prices prompted the country to focus on coal for the future [13].

To restrict and reduce foreign involvement in the country – mainly the prevalent dominance of French actors – the Moroccan government implemented a "Moroccanisation decree" in 1973, limiting foreign ownership to 49% for the industry, commercial and service sectors [18], after Morocco's independence in 1956 [19].

Morocco's lack of fossil resources and predominant use of coal (rather than oil or gas) differentiates it from other MENA countries. Efforts to supplement or replace coal with gas have been challenging. During the 1960s, geopolitical tensions between Morocco and its gas-exporting neighbour Algeria initially prevented the construction of a gas pipeline from Algeria across Morocco towards Spain [20]. Although the Maghreb-Europe gas pipeline was finally built at the beginning of the 1990s, geopolitical problems in the late 2010s led Algeria to stop gas delivery in 2021 [21]. Lacking an LNG-terminal (Liquified Natural Gas) and given the limited natural gas trade between MENA countries [22], Morocco started to import re-gasified LNG through the Maghreb-Europe pipeline from Spain in 2022 [23] to further operate its gas-fired power plants.

Starting in the 1990s, the evolving discussions about producing solar electricity in African desert countries for export to Europe (today known as the Desertec vision) increased awareness of the potential of Moroccan renewable electricity and its ability to generate export revenue over the long term [24]. Although the entire Desertec vision failed for several reasons – e.g., incorrect price predictions for concentrated solar power (CSP) and photovoltaic (PV) power plants, the evolving political instability in the entire MENA region, and the global financial crisis in 2008-2009 [24] – the goal of exporting solar energy never disappeared from King Mohammed VI's agenda. The king has been a driving force and an important enabler of the Moroccan energy transition. Already before his inauguration in 1999, he was involved in international activities related to climate change, which was one of his priorities [25]. Aiming to be a renowned environmental activist and to make Morocco a leading country in Africa [25], the king announced the more ambitious target of installing 52% renewable capacities by 2030 within the framework of the 2016 COP 22 in Marrakesh [25] and now leads strategic political decisions in which he often mediates between high-level politicians [26]. However, the results section will also show that the royal family's company is involved in operating a coal-fired power plant.

Morocco's future energy transition is mostly based on the expansion of renewable electricity, but it also foresees adding further gas-fired power plants, LNG ports for importing natural gas, [27] and using its coal-fired power plants until the end of their lifetimes (but not constructing new ones) [28]. Alongside its electricity generation goals and initiatives, in 2021 Morocco published its National Hydrogen Strategy, which focuses on producing green hydrogen and reducing emissions – especially from domestic fertilizer production [1] – over the long term.

1.2 Electricity Generation After 1990

Besides the aforementioned more general historical developments, this section presents more findings on generating electricity after 1990. Figure 1 shows the development of the Moroccan electricity generation between 1990 and 2020. The period can be divided into three sub-periods: (1) the partial liberalisation of the country's electricity generation between 1994 and 2004; (2) the diversification of energy sources between 2005 and 2013; and (3) the rise of the renewables and expansion of coal after 2013.

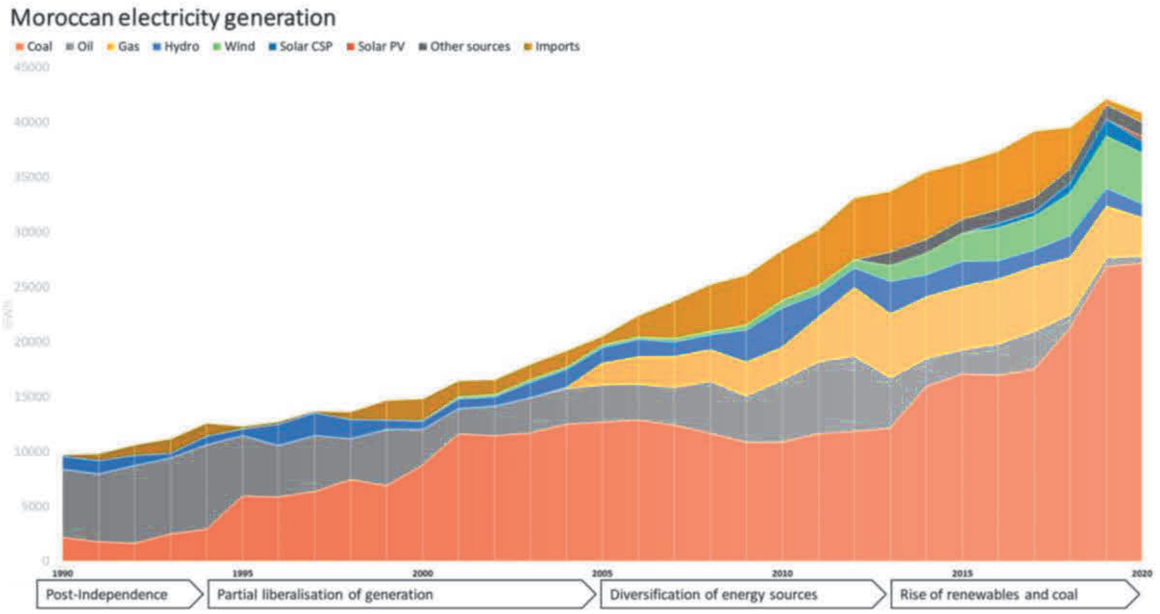

Figure 1 Moroccan electricity generation between 1990 and 2020; author's illustration based on [11], [26], [29]

Partial liberalisation of electricity generation (1994-2004)

In 1994, Morocco began implementing law 2-94-503, which opened its energy sector to independent power producers (IPPs), to lower the pressure on the public utility ONEE (Office Nationale de l'Electricité et de l'Eau).

According to Usman and Ameground [26] the country's energy demand increased during the 1980s, leading to high energy imports and financial obligations for ONEE, resulting in increased electricity tariffs for end consumers. Opening electricity generation for IPPs allowed readjusting electricity tariffs to lower prices and concentrating on electrifying rural areas while at the same time enabling the construction of new power plants to stop electricity shortages [26]. The year 1994 marked therefore the start of the liberalisation of the electricity sector, which was a partial process because energy distribution and transmission were not affected. IPPs were allowed to enter into power purchase agreements (PPA) with ONEE, which ensure the payment of a fixed price per kilowatt hour for a 20-30 year period [13]. ONEE acted as a single buyer of the electricity produced, which it sold to consumers at competitive prices [26]. In cooperation with the World Bank and the International Monetary Fund (IMF), the implemented ownership regulation (maximum of 49% foreign ownership) was stepwise removed so that no domestic ownership obligations have been in place since the 1990s [18]. The shift to PPAs caused a gradual drop in ONEE's share in electricity generation after 1994, which reached 22.65% in 2019 (see section 4.2 for more details). Besides the construction of two coal-fired power plants during this period, Africa's first wind farm was commissioned in the very north of Morocco in 2000 [30].

Diversification of energy sources (2005-2013)

The construction of the Maghreb-Europe gas pipeline enabled Morocco to further diversify its energy sources by building two combined-cycle gas-fired power plants in 2005 and 2010. The period between 2005 and 2013 was characterised by a significant increase in domestic electricity demand, leading Morocco to expand its electrical interconnections with Spain and to develop a new interconnection with Algeria [26]. *Inter alia*, the rise in demand can be explained by the progress of electrification [26]. In 2009, Morocco published its new national energy strategy for the period up to 2030 as well as integrated wind, solar, and hydro plans for expanding renewable capacities until 2020. The Moroccan Solar Plan was meant to serve as the basis for the Desertec vision. The national energy strategy defined the country's plan to expand the different types of generation capacities, which aimed to achieve 42% renewable capacities by 2020, combined with coal-fired power plants as the main energy source [31]. Coal was chosen because of its more stable price development compared to oil and a supposedly cheap power generation [31].

Rise of renewables and expansion of coal (after 2013)

Since 2016, the installed capacities of CSP, wind onshore and PV increased significantly to around 4 GW, such that together they made up 38% of total electricity generation capacity in 2020 [32]. Additionally, three coal-fired power plants (Jorf Lasfar 5+6, Jerada 4 and Safi) with a total capacity of 2.4 GW were commissioned between 2014 and 2019. Since 2019, the rise of coal-fired power plants combined with solar and wind power has enabled the country to decrease electricity imports to nearly zero. In 2020, Morocco closed the last coal mine, which however only provided a small share of coal due to its economic inefficiency [16] and in 2021 signed a statement in frames of the COP26 in Glasgow to not build any new coal-fired power plants [28], even though two more coal-fired power plants were under development until that time. The total phase-out of coal at the latest by 2040 – which was also part of the statement – was however not supported by the Moroccan government and the use of coal for electricity generation will play a role until the end of the lifetime of currently installed capacities, or at least until the year 2044 [33].

The commissioning of Morocco's first CSP power plant, called Noor I, began in 2016 but after building two more units of this CSP power plant (Noor I-III), Morocco decided to focus instead on building PV and wind power plants, which are more economically feasible.

2 State of Research and Contribution

This study contributes to the interdisciplinary body of research on distributional implications of energy transitions by answering three overarching research questions:

(1) Which positive and negative impacts occurred from liberalising the Moroccan electricity generation?
(2) What is the role of foreign investments and foreign ownership in this liberalisation?

(3) Who are the winners and losers of the energy transition and how beneficial is the transition for the Moroccan society?

2.1 Liberalisation and Role of Foreign Investments

Morocco is one of the leading economies on the African continent in terms of attracting foreign direct investment (FDI) for renewable electricity [34]. In total, more than 500 billion Dirhams (US$$_{2020}$ 56 billion) of FDI were received between 2007 and 2021, ranging annually between 26 billion Dirhams (US$ 2.7 billion) in 2020 and 46 billion Dirhams (US$ 4.8 billion) in 2018 [35], with an average of 6% of yearly FDI going into the energy and mining sector. FDI originated mainly from France, the United States, the United Arab Emirates, the United Kingdom, Spain, Luxemburg and Germany [36]. China's role in Morocco's FDI is increasing but still lower than that of the aforementioned countries.

The role and effects of foreign investments on economic growth are discussed both positively and negatively in the literature but there is not a clear consensus on the specific impacts and outcomes in different countries [37]. Literature on FDI in Morocco is limited to time periods in the past in which the electricity sector was not yet liberalised or presented a broader analysis beyond electricity generation. After the French Protectorate, the Moroccan government introduced a law to limit foreign ownership in the Moroccan economy. Bouoiyour [18] analysed historical developments of FDI and the way the country turned to a fully open economy but it does not specify the situation of the energy sector. According to this study, foreign companies had higher labour productivity, average wages, added value of exports, and better technological advancements compared to domestic companies between 1987 and 1996. This indicates that a positive spillover from foreign to domestic companies could not be achieved during this time. Hakimi and Hamid [38] found that between 1971 and 2013 foreign investors brought money to the country but not new technological advancements from which the country could have profited.

The classical and less critical literature often argues that foreign investments are coupled with economic growth because of capital accumulation and technological improvements [37]. However, the spillover effects are different in each country depending on the economic, social and political situation. Stöbich [37] concludes that FDI is only positive, if the investments could not be made by domestic companies instead and if the increased competition in the country has not only negative effects for the domestic companies. He further indicates that FDI in general had an impact on economic growth in Morocco especially because of the trade freedom and openness of the country. In contrast, Leonard et al. [39] identified a risk of economic dependence on foreign stakeholders and its political and economic influence in Morocco, which would add to the already prevalent resource dependence.

Morocco's liberalisation of its energy sector in 1994 occurred relatively early compared to other African countries such as Uganda [40] or Ghana [41], which started its liberalisation in 2001 and 1999, respectively. For countries with high shares of rural areas, liberalising the electricity sector does not always provide positive effects, which is particularly clear when the primary focus is to develop large-scale grid-connected power plants instead of achieving full electrification [42]. In Morocco, the liberalisation specifically enabled full electrification [26], which will be examined in the results section of this paper.

An analysis of positive and negative impacts of FDI related to liberalising electricity generation in Morocco does not exist in the scientific literature, which is why this paper contributes to this research gap.

2.2 Social Justice in Energy Planning

Research on the social dimension of Morocco's energy transition has focused on issues of social justice and the potential benefits of undergoing an energy transition. This section will now briefly introduce both topics before moving on to examine the Moroccan case. Williams and Doyon [43] describe justice in general terms as "the fair, equitable, and respectful treatment of humans, other species, and the environment". Concepts of distributional justice, recognition justice, procedural justice and cosmopolitan justice are all relevant to energy transition matters [43]–[47]. These concepts describe where injustice occurs regionally, which social groups are treated unjustly or unequally, how these inequalities are cemented in decision-making processes and which global externalities exist [45]. A definition of sustainable or low-carbon energy transitions can be found in [48], saying "major changes in buildings, energy, and transport systems that substantially enhance energy efficiency, reduce demand, or entail a shift from fossil fuels to renewable inputs. These system transitions entail not only technical changes, but also changes in consumer behaviour, markets, institutions, infrastructure, business models and cultural discourses" [48]. Without taking social justice into account, an energy transition cannot be sustainable in the sense that the social dimension of the transition will never have the same importance as the ecological and economic dimension. Neves et al. [49] proposed a standardised methodology of how to develop decision-making processes on local needs and how to include local actors to remedy at least some of the procedural injustices.

Research on the social dimension of the Moroccan energy transition is mostly limited to impact analyses of the first CSP plant in Noor. Terrapon-Pfaff et al. [50] and Hanger et al. [51] have looked at the acceptance of the power plant, as well as its positive and negative outcomes; however, the expert consultations and interviews used in their study were carried out in 2014, before the power plant was commissioned in 2016. In both publications, interviewees expected the power plants to have mostly positive effects, like a regional reputation boost or the creation of a local value chain [50] and generally expressed their positive acceptance of the plant [51]. Most recently, Rignall [52] and Moustakbal [13] have offered a sociological and environmental activist perspective on different social aspects of the Moroccan energy system. Both studies point to various negative impacts, some of which were already detected in the much older mining sector, concluding that Morocco has been following a socially unjust energy transition.

Cantoni and Rignall [53] critically analysed the Moroccan solar strategy providing an overview of historical decisions that led to the construction of the first CSP power plant and pointed to a lack of integration of local communities in decision-making processes. Accordingly, local communities were only involved in planning processes after decisions regarding the location have already been made on the ministerial level. They further conclude that constructing large-scale power plants supports the centralised power of the government and political decision-makers to control economic incomes, including those potentially generated through future electricity exports. Combined with the relevance of foreign investment, Cantoni and Rignall [53] identified a "soft power exerted by German research institutions over the Moroccan government and the King through studies", which influenced central decisions that were made in the design of the solar power plant. A critical analysis of Morocco's energy strategy was published by Rignall [54], discussing problems related to land grabbing and participation. The majority of scientific literature is centred around negative aspects such as land grabbing, a lack of participation of local communities and centralised decision-making processes, which result from the political economy of the country aiming at centralising the power at the highest political levels.

Among African countries, Morocco is not alone with its unjust energy transition. Müller et al. [40] did a comparative analysis of 34 African countries on different dimensions of energy justice, identifying important deficiencies in this regard in many of these countries, like in Morocco. Countries, in contrast, which consider energy justice in their energy transition have a high domestic ownership and strong stakeholder involvement in common.

Environmental and social impact assessments are an attempt to estimate potential positive and negative impacts and can be found online for many of the Moroccan power plants. Analysing predicted socio-economic impacts of wind and solar projects, positive effects can be associated with creating direct and indirect employment during the construction and operational phase. Negative socio-economic impacts – except increased temporary traffic noise and construction activities – are normally not foreseen. However, Cantoni and Rignall [53] criticise a missing comprehensive approach to environmental and social impact assessments omitting "multiple domains – economic, political, cultural – and over time". Even though some impact assessments explicitly mention the recruitment of local workforce [55] and possible empowerment of women, a high unemployment rate in rural areas and especially among women [56] as well as the lack of suitable education and training possibilities [57], prevent the local workforce from benefitting from the created employment.

Based on the knowledge provided by these publications on how socially just the Moroccan energy transition seems to be, the result and discussion section will further discuss what are the winners and losers of the Moroccan energy transition, which injustices exist and how beneficial the transition is for the Moroccan society.

3 Methods

To answer the research questions a three-step mixed-method approach was used to collect the data. Some of the data used to address the research questions of this paper were collected through a research project called MENA Select[1] [58]. Between 2016 and 2018 stakeholder workshops and expert consultations in Morocco, Jordan, and Tunisia were conducted in frames of this project in which the author co-organised and co-conducted the country-specific workshops. The overall aim of this project was to develop future electricity scenarios for each country and assess stakeholder preferences concerning various future technological alternatives. Therefore, discussions related to different electricity generation technologies were made, followed by the participatory development of different future scenarios for electricity generation until 2050. One workshop per country involving approximately 30 participants per workshop was conducted with national stakeholders from the private and public sector, academia and civil society [58]. Most stakeholders already participated in previous workshops on inter-sectoral discussions about sustainability of the energy transition. The aim of the entire project was to identify different pathways to generate electricity in the near future (by 2050) in ways that are cost efficient, beneficial for a sustainable development, conflict-sensitive, and socially acceptable [58]. The participatory workshops were conducted with local and national stakeholders to identify the needs and visions of the local population and to draw conclusions about the requirements of the future electricity system. This field work yielded important insights into domestic processes and developments within the countries. The second step for collecting data for this paper was an intensive review of scientific and grey literature. The literature reviewed was written in both English and French. Finally, additional expert interviews were conducted to add insights – mainly about the social dimension of the energy transition – that could not be obtained from the workshops or the literature review. In total, seven semi-structured interviews were conducted online between February and October 2022 with stakeholders from the private sector, the public sector, civil society, and from academia; these interviews are listed in Table 1. References to the interview results can be found in small brackets such as [s1, p1, or b2].

Data analysis was based on the *Enabling Framework to support the Sustainable Energy Transition at the National Level* by Blohm [59] but concentrated only on those criteria related to the social and economic dimensions of the transition that had turned out to be decisive as they deepen the challenges that prevent Morocco from fully benefiting from the energy transition. This article focuses on this limitation because it is sufficient to answer the research questions (see Section 2).

4 Results

Following the historical developments in the energy sector, the results section provides information on how foreign or domestic developments have shaped the rise of fossils and renewables in Morocco and which social injustices exist.

4.1 How Foreign Investments Have Shaped the Rise of Fossils and Renewables

Chapters 1.1 and 1.2 have shown that Morocco is successful in promoting its renewable transition but at the same time achieved to more than double its electricity generation from coal between 2010 and 2020 [11]. This subsection will show how international financial institutions and companies have shaped this contradictory development through foreign investments and ownership.

There are many different credit institutions and organisations active in the Moroccan energy sector, such as the World Bank, the European Investment Bank, the Arab Fund for Economic and Social Development, the African Development Bank, the German KfW and, for some years, also two Moroccan banks, which are the Attijari Wafa Bank and the Moroccan Bank of Commerce and Industry (MBCI). The institution that has influenced the country's pathway the most, seems to be the World Bank. The first loan of US$ 25 million that was granted by the World Bank Group to Morocco – to ONE to be more precise – in 1973 financed partly the construction of a small-scale gas turbine and a new transmission line [60]. In the following years, the World Bank Group financially supported the operation and expansion of the coal mine in Jerada [61] as well as the construction and operation of the coal-fired power plant in Jorf Lasfar [62]. Since the World Bank decided to stop funding for coal in 2013 [63], it got very active in supporting the renewable expansion in Morocco, such as through supporting the CSP and PV power plants Noor Ouarzazate and Noor Midelt [64]. Evaluating and withdrawing a loan for the coal mine in Jerada even led to the closure of the mine [65] after assessing the project as being "unsatisfactory, its benefits as unsustainable and institutional development as negligible" [66]. The two newest coal-fired power plants Jerada 4 and Safi got support from the Chinese Exim Bank (Jerada 4) [67] as well as from the Bank of Japan, the Islamic Development Bank, the Attijari Wafa Bank and the MBCI (Safi) [68]. After having achieved more than 65% coal-fired electricity in 2020 [11] it seems easy for the country to support the Glasgow agreement, as the available fossil capacities are expected to be sufficient to meet the electricity demand in 2030 [69].

The renewable sector, in contrast, is dominated by the German KfW, the European Investment Bank, the African Development Bank, the World Bank as well as the Arab Fund for Economic and Social Development. All of these institutions, except for the World Bank, also supported the electrification program PERG [26]. Focussing on renewable energies began mainly during the 2000s with the development of the national energy strategy as well as the related integrated wind and solar plans and aimed at reducing the country's energy dependence and energy imports [31]. Technological decisions during that time were not always based on the most cost-effective solutions but were also influenced by foreign stakeholders and the royal vision of becoming an electricity exporter [24]. Yet the government's decision to favour CSP over PV to ensure electricity production even in the absence of sunshine was misleading and cost-intense for the energy transition [24], [53]. According to Schmitt [24] this decision was based on the incorrect price predictions made by the German DLR in its MED-CSP study in 2005, which foresaw lower future prices for CSP than for PV. Cantoni and Rignall [53] identified "a combination of German soft power [to influence the potential Moroccan electricity export through the Desertec initiative and aforementioned study] and the highly centralised political system" as the main reasons for choosing CSP as a technology. Electricity production of Noor 1 turned out to be very cost-intense for MASEN (Moroccan Agency for Sustainable Energy), which sells the electricity at a lower price per kWh than the actual electricity production costs [13], [70]. The World Bank even supported this subsidisation with the help of a loan [64].

Besides the described international funding support, the involved stakeholders and power plant owners come from very diverse countries. Figure 2 presents the power plant inventory of 2019 combined with the respective stakeholders including the names of the power plants and their owners, as well as the distributed share of public versus private capacities. Green boxes mark the name and type of fossil power plants, grey boxes the renewable power plants, blue boxes renewable power plants that are for self-production or direct sale to consumers only, red boxes mark responsibilities of the public utility ONEE, and yellow boxes the name and country of private stakeholders.

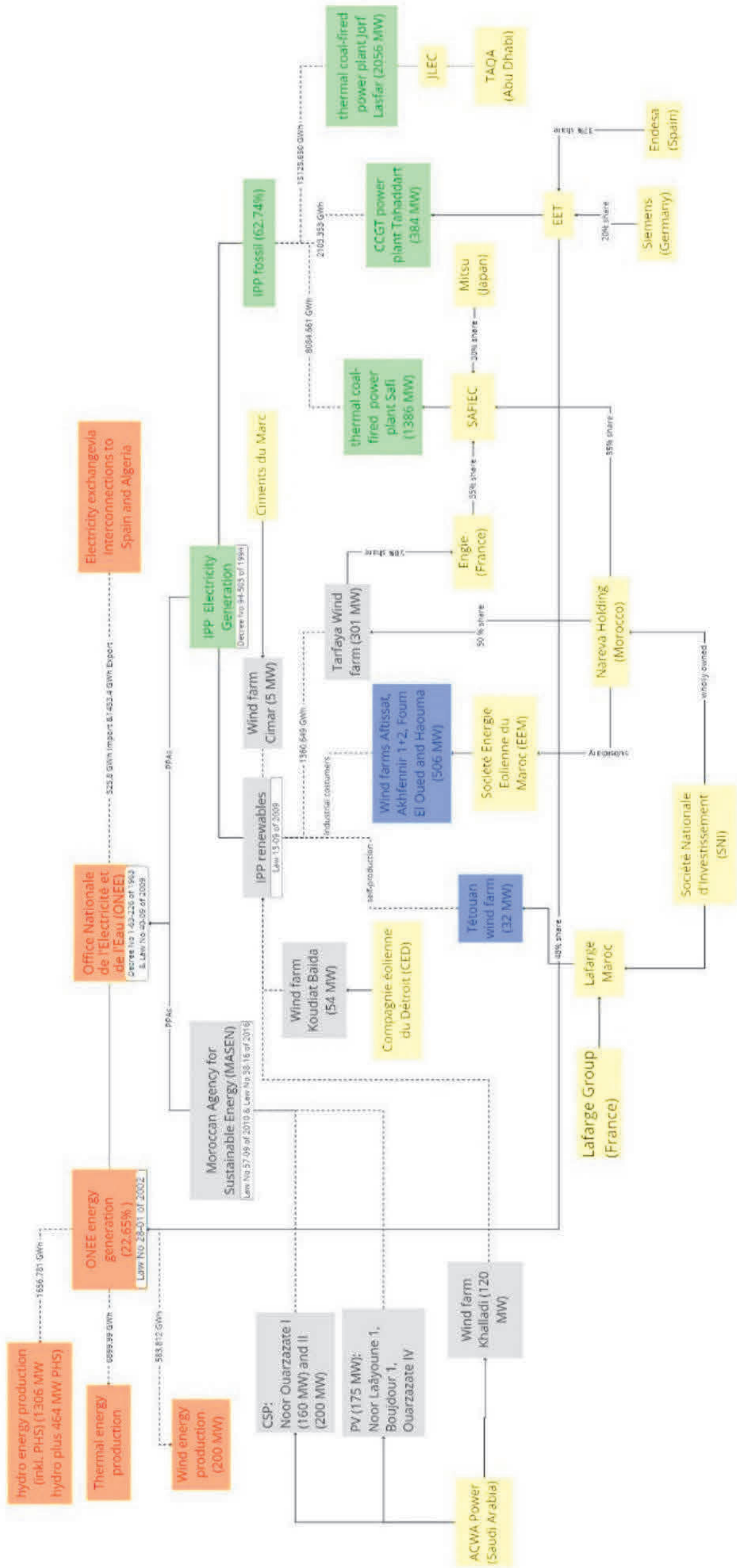

Figure 2 Power plant ownership of installed and operational capacities in 2019

9

The dominance of foreign stakeholders is evident, which own about 73% of installed capacities. Private foreign stakeholders include, for example, ACWA Power from Saudi Arabia, TAQA from Abu Dhabi, Siemens from Germany, Endesa from Spain, Engie from France, and Mitsu from Japan. Besides these foreign stakeholders, the royal company Société Nationale d'Investissement (SNI) with its subsidiary Nareva Holding plays an important role in the electricity sector; SNI is involved in about one-third of installed capacities, including both wind farms and coal-fired power plants. This royal involvement runs counter to the important role of King Mohammed VI as an active force promoting the energy transition (see Section 1.1) since Nareva Holding is not only constructing renewable capacities but also commissioned the newest coal-fired power plant in 2018 [71].
Regarding the power plants under development, their shareholders include, for example, *Green of Africa* – a joint venture of rich Moroccan families that are friends of the royal family [13] – Enel from Italy, ACWA Power from Saudi Arabia, and Nareva Holding. ONEE is also planning more new power plants, including a new gas-fired power plant and a second pumped-hydro storage system. This can be seen as a strategic decision by ONEE to increase its involvement in the country's future electricity generation while remaining uninvolved in the financing of the power plants [b3]. Injustices related to this centralised electricity generation that supports large-scale and mostly foreign ownership will be discussed in Chapter 4.3.

4.2 Liberalisation of the Energy Sector

The liberalisation of electricity generation in 1994 was an understandable and necessary step for the Moroccan energy sector as it aimed to reduce financial pressures on the public utility ONEE, which during the 1980s faced serious problems related to rising fuel costs [26]. The implementation of different laws between 1994 and 2016 opened up several possibilities for electricity producers, enabling them to enter into a PPA with ONEE or another end-user, distribute electricity via the medium- and high-voltage level grid network, or consume self-generated electricity. As the energy sector was established as a single-buyer market in which ONEE buys all of the electricity produced and sells it to the consumer, ONEE has a strong market power [26]. PPAs need to be negotiated bilaterally between the IPP and ONEE (for fossil power plants) or between the IPP and the MASEN, (for renewable power plants). This separation was made to cluster renewable generation under one agency, MASEN, and leave fossil as well as hydroelectricity production with ONEE. Due to the increasing scarcity of water, further expansion of hydropower (except for pumped storage) was not planned and was therefore left to ONEE. The PPA guarantees a fixed price per kWh to the producer and projects are granted based on tenders but present at least two disadvantages. First of all, ONEE bears the risk of price fluctuations because it is responsible for resource imports [26]. If coal prices increase significantly, only ONEE must pay the difference; the price per kWh produced remains the same for the IPP. Additionally, ONEE needs to approve the project's compatibility with the national grid [72]; regulatory definitions of the rights and obligations of the grid operator are still lacking, however, precluding any transparent and consistent calculation of grid charges [73]. The process and basis for decision-making were judged by project developers to be opaque due to a lack of transparent information on free grid load and the possible connection of renewable capacities[72], [74]. The bilateral negotiations on grid connections, and within this, the necessary power of IPPs vis-a-vis ONEE or MASEN to gain approval for specific projects, is also a reason why large-scale companies are acting as IPPs for energy projects [70]. No support mechanisms for renewable electricity (such as a feed-in tariffs or subsidies) are in place [73]. In 2016, the National Electricity Regulatory Authority (ANRE) was created by law to improve the regulatory framework governing grid access and to create consistent regulations for allocating grid connection costs, which are currently missing [73]. One of ANRE's objectives is to develop "an efficient electricity market, by ensuring transparent and equitable rules of access and establishing grid access and use tariff that valorises investments and fosters innovation" [75] to eliminate the aforementioned problems. The lack of any kind of renewable support mechanism regarding the grid connection mean that small-scale power plants are overlooked. At the same time, a more decentralised electricity generation would enable the construction of small-scale renewable projects owned by private households or community-based stakeholders, generating economic benefits and participating in their energy independence. This would help reduce the share of foreign involvement and the decentralised electricity production would also prevent the formation of a large-scale grid extension [72], [s1]. Unfortunately, only the Moroccan private sector and the civil society – not the relevant decision-makers – support the decentralisation of its energy transition and (as part of this) the building of small-scale decentralised, renewable energy capacities [b3]. However, it is important to mention the socio-economic benefits that have accrued from the positive impact of increasing electrification throughout the country [26].

4.3 Social Injustices of Planning Processes and Electricity Production

While the expansion of renewable energies in Morocco has progressed a lot in recent years, the social dimension of this development is based on multi-layered injustices. This section analyses the unequal treatment and missing involvement of the local population in Moroccan energy projects based on the literature review and conducted interviews and is structured according to the three approaches of justice: procedural, distributional and recognition justice [44], [45]. Due to the focus of this analysis, cosmopolitan justice is not included.

Procedural injustices

Procedural injustices, the injustices that exist related to a missing or not adequate participation and involvement of local populations in decision-making processes [45], are cemented in the structures of the Moroccan society, economy and policy-related processes of energy planning [a1]. They range from decision-making practices centred on the highest political-levels including the royal family to the local (and especially rural) population's lack of awareness of their civil rights and their lack of participation in the energy transition. For example, residents of the area in which the CSP plant Noor should be constructed, were not involved in planning processes due to missing involvement procedures, but were only informed about this decision when King Mohammed came to the community to officially inaugurate the project [54]. Rural organisations also claim the disregard of community control and community needs such as women empowerment [76]. Moreover, grabbing land of the poor and rural population without paying appropriate prices or even accepting the owner's refusal to sell the land can be traced back from the mining sector to today's energy transition [52], [77]. The enactment of a new land law in 2019 even cemented these injustices since land can now be taken more officially for private investments in energy projects to support Morocco's national development [52].

It was expected by King Mohammed VI that he would jump-start the liberalisation and democratisation of the country, but thus far he has only managed to take "steps toward reconfiguring authoritarianism rather than a process of democratisation" [78]. The king's decisions and actions aim to stabilise and centralise the influence, power, economic benefits, and all related economic activities [52] within the circle of the royal family and ruling elite. Involving local communities would be a first step towards procedural justice, although decision-making processes would have to allow for real participation of local people in energy projects.

Recognition injustices

Recognition injustices of energy planning in Morocco include the grabbing of land, exclusion of vulnerable groups and a lack of awareness of citizens' right. In general, the availability of land does not seem to be a problem in Morocco; rather, it is the availability and use of land in resource-rich locations that seems to be more and more problematic [79]. At the community and local levels, this constellation means that land is taken without appropriate compensation or any consideration of its current use. A strategic disengagement of vulnerable people is present due to the previously described procedural injustices and results in different forms of recognition injustices. Information on planning procedures or outreach of the Noor power plant was to a certain extent only available online and not in local dialects, which led to an unequal treatment of rural residents [80]. Additionally, it appeared that the land that was taken for the energy production was not being occupied by local residents; in reality, however, the entire regional area is used by traditional nomads who move seasonally with their animals from one place to another [s1], which disproves the myth of the empty desert. In all likelihood, overcoming the procedural injustices through involving community in local planning activities would have unveiled this usage, making it possible to develop a just solution for all parties [a1].

There is a lack of awareness by local communities about their rights and how they intersect with different aspects of the energy transition [13], [52], [81]. Rignall [52] calls for a 'democratisation of knowledge' about laws, legal frameworks, administration, taxation and many other issues of state legitimacy and human rights "with the objective of supporting local and regional movements for a just transition" [52].

Distributional injustices

Distributional injustices relate to the unequal distribution of socio-economic benefits among the Moroccan population, which is supported by the political economy of the centralised Moroccan constitutional monarchy [24]. The government's decisions and actions aim to stabilise and centralise the influence, power, economic benefits, and all related economic activities [52] at the highest political levels.

As shown in Section 2, foreign investments can have both positive and negative impacts on a country's socio-economic development. Supporting large-scale power plants and with this, the involvement of international companies reflects the country's centralised power structures of decision-making because grid-connected power plants are better to control than small-scale and or even off-grid home solutions [53]. Electricity production from large-scale centralised power plants, such as the CSP plant, creates higher economic benefits for electricity producers [53]. These benefits are interesting for large international companies and are probably one reason why Morocco is successful in attracting foreign investments. Even though small-scale power plants compared to large-scale power plants do not per se create more benefits for the overall country, the involvement of community or privately-owned small-scale PV plants would increase the energy independence and create economic opportunities for local Moroccan. Additionally, it is much easier to design small-scale projects socially just compared to large-scale projects. Besides these missing economic opportunities, rural organisations also claim the missing or inadequate transfer of knowledge, which results in missing employment possibilities [76]. There is a mismatch between available educational training capacities and skill requirements for employment possibilities, which prevents an equal distribution of socio-economic perspectives [57]. Although the Moroccan government tries to strengthen the local content and employment creation, local content requirements were only voluntarily required so far [57].

5 Discussion

Some basic changes would enable Morocco to achieve an inclusive and just approach towards social participation, one that actively involves the local population. If the consideration of local needs were to be a priority in planning, an interview partner concluded that "this renewable energy transition would look very, very different. It would be a very decentralised kind of reworking of the grid to enable regional generation of electricity for the benefit of people whose bills have not changed, who still pay an inordinate amount of money." [a1]. In short, one can finally conclude that the centralised political economy of the country does not support a more decentralised and participative decision-making, missing to democratise and socialise economic benefits from energy transition. The lack of involvement combined with an insufficient knowledge transfer is the bases for many of the mentioned injustices. Some of these factors were uncovered in surveys [50], [51] dating back to 2014, and could have been taken into account by national decision-makers to achieve a positive social acceptance of and participation in the Noor power plant. Even though the aforementioned propositions would not mean a fundamental change of the entire system, it would be a first step to making processes more transparent and inclusive for the rural population.

Promoting the transition to renewable energies while at the same time silently expanding their coal-fired capacities was one of the most important developments of the Moroccan energy transition during the last decade. It was argued in the national energy strategy that coal represents the cheapest source of electricity generation and that renewables are needed to diversify electricity generation and reduce energy imports [31]. However, the increased use of coal tends to lead to an increased need for energy imports as renewables do not replace coal but complement it due to the rising energy demand of the country. Furthermore, the target of installing 42% renewables by 2020 seemed to be ambitious and in line with achieving long decarbonisation goals but is less worthwhile when expanding the use of coal at the same time. As a result, more than 65% of electricity from coal and only 19% from electricity renewables were produced in 2020 [11]. Developing generation-related instead of capacity-related future targets would have been more transparent.

Foreign as well as royal involvements have shaped this contradictory pathway and resulted in several winners and losers of the energy transition in Morocco. Winners relate to profiteers of the centralised and on foreign investments dependent energy sector, loser, by contrast, relate to disadvantaged groups that do not participate in or have access to the benefits of renewable electricity generation. This study unveiled at least three groups of winners and four groups of losers of the Moroccan liberalisation and energy transition. Winners are large-scale and mostly foreign, electricity producers, the state and some parts of the rural population. Electricity producers profit from the centralised power generation and receive income and economic benefits from large-scale electricity generation facilities. The state holds the control over the centralised way of electricity generation and attracts more and more foreign investment with this type of generation compared to focusing on small-scale projects. Moreover, the rural population, which was not electrified until ONEE's electrification program started, benefitted from the process of electrification. Losers are private households, rural communities, rural companies and rural workforce. Private households have only limited possibilities in participating in electricity generation such as through PV home solutions and cannot generate income with it. Rural communities lack transparent decision-making processes and a missing provision of information about energy projects. Rural, and mostly small and medium size companies are only partly integrated in constructing and operating large-scale power plants. Finally, rural workforce lacks employment possibilities but because of a mismatch between education and training possibilities, they do not possess the skills to work in the energy sector. Rural organisations claim that empowerment and education are the backbone of a socially just energy transition that creates benefits for all parts of the society, but which is lacking in today's energy transition in Morocco. A more transparent approach to providing information and knowledge, combined with openness towards a more decentralised energy system, would enable the implementation of small-scale renewable community projects. This, in turn, would enable an energy transition unfettered by a disproportionately high share of foreign investment. Higher shares of small-scale PV systems, for example, would help the country to manage its missing investment in the grid extension described above and would transfer economic benefits to private households or local communities.

The closure of the rotor blade factory is a first indicator that international companies primarily react to global changes and are not focused on staying in a country when profits fail over a short period.

Future research should focus on developing appropriate and socially accepted decision-making processes which will enable the local population to have a say in Morocco's future energy transition and its design, such as based on the work by Neves et al. [49]. On the issue of how to transform energy systems, the concepts of energy justice can guide decision-makers through the various possibilities. The focus on a more decentralised and small-scale expansion of renewable capacities would be a first step, but all levels of decision-makers must be open to creating benefits also for the rural areas. More field work in Morocco needs to be conducted to identify the needs of the local populations and ways local communities could be included in electricity generation projects to benefit from it.

The results of this study are limited to scholarship written in English and French and it is unclear whether bringing in an assessment of Arabic research would have added more important findings. Moreover, the identified injustices are not all-embracing but summarise the results derived from the literature review and conducted interviews.

6 Conclusion

The previous chapters have shown that the opening of the energy sector in 1994 was very beneficial to the Moroccan energy transition, enabling a large number of foreign investors to expand the installed capacities after that date. The country has ambitious long-term targets for the energy transition and is not only focused on the construction of generation capacities. To achieve a sustainable industrial development, Morocco also aims to implement the necessary technology and knowledge transfer, which is however not focused on rural workforce. Besides using renewable electricity, the country was also focused on expanding its coal-fired capacities during the last years. Foreign financial institutions, such as the World Bank as well as foreign project developers, have shaped these contradictory developments. The insights yielded by this study are of fundamental significance to Morocco as it expands its renewable capacities in the future, since they may help the country achieve a more socially just energy transition and prevent it from repeating past mistakes such as land grabbing or a missing participation of the local population. The country has ambitious targets for expanding renewables for electricity generation, and will also start to ramp up its Power-to-X production for which more renewable generation capacities are required. Knowledge about possible benefits of renewable electricity generation as well as positive and negative impacts of foreign investments can lead to the design of a more socially just and beneficial energy transition also for the rural population.

7 Annex

Table 1 Interview partner

Abbreviation	Sector	Date	Length
p1	Private sector	16.02.22	60 minutes
s1	Civil society	24.03.22	60 minutes
b1	Public sector	06.05.22	60 minutes
a1	Academia	20.05.22	45 minutes
b2	Public sector	27.07.22	80 minutes
p2	Private sector	08.07.22	60 minutes
b3	Public sector	10.10.22	45 minutes

Abbreviations

ANRE	National Electricity Regulatory Authority
COP21	Conference of the Parties Number 21
CSP	Concentrated Solar Power
EIA	Environmental Impact Assessment
IMF	International Monetary Fund
IPP	Independent Power Producers
LNG	Liquified Natural Gas
MASEN	Moroccan Agency for Sustainable Energy
MENA	Middle East North Africa
NDCs	National Determined Contributions
ONEE	Office Nationale de l'Electricité et de l'Eau
PPA	Power Purchase Agreement
PV	Photovoltaic
SNI	Société Nationale d'Investissement

CRediT authorship contribution statement

The author did all work on its own and only received feedback on language editing.

Declaration of Competing interests

The authors declare that they have no competing interests.

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7 Green Hydrogen Production: Integrating Environmental and Social Criteria to Ensure Sustainability[6]

Marina Blohm

Franziska Dettner

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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

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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)).

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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

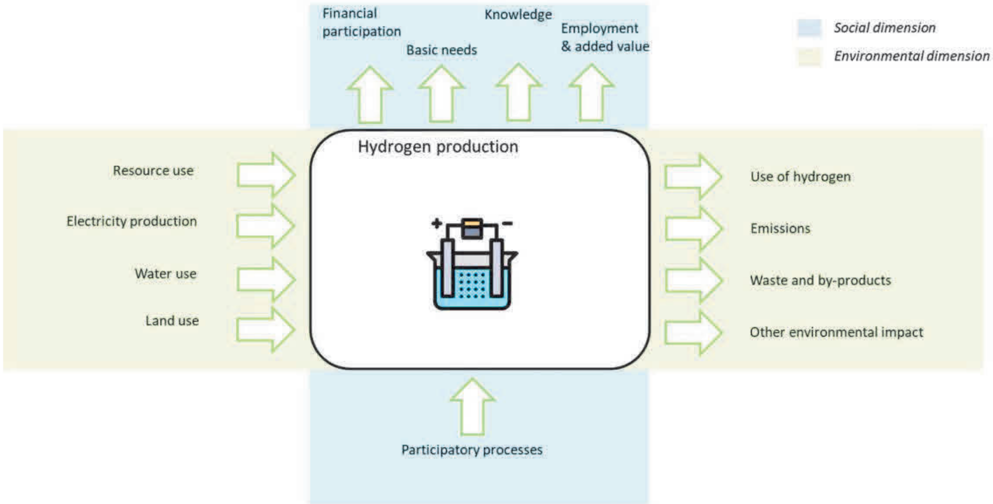

Fig. 1. Inputs and outputs of a sustainable production of green hydrogen, based on the Table 1 and conclusions drawn from section 2, *environmental dimension* depicted in green, *social dimension* depicted in blue.

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.

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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.

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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

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Part III – Synthesis and Conclusion

8 Discussion and Research Outlook

8.1 Synthesis of Research Results

This chapter synthesises the results of the five scientific articles. Chapter 8.1.1 discusses the results of a sustainable energy transition without a regional focus, while Chapter 8.1.2 concentrates on the results of the Moroccan energy transition.

8.1.1 Towards a Sustainable Energy Transition

Even though the consequences of increasing GHG emissions have been known for many decades, prevailing barriers in current energy systems remain to prevent a fast shift from fossil fuels to renewable energies in many countries around the globe (Blohm, 2021). The extraction and processing of domestic fossil fuels were expensive in a number of countries (like Germany), which is why supportive measures, such as financial subsidies, needed to be implemented in the past to make the use of fossil fuels cost-effective and competitive (Zerzawy et al., 2017, p. 19). Today, these supportive measures prevent a competitive use of different energy sources and can act as barriers for renewable energies or lock-in factors for fossil technologies. Identifying these barriers, that have historically supported centralised power generation from fossil fuels, in order to remove them with the help of a favourable framework in which renewables should not compete with subsidised fossil fuels, is part of the first article of this dissertation. Chapter 3 shows the possible composition of such a framework that can be applied to various status quo energy mixes in different countries, with regional adjustments of the criteria, if necessary. Not only do political or technological factors exist which influence developments in the energy sector, but also environmental, social or institutional barriers that can negatively influence the expansion of renewable energies or that can favour the use of fossil fuels. Besides a beneficial governmental support for renewable energies, the social dimension, including social acceptance and awareness as well as equity and justice, seems to be at least of the same importance when targeting sustainable energy transitions. Chapter 4 (Zelt et al., 2019) includes this social perspective and presents future electricity scenarios for Morocco, Jordan and Tunisia, which were developed in a participatory manner and ranked according to stakeholders' preferences with the help of a multi-criteria analysis. Future scenarios with the highest shares of renewable capacities (fully renewable in Morocco and Tunisia) were ranked first in all three countries. Decisive for the positive ranking were the criteria "Energy independence" (25 %), "System costs" (16 %), "System flexibility" (12 %) and "Water consumption" (12 %) in Morocco; "Safety" (27 %), "Air pollution (health)" (14 %) and "Hazardous waste" (14 %) in Jordan; and "Energy independence" (16 %), "System costs" (13 %), "Water consumption" (13 %) and "Air pollution (health)" (13 %) in Tunisia. A clear preference for renewable energies compared to fossil fuels could be observed during the workshops, mostly based on criteria which increase the energy independence of the country. However, discussions during the workshops have also shown that future electricity prices need to be affordable for the people and that looking at the pure system costs gives the impression that transitioning to renewable energies is much more expensive compared to fossil fuels. However, these differences may also result from the fact that existing lock-in factors make the use of existing fossil fuels much cheaper compared to a new construction of renewable energies. Therefore, the external costs of air pollution from fossil based energy generation in Morocco are calculated in Chapter 5 (Dettner & Blohm, 2021) to integrate the

health and related economic perspective of Morocco's energy generation for the example of year 2015. The results show that air pollution creates many health-related illnesses because large-scale fossil power plants are mainly located in the vicinity of urban centres. The results can provide helpful information for decision-makers about energy-related health costs and the consequences of ignoring these external costs of fossil-dominated energy systems, which leads to a distortive view on the costs of fossil and renewable-based energy systems. Reducing such health impacts could result in increased socio-economic benefits for the overall population.
The thematic introduction in Chapter 2 shows, that a potential future production of green hydrogen could provide many opportunities for MENA countries to increase their sustainability, such as replacing export revenues from fossil fuels with those from green hydrogen. Therefore, this topic is introduced in Chapter 7, with the aim of designing hydrogen sectors based on sustainability aspects from the beginning and avoiding inequalities, that currently exist in energy sectors. Accordingly, sustainability criteria for the production of green hydrogen can ensure that basic needs of the population will be respected and that socio-economic benefits can be generated for civil societies. The topic is important for the countries of the MENA region, because many of the announced large-scale projects are planned to produce green hydrogen for export-purposes so that the countries would only indirectly benefit or directly suffer from these projects, if sustainability criteria were not implemented properly. These inequalities could result, for example, from existing power relations between high political actors and big, sometimes foreign, companies, such as it is the case in the Moroccan energy sector (cf. Chapter 6).

8.1.2 Performance of the Moroccan Energy Transition

Chapter 6 demonstrates that Morocco relies on imported fossil fuels and has been successfully expanding both fossil and renewable energy capacities in the past, even though the country has neglectable amounts of fossil reserves. At this point, it is important to highlight the findings of Chapter 6, which present that Morocco managed to install around 4 GW of renewable capacity, but, at the same time, had built two new coal-fired power plants between 2014 and 2019, so that by 2020 a total of 4 GW of coal powered capacity had been installed. This historically conditioned path of favouring coal can be interrupted by analysing the existing barriers and lock-in factors that prevent Morocco from taking full advantage of its abundance of renewable resource potential. The following section synthesises the results related to the Moroccan energy transition with the help of the developed enabling framework to identify existing barriers that prevent the country from achieving a sustainable energy transition. However, not all categories and criteria of the enabling framework could be used for further analysis in the scientific articles, due to the specific focus of the articles or the lack of suitable interview partners.

<u>The Moroccan energy sector</u>
(Analysis based on the framework categories *Energy markets*, *Legal requirements*, *Infrastructure*)

In Chapter 3, an enabling environment for transitioning the energy sector towards a more sustainable system is defined *inter alia* as being liberalised, without implemented trade barriers, well-managed and with private sector participation, to enable decentralised and cost-effective renewable electricity generation. Chapter 6 considers many of these aspects and analyses the manner in which electricity generation has been liberalised and which factors influenced the rise of renewables and coal in Morocco. Accordingly, liberalising Morocco's electricity generation in 1994 – distribution and transmission are still not liberalised – was beneficial for the public utility ONEE, as it allowed it to reduce its financial pressure caused by rising fossil fuel prices and focus instead on rural electrification (Usman & Amegroud, 2019). Since then, electricity generation has been dominated by the private sector and ONEE remained to produce 22 % of the total electricity generated in 2019 (ONEE, 2020, p. 4). The stakeholders in the energy sector are mostly large, foreign companies that have constructed large-scale power plants and the findings indicate that mainly these large-scale actors gain the economic benefits from electricity generation. Small-scale actors have not been involved in relevant activities in the energy sector so far. Until now, there are few trade barriers in place and generating electricity is basically very open for foreign ownership and investments (Fink, 2017, p. 211). The management of the energy sector – including legal and infrastructural requirements – seems to cause problems for private investors such as a very non-transparent and not standardised development of action plans and grid access agreements (Usman & Amegroud, 2019, p. 22). The unbundling of problems related to the grid access as well as the elimination of administrative barriers, which are identified as being important in Chapter 3, have been considered by the Moroccan government by creating a new agency, called National Electricity Regulatory Authority (ANRE), which is now in charge of dealing with transparency and standardisation (see Chapter 6). ANRE will most likely not only remove existing barriers for renewable electricity generation but also create positive impacts on the planned green hydrogen and green ammonia production, which also require transparent and reliable policies for project planning and electricity supply, as described in Chapter 7. These results on the Moroccan energy sector indicate that even though most of the enabling criteria for a supportive treatment of renewable energies seem to be in place, not only the rise of renewables but also the intensive expansion of coal has been supported during the past years. Influenced by foreign institutions and companies, the increase of coal-fired power generation has been achieved without international attention and only the transition towards renewables has been discussed and highlighted internationally. With regard to this development, one cannot speak of a sustainable energy transition because renewable electricity only adds to and did not replace any fossil electricity.

Transitioning to sustainable energy systems does not only include the use of fossil-free technologies but also incorporating environmental impacts and social needs which offer benefits for the local population to improve their current standard of living (Blohm, 2021, p. 10). This is especially important in Global South countries, which could profit from socio-economic and ecologic benefits of energy transitions. However, the pure transfer of clean technologies or knowledge is not enough to support and strengthen domestic economies to achieve the integration within the local value chain (Blohm, 2021). The strengthening of domestic economies, which is part of the enabling framework, has been an important discussion point for Moroccan workshop participants, but has apparently not been managed properly enough during the last years to benefit Moroccan companies. Chapter 6 deals with the topic of how Morocco failed to include and support domestic companies and instead has been more focused on attracting foreign investors without imposing necessary suitable technology and knowledge transfer mechanisms. Unfortunately, foreign ownership has not been successful in creating a spillover effect from foreign to domestic companies (Bouoiyour, 2011, pp. 9–11), with an exception of the Research and Development (R&D) sector. Moroccan research institutes, universities and ministries created bilateral energy partnerships, for example, with German research institutes and ministries, which has enabled a transfer of knowledge between the two countries. These cooperations and partnerships can be both beneficial and problematic when the involved stakeholders are not following the domestic interests, as it has been shown within the Desertec project (Schmitt, 2018). Related to the research on green hydrogen, it has been shown that domestic companies and research institutions are involved in the ramp-up of this new technology to learn and shape the future design of this evolving sector (see Chapter 2.1.3). This important spillover effect, which is also mentioned in the enabling framework under the criteria *Strengthening domestic economies* and *National systems of innovation*, needs to be further developed so that more Moroccan companies along the entire value chain can be involved in participating in and thus benefitting from the energy transition. It will be especially important that the skills that are required to get an employment in the sector are properly offered to the domestic workforce.

Additionally, Morocco's growing green hydrogen sector could learn from the experiences that have been made in the energy sector related to the impacts of foreign investment, foreign ownership and the missing creation of socio-economic benefits. In Morocco, a country that is highly vulnerable to the consequences of climate change, water is a particularly scarce resource (Government of Morocco, 2021, p. 20). Therefore, desalinating seawater not only for the production of green hydrogen but additionally for supporting basic social needs of the population could increase the sustainability of these projects. Otherwise, it would be important that not only economic benefits will be created for the so far involved larger companies, but that additional socio-economic benefits can be created for the local population. The consideration of the developed sustainability criteria, not only in the expanding hydrogen sector but also in the regular energy sector, could increase the overall sustainability of the entire energy transition.

The political economy of Morocco's energy system

(Analysis based on the framework categories *Energy policy, Energy markets, Institutions* and *Clash of interests*)

The political economy of Morocco is elusive because it seems that the political decision-making is influenced by decisions made by the king as well as by influences from foreign stakeholders. Chapter 6 analyses the successful expansion of renewable energies in Morocco to date and describes how decisions in the energy sector are often not based on informed choices, which would be important for the civil society to understand and support necessary changes (see Chapter 3). The former Desertec vision, which foresaw the production of electricity in desert regions and its export to Europe (Schmitt, 2018) would have enabled Morocco to increase its economic and industrial activities. Due to misleading price predictions as well as interventions from German stakeholders, the country started to construct large-scale CSP plants instead of cheaper PV systems (Schmitt, 2018, pp. 766–767). Electricity from the CSP plants has been subsidised by the Moroccan energy agency MASEN with the help of a World Bank loan, so that the produced electricity can be sold at competitive prices to the consumer (World Bank, 2018, p. 11). The results in Chapter 4 also indicate that workshop participants did not favour CSP over PV and that, according to today's economic reasons, no new CSP power plants should be constructed in the future, which the respective decision-makers already considered in the long-term planning after knowing the real cost of CSP electricity generation.

Chapter 3 indicates that governmental support for transitioning to renewable energy systems is beneficial as strategic long-term decisions might otherwise favour fossil fuels. The general governmental support for renewable electricity in Morocco that is given, can be seen in the long-term targets of installing 52 % renewables by 2030 and 80 % by 2050 (Anouar, 2022). However, no support mechanisms, such as feed-in tariffs, are in place, which make the expansion of renewables less economically attractive than it could be (see Chapter 6). Implementing feed-in tariffs, optimally combined with a priority feed-in for renewable electricity, would lower the risks for project developers and create predictable production and operation costs as well as revenues in the long term, which would be especially important for small-scale domestic project developers and owners (Abolhosseini

& Heshmati, 2014, p. 6). This would allow rural areas to shape power generation to their own needs and future visions and make small-scale electricity projects competitive compared to large projects.

Even though the government supports the expansion of renewables, coal was mentioned as the most important and most cost-effective source for electricity generation in the national energy strategy of 2009 (MEME, 2009, p. 23). In times of an urgent need for reducing CO_2 emissions and decarbonising the entire economy, the true costs of coal-fired powerplants seem to be neglected. To achieve long-term decarbonisation goals, carbon pricing policies would make the use of coal much more cost-intensive and not the cheapest source of electricity generation (OECD et al., 2015). While the Moroccan government stopped the construction of new coal-fired power plants in 2021, the rapid coal phase-out has not been supported (UK Government & United Nations Climate Change, 2021). The removal of existing pervasive subsidies, which currently make the use of fossil fuels cheaper, would be a first step towards enabling a fair competition between fossil and renewable electricity production (Peszko et al., 2019).

Therefore, Chapter 5 calculates the external costs of air pollution from electricity generation in Morocco. It is shown that the current type of electricity generation has significant negative health effects, such as respiratory diseases or even premature mortality. Large-scale fossil power plants are usually located near urban areas due to grid constraints, which causes the population to suffer from this form of electricity generation. These costs are currently borne by the general economy. Internalising external costs unveils the true cost of electricity generation, showing that electricity from coal-fired power plants is not cheaper than electricity generated by renewable power plants, which makes a comparison of different energy systems beyond system costs even more important. It is important to note that Chapter 5 focuses on the external costs of air pollution and its impact on human health and does not assess the impacts and costs of other greenhouse gas emissions on the global climate as well as effects on the built and natural environment. Methane in particular, but also other pollutants, such as nitrous oxide (N_2O) or carbon tetrafluoride (CF_4), have high global warming potentials (Myhre et al., 2013, p. 714), affecting physical climate patterns on Earth and leading to rising global temperatures. Due to the high marginal abatement costs (Johansson et al., 2006, p. 304), it would be important to also consider and analyse the share of these external costs. The cost rage for external costs of climate change are very large due to the various regional-specific impacts on human systems such as water scarcity, food production, health and wellbeing, cities, settlements and infrastructure as well as impacts on changes in ecosystems such as changes in ecosystem structures, species range shifts and changes in timing (IPCC, 2023, p. 10).

Chapter 4 shows that system costs were evaluated as being very important by Moroccan stakeholders to make electricity affordable for everybody. If external costs of fossil power generation were internalised in the cost of electricity, energy prices would rise and the government would have to inform the population about the reasons for using coal.

Energy independence was one of the most important criteria for future electricity systems that were mentioned by workshop participants (see Chapter 4). Increasing the share of renewable electricity supports this objective as Morocco has no domestic fossil reserves but high renewable wind and solar potentials. However, increasing energy independence should not result in an increased economic dependence, such as on FDI, as described in Chapter 6. Additionally, the increased use of coal-fired electricity, which was not replaced by renewable energies, did not increase Morocco's energy independence but increased the amount of imported coal (The Global Economy, 2023). In general, technological decisions that have been made in Morocco in the past, such as favouring large-scale and centralised power generation, seem to follow the same patterns as at the political level. The political economy is centralised at the highest political level and the operation of large-scale power plants brings economic benefits primarily to actors involved, which are either foreign companies or related to the royal family. Preferring large-scale, centralised power generation to small-scale, decentralised power generation is only one example that seems to impede the empowerment of domestic actors at the community or individual level. These decisions and interests of the monarchy can be compared to powerful lobbies that influence politicians to adhere to existing structures and that do not enable energy transitions as described in Chapter 3.

Social participation to achieve a sustainable energy transition
(Analysis based on the framework categories *Society, culture and behaviour*, *Equity and justice* and *Knowledge*)

The results of Chapter 6 show that the Moroccan energy transition towards high shares of renewables did not empower small-scale, local actors but seems to favour large-scale actors, which apparently creates social injustices. Chapter 3 identifies criteria, such as equity, justice, knowledge transfer and social acceptance, as being important to enable and ensure a socially just energy transition. Accordingly, gaining acceptance for removing existing barriers and for changes related to the energy transition, transparency and participation seem to be key enablers to achieving a willingness to accept necessary changes and to empower civil societies. Citizens should not only be informed about decisions that cannot be influenced any more, but should optimally be involved in actively shaping the necessary decisions at an early stage. Chapter 6 shows weaknesses related to involving communities in decision-making processes in Morocco. The construction of the first Moroccan CSP plant was decided at the highest political level. The respective community, in which the power plant had been constructed, was confronted with the decision at a very late stage, which caused fear and uncertainties about the resulting consequences (Terrapon-Pfaff et al., 2019, pp. 9–10). An early involvement might not only be important when it comes to expanding renewable energies but also in the case of producing green hydrogen, as described in Chapter 7. Energy planning and energy system transformation should be in line with societal preferences to correspond with technological priorities and social needs (see Chapter 3). Workshop discussions (see Chapter 4) and subsequent interviews (see Chapter 6) have shown that Moroccan stakeholders generally support the use and further expansion of renewable energies – also at the community level – but local needs would need to be considered more to achieve a just and fully socially accepted energy transition. Creating awareness for climate change and transferring knowledge and skills to the domestic workforce are important to be considered in the energy sector, but are currently missing, or at least not coordinated properly. Knowledge transfer is, to a limited extent, initiated, but seems to not match with the skill requirements that would lead to an increased employment within the sector (see Chapter 6). This mismatch excludes the local population and the local workforce. Pure financial participation of local citizens in energy projects, as it is for example the case in Germany (see Chapter 3), is unlikely to create socio-economic benefits because energy planning would remain in the hands of the government and foreign companies, which are not obliged to locally create socio-economic benefits. Additionally, not many people might have the financial capacities to participate financially in such large-scale projects.

The here presented findings indicate that an enabling framework to overcome existing barriers in the energy sector and to enable a sustainable transition, as developed in Chapter 3, can only partially be found in Morocco because many barriers or lock-in factors still exist. The country has achieved to expand renewable capacities in the past years, but due to the still strong support for fossil energies, the Moroccan pathway cannot be called a sustainable energy transition.

8.2 Comparison of the Enabling Framework with Other Existing Frameworks

This chapter compares the enabling framework developed in Chapter 3 with three other existing analytical frameworks, which are used to study energy transitions or specific problems in this field. In general, many other frameworks exist, each of them having a different analytical scope, and it would not be possible to provide an all-encompassing analysis in this dissertation of this emerging research field. Therefore, only three frameworks were chosen for a detailed comparison, based on their specific focus and application in different case studies. The three frameworks are the Actors, Objectives, and Context (AOC) framework by Jakob et al. (2020), the Meta-Theoretical Framework (MTF) by Cherp et al. (2018) and further developed by Brauers et al. (2021) and the Multi-Level Perspective (MLP) Framework by Geels (2002). Even though some of the frameworks have their origin in other publications by other authors, the here referenced publications were used to make the comparison. Table 8-4 summarises the information on the three frameworks and provides information on specific differences to the enabling framework.

Table 8-4 Comparison of three existing frameworks with the developed enabling framework in Chapter 3

	Objective of framework	Categories /Dimensions /Criteria included	Characteristics of the framework	Conclusion
Actors, Objectives, and Context (AOC) **(Jakob et al., 2020)**	Analysis of policy outcomes influenced by the political environment and institutions as well as economic structures.	• Identifying societal and political actors, which influence policy making • Identifying direct and indirect objectives of the societal and political actors • Conducting a context analysis to analyse the environment of political decision-making (techno-economic, institutional, discursive, environmental criteria included)	• Analysing specific interests of actors which shape political decision-making • Determining the influence of these interests on a country's energy transition. • Comparing different case studies in a structured manner	Analysing the performance of the Moroccan energy transition would have been possible with this framework even though not all existing barriers are related to policy formulation. The challenge of applying this framework would have been to identify the actual and underlying objectives of actors, such as of royal family members and companies. Additionally, the AOC framework does not aim to achieve sustainability, which is the overall goal of this dissertation.
Meta-Theoretical Framework (MTF) **(Cherp et al., 2018)** ***and*** **(Brauers et al., 2021)**	Identifying lock-in factors of specific developments in energy transitions.	Material analysis • The political realm includes an analysis of the political system in which policies influence energy transitions and specific interests influence policy-making • The techno-economic realm analyses how energy markets are structured to achieve transitions to low-carbon energies • The socio-technical realm analyses the resilience of energy transitions as well as the role of businesses and technologies in socio-technical developments Actor analysis • Identification and analysis of important actors and their objectives and influences	• Actors oriented analysis with a focus on identifying lock-in factors of specific developments • Identifying mechanisms and lock-in factors of specific problems in energy transitions	Applying this framework to analyse the performance of the Moroccan energy transition would have been possible with this framework. However, the MTF is better applicable to specific questions, such as lock-in factors of natural gas, than to broader research questions, such as how to achieve sustainable energy transitions, which is the overall goal of this dissertation.

	Objective of framework	Categories /Dimensions /Criteria included	Characteristics of the framework	Conclusion
***Multi-Level Perspective (MLP) Framework* (Geels, 2002) *and further developed inter alia by* (El Bilali, 2019; Grin et al., 2010)**	Analysis of transition processes (system transformations) by identifying how niche innovations grow within a socio-technical regime that is influenced by socio-technical landscapes.	• Analysing landscape developments, in which actors interact with each other and which slowly change over time • Identifying and analysing the socio-technical regime, which consists of a multi-actor network that interacts with each other • Analysing how technological niches evolve over time and how the transition of a technology interacts within the network of actors and in the landscape developments	• Analysis of how niche technologies evolve over time, which is a step-wise process • Identifying other developments which happen over time and how they impact technological transitions	It would have been possible to use the MLP framework for analysing the performance of the Moroccan energy transition over time. However, as the Moroccan energy transition is very much influenced by political decisions without techno-economic reasoning, such as the construction of CSP, it seems as if this framework could only give an incomplete picture in this regard.

All frameworks include technical, social and economic aspects of energy transitions, which develop in frames of specific contexts or landscapes. However, there are some differences between the frameworks compared to the enabling framework, which are shortly highlighted. At least two of the three presented frameworks, namely the AOC framework and the MTF, focus on actors and their objectives. To research and understand specific developments and who influenced these developments, such as cementing lock-in factors or supporting renewable energies, the focus on actors, their objectives and the power to implement the objectives, is very important. However, researching specific objectives might have been challenging in the Moroccan case due to the ruling monarchy. Monarchies and their mostly non-public and rather impenetrable objectives, are extremely difficult to identify and analyse. For this reason, one of the most influencing factors with its underlying specific barriers would only be insufficiently considered in the analysis.

None of the frameworks in Table 8-4 have sustainability at the centre of their analysis, like the enabling framework has, but it seems to be possible to identify barriers that prevent sustainable energy transitions. Furthermore, the MLP and MTF are better applicable to specific barriers or lock-in factors, whereas the enabling framework is mainly applicable to the broader questions of identifying barriers and enablers of energy transitions. The AOC framework combines both approaches of studying specific lock-ins in frames of a broader context analysis.

This short analysis provides additional information to the state of literature in Chapter 3 and shows that other analytical frameworks with a comparable focus already exist, but that all of them have their own nuances and specialties. Therefore, the frameworks are comparable with each other and could probably generate comparable results, if the same research question was analysed.

8.3 Limitations

This section critically discusses the limitations of this dissertation which are not only related to the results but to biases associated with the chosen methodologies. The first three topics – *Data collection*, *Participatory workshops and scenario development* and *Author's nationality* – are related to methodological limitations, while the last aspects – *Developed frameworks* and *External cost calculation* – are content-related limitations.

Data collection

Conducting workshops always includes a bias of personal opinions that mostly do not represent the majority of the population. One workshop per country was conducted including 25-30 participants, each from different disciplines (academia, public sector, private sector), for generating the results of Chapter 4. More workshops or surveys with different societal groups in different regional areas of the countries would have been needed to capture the broader national visions of the energy transitions. Only such a broad involvement of all layers of society could unveil the full range of socio-economic needs and societal long-term visions. The here included workshop participants had mostly positive views on renewable energies, which is why the more sceptic or reluctant and opposite part of the population was missing. Chapter 4 shows, however, that groups with different preferences (economic, environmental, technical) came nearly to the same results. It is therefore uncertain, how big the personal biases of the involved workshop participants were. It must be assumed, that other workshop participants would have created different scenarios. However, pure desk research or conducting a high number of individual interviews or surveys instead of conducting workshops would not have been able to achieve a more representative result as it would not have resulted in developing consistent and supported scenarios but only in identifying individual objectives.

Results on the performance of the Moroccan energy transition (see mainly Chapter 6) are mostly based on a literature review and online interviews. Conducting a high number of on-site interviews combined with distributing survey documents would have increased the validity of results and would have unveiled more specific weaknesses of the Moroccan energy transition. However, such field trips were not possible during the writing of this dissertation due to travel restrictions during the COVID-19 pandemic.

Participatory workshops and scenario development

The development of future electricity scenarios represents a possibility to systematically analyse future alternatives, which are not based on projected real developments, such as business-as-usual scenarios, which are based on political developments, but on storylines or narratives (Dieckhoff et al., 2014, p. 10). They are based on current assumptions and knowledge to analyse an ideal possible situation in the future. Even though inputs and assumptions are based on state-of-the-art techno-economic parameters, the future reality will probably lie in between all different scenarios and their results. Additionally, fast-decreasing LCOEs can make scenario costs already outdated after a short period, which is due to the fact that technological improvements for renewable energies happen fast during the current time (IRENA, 2022g, p. 31). The participatory development of future scenarios during stakeholder workshops, was a necessary step to include stakeholders' preferences while directly visualising infrastructural and economic effects, such as changing system costs or excess electricity. The use of a simplified spreadsheet model in Excel during the workshops was a first attempt to enable discussions among different stakeholder groups on how the electricity future could look like. After the workshops, the developed scenarios were modelled with the open source energy system model *renpassG!S,* which is a more precise open source energy system model but which has a long computing time, which is why it was not used during the workshops. The here presented results must be seen within the conditions that were state-of-the-art during the year in which the workshops took place and as one possibility of how a preferred future system could look like. Re-modelling scenario results at a later stage would lead to different results as behavioural changes and new innovations will impact future pathways (Ekins & Zenghelis, 2021). Choosing another methodology of, for example, developing cost-optimised electricity scenarios instead of defining installed capacities, would have resulted in the creation of different scenarios. However, developing future scenarios based on storylines or narratives instead of a cost-optimisation enabled us to directly show the modelling results during the workshops, which would not have been possible otherwise. Additionally, the three energy systems in Morocco, Jordan and Tunisia were modelled as isolated systems to create an easy-to-use tool for workshop participants. Interconnections would have increased the modelling effort and would have created differences between the simplified spreadsheet model in Excel and the energy system model, because not everything is possible to model with Excel. Missing elements of a more precise modelling, including cost-optimal solutions, interconnections and sector-coupling technologies – as they are more and more important in current and future energy systems – are therefore important limitations related to the findings of Chapter 4.

Author's nationality

Another methodological limitation results from the author's nationality. Being a researcher born in the Global North, my perspective on energy transitions in the Global South most likely differs from those of people or researchers born in the Global South. For that reason, I tried to be very critical with analysing the collected information and tried to develop solutions that fit the local circumstances so that socio-economic benefits could be created for local populations instead of international stakeholders that are involved either in generating electricity or importing the produced hydrogen from the countries under study. However, having the Global North perspective in mind, I might have difficulties to find appropriate solutions that match with the requirements of people living in the Global South.

Developed Frameworks

Both developed frameworks, the enabling framework to support the sustainable energy transition at the national level in Chapter 3 as well as the sustainability criteria for the production of green hydrogen in Chapter 7, present barriers, enablers and criteria that are not independent of each other and which can be fulfilled by following different approaches. Energy transitions are “dynamic processes” (Kitzing & Mitchel, 2014, p. 1), which should resolve “market imperfections” (Kitzing & Mitchel, 2014, p. 1) and which are different from country to country. There is no universal solution for successful energy transitions and different regional circumstances can lead to different best-practise examples and ways a country will transform. To prove the robustness of the framework, more case studies need to be conducted based on the framework’s categories. Therefore, the here presented results must be seen as a proposition of criteria that can lead to sustainability but without promising successes when transferring the results to other countries or regions. A regional analysis of social preferences and socio-economic needs as well as existing techno-economic structures must be the basis for a further decision on which approach will be the best for a specific country. Additionally, both chapters lack a prioritisation or ranking of more or less important criteria because many criteria influence each other. These interdependencies are not part of this dissertation, which is why a prioritisation of the criteria cannot be presented here either.

External cost calculation

The calculation of external costs in Chapter 5 is limited to the impacts of air pollution on human health and does not take into consideration other external costs from energy generation, such as the costs of damage or avoidance of GHG emissions related to climate change.

Additionally, the bottom-up approach needs to be evaluated critically because of two reasons. First, assumptions concerning the power plant set up and related emission quantities were made as no actual emission measurement data was available to compare the computed results to. Second, more detailed modelling of external costs, including atmospheric chemistry modelling to assess secondary pollutants, would have better represented the actual effects. However, the objective of the article was to develop and apply a straightforward approach using less modelling effort to enable decision-makers to understand the modelling results.

8.4 Research Outlook

The synthesis and limitations sections show that several further research topics exist, which could either confirm or further develop the presented findings. Each of the scientific articles in Chapters 3 to 7 includes an outlook on further research topics but this section synthesises the results and highlights important research gaps related to the social dimension of sustainable energy transitions, the Moroccan energy transition as well as to the production of green hydrogen in Morocco.

The social dimension of sustainable energy transitions

It has been shown that the social dimension of both electricity generation and hydrogen production has been researched the least related to topics such as participation, social involvement or the generation of socio-economic benefits for local populations. Further research on these topics could be related to (1) identifying regional knowledge transfer opportunities or education requirements to give the local workforce the ability to require necessary skills for open employments; (2) finding appropriate decision-making and participation processes to involve local communities in energy planning procedures; (3) developing future concepts for communities to capture societal preferences and visions and (4) studying advantages and disadvantages of local content requirements to eventually restrict foreign involvement, if necessary, but to implement beneficial requirements instead of creating additional barriers.

The Moroccan energy transition

Based on the derived findings, there are at least four important research gaps to better understand the political economy of the Moroccan energy sector and to overcome existing barriers. These are (1) identifying future objectives of high-level Moroccan stakeholders to understand the contradiction between supporting renewable energies and relying on fossil fuels, mainly in the case of coal; (2) analysing direct and indirect geopolitical influences in the energy and hydrogen sector to identify domestic needs and international objectives; (3) identifying socio-economic needs of rural communities to respect and include them in the national energy strategy and (4) developing future electricity scenarios or pathways including social, environmental and economic criteria to design a socially just and economically beneficial coal phase-out.

Green hydrogen production in Morocco

Due to the fact that Morocco has ambitious targets related to the production of green hydrogen and also because of the presented findings on missing socio-economic benefits of electricity generation, research on the growing green hydrogen sector is important. Further research is needed on, and not limited to (1) analysing advantages and disadvantages of exporting either green hydrogen or green ammonia and identifying the safest and economically beneficial solution for the country; (2) creating socio-economic benefits of green hydrogen production for projects that are planned for export-purposes; (3) identifying challenges and benefits of additional water desalination in connection to green hydrogen productions to meet domestic needs; (4) analysing measures to strengthen domestic economies and companies related to economic and industrial activities; (5) integrating sustainability along the value chain of fertilizer production also focusing on mining activities; (6) studying impacts of the green hydrogen production on the overall energy transition due to an increased need for renewable capacities and (7) analysing how to attract foreign investments while generating local impact at the same time.

9 Policy Recommendations

Based on the presented findings, this chapter gives policy recommendations to enable sustainable energy transitions. Chapter 9.1 focuses on the Moroccan energy transition considering the domestic perspective of decision-making, while Chapter 9.2 addresses international actors that are active in foreign electricity sectors or in the global green hydrogen sector. However, based on the already mentioned limitation related to the author's nationality, the context, that a Global North researcher gives recommendations to find beneficial solutions for Global South energy transitions, is important to keep in mind.

9.1 Policy Recommendations for the Moroccan Energy Transition

Chapters 3 to 7 analyse different research questions and find barriers and enablers of the Moroccan energy transition. These results are the basis for the here presented recommendations to enable a sustainable energy transition in a country that is not only focused on the expansion of renewable energies.

Table 9-5 Policy recommendations for the Moroccan energy transition

Updating the national energy strategy and developing a Moroccan roadmap with intermediate targets to achieve long-term goals

A precise roadmap until the year 2050, including intermediate and achievable targets, would ensure the compliance of renewable targets and could lead to a full decarbonisation of the country, which is currently lacking. The targets should be related to the overall use of energy with a focus on targeting capacities. To define these targets, representatives of the population should participate in the development process to ensure support and social acceptance of necessary changes.

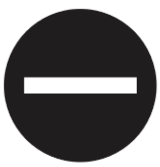
Involving the Moroccan society in the energy transition

Instead of deciding centrally about energy planning in rural communities, participation and involvement of the local, rural population in decision-making processes could be supported to design the energy future based on basic needs and social preferences. This could, for example, be done through a community-based energy planning system and a compulsory consultation of community representatives in which energy projects could be developed.

Creating participation possibilities for small-scale domestic actors

Small actors such as individuals or communities should economically benefit from the energy transition which can, for example, be achieved by enabling to construct small-scale power plants combined with a financial support scheme, such as a feed-in tariff, or a possibility to get inexpensive loans or well-done knowledge transfer to gain employments in the sector.

Local content requirements for specific aspects such as employment or domestic value chain creation should be further researched but implemented only, if they increase the creation of domestic benefits.



Focusing on suitable renewable technologies and limiting air pollution

Energy system modelling indicates that nuclear and coal-fired electricity are not needed in the future Moroccan energy system. The phase-out of coal-fired power plants could be brought forward combined with a fast expansion of renewable energies, such as wind onshore and PV plants. Until the entire phase-out of coal is achieved, one option would be to install state-of-the-art filter systems combined with measurement stations in the surroundings of fossil power plants to reduce external costs of air pollution. Besides pumped-hydro power stations, other storage technologies could be taken into consideration because of the decreasing future availability of water.

Following domestic needs instead of foreign demands
Export-only projects that include the use of electricity and water (such as the production of green hydrogen) should, if possible, only be operated once the domestic needs of the affected population for these resources are met.

Increasing the overall sustainability of the energy transition
Implementing sustainability criteria for the production of green hydrogen as well as for electricity generation would probably lead to a more socially just, socially accepted and environmentally friendly energy transition that is built upon social needs and future visions. Both electricity generation and green hydrogen production should be beneficial for the local population.

9.2 Policy Recommendations for International Stakeholders in The Global Electricity and Green Hydrogen Sector

The results of this dissertation show that involving foreign stakeholders in domestic energy transitions might lead to positive and negative effects. Table 9-6 summarises policy recommendations for international stakeholders to support energy justice and sustainability in the electricity and hydrogen sector.

Table 9-6 Policy recommendations for global energy transitions

Asking the local population about their needs as part of energy planning processes
Integrating the local populations in energy planning processes might lead to a higher acceptance for the projects and enables the project to be built upon local needs and requirements. Even if these consultations might not be required by national governments, they should still be conducted.

Providing access to electricity and water with energy projects, if needed
There are many regions around the world in which the local population lack basic needs such as electricity or water. Constructing additional capacities of renewable electricity and freshwater desalination capacities, for example in connection to green hydrogen projects, may help to solve this problem. Of course, electricity and water need to be affordable for the population and should not be sold at high prices. Through this, companies could help to overcome energy poverty and water scarcity.

Creating domestic value chains and leaving economic benefits in countries of the Global South, especially for export-oriented projects
The local workforce and domestic companies should be involved in all stages of the value chain in the electricity and hydrogen sector in order not only to increase the economic participation but also the acceptance and support from the local population. The involvement of foreign workforce could be limited to those areas in which the expertise of domestic workforce is missing.

In this case, capacity building measures could be implemented to increase the domestic involvement in the long term. Especially export-oriented projects should create a positive impact in the local economy.

Implementing sustainability criteria for the production of green hydrogen at the global-level
Implementing beneficial sustainability criteria for the production of green hydrogen should be fostered at the global-level so that international stakeholders will not choose to be active in a country in which no requirements are in place. This would ensure a fair global competition while creating socio-economic benefits in countries of the Global South.

Preventing neo-colonialism and resource exploitation in countries of the Global South to achieve sustainable energy transitions in the Global North
Trade activities should not be built on neo-colonial structures but should be beneficial for all trading partners. Resources, such as freshwater or raw materials, should be protected and used primarily by local populations. All activities in which foreign stakeholders are involved should optimally follow the same standards and support a responsible treatment of resources, that are implemented in the home country. If no standards exist, implementing global standards would be beneficial.

10 Conclusion

This dissertation is focused on research activities regarding the energy transition in Morocco, a country that is embedded in the geopolitical structures and characteristics of the MENA region but which differs from the other countries for varies reasons, such as having a ruling monarchy and lacking fossil reserves. Not only the current and future electricity generation is analysed, but also the sustainable production of green hydrogen. It can be concluded that Morocco started the construction of renewable energies relatively early in the 2000s, initiated by liberalising electricity generation and allowing foreign investments and ownership without many limitations. Looking only at expansion rates of renewable energies, Morocco seems to be one of the most successful countries of the MENA region. Lacking fossil reserves but having promising renewable potentials combined with attractive economic opportunities are important underlying reasons why the country has been successful so far. Foreign involvements enabled technology and knowledge transfer to strengthen domestic economies and, in theory, created long-term possibilities for local workforces. However, a positive spillover effect to domestic businesses is still in its infancy and the energy transition is currently not as beneficial to the population as it could be if it were geared to local needs and social preferences.
On the downside of this development is the missing involvement of local populations in decision-making processes and concentrating economic benefits at the company-level from which the civil society can only benefit to a small extent. It will be important for the country to hold the prevailing preference and acceptance for renewable energies in the future and to prevent social protests against large-scale projects among the population. Even though a shift towards more small-scale projects would not solve all of the presented problems, it would be a possibility to enable a socialisation of economic benefits and enable the local population to shape the energy transition based on social

preferences and social needs. However, financial support mechanisms and a more precise technology and knowledge transfer would be necessary to achieve this goal. All of these aspects indicate that Morocco is currently not following a sustainable energy transition but rather successfully enabled the construction of renewables to meet the rising electricity demand, while neglecting the social dimension of involvement and participation.

The Moroccan King Mohammed VI desires to play an important role in producing green hydrogen and ammonia in the future and exporting high volumes of it abroad, mainly to Europe. Experiences which were made in the electricity sector could be transferred to the hydrogen sector, at least to a certain extent, to strengthen the domestic economy from the beginning and to find individual solutions for involving local communities and the local workforce in this sector. Implementing sustainability criteria for the production of green hydrogen would be one possibility to achieve this empowerment. The overarching goal should be that energy transitions could be beneficial for societies of transitioning countries, especially if countries support other countries with their energy transition, such as through delivering green hydrogen.

Transferring research results from Morocco to other MENA countries is extremely difficult due to many differences that were mentioned in the introduction such as the availability of fossil resources or the political economy of the Moroccan monarchy. The high renewable resource potential throughout the entire region, however, could be one of the most important drivers and enablers for all countries to expand renewable capacities at comparable low costs. Something the countries under study also had in common was that workshop participants were focused on expanding renewable energies for electricity generation instead of reacting to more short-term demands such as covering rising electricity demands or reducing the overall amount of CO_2 emissions. Covering socio-economic needs seemed to be more important for the stakeholders than combating against the global problem of climate change in general. This dissertation started the dialogue of connecting actors from different disciplines. The developed results can be further developed and implemented to achieve sustainable energy transitions in different countries.

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