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TECHNICAL AND ECONOMIC ALTERNATIVES FOR TRANSITIONING TOWARDS 100% RENEWABLE ENERGY SYSTEMS

BY
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AALBORG UNIVERSITY
DENMARK

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by

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ENGLISH SUMMARY

The energy sector faces a number of challenges, including security of supply, resource availability, energy costs, access to energy, land use effects and implications for the environment and climate. These energy sector challenges may be addressed through the transition to high-renewable energy systems. This dissertation is based on the design of this transition. Specifically, the objective is to enhance the understanding of how future energy systems can be designed to achieve 100% renewable energy. The scope is primarily technical and infrastructure aspects and implications of the design of future energy systems in Europe towards the year 2050. To evaluate the effects for society, focus areas include all energy sectors.

A literature review is applied to clarify the solutions that have previously been suggested for this research area and to position this work within current research. The analytical framework is guided by the choice awareness theory about putting forth alternatives in order to evaluate and compare them. This is carried out by applying the smart energy systems concept, which emphasizes the importance of system integration and the implementation of multiple solutions rather than sole solutions; e.g., in the electricity sector. The theory is used for creating technical alternatives to demonstrate that choices exist for the development of the future energy system.

The aim of this dissertation is hence to investigate how analyses of technical and economic alternatives for energy systems and technologies can support the design of 100% renewable energy systems.

An energy system analysis tool is applied to create alternative scenarios and to evaluate their impact on the full energy system. The EnergyPLAN tool was selected for this purpose because its characteristics match the requirements of the analysis.

The analysis is divided into three: 1) the analysis of concrete technologies, 2) the analysis of the influence of applying two types of cost estimation methods for feasibility evaluations and 3) the development of strategies for designing 100% renewable energy systems for Germany in the year 2050.

The first analysis shows that individual technologies and solutions such as heat savings and solar thermal will provide valuable contributions to the transition to future 100% renewable energy systems, but that these solutions are insufficient in terms of achieving this ambition for the entire energy system. In addition, the analysis reveals the influence of the energy system context, as solar thermal in some scenarios benefits the energy system and in others counteracts the integration of other renewable sources; thus, increasing energy system costs.

The second analysis demonstrates the significance of selecting appropriate methods for feasibility evaluations to raise the awareness of how feasibility studies are and should be carried out. Concretely, the Levelized Cost of Energy (LCOE) method and an energy system analysis approach are compared and evaluated in terms of their influence on future energy priorities. The analysis shows that the LCOE method neglects a range of energy system dynamics that influence the energy system costs and feasibility. This indicates that the energy system context is crucial to the design of future 100% renewable energy systems.

The third analysis presents a range of alternatives for designing 100% renewable energy systems in Germany in 2050. These alternatives implement changes to all energy sectors and differ in terms of the main technologies in the transport sector and the extent to which the full renewable energy potential is installed. Some scenarios exploit the full potential of wind and solar power, which results in excess energy production, but a low biomass demand. Conversely, other scenarios implement less renewable energy to reduce excess energy, but this leads to increasing biomass demands. These alternatives can be used for debating desirable paths for the German energy transition.

The dissertation concludes that 100% renewable energy systems are feasible and will contribute to addressing the key challenges in the energy sector. These 100% renewable energy systems cannot be designed from single technologies or solutions but require a full energy system perspective. The strategies designed in this dissertation indicate that energy system costs are comparable to the costs of fossil fuel alternatives.

The analysis demonstrates that the smart energy systems approach is suitable for developing 100% renewable energy systems. If a full energy systems perspective is not applied, numerous energy system dynamics are neglected, which could substantially affect the findings and feasibility of future energy strategies.

This research has contributed to enhancing the understanding of 100% renewable energy systems design, but countless areas still require further work.

DANSK RESUMÉ

Energisektoren står over for en række udfordringer, herunder forsyningssikkerhed, ressourcetilgængelighed, energiomkostninger, adgang til energi samt konsekvenser for arealanvendelse og miljø og klima. En måde at løse disse udfordringer i energisektoren på, er gennem omstilling til energisystemer med en høj andel af vedvarende energi. Denne afhandling er baseret på et design for denne omstilling. Konkret er formålet at underbygge forståelsen af, hvordan fremtidens energisystemer kan udformes med målsætningen om at opnå 100 % vedvarende energi. Afhandlingen fokuserer primært på tekniske og infrastrukturmæssige aspekter og konsekvenser af fremtidige energisystemers udformning i Europa frem mod år 2050. For at evaluere effekterne for samfundet er alle energisektorer inkluderet i analyserne.

Ved hjælp af et litteraturstudie klarlægges løsninger, der tidligere er foreslået inden for forskningsområdet, og denne afhandling positioneres i forhold til øvrig nuværende forskning. Den analytiske ramme styres af choice awareness-teorien om, at forskellige alternativer skal præsenteres for, at disse kan evalueres og sammenlignes. Dette gøres ved at anvende smart energy systems-konceptet, der understreger vigtigheden af systemintegration og implementering af flere løsninger, frem for enkelte løsninger i eksempelvis elsektoren. Teorien bruges til at skabe tekniske alternativer og dermed demonstrere, at der findes forskellige valgmuligheder for udviklingen af fremtidens energisystem.

Formålet med afhandlingen er således at undersøge, hvordan analyser af tekniske og økonomiske alternativer inden for energisystemer og teknologier kan bidrage til udformningen af 100 % vedvarende energisystemer.

Til denne analyse anvendes et energisystemanalyseværktøj, som udvikler alternative scenarier og evaluerer deres indvirkning på det fulde energisystem. EnergyPLAN-værktøjet er udvalgt til dette formål, da dets egenskaber stemmer overens med kravene i analysen.

Analysen er opdelt i tre: 1) analyse af konkrete teknologier, 2) analyse af virkningen ved anvendelse af to forskellige metoder til omkostningsberegning og 3) udvikling af strategier for design af 100 % vedvarende energisystemer i Tyskland i år 2050.

Den første analyse viser, at individuelle teknologier og løsninger, som eksempelvis varmebesparelser og solvarme, kan bidrage til en omstilling til 100 % vedvarende energisystemer, men at disse løsninger ikke er tilstrækkelige til at opnå denne målsætning for hele energisystemet. Desuden viser analysen vigtigheden af konteksten for energisystemet. I nogle scenarier gavner solvarme energisystemet, og i andre scenarier modvirker solvarme integrationen af andre vedvarende energikilder og øger dermed omkostningerne i energisystemet.

Den anden analyse demonstrerer vigtigheden af at anvende passende metoder til feasibility-evalueringer og øger derved bevidstheden om, hvordan feasibility-studier bliver udført og bør udføres. Konkret sammenlignes Levelized Cost of Energy (LCOE)-metoden med en energisystemanalysetilgang i forhold til deres effekt på prioriteringen af fremtidige energisystemer. Analysen viser, at LCOE-metoden forsømmer at inkludere en række dynamikker i energisystemet, som påvirker energisystemets omkostninger og gennemførlighed. Dette indikerer, at energisystemets kontekst er afgørende for udformningen af fremtidens 100 % vedvarende energisystemer.

Den tredje analyse præsenterer en række alternativer for udformningen af 100 % vedvarende energisystemer i Tyskland i år 2050. Disse alternativer medfører ændringer i alle energisektorer og varierer i forhold til, hvilke teknologier, der er de vigtigste i transportsektoren, og hvorvidt det fulde potentiale for vedvarende energi er udnyttet. Nogle af scenarierne udnytter det fulde potentiale for vind- og solkraft, hvilket resulterer i overskydende energiproduktion, men et lavere biomassebehov. Omvendt er andelen af vedvarende energi mindre i andre scenarier, hvilket reducerer overskydende energiproduktion, men medfører et højere biomassebehov. Disse alternativer kan anvendes til at debattere mulige veje til den tyske energiomstilling.

Konklusionen er, at 100 % vedvarende energisystemer er gennemførlige og vil bidrage til at løse de vigtigste udfordringer inden for energisektoren. Disse 100 % vedvarende energisystemer kan ikke udformes baseret på enkelte teknologier eller løsninger, men kræver et perspektiv, der har fokus på det fulde energisystem. Denne afhandling indikerer, at energisystemomkostninger vil være på et niveau, som er sammenligneligt med niveauet for fossile alternativer.

Analysen demonstrerer, at smart energy systems-tilgangen er velegnet til udviklingen af 100 % vedvarende energisystemer. Hvis energisektoren ikke anskues i et fuldt systemperspektiv, vil adskillige dynamikker i energisystemet kunne overses, og dette vil påvirke resultaterne og gennemførligheden af fremtidens energistrategier.

Forskningen i denne afhandling har bidraget til at øge forståelsen af udformningen af 100 % vedvarende energisystemer, men der er stadig talrige områder, hvor yderligere forskning er påkrævet.

ACKNOWLEDGEMENTS

This PhD dissertation is the result of work carried out between August 2015 and July 2018. The work was conducted in connection with the research projects “IEA SHC Task 52: Solar Heat and Energy Economics in Urban Environments” under the IEA Solar Heating & Cooling program. This project received funding from the Danish Energy Agency through the EUDP Programme. In addition, the work has been part of the Strategic Research Centre of 4th Generation District Heating (4DH), which has received funding from the Innovation Fund Denmark. Finally, the work was also part of the ForskEL project – Towards solid oxide electrolysis plant in 2020.

This dissertation would not have been possible without the support from certain people. I would therefore like to thank my supervisor Brian Vad Mathiesen, who provided valuable feedback and guidance throughout the PhD period.

In addition, I am grateful to my colleagues in the Sustainable Energy Planning research group at Aalborg University who are always supportive and provide a great atmosphere for conducting inspirational research.

Furthermore, thanks goes to my colleagues at other universities and organisations whom I collaborated with for providing valuable data, discussions and feedback on findings.

Finally, I would like to thank Professor Mark Z. Jacobson and his colleagues in the Atmosphere/Energy research group at Stanford University in California. They provided me with the opportunity to carry out an external research stay with the focus on 100% renewable energy systems. This opportunity turned out to be a very special period during the PhD for learning about state-of-the-art research and experiencing the Californian way of living.

I hope you will find this dissertation interesting and enjoyable to read.

TABLE OF CONTENTS

NOMENCLATURE

CCS – Carbon Capture and Storage

CHP – Combined Heat & Power

DEA – Danish Energy Agency

ESA – Energy system analysis

EU – European Union

GHG – Greenhouse gas

HP – Heat Pump

ICT – Information and Communication technologies

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

IRENA – International Renewable Energy Agency

LCA – Life cycle analysis

LCOE – Levelized cost of energy

LULUCF – Land-Use, Land-Use Change and Forestry

O&M – operation and maintenance

PES – Primary Energy Supply

PP – Condensing power plants

PV – Photovoltaics

RES – Renewable Energy Sources

TSO – Transmission system operator

V2G – Vehicle-to-grid

LIST OF PAPERS

This dissertation is based on a collection of papers. These papers are summarized in Chapter 4 and can be found in their full version in the appendix. Throughout the dissertation the papers are referenced as Paper 1, 2, 3, 4 and 5.

Primary publications:

- Paper 1: Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat, Energy, 2016, doi:10.1016/j.energy.2016.06.033 [1]
- Paper 2: Comprehensive assessment of the role and potential for solar thermal in future energy systems, Solar Energy, 2018, 169:144–52. doi:10.1016/J.SOLENER.2018.04.039. [2]
- Paper 3: Comparison of Levelized cost of Energy across electricity, cooling and heating, Working Paper, 2018 [3]
- Paper 4: Decision-making based on energy costs: Comparing Levelized Cost of Energy and Energy System costs, Submitted to Energy Strategy Reviews, 2018 [4]
- Paper 5: Full energy system transition towards 100% renewable energy in Germany in 2050, Submitted to Sustainable and Renewable Energy Reviews, 2018 [5]

Secondary publications:

- Beyond sensitivity analysis: A methodology to handle fuel and electricity prices when designing energy scenarios, Energy Research & Social Science, 2018;39. doi:10.1016/j.erss.2017.11.013 [6]

CHAPTER 1. INTRODUCTION

“Our dependence on fossil fuels amounts to global pyromania, and the only fire extinguisher we have at our disposal is renewable energy” [7].

This chapter describes the main challenges in the energy sector and discusses why it is crucial to address them in future energy systems. The key elements in an energy system are then presented along with the research question, which will guide the research in this dissertation. Finally, the scope and structure of the dissertation is outlined.

1.1. ENERGY SECTOR CHALLENGES

This dissertation deals with specific challenges for the energy sector. These challenges can be grouped into the following categories: security of supply, resource availability, energy costs, access to energy, land use implications and implications for the environment and climate. The results and findings of this dissertation are presented in Chapter 4 and are then discussed in relation to these challenges in Chapter 5.

Security of supply implies two aspects: that energy is delivered to consumers at the right time and place (i.e. balancing of grids) and that energy resources are available (availability of fuels and energy). Typically, national or regional transmission system operators are responsible for balancing grids in terms of frequency and for ensuring that sufficient production capacity exists in line with changes in energy demands. The balancing of grids is becoming more challenging due to the ongoing shift from storable fossil fuels to variable renewable energy sources. Energy resources, especially fossil fuels, are often concentrated in specific regions of the world. This certainly applies to oil resources, which are concentrated in regions such as the Middle East, Russia, USA, Venezuela and Canada [8]. Due to this high level of resource concentration, geopolitical events influence the availability of energy.

Resource availability is mainly related to the depletion of resources or a shortage of energy capacity. The majority of the world’s current energy consumption is based on finite resources that, over time, will become more scarce depending on consumption rates and the exploration of additional energy reserves. In particular, fossil fuels are finite resources that will most likely become scarcer in future energy systems. There is, however, considerable uncertainty regarding the size of fossil fuel reserves, and estimates change depending on who one asks. Advocates of peak oil, for instance, suggest that oil production will soon decline, while major oil companies claim that oil reserves can last for decades [9]. Most renewable resources, on the other hand, do not face the challenge of depletion. The one exemption is biomass, which is the only renewable resource that can be depleted.

Energy costs are a concern for most consumers and for society as a whole. Countless studies and policies use cost-efficiency as the key evaluation factor for assessing possible energy solutions (see e.g. [10–13]). However, energy costs can be measured in various ways, which can significantly affect the overall findings. Awareness of this difference is crucial during decision-making and when comparing energy sector solutions. In many cases, cost-efficiency is prioritized above other energy targets. The energy costs must therefore be evaluated in connection to the effects on other key parameters, such as security of supply and health impacts.

Access to energy is concerned with consumers' ability to access energy to, for example, heat a home to a sufficient level of comfort and health. A term that describes a lack of access to energy is called fuel poverty, which is defined as a situation in which a household cannot afford to adequately heat its home at a reasonable cost [14,15]. In the UK, this threshold has historically been defined as spending more than 10% of a household's income on heating. Causes of fuel poverty might include poor housing stock or increased energy prices and it may lead to effects on health or indebtedness. Studies have assessed that 1 in 7 households throughout Europe live in or on the margins of fuel poverty [14], while [15] estimated that around 11% of EU citizens are living in fuel poverty. However, the definition of fuel poverty and the calculation of heat prices both impact the measured level of fuel poverty [16].

Land use implications addresses the limited availability of land and the need to accommodate multiple purposes beyond energy production, such as agriculture, urban infrastructure, forests and other ecosystems. Land use intensity differs substantially between different sources of energy, ranging from below 1 m^2 per MWh of electricity generated from nuclear energy, natural gas and coal, to approximately 1 m^2 for wind power, 3-10 m^2 for hydropower with large dams, around 10 m^2 for PV production, and in the range of hundreds of m^2 when using biomass crops for electricity production [17]. The future design of energy systems will therefore have a significant effect on global land use, especially when considering that populations are expected to continue growing, thus requiring additional land area for food production and urbanization.

Environmental and climate concerns related to the energy sector have grown in the past decades. These include e.g. greenhouse gas (GHG) emissions (climate change), deforestation, decreasing biodiversity, water use, etc. All of these are impacted by the energy sector via emissions from fuel combustion, production of resources or mining and resource extraction. These concerns have resulted in international agreements such as the 2015 Paris agreement to reduce the harmful effects of the energy sector on the climate. Figure 1 illustrates the GHG emissions in 2010 divided into economic sectors. This suggests that the energy sectors (as defined in Figure 2) are responsible for more than 65% of global emissions. The energy sector is therefore decisive if the ambition is to reduce global emissions and minimize climate change.

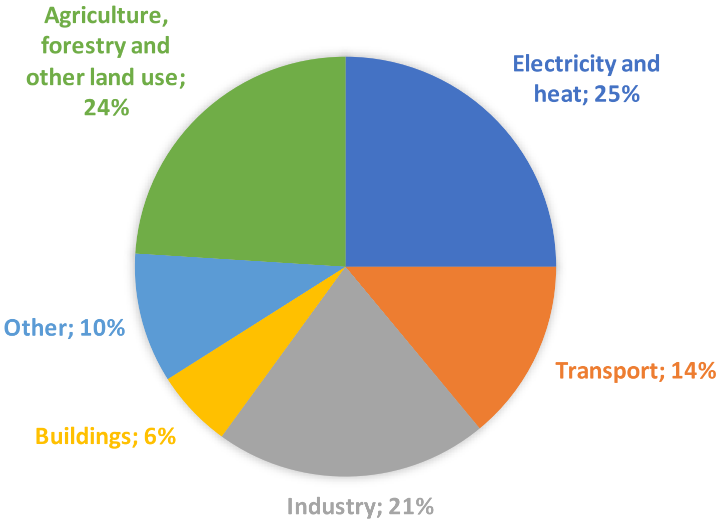

Figure 1: Global GHG emissions in 2010 based on economic sectors. Reproduced from [18].

These challenges are evaluated in the analysis in Chapter 4 by quantifying specific parameters. Security of supply, resource availability and access to energy are assessed through the changes in primary energy supply, energy system flexibility and the type of energy sources. Energy costs are evaluated based on energy system costs while implications on the environment and climate are assessed through the quantification of CO_2-emissions to the atmosphere. Land use implications are not quantified, but included in the discussion in Chapter 5.

Many other challenges are also associated with the energy sector, but they are not directly addressed in this dissertation. These could include health related effects, public acceptance and support, ownership and democracy, safety concerns (related to e.g. nuclear accidents and waste, cyber-attacks, etc.) and innovation to benefit society.

1.2. ENERGY SYSTEM ELEMENTS

Energy systems may be defined in numerous ways. Some view them as a connection of technologies and demands (e.g. micro-grids); others see a system within a limited geographical scope such as a city, while others still think of energy systems from a continental or global scale. It is therefore crucial to define how energy systems are understood within the context of this dissertation.

This dissertation defines energy systems as the connections between energy resources, conversion and transformation technologies, storage and exchange technologies as well as end-user energy demands. Figure 2 illustrates an energy system given this perspective. It should be noted that some elements are excluded in this context, such as fuel extraction and refining, which occur "before" the boundaries of the illustrated energy system. Furthermore, elements such as the end-of-life phase are also excluded; this phase includes energy consumption for dismantling, recycling or decomposing technologies and materials. Hence, the present analysis of energy systems differs from other methods, such as Life cycle analysis (LCA), in which these and other elements can be included to establish a full overview of a given system's cradle-to-grave impacts. There are no CO_2-neutral energy production technologies in an LCA perspective, as emissions occur during manufacturing, maintenance, fuel combustion and possible leakages [19–21]. However, it is common to assume that renewables and other technologies, such as nuclear and CCS, are CO_2-neutral within the boundaries of the energy sector. The aforementioned emissions are instead assigned to the Agriculture, Forestry and Other Land-Use (AFOLU) sectors to avoid double counting, according to the IPCC and EU Commission definitions [22]. In addition, emissions from biomass combustion are assigned to the country where the biomass is produced rather than where it is consumed. These definitions are subsequently applied in this study.

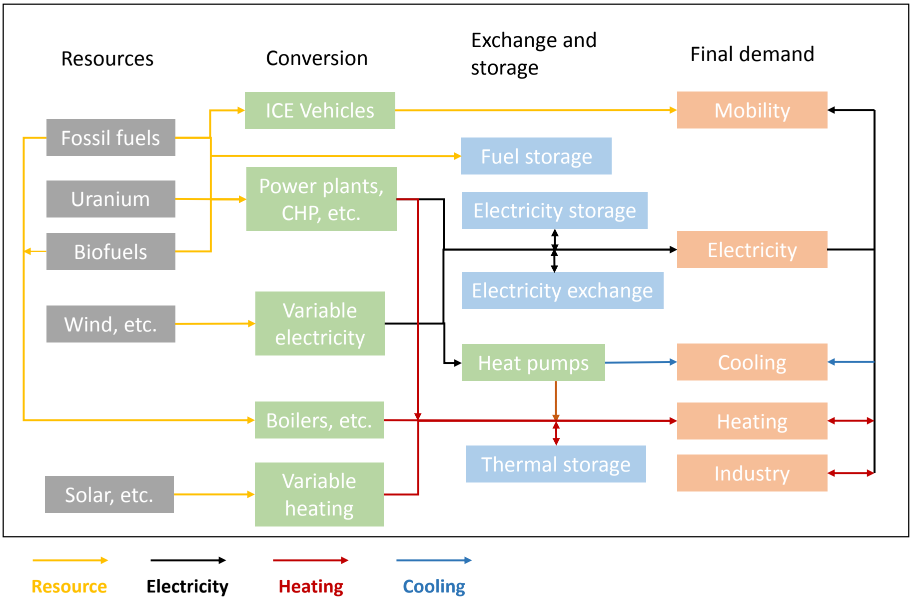

Figure 2: Illustration of elements in an energy system.

Energy systems can be divided into several different sectors according to the energy service they provide to the system's end-users. In this study, five energy demand sectors are used: Electricity, heating, cooling, mobility and industry.

Energy systems can be further divided into a range of primary energy sources (before refinement, conversion or transformation into a different energy carrier or product).

The primary energy supply (PES) for OECD Europe is illustrated in Figure 3; a significant increase in total PES can be seen from 1970 to the late 2000's. This indicates that overall energy demands have increased in this period, despite the fact that some countries actually maintained a constant PES (e.g. Denmark, Finland, etc.). If this trend continues in the coming years, it might be difficult to convert to a higher share of renewable energy sources.

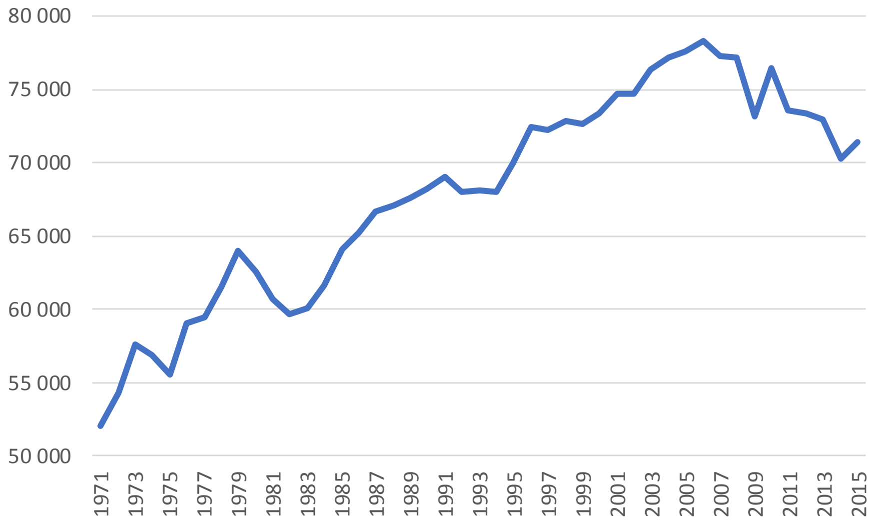

Figure 3: OECD Europe primary energy supply from 1971-2015 in PJ [23].

1.3. SOLUTIONS TO ENERGY SECTOR CHALLENGES

Numerous solutions have been proposed and debated in the past to address all or some of the challenges in the energy sector. These include, for example:

- Nuclear power [24–27]
- CCS [24,25,28,29]
- Energy demand side solutions (e.g. energy efficiency or "de-growth") [30]
- Reforming fuel subsidies [31,32] and other policies such as Clean Development Mechanisms [33]
- Using biomass for climate change mitigation [34]
- Variable renewable energy integration (such as wind and solar power) [35–38]

However, some of these solutions pose a number of problems. For example, some solutions, such as higher penetrations of nuclear power and CCS technologies, would only address a portion of the energy sector challenges, as these technologies are primarily applicable in the electricity sector. Other sectors (e.g. heating) would remain unchanged and thus still consume fossil fuels. Moreover, these solutions have not yet been proven on a scale that would justify their viability as the main technologies for supplying all energy demands. CCS technologies and future nuclear technologies, such as nuclear fission and thorium reactors, are still in the development and demonstration stages; it is unclear if and when these technologies will be ready for full commercialization. In addition, unresolved issues exist in connection with methods for handling nuclear waste.

Energy demand side solutions and the integration of biomass resources will most likely be critical for meeting several key energy sector challenges, but these solutions are limited in terms of energy potential and cost. For example, Paper 1 demonstrates how costs for heat savings increase significantly after reaching a certain threshold. Furthermore, biomass resources are scarce; Paper 5 demonstrates the challenges associated with relying on limited biomass potentials, even in energy systems with large energy savings and contributions from other renewable sources.

Variable renewable energy integration meets most of the critical energy sector challenges including security of supply, reduction of GHG emissions, energy costs and resource availability. Furthermore, numerous studies have demonstrated their potential as replacements for all fossil fuel consumption (see 0). Unlike CCS and future nuclear technologies, variable renewable energy technologies are proven technologies that have been utilized on a large scale in multiple regions around the world. Further arguments for prioritizing variable renewable energy resources (together with hydropower and smaller shares of other renewable sources) are presented in [39], which also focuses on other relevant effects such as particle emissions and safety issues related to nuclear technologies.

By combining some of these measures, such as energy demand side solutions, biomass integration and variable renewable energy, it is assumed and will be analysed whether the majority of the energy sector challenges can be addressed in future energy systems. This combination approach entails radical technological changes and results in the design of 100% renewable energy systems. This study will therefore use the framework of 100% renewable energy systems to address the energy sector challenges and further explore the previously suggested solutions.

However, a number of open questions remain regarding how exactly to design these future systems, as no 100% renewable energy systems currently exist when considering all sectors and because many different solutions have been proposed (see 0). Some of the key questions relate to:

- Which energy carriers should be prioritized in the future (electrification, hydrogen, bioenergy, etc.)?
- Which technology mix is desirable within the energy sectors?

- How should greater flexibility be created in the energy system to allow for more variable renewable energy production?
- Which changes to existing and future network infrastructures are necessary (gas, electricity and thermal grids)?
- Which energy storage types should be utilized and what role should they play in the future?
- How should energy costs be evaluated?

These questions are addressed throughout this dissertation by applying the smart energy approach and are summarized in Paper 5, which analyses an entire national energy system.

The choice awareness theory provides a perspective on how to deal with these questions and is further elaborated in Chapter 3.

1.4. RESEARCH QUESTION

Based on the energy sector challenges described above, the following research question has been formulated:

How can the analysis of technical and economic alternatives for energy systems and technologies support the design of 100% renewable energy systems?

Sub questions:

- How can choice awareness theory support the transition towards 100% renewable energy scenarios and smart energy systems?
- How influential is the energy system context and design on the development of strategies towards 100% renewable energy systems?
- How are primary energy, CO_2-emissions and socio-economic costs affected when developing concrete alternatives and technologies for this transition?

The understanding and definitions of renewable energy sources, 100% renewable energy systems and the approach for energy systems analysis used in this dissertation are described in more detail in Chapter 3.

1.4.1. LIMITATIONS AND SCOPE

The focus in this dissertation is primarily on energy system infrastructure, which includes grids and networks (electricity, gas and thermal), as well as on the technologies utilized and the fuels consumed in the energy system. Hence, the investigated energy system elements are reflected in Figure 2; solutions for e.g. extraction and refining of fuels are excluded.

This focus entails that few social aspects are considered, such as ownership structures and identifying winners and losers from further integration of renewables, even though this is a highly relevant topic.

After designing energy system infrastructure strategies, it is necessary to consider how to implement them within the context of the surrounding society. Relevant topics could include existing market conditions and democratic decision processes. This is, however, not included in the present work and should thus be a topic for future research. The redesign of markets to enable high-renewable smart energy systems has been analysed in detail in [40]. These topics are highly relevant when investigating the transition to a future 100% renewable perspective and are further explored in [41].

Further challenges might be relevant to analyse when considering 100% renewable energy systems but are not included in this study.

Finally, the geographical focus in this work is primarily on Europe, even though similar challenges exist elsewhere (see 0). For practical reasons, data and case countries are limited to a European context.

1.5. PURPOSE AND CONTRIBUTION OF DISSERTATION

The idea behind this dissertation is to condense the findings and learnings from a number of papers and contribute to the understanding of how future energy systems can be designed to achieve 100% renewable energy systems. The research question guides the approach of this work and is concretely purposed to add knowledge to the field in the following ways:

- Provide a summary of previous solutions and trends for designing 100% renewable energy systems.
- Analyse the role of concrete measures and technologies for designing high-renewable future energy systems.
- Apply the smart energy concept for creating alternatives in energy systems in cases where this has not been previously applied.
- Method development regarding the smart energy concept.
- Compare different cost evaluation methods and their importance on energy priorities.

1.6. STRUCTURE AND READING GUIDE

The overall structure of this dissertation is visualized in Figure 4.

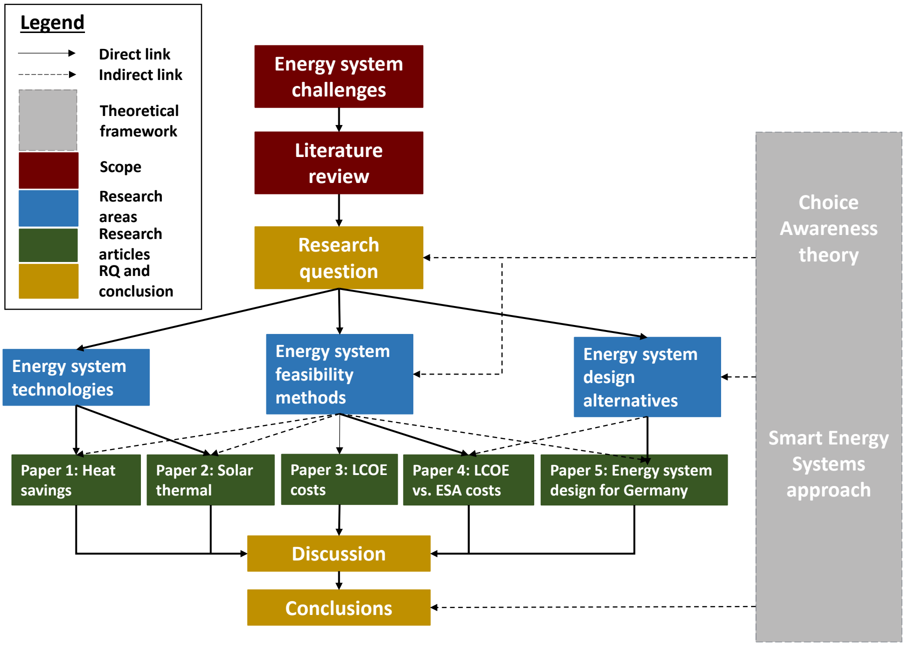

Figure 4: Overview diagram of the content in this dissertation and the relation between different chapters and sections.

This dissertation begins with a description of the main energy sector challenges and previous solutions for addressing these issues. These concepts are elaborated upon in 0 through a literature review to position this dissertation within the current literature and to further define the research question. This leads to a presentation of the theoretical framework and methodologies used for carrying out the analysis. These are described in Chapter 3, which also presents the modelling tool used. In Chapter 4, the results from the analysis of energy system technologies, energy system methods and energy system design alternatives are presented. These results are discussed and condensed in Chapter 5, which is followed by conclusions in 0. The dissertation ends with a list of references as well as an appendix containing all the publications on which this dissertation is based.

CHAPTER 2. TRENDS IN CURRENT LITERATURE

This chapter presents the literature review conducted as a part of this dissertation. The chapter begins by describing the search strategy. This is followed by an overview of the current literature within the 100% renewable energy strategies field. Finally, trends in the literature are identified and summarized. The purpose of the literature review is to position this dissertation within the appropriate research area and to identify possible knowledge gaps that should be filled in.

2.1. SEARCH STRATEGY

A concrete search strategy was developed before conducting the literature review to enhance the credibility of the review as well as to ensure that it aligns with the research question posed in this dissertation. A conventional structured subject search was used to identify possible studies for the review. In addition, elements of pearl growing strategies were applied and relevant experts were contacted.

The topic of the review is established from the main components of the research question: 100% renewable energy systems and energy system analysis.

These terms were used in a block search of selected databases as specified in Table 1 to ensure that all reviewed studies concerned 100% renewable energy systems and energy system analysis or similar variations.

Table 1: Block search terms used for the literature search.

Block 1	"100% renewable energy system*" OR "100% renewable*" OR decarbonization OR Low-carbon
	AND
Block 2	"energy system analys*" OR modelling OR scenario*

Two different search databases were used to identify peer-reviewed literature, specifically Scopus and Web of Science. Numerous other databases are available but limiting the search to these two ensured that the studies were peer-reviewed, applicable and of the highest quality. In addition, the search was limited to English language peer-reviewed articles published between 2014 until the last update of the search (June 10th, 2018). An overview of the search and selection process is illustrated in Figure 5. The searches resulted in 90 and 97 hits in Scopus and Web of Science, respectively. The two search results were combined and duplicates removed, resulting in a total of 115 hits between the two databases.

Next, a number of inclusion criteria were defined to decide whether a study was relevant to include in the review considering the research question. The inclusion criteria were:

- The study must analyse high levels of renewable energy integration or decarbonization.
- The study must apply an energy systems approach (e.g. using a tool) rather than only descriptions of technologies, etc.
- The study should focus on longer-term energy strategies towards 2050 or other time horizons.
- The study should preferably include the entire energy system but could also focus on specific energy sectors such as the electricity sector (otherwise, the majority of studies would have been excluded).
- All technologies are considered (including CCS and nuclear), even though these are not part of the research question definition. This was done to ensure that all academic trends were identified.
- Only technical analyses should be included (no policy, climate or solely economic analyses).
- Energy systems should be on at least city scale (no micro-grids or building level).
- The study should apply quantitative analysis (no solely qualitative descriptions of possible future scenarios).

After applying these criteria, the number of relevant studies was reduced to 71. In addition to those identified from the database search, a number of studies (10) were added based on suggestions from Professor Mark Z. Jacobson. Finally, (13) additional studies were included after being identified throughout the three-year period of the PhD programme. The total number of studies in the literature review thus amounted to 94.

The inclusion of studies that were not part of the database search resembles elements of pearl-growing strategies, but in an unorganized manner. Hence, it should be considered whether this enlarges bias in the literature review because these extra studies likely resemble research methods or results that are similar to the authors' own. For example, several of the additional studies (6) use the EnergyPLAN tool; these were used as inspiration when designing some of the analytical methods. However, the influence of bias is not expected to be large in this case, as this group of additional studies only amounts to 23 out of the 94 total studies included in the review. The studies from the database searches are [24,35–38,42–108], from the authors own database [109–121] and from the expert contact [25,29,122–129].

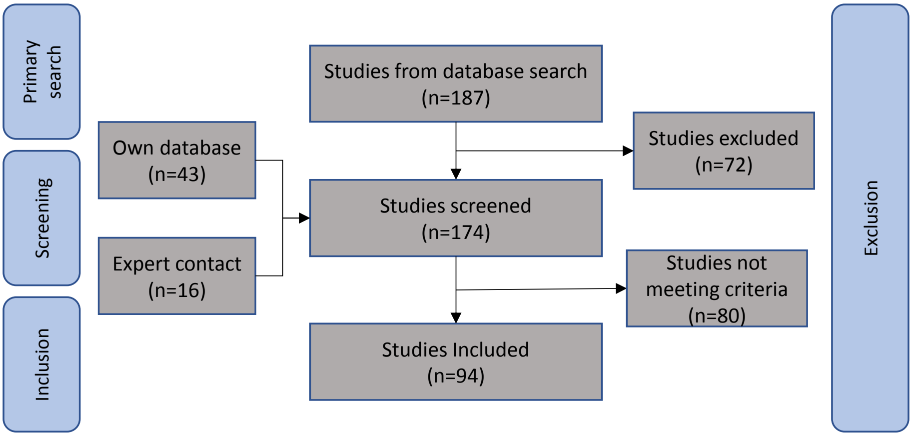

Figure 5: Illustration of the search and selection process.

Finally, a strategy was drafted to critically evaluate the studies. This strategy included a number of questions designed to ensure that sufficient and relevant information was extracted from the studies. The questions were:

- What is the purpose of the study?
- Which general methods are applied?
- Which tools (and type) are applied?
- What is the geographical scope?
- What is the temporal scope and time horizon?
- Which sectors are included?
- What are the main solutions (technologies) proposed?
- What are the main findings?

These eight questions provide the structure for the remainder of this chapter.

2.2. TENDENCIES AND TRENDS IN LITERATURE

The tendencies revealed during the literature review are presented in this section. The review showed that the 100% renewable energy systems field has been studied for several years and that many variations of energy system analysis have been applied. The general overview of the literature is provided below according to the questions used for critically reviewing the studies.

In some of the studies, it is unclear exactly what is included and excluded, for example in terms of energy sectors or the timeframe. This information has instead been deducted from the respective studies by the author, but might still represent some uncertainty regarding the review findings.

2.2.1. PURPOSE OF STUDIES

The purpose of the reviewed studies varies significantly and affects many other important parameters such as the temporal and geographical scope, the tools used and the sectors included in the analysis.

The most common purpose identified is to explore the opportunity for 100% renewable energy in a given location (global, national, regional or city). Examples of this include studies on Europe [84], Iran [42], Brazil [66], Macedonia [115], globally [114] and many more (e.g. [35,38,51,57,64,72,78,82,83,86,96,98,102,123]).

The definition of 100% renewable energy, however, differs between the studies. Some include all energy sectors, such as [83–85], whereas the majority only consider the electricity sector (e.g. [42,51,58,73,95]). This might be counterintuitive as a more appropriate term for this latter group of studies could be 100% renewable electricity systems. More information on this issue is provided in section 2.2.6.

Another common purpose in the relevant literature is to analyse the role of specific technologies or solutions in high-renewable energy systems. Some examples address various types of storages (primarily electric) [52,93] or the problems with storing energy [79]. For example, power-to-gas as a storage option is explored in [46,78,87]. Other typical solution studies include the importance and requirements of electricity transmission and distribution grids in the UK [94], Germany [54], Australia [80] and Europe [120]. In addition, the need for control reserves and balancing are analysed in a number of studies [97,125,128] as well as the flexibility requirements of the system [48,130]. The contributions to high-renewable systems from specific technologies are also analysed including from PV [61], desalination [47], demand response [75], heat pumps [131] and nuclear power in combination with thermal storage (of electricity) [126].

Other studies focus more on the energy system design and the integration of sectors rather than on the contribution of individual technologies [43,109]. They may also investigate these challenges from a technical perspective in addition to considering economic, institutional and political aspects [49]. High-renewable energy systems is the principal purpose for most studies, but might also be complemented by the goal of designing energy independent systems, in particular for smaller island systems [37,53,56,63,132]. Finally, some studies focus on solutions for sectors other than the electricity sector, such as heating [55] and transport [50,106], with particular attention given to the integration of electric vehicles [75,77,99,100].

2.2.2. METHODS

The reviewed studies employ a variety of methods based on the purpose of the analysis, the tools applied, etc.

However, some general methodological trends can be clearly identified across the majority of the studies. In 81 of the studies (86%), some form of scenarios are developed. These are used to envision and create strategies for how future energy systems might appear. In most studies, more than one scenario is developed. These often include comparisons between an existing system and a future scenario, intermediate scenarios towards a final year (e.g. 2030 and 2050 scenarios) or different alternatives for achieving the same target (high-renewable energy systems) but using different means and solutions. The scenarios provide a basis for drawing comparisons across different alternatives, leading to recommendations for future development trajectories.

Scenarios are therefore a key method for conducting energy system analysis in the context of developing 100% renewable energy systems.

A few of the studies (7 or 7%) primarily use reviews of other studies to create their recommendations. These focus on renewable energy potentials in a country (Nigeria) without assessing whether it would be possible to integrate these [60], possible energy storage technologies [46], types of flexibility and costs in 100% renewable energy systems [48], the feasibility of 100% renewable energy and the most critical barriers [49,71], transport solutions for moving away from fossil fuels [50] and the challenges associated with storing energy [79].

2.2.3. TOOLS FOR ANALYSIS

The majority of the studies take advantage of energy planning tools to either replicate an existing energy system or to describe possible future changes in an energy system. A large variety of tools were used and are classified here into two different archetypes, even though a more detailed breakdown could be done as in [133]. The two classifications are defined as optimization tools and simulation tools, see also [134] and the description in 3.7.

From the 94 reviewed studies, 75 (80%) apply some sort of energy system analysis tool. For the remaining 19 studies, either no energy system analysis tool is used, it is not described in the paper or it is unknown. The most common type of energy system analysis tool is optimization (47% of the studies) while simulation tools are used in 31% of the studies.

Within the optimization tools archetype, the most frequent tools are the TIMES/MARKAL tool (e.g. [58,78,88,104,131]), the NEMO tool used for analysis of the Australian electricity market [35,74,86,92,101] and the LUT energy system model for various regions of the world [52,57,61,67,68,72]. Other optimization tools include REMod-D [105], MRESOM [121], REMix [54,65,66,96], the R statistical environment [70], MATLAB [44,98,119], SWITCH [125], the NEWS tool [122], SEEEM [113], REFlex [126] and SILVER [75], among others.

By far, the most frequent simulation tool is the EnergyPLAN tool, which is used fully or partly in 24 studies (e.g. in [36,38,56,63,81]). Eighteen of these EnergyPLAN studies were identified as part of the database search while the remaining studies were added afterwards. Other simulation tools include the MESAP/PlaNet [59,65] and H_2RES, which combines elements of simulation and optimization [116].

A few studies also include examples of combining optimization and simulation tools in the same analysis (EnergyPLAN and TIMES) [135] and (EnergyPLAN and H_2RES) [136]. Finally, [29] presents a compilation of 18 different models used to supplement each other to form the final conclusions.

It should be noted that the type of energy system analysis tool used affects the temporal scope of the analysis, which is further discussed in section 2.2.5.

2.2.4. GEOGRAPHICAL SCOPE

The reviewed studies were grouped into four types of geographical scopes; city, sub-region (smaller than national), national and regional (larger than national).

The most frequent geographical scope addresses a national framework (Table 2). This offers the benefit of having a clearly defined boundary in terms of energy demands, economy and population. After national, larger regions are most frequently analysed along a global or continental scale or across different countries. Some studies analyse smaller regions within a country, which could be clearly defined island energy systems or regions of a country. Finally, a few studies adopt a city scope.

Table 2: Geographical scope of the 94 reviewed studies

	City	**Sub-region (smaller than national)**	**National**	**Regional (larger than national)**	**Other/un-known***
#	4	14	45	27	4
%	4%	15%	48%	29%	4%

* Other and unknown studies include testing the analysis on an IEEE test bus system and performing reviews of solutions without describing the geographical scope.

The most frequently studied country is Australia, followed by Germany, Denmark and Portugal. The review indicates that 100% renewable energy systems have been analysed for many areas of the world, with all continents (except for Antarctica) represented.

Table 3: The geographical distribution of national studies in the review.

Number of national studies	
8	Australia
4	Germany, Denmark, Portugal
3	UK, USA
2	Finland, Ireland
1	Iran, Nigeria, Saudi Arabia, India, Pakistan, Mexico, Brazil, Turkey, France, Bangladesh, Hungary, Croatia, Serbia, Macedonia, New Zealand

Figure 6 shows the distribution of studies with respect to continents. More than 40% of the studies evaluate either cities, sub-regions, countries or regions in Europe, which is clearly the most frequently studied continent. The second most common continent is Asia with 14% of the studies, followed by North America (13%) and Oceania (12%). Rather few 100% renewable energy studies have been performed for Africa (2%) or South America (1%). Some studies investigate multiple countries across continents (5%) while 7% of the studies focus on a global scale.

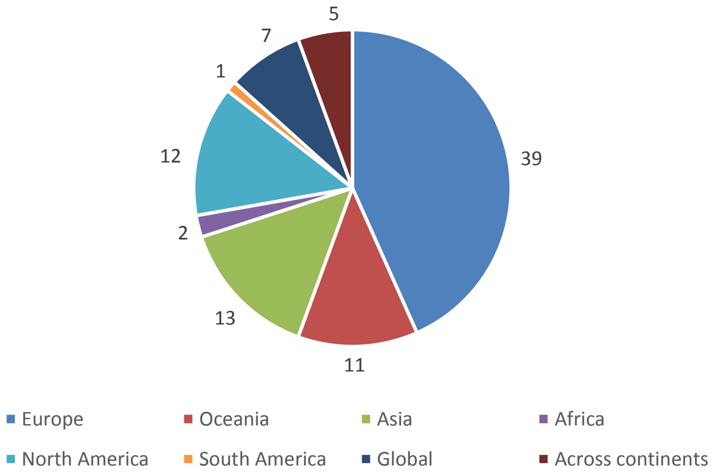

Figure 6: The geographical distribution of the studies according to continents.

2.2.5. TEMPORAL SCOPE

The temporal scope was reviewed according to two aspects: the temporal resolution of the energy system analysis tool and the time horizon applied for realizing the future energy systems.

The temporal resolution in the models typically take on a sub-hourly, hourly, annual or time slice resolution according to the study's objective and the energy system analysis tool used.

From the reviewed studies, 63 or 67% apply an annual resolution for the energy system analysis, which is by far the most common one. However, only three studies apply an annual resolution in the tool. Other tool resolutions include time slices of certain periods of the year (e.g. [90,104,123]), critical grid hours [54], sub-hourly (15/30 minutes) [53,87] or the resolution is not stated in the paper. Furthermore, papers conducting reviews and policy analysis do not use an energy system analysis tool and thus have no resolution.

The second aspect regarding the timeframe of the studies shows that the majority (42%) look towards 2050 for their energy system analysis. 2030 is also frequently used (sometimes as an intermediate step towards 2050), with 28% using 2030 as the final year. Other studies use either 2020 or 2035 as the time horizon while a number of papers do not state the year in which their solutions should be carried out. Finally, a number of studies use the existing system or a historical reference year as their timeframe to analyse whether the existing system is capable of integrating further renewable energy.

2.2.6. SECTORAL SCOPE

The studies were reviewed to determine which energy sectors they include in their energy system analysis. The five sectors are electricity, heating, cooling, transport and industry. Small uncertainties exist in categorizing the sectoral analysis of the studies as the included sectors are not always clearly stated in the papers. For example, it can be difficult to determine whether cooling is included in a study if it is not specifically mentioned, because cooling, to a large degree, is based on electricity demand and could therefore be included under this sector.

The most frequent sector included in the studies is undoubtedly the electricity sector as visualized in Figure 7. More than 90% of the studies evaluate the electricity sector. Moreover, considering that the remaining studies include compilations of multiple models focused on unspecified sectors such as the ‘buildings and transformation’ sectors [59], virtually all of the reviewed studies focus to some degree on the electricity sector. Furthermore, 60% of the studies focus exclusively on the electricity sector, going so far as to exclude the demand and supply in other sectors. The second most frequent inclusion is the heating sector, for which approximately 30% of the studies provide analysis, followed by the transport sector with a similar share of around 30%. The cooling and industrial sectors are only directly included in 16% of the studies. Only a very few studies exclude the electricity sector to focus exclusively on other sectors such as the transport sector [50,106] or the combination of the transport and industrial sectors [59].

Around 35% of the studies analyse multiple sectors (at least two sectors). When considering studies that include at least four sectors this share decreases to 20%. Therefore, a relatively small proportion of the studies consider the entire energy system (as it is defined in this work). Of the 19 studies that evaluate at least four sectors, 14 (almost 75%) apply the EnergyPLAN tool. This shows the tradition of using the EnergyPLAN tool when considering the full energy system.

Of the 56 studies that analyse only the electricity sector, 40 of these (71%) use optimization tools while only two (4%) use simulation tools [36,102]. The remaining studies either do not apply an energy system analysis tool (reviews), perform mainly policy analysis or the specifications of the tool are unknown. This indicates that optimization tools are primarily useful when conducting single-sector analyses and that studies employing them have a long tradition of including the electricity sector. It should, however, be mentioned that several optimization tools also include at least four energy sectors such as in [78].

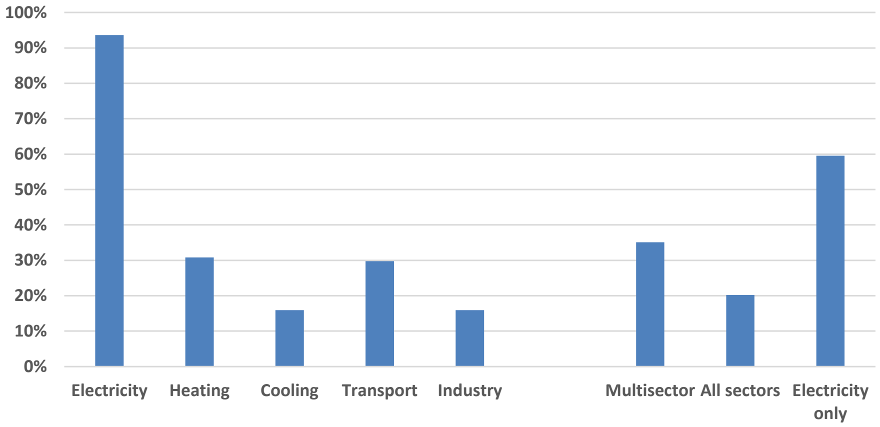

Figure 7: Sectoral scope of the 94 reviewed studies.

2.2.7. MAIN SOLUTIONS

The main solutions suggested in the reviewed studies are identified in terms of the key technologies proposed or according to the overall energy systems approach (e.g. integration of sectors).

The most commonly proposed solution is to increase the share of renewable energy sources, typically in the form of variable PV and wind generation. This is the key solution in at least eight studies [35–37,114,118,122,127,129], which attempt to identify an optimal mix of variable energy. Several more studies stress the importance of specific renewable sources such as PV [57,61,76,83,104], wind power [92] or hydropower [116]. Hence, this group of studies focuses primarily on potential supply side solutions.

Another group of studies focuses on the transmission and distribution grids (and the expansion of such grids) to provide better conditions for integrating renewable energy [94,96,102,120,123]. Some even use the term supergrids as a key solution [82,95]. The inclusion of grid costs within the heating and electricity sectors are also analysed in terms of their impact on total energy system costs [54,55]. Finally, some studies emphasize technical grid operation aspects such as control reserve requirements [97].

Another key solution to high-renewable energy systems is the expansion of energy storages [42,46,52,62,79,93,115,121,125], especially electricity storages designed to use the stored energy as electricity (rather than transfer it to another sector). Another proposition is to use electricity storages to enhance the operation of nuclear power plants [126]. This solution is intended to enable higher penetrations of renewable energy and reduce losses in the system.

The integration of energy sectors is also fundamental in a number of studies. Rather than relying on single technologies, this approach emphasises inter-sector connections to achieve high-renewable energy systems [38,43,63,65,66,84,85,109]. Within this category, a few authors point to Power-to-gas technologies as a key solution for the integration of energy sectors and storage purposes [78,87]. Some of these studies use aspects of the smart energy systems approach as described in section 3.5.

Other studies highlight the need to electrify the energy system in general [25] and in particular the transport sector through the integration of electric vehicles [50,59,99,100]. Indirectly, this could also be considered the main argument in studies that suggest hydrogen generation as a means of increasing renewable energy shares [56], for example by implementing fuel cell vehicles [77] or producing synthetic fuels [106].

Another key element in the literature is to increase overall system flexibility [88], for example via load shifting solutions [119] or by highlighting the importance of flexible thermal power plants when integrating more wind power [112].

A limited number of studies underline the significance of the heating sector by proposing the substantial integration of heat pumps [89], expanding district heating network [81,117] or utilizing waste-to-energy and CHP plants [108]. However, solutions that focus on the heating sector are much less common than those geared towards the electricity sector.

While much of the relevant literature focuses on either supply side measures, such as integrating large shares of variable renewable energy, or utilizing more efficient technologies, such as electric vehicles or storages, only a few studies also stress the importance of altering energy demands. This is the case in e.g. [103,105,109], where energy savings are seen as crucial in combination with other measures such as storages, flexible demands and integrating additional renewable sources.

Finally, a small number of studies demonstrate the significance of certain technologies such as CCS for reducing emissions to the atmosphere [101], the combination of CCS and nuclear energy [24] or CCS and bioenergy [29].

In summary, most studies focus either on supply side solutions, such as renewable energy generation, or on improving the system’s transformation and storage technologies. Furthermore, most solutions are directly related to the electricity sector as also concluded in section 2.2.6. Only a few studies have their main emphasis on demand side changes such as energy savings in e.g. the electricity and heating sectors. However, according to the smart energy systems approach as described in section 3.5, all three aspects (supply, savings and transformation/storage) are crucial. For this reason, several of the associated papers address one or more of these topics: Paper 1 deals with energy savings, Paper 2 investigates supply side changes through renewable generation and Paper 5 investigates all three aspects.

2.2.8. MAIN FINDINGS

The main findings of the literature review are summarized in Table 4 according to the sectors included, the level of renewable energy penetration and the effects on energy costs. Not all of the reviewed studies are included in Table 4 because some examine a specific technology and its associated effects rather than considering the total energy system.

The main findings shown here only relate to the technical feasibility aspect of the energy system analyses and do not consider issues related to e.g. implementation, politics or institutional feasibility. Moreover, considerations of how the energy system analysis tools model grid constraints are not included.

The main findings show that high-renewable energy systems have been demonstrated by a number of studies on the electricity sector. Four studies estimate cost levels similar to those in the alternative scenarios while one study finds that the costs will increase with higher renewable energy penetration.

With respect to the electricity sector, at least 38 studies demonstrate that 100% renewable electricity systems can be designed. The contexts in these studies differ in terms of climate, size of the system, mix of renewables and whether it is for islands, countries or globally. Some of these studies also consider the effect on energy costs as eight of the 38 studies estimate that costs will remain at the same level or change slightly compared to the alternatives when transitioning to a 100% renewable electricity sector. Moreover, six studies (notice that a number of these are by the same authors) estimate that costs will decrease compared to the alternatives in a 100% renewable electricity sector. Conversely, five studies find that energy costs will increase in a 100% renewable electricity system, ranging from unacceptably high capital costs to cost increases of above 30%. One study concludes that 100% renewable electricity systems are unlikely to be achieved.

One study demonstrates how a transition to 100% renewable energy could be designed in the transport sector.

When considering multiple energy system sectors (two or more), four studies demonstrate how this transition might occur in different locations. In addition, two studies estimate that 100% renewable energy in multiple sectors will have a limited effect on overall energy system costs compared to alternative scenarios.

Finally, 12 studies demonstrate that it is possible to design 100% renewable energy systems including at least four sectors. Five studies find that no significant changes to energy costs will occur from this transition, while two estimate that costs will decrease. Conversely, one study finds that costs will increase by 10-15% due to the transition to 100% renewable energy when considering the entire energy system.

Table 4: Main findings according to sectors included, level of renewable energy penetration and the effects on energy costs.

Sectors included	**Finding**	**Studies/geographical scope**
Electricity only	High-RES demonstrated	85% RES Western Electricity Coordinating Council (USA, Canada, Mexico) [125], max 74% RES possible in California [25], 80% RES Croatia [111]
	High-RES and low/same costs	50% RES Zagreb, Croatia [43], 90% RES South West Interconnected System in Western Australia [74], 80% RES USA [122]
	High-RES and higher costs	Australia (costs of electricity systems are likely to increase approximately linearly as the RES share grows from zero to 80%) [86]
	100% RES demonstrated	Iran [42], Nigeria [60], Sub-Saharan Africa [45], Java-Bali [51], Australia [68], South west of Western Australia [73], Nordic Countries [78], Rhineland-Palatinate, Germany [87], Wang-An Island, Taiwan [37], Germany and Europe together with North Africa (if large storages are constructed) [96], Southwest, South Central, and Southeast regions of the United States [98], Portugal [102,116], New Zealand [119], Globally [121], PJM (Eastern USA) [129], review of multiple countries [48,49]
	100% RES and low/same costs as alternatives	Australia [35,92], India [52], Pakistan [57], Turkey [72], Ontario, Canada [75], Bangladesh [104], EU-27 + MENA (at moderate costs) [123]
	100% RES and lower costs than alternatives	North-East Asia [82,95], South and Central America [76], Southeast Asia and the Pacific Rim [67], SAARC (South Asian Association for Regional Cooperation) [69], Australia [101]

	100% RES and higher costs	Reunion Island (for transport costs) [58], Australia (100% renewable power supply is not likely to be achievable at an acceptable capital cost) [79], Australia (100% renewable system to meet Australian energy demand would involve costs that would probably constitute an unacceptably large fraction of GDP) [80], France (additional overall cost of integrating RES is assessed at 30%) [88], Australia (nuclear scenario has lower costs) [24] Europe (increase of between 11% and 44% compared to the total system costs when no CO_2 reduction targets) [124]
	100% RES not possible	No convincing evidence that 100% RES is possible [71]
Transport only	100% RES demonstrated	Global [50]
For multiple sectors (two or more)	100% RES demonstrated	Portugal [99], Dubrovnik region, Croatia [100], South West Region of Ireland [108], Beijing, China [81]
	100% RES and low/same costs as alternatives	Brazil [66], Germany [105]
For four sectors or more	100% RES demonstrated	Åland island [63], UK [103], Macedonia [115], Ireland [117]
	100% RES and low/same costs as alternatives	Finland [83], La Gomera [56], Ireland [38], Denmark [109], Global [114]
	100% RES and lower	South East Europe [85], Washington State [118]

	costs than alternatives	
	100% RES and higher costs	EU (10–15% higher than a business-as-usual scenario) [84]

In summary, a large number of studies (38 or more) demonstrate that it is possible to design a future 100% renewable electricity sector, though with varying effects on the energy costs. Additionally, six studies demonstrate that renewable energy penetrations of 100% are achievable in multiple energy sectors, while 12 studies demonstrate the feasibility of 100% renewable energy systems for at least four sectors. A limited number of studies fail to demonstrate the feasibility of very high levels of renewable energy in at least one of the energy sectors. However, the economic consequences of the transition to high-renewable energy systems are uncertain according to the literature, with some studies indicating cost levels that are similar to the alternatives, while other studies find either decreasing or increasing cost levels.

2.2.9. OTHER TRENDS

Another trend worth mentioning is the growing number of studies researching 100% renewable energy analysis. Figure 8 shows the number of reviewed studies found via the database search according to the year of publication. A clear trend can be seen showing an increasing amount of publications in this area in recent years.

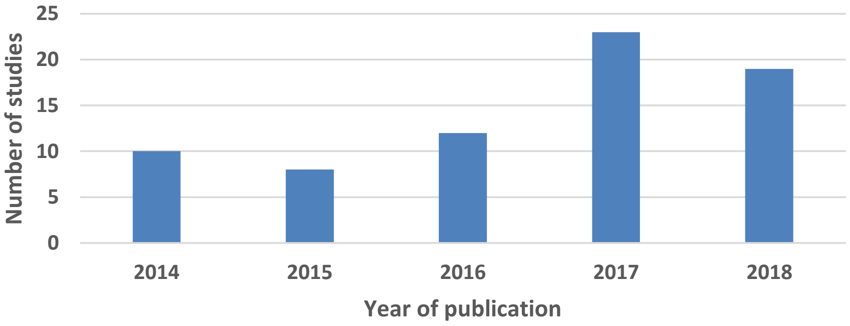

Figure 8: Reviewed studies from the database search according to the year of publication. Note that only studies published in the first half of 2018 are included.

2.3. POSITIONING THIS DISSERTATION IN THE LITERATURE

This section describes how this dissertation is positioned in relation to the literature. This is discussed with respect to the type of methods and energy system analysis tool used, as well as its scope and main solutions. The main findings' relations to the existing literature are discussed in Chapter 5.

This dissertation contains analysis of individual technologies and solutions as well as full energy system design alternatives. Both of these types of analysis are common in the literature, but this dissertation covers different topics. For example, the literature review did not find any studies focusing on solar thermal for heating purposes (Paper 2), especially in the context of a high-renewable energy system. Furthermore, few studies focus on the importance of energy savings as analysed in Paper 1.

The most common methodology in the literature is the development of scenarios based on energy system analysis. This method is also heavily applied in this dissertation. However, most energy system analysis tools in the literature use an optimization framework designed to find optimal solutions to an objective function. This differs from the approach in this dissertation where a simulation methodology is used for creating a range of alternatives. The most common simulation tool in the literature is the EnergyPLAN tool and this is also selected for the analysis here.

The geographical scope of this dissertation is primarily on European national energy systems, which corresponds with the dominating trend in literature. Moreover, most studies apply an hourly resolution for their energy system analysis with only few analyses based on either annual or sub-hourly modelling, which also corresponds to the methods in this dissertation. On the other hand, this dissertation adopts a more inclusive sectoral scope than is common in the literature. While this dissertation includes all energy sectors, as suggested by its theoretical framework, the majority of the reviewed studies focus primarily or solely on the electricity sector with only a few including multiple or all sectors. Furthermore, this dissertation applies its all-sector scope to national energy systems for which this type of analysis has not been previously performed (Germany, Italy and Austria).

With respect to the main solutions proposed, a large share of the studies focus either on supply side solutions, such as the integration of high shares of renewable energy, or on improving system efficiency (conversion, exchange and storage elements) through the implementation of (electricity) storages, electrification, enhanced flexibility or integrating sectors. Only a few studies focus on energy savings and changes to energy sector demands. In this dissertation, the main solutions include all of these aspects, as analysed in Paper 5, in which the smart energy systems approach is applied to a national energy system.

Finally, some studies focus on specific solutions for high-renewable energy systems such as interconnectors and transmission grids related to electricity and electricity storages. Likewise, a few other studies propose using technologies such as nuclear power and CCS as key solutions for decarbonization. These types of solutions are not analysed in great detail in this dissertation.

CHAPTER 3. THEORY AND METHODS

This chapter describes the theoretical framework of the dissertation as well as key methods that have been applied. First, the definition of 100% renewable energy systems is provided followed by a description of the choice awareness theory and the smart energy systems concept. Finally, the energy system analysis tool is presented along with the evaluation factors that are used in the analyses.

3.1. THE CONCEPT OF 100% RENEWABLE ENERGY SYSTEMS

This dissertation is about 100% renewable energy systems, but this concept can be defined and interpreted in numerous ways. This section defines the notion as applied in this dissertation and reflects on how it differs from other related concepts such as sustainable energy and decarbonization.

Renewable energy in this work is defined as:
"[...] energy that is produced by natural resources – such as sunlight, wind, rain, waves, tides and geothermal heat – that are naturally replenished within a time span of a few years." [137][1].

Concretely, using this definition the renewable natural resources are:

- Wave, wind, tidal and hydropower
- Solar power, solar thermal and geothermal
- Biomass and biofuels
- Renewable fraction of waste

This definition is slightly different from that used in connection with the work on the IPCC fifth assessment report on energy systems, which posits that some renewable resources may be extracted at rates that exceed the natural rate of replenishment[2].

"[...] renewable energy (RE) is defined [...] to include bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy." [138][3].

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[1] Page 8

[2] "Note that, in practice, the renewable energy sources as defined here are sometimes extracted at a rate that exceeds the natural rate of replenishment (e.g., some forms of biomass and geothermal energy). Most, but not all, renewable energy sources impose smaller GHG burdens than do fossil fuels when providing similar energy services." [138]

[3] Page 525

It is also essential to understand that renewable energy sources can be classified in various ways with respect to their production profiles and impacts on local environments. For example, renewable energy sources can be divided into dispatchable or non-dispatchable resources depending on their ability to regulate production according to demand patterns. Dispatchable resources include hydropower and thermal plants based on renewable sources, while non-dispatchable resources include wind and solar power, which have no ability to regulate their production and only produce energy when there is wind or sunlight. Furthermore, some renewable sources, such as bioenergy, emit particles and greenhouse gases during combustion that might affect the local environment. For this reason, some researchers exclude all sources that require combustion (i.e. biomass) from strategies for converting to 100% renewable energy systems and instead primarily rely on wind, water and solar resources [39,139].

The 100% renewable energy definition adopted in this dissertation is concerned with the complete conversion of a system, i.e. no compensation or offsetting is allowed from exporting renewable energy to replace non-renewable fuels elsewhere. Examples of 100% renewable energy systems do exist, but only due to an excess production of renewable electricity, which is exported to other systems to offset the use of non-renewable sources [140]. In this manner, fossil fuels can continue to be consumed in e.g. the transport and industry sectors to create a “gross” 100% renewable system. However, this is problematic in a future with higher global shares of renewable energy, because it will be less feasible to offset non-renewable sources in one system by exporting renewable energy to another.

Policies might also refer to the term sustainable energy systems. Sustainable energy can be defined as: “energy sources that are not expected to be depleted in a time frame relevant to the human race” [137][4]. There are some clear differences between this and the renewable energy definition, most concretely in the inclusion of nuclear energy. It can be debated whether nuclear energy, which relies on scarce uranium resources, is sustainable within the stated time frame [137]. Likewise, discussions about carbon capture and storage (CCS) are relevant within the context of sustainability, as this technology allows for the continued burning of fossil fuels.

Other terms, such as decarbonization, low-carbon and carbon neutral objectives, might also include aspects of the renewable energy definition. These have a primary focus on carbon (CO_2-emissions) due to its associated climate and environmental degradation, which are key objectives in many political agreements. However, if the sole focus is on carbon emissions then a number of other relevant aspects in renewable energy systems are neglected. These include, among others, security of supply regarding the exchange of energy and resources to ensure that energy is available when required, which can be disrupted for geopolitical reasons, external events, etc.

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[4] Page 11

Other aspects are health impacts, job creation from increased capital investments instead of fuel costs, influence on ownership structures and democracy through decentralization, risk of proliferation, accidents and waste disposal (nuclear energy) and perhaps most importantly, the overall energy system economy. Additional benefits when considering a renewable energy system perspective might relate to energy efficiency, technological innovation, industrial innovation, rural development and balance of payment [137].

Due to the multitude of implied meanings in these seemingly related concepts, it is imperative to understand that the terms used when formalizing policy objectives influence the technologies that will be integrated in future energy systems.

A prime example of this is related to the development of Danish energy policy over the last 3-5 years, during which time the ruling government has changed. Prior to 2015, the policy objective was to become 100% renewable by 2050, including all sectors [141]. However, after the 2015 election, this objective was changed into becoming a fossil-independent energy system by 2050 [142]. These might sound like similar objectives, but they vary considerably in the ways they are measured. Under the previous 100% renewable energy objective, no fossil fuel consumption would be allowed in the Danish energy system. In the fossil-free interpretation, however, fossil fuel consumption is permitted, as long as Denmark produces and exports enough renewable energy (wind and solar power) to displace a similar amount of fossil fuels in other countries. This will significantly influence the design of Denmark's future energy system and emphasizes the immense importance of policy terminology.

To summarize, a number of concepts influence the design of future energy systems and the types of technologies that will be employed. Even within the different conceptual branches, there is no clear consensus as to what each term implies, and it is therefore necessary to clearly define how these terms are used and understood in each case.

3.2. CHOICE AWARENESS

This section contains a description of the choice awareness theory and the smart energy systems concept, which are used as a foundation for the analysis in this dissertation. A discussion of how this theory influenced the analytical methods and results are outlined in Chapter 5.

This section is based on the description and development of the choice awareness theory as explained in [137], in which further details are available.

The choice awareness theory deals with how to implement radical technological changes in the future. These are changes in technology, including organizational and institutional changes, and one example is the transition from fossil and nuclear based energy systems to renewable energy systems. Technologies are defined as the elements of technique, knowledge, organization and product. The technological changes qualify as radical when more than one of these dimensions changes.

As the name implies, the theory is concerned with the notion of choices and introduces terminology for different types of choices. The first type are true choices, where two or more real alternatives exist; the second are false choices, where choice is some sort of illusion. These notions are used to assess whether alternatives are developed in relation to a decision-making process or not. Furthermore, choices exist at both the individual and the societal level. Choice awareness theory primarily deals with the societal perspective, which entails many organizations and individuals rather than focusing on private entities or businesses. The societal level is inspired by other theories, such as discourse theory, and is also referred to as a collective perception.

Choice awareness theory has two different theses:

The first thesis of choice awareness says that existing organizations will work to maintain the current situation. This may result in situations devoid of actual choice, where society is presented with only one viable option. Existing organizations and institutions are often motivated to hinder radical technological change in order to avoid losing power and influence. For this reason, a number of choice-eliminating mechanisms exist to ensure that either no alternatives are presented or that existing organizations and institutions maintain their current power and influence in any future systems. Some mechanisms involve eliminating choices in the public debate and collective perception by disregarding alternatives, claiming that alternatives are based on incorrect data or by using generic arguments related to e.g. national security. An example of the latter mechanism can be found when examining CCS solutions. Some argue that this type of solution would meet environmental objectives, but it would not require radical technological changes, nor would it shift power away from existing organizations.

Ownership structures are crucial when discussing the transition to renewable energy as existing organizations will promote solutions and technologies that fit with the existing institutions. Alternatives involving new ownership structures and institutions require new organizations to be promoted and constructed, but these have less financial and political capital in the existing context. Existing organizations will, in many cases, not perceive radical technological changes as a viable option. Existing technologies are well represented in the democratic decision-making infrastructure, while potential future technologies are poorly represented.

The second thesis of choice awareness is about raising awareness within society that alternatives do exist and that it is possible to make a choice. The solution is to develop strategies for the design of technical alternatives, feasibility studies and public regulation to emphasize that there is a choice. These strategies also reflect certain research methodologies and can be divided into a number of steps:

1. Technical alternatives

The technical alternatives strategy is crucial for putting forward and promoting concrete alternatives to the given “status-quo” solution. This strategy allows for the direct comparison of alternatives and ensures that a choice does indeed exist. The evaluated alternatives often relate to certain political goals. When developing a range of alternatives, discussions often become more complex than when discussing a single solution as the only option. Some guidelines for developing alternatives are that they must be designed so that they are equally comparable in terms of the central parameters (e.g. capacity and production). Furthermore, elements of all three aspects of renewable energy systems should be involved (demands, efficiency improvements and RES sources). Finally, the alternatives should be designed in such a way that the direct costs correspond to those of the main proposal.

2. Economic feasibility studies

The second step addresses feasibility studies, specifically in terms of raising awareness of how feasibility studies are and should be carried out. Feasibility studies should evaluate social, environmental and economic costs; the innovative potential of alternatives; institutional conditions that influence implementation and the socioeconomic effects. Feasibility studies should be designed so they can identify opportunities to benefit both the environment and the economy and a process for outlining institutional policies necessary to implement such benefits should be built in.

3. Public regulation

The public regulation step deals with defining the context in which the alternatives should be implemented. An important aspect involves the prevailing market conditions, specifically whether implementation is discussed in the context of a real market or a free market (see more in [137]). Other aspects that deserve debate are the suggested alternatives’ impacts on businesses as well as their socio-economical effect.

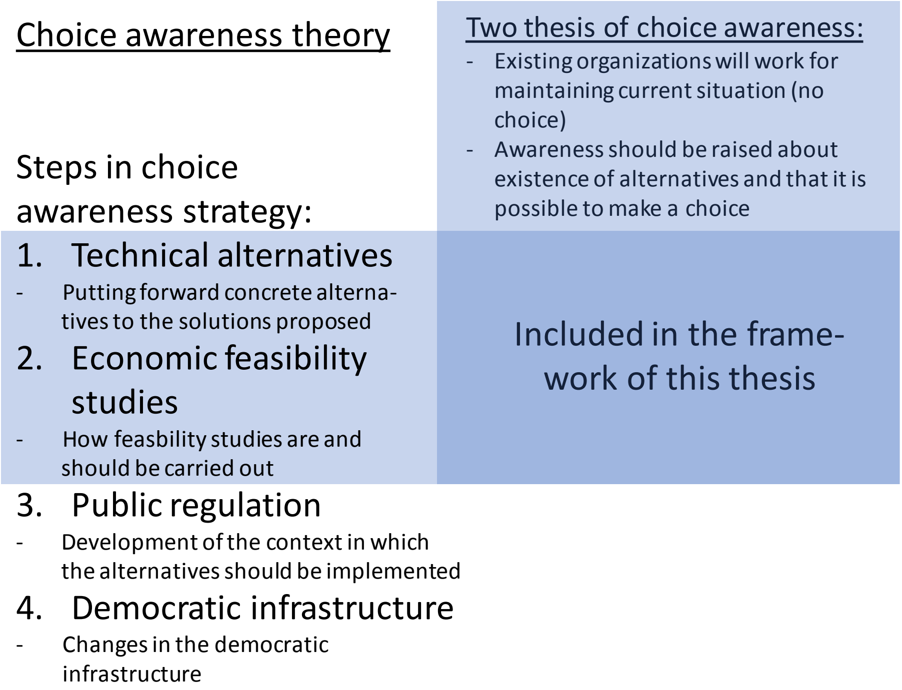
In feasibility studies, it should be possible to perform a technical sensibility analysis (links between economics of a project and future technological changes), an institutional sensibility analysis (what if market conditions change) and a political sensibility analysis (who has the motivation to “kill” newcomer technologies).

4. Democratic infrastructure

Changes in the democratic infrastructure may be the key to success for the other three strategies (technical alternatives, feasibility studies, public regulation). Typical questions in this phase involve who should carry out all the necessary initiatives.

3.3. APPLICATION OF CHOICE AWARENESS THEORY

In this dissertation, the choice awareness theory has been applied as the principal perspective for designing the analysis and strategies.



Choice awareness theory

Two thesis of choice awareness:

- Existing organizations will work for maintaining current situation (no choice)
- Awareness should be raised about existence of alternatives and that it is possible to make a choice

Steps in choice awareness strategy:

1. Technical alternatives
   - Putting forward concrete alternatives to the solutions proposed
2. Economic feasibility studies
   - How feasbility studies are and should be carried out
3. Public regulation
   - Development of the context in which the alternatives should be implemented
4. Democratic infrastructure
   - Changes in the democratic infrastructure

Included in the framework of this thesis

Figure 9: The choice awareness steps and the parts included in this study.

The main objective of choice awareness theory is to raise awareness about alternatives and methodologies. This can be seen in Papers 1-5, which all put forth alternative solutions for various technologies, methods or strategies for designing renewable energy systems. The emphasis in the present analysis and the related papers are on steps 1 and 2, which involve designing concrete technical alternatives and evaluating the economic effects of transitioning towards renewable energy systems. Less emphasis is placed on steps 3 and 4, which address public regulation and democratic infrastructure as illustrated in Figure 9.

This analysis applies feasibility studies to compare alternatives from a societal perspective in order to identify recommendable solutions and strategies. These comparisons are primarily based on energy costs, but also include effects on other evaluation factors (see section 3.8).

Concrete technical alternatives and related analyses are presented in Papers 1, 2 and 5 for individual measures and technologies as well as for an entire smart energy system design for a national energy system. Papers 1 and 2 analyse the economic feasibility of the concrete technologies and measures that are part of an overall transition towards 100% renewable energy systems. In these analyses, the individual measures are investigated in the framework of the entire energy system to identify their feasibility from a full energy system perspective, rather than solely as an individual technology.

Papers 3 and 4 deal with methodologies for conducting economic feasibility studies as no consensus on this currently exists. Concretely, two methods are compared and analysed to identify their effects on ensuing recommendations and strategies.

Further reflections about choice awareness theory and how it has been applied in this analysis are included in the discussion in Chapter 5.

3.4. SMART ENERGY SYSTEMS

The concept of smart energy systems is used as an overall framework for the work carried out in this dissertation. It is linked to the choice awareness strategy regarding designing and comparing alternatives and involves the evaluation of costs related to both the environment and social impacts.

The key feature of the smart energy system perspective is that it includes all aspects of an energy system when discussing infrastructure designs and the operation of future energy systems. The smart energy systems approach results in the most effective and lowest cost solutions when compared to other solutions, such as smart grids, which focus only on the electricity sector. In future renewable energy systems, technologies will influence one another as well as other sectors across the energy system. Therefore, it is imperative to apply this full perspective on the energy system [137].

The smart energy systems perspective is intended to aid in the design of alternatives for 100% renewable energy systems with a focus on a range of evaluation factors.

> *"Smart energy systems are defined as an approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system"* [137][5].

The smart energy systems concept focuses on three types of grids in a future energy system: electricity, thermal and gas.

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[5] Page 139

The smart electricity grid of the future will be supplied by a higher proportion of variable renewable sources, such as wind and solar power, which may present a challenge when it comes to balancing the grid. The smart grid terminology is used for many future electricity systems, but no common definition exists. Despite this lack of consensus, many definitions state that ICT (Information and communication technologies) plays a key role in integrating users and generators. The smart electricity grid is solely concerned with the electricity grid and the users and suppliers connected to this network.

"Smart electricity grids are defined as electricity infrastructures that can intelligently integrate the actions of all users connected to them – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic, and secure electricity supplies" [137][6].

Smart thermal grids concern district heating and cooling networks that distribute heating and cooling through a piping network, typically in areas with high thermal densities. These thermal grids are able to utilize and integrate a range of energy sources, some of which would otherwise be wasted, in order to ensure that future energy systems can fully rely on sustainable resources. These energy sources include CHP production; excess heating from industries, waste incineration plants and refineries; solar heating and geothermal as well as large heat pumps and electric boilers. Smart cooling grids can either be supplied by heating, which is then converted to cooling in individual buildings by an absorption unit, or through a centralized cooling network that harvests cold from rivers, seas or chiller units.

"Smart thermal grids are defined as a network of pipes connecting the buildings in a neighbourhood, town center, or whole city, so that they can be served from centralized plants as well as from a number of distributed heating and cooling production units including individual contributions from the connected buildings" [137][7].

Smart gas grids of the future face the challenge of converting from fossil-based natural gas to renewable gasses based on biomass or some sort of biogas or synthetic fuel. This should be seen in relation to an enhanced integration with the other grids, where electricity is used to a larger degree for producing renewable gasses (power-to-gas) and for reducing the dependence on scarce biomass resources.

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[6] Page 134

[7] Page 136

"Smart gas grids are defined as gas infrastructures that can intelligently integrate the actions of all users connected to it – suppliers, consumers, and those that do both – in order to efficiently deliver sustainable, economic, and secure gas supplies and storage" [137][8].

These grids are crucial for distributing and storing energy in various ways and integrating these networks is imperative as described further in section 4.3. All three grids have an important role to play when converting to 100% renewable energy systems.

3.5. APPLICATION OF SMART ENERGY SYSTEMS APPROACH

The smart energy systems approach is used as an overall framework for the analysis in this dissertation. Figure 10 illustrates the elements in a smart energy system, including resources, conversion, exchange and storage technologies as well as demands. These elements all have a role to play if the ambition of 100% renewable energy systems is to be achieved. Notice that some of the elements in Figure 10 differ from those shown in Figure 2. This is because fossil fuels and nuclear energy should be replaced by renewable sources, while a few new technologies (e.g. electric vehicles) are introduced to the system as well.

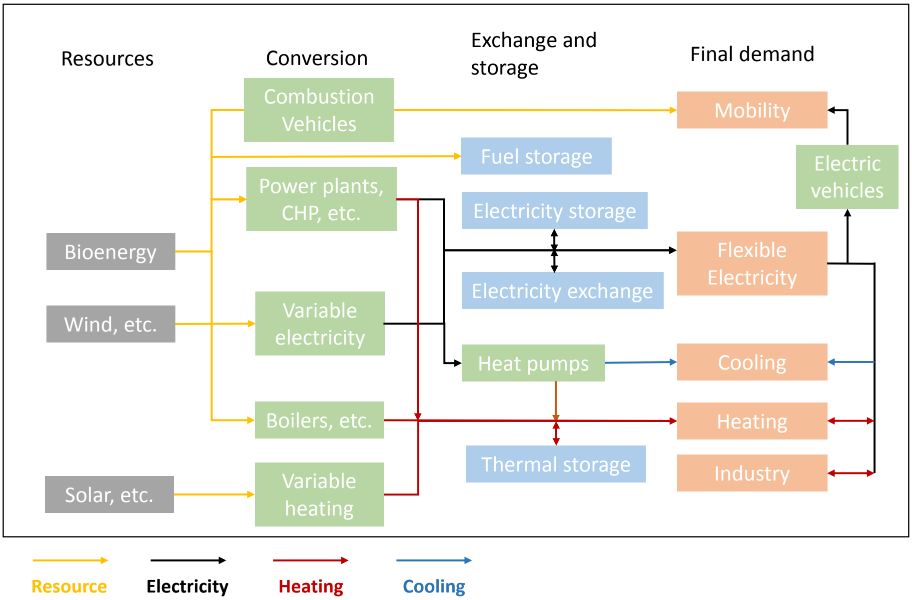

Figure 10: Elements in a smart energy system.

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[8] Page 137

In smart energy systems, three types of measures are necessary to achieve a 100% renewable energy system. They can be grouped as follows:

- Changes on the demand side

These measures are concerned with the demand for energy. In particular, end consumers must reduce their demand for heating, cooling, transportation, etc. These changes are placed under the “final demand” elements in Figure 10. By reducing these demands, less energy production is required, thereby also reducing energy losses associated with producing energy (e.g. ~60% loss of energy when producing electricity at a condensing power plant). Typical measures within this category include building refurbishments, improvements in technology efficiencies (e.g. in industries) or reductions in mobility demands.

- Changes to system efficiency

This category is concerned with the organization and design of the energy system in order to enhance overall system efficiency. These measures do not adjust final demands or energy production, but rather change how the system “in between” these two end points is designed. These changes are placed under “Conversion” and “Exchange and storage” technologies in Figure 10. Typical measures could include the integration of heat pumps, CHP plants, energy storages or electrical vehicles to deliver similar energy services as found in traditional systems, but at a higher efficiency, thereby reducing overall primary energy consumption in the energy system.

- Changes to resources and production technologies

The final category addresses how energy is produced and the types of energy resources that are consumed. These measures often involve converting from fossil sources to renewable sources and are placed under the “resources” elements in Figure 10. Typical actions include the integration of further renewable electricity sources, such as wind, solar power and biomass technologies, as well as renewable thermal sources such as solar thermal and geothermal.

Measures must be taken in all three categories to achieve a future 100% renewable energy system. For example, improving system efficiency is necessary to enhance system flexibility, which then allows for the integration of larger amounts of variable renewable electricity and heating sources. In addition, demand side adjustments are required to ensure that primary energy consumption remains within the limits of available sustainable resource potentials and to ensure least cost systems. Examples of analyses using these three types of measures are presented in Chapter 4.

3.6. ENERGY SYSTEM ANALYSIS TOOL

The purpose of this dissertation is to design alternatives for technologies, methods and system integration pathways for smart energy systems. However, energy systems are complex and consist of multiple inputs and outputs that influence each other. For this reason, it is necessary to apply an energy system analysis tool to identify and quantify the impacts of the different alternatives. Energy modelling can, in many cases, identify key trends that are not intuitively evident in the energy sector.

The criteria for an energy system analysis tool to be effective within the context of the research question are as follows:

- The tool should be able to model the entire energy system (smart energy systems approach), including electricity, heating (individual and district heating), cooling, transport and industry.
- The tool should be able to model energy systems in high resolution due to the increase in variable renewable sources.
- The tool should be able to quantify impacts according to both environmental and economic parameters (smart energy systems approach).
- The tool should be able to model all technologies that could be present in a 100% renewable energy system (radical technological changes).
- The tool should be able to develop a high number of alternative scenarios within given time and resource constraints.
- The tool should be able to model energy systems on a national scale.
- The tool should provide replicability for results to be scrutinized.

One energy system analysis tool that meets all of these criteria is the EnergyPLAN tool. This tool is based on a high-resolution (hourly), full energy system approach and enables the modelling of scenarios with radical technological changes on a country level. Other well-known tools do not meet all of the above criteria. The MARKAL/TIMES model, for example, does not operate on an hourly resolution, HOMER only includes the electricity sector and EnergyPRO is more suited for optimizing local or single plant systems. Numerous energy system analysis tools are available (see e.g. [71,133] and 0), but EnergyPLAN is the only tool that meets all the stated criteria. The EnergyPLAN tool is therefore selected to conduct the energy system analysis in this dissertation.

3.7. DESCRIPTION OF THE ENERGYPLAN TOOL

The EnergyPLAN tool is a deterministic input-output tool assisting in the design of energy system strategies and investments by simulating a complete energy system hour-by-hour for one full year. It has been continuously developed by the Sustainable Energy Planning research group at Aalborg University since 1999 and has more than 10,000 users in over 100 countries. It is publicly available as freeware from [143], where extensive documentation, training exercises and case studies are available to ensure transparency regarding the model. It is possible to scrutinize models developed in EnergyPLAN by accessing and replicating the models via the webpage.

The tool is deterministic in the sense that similar inputs will always generate the same outputs, unlike other approaches such as Monte Carlo methods. The model is based on inputs into a number of categories, such as production capacities, efficiencies and costs, along with hourly demand and production profiles. In addition, energy system costs are specified as investments, operation and maintenance, electricity exchange, fuel costs and CO_2 costs. The inputs are aggregated for the entire system, so details are not included for individual plants or consumers. This also means that outputs are presented for the entire energy system; as such, local details should be investigated further in subsequent analyses. In addition, there are no geographical details regarding the location of plants and consumers, which are aggregated for the entire energy system (e.g. a country). Furthermore, EnergyPLAN models energy grids (electricity, thermal and gas) as copperplate grids, with no internal constraints for congestion, bottlenecks, etc. This should be considered when analysing scenarios with high shares of variable renewable sources, which might challenge future grid infrastructures.

A full overview of input and output categories is displayed in Figure 11 along with the possible distribution data files and regulation strategies.

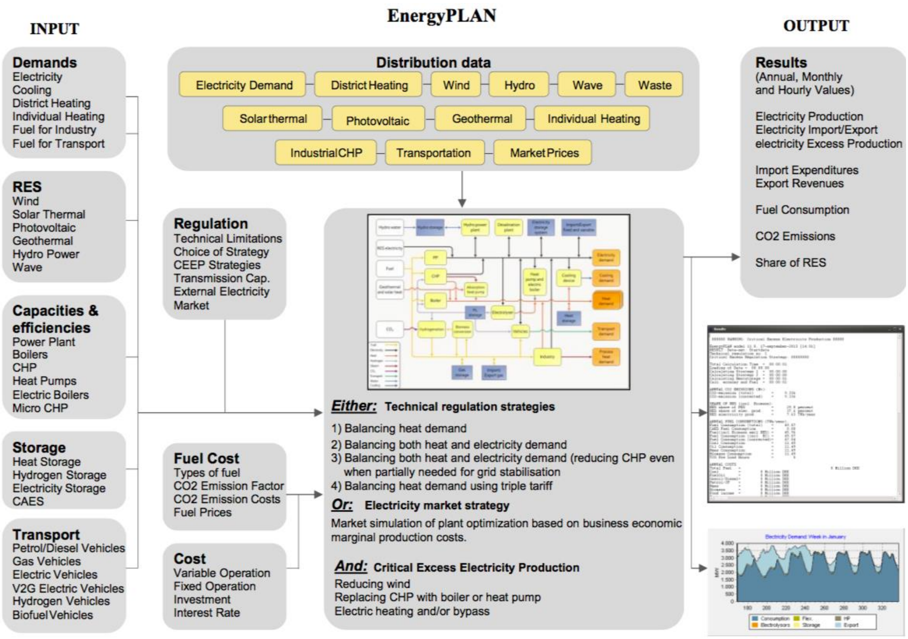

Figure 11: The inputs and outputs in EnergyPLAN as well as possible distribution data and regulation strategies.

In general, energy system analysis tools can be categorized within two archetypes; optimization tools and simulation tools.

Optimization tools are designed to perform investment optimizations of an energy system to find the optimal solution given an objective function and system constraints [134].

Simulation tools are designed to analytically simulate an energy system given a defined set of conditions for the system. This type of tool is typically used in connection with an alternatives assessment approach [134].

Theoretically, the main difference between the archetypes is that "*simulation models only intend to envisage the performance of a given system, given certain assumptions, whereas the optimisation models are searching for the optimal system design*" [134][9]. In this regard, optimization tools make all the optimization decisions to provide a single optimal solution, whereas simulation tools leave it to the user to make the decisions based on a number of considerations. In essence, optimization tools prescribe the optimal future while simulation tools are well-suited for debating the desired future [134].

The EnergyPLAN tool is a simulation tool that aims to identify optimal energy system designs and operation strategies on an hour-by-hour basis for one year. The EnergyPLAN tool optimizes the operation of the system, rather than optimizing the investments in the system. The tool has primarily been used to model national or regional energy systems, though it has also been scoped for more local energy systems [144]. In addition to electricity, EnergyPLAN develops hourly balances for district heating, hydrogen, gas grids and cooling to identify temporal mismatches between production and demand in every hour. Similarly, a range of storages are available, including for electricity, thermal (small and large scale), hydrogen, gas and liquid fuels.

The EnergyPLAN tool can optimize the operation of energy systems according to two general simulation strategies: technical and market-economic simulations. The technical simulation strategy pursues a least fuel-consuming operation of the system, which, for example, prioritizes integration of renewable sources before electricity exchange. This simulation strategy is less influenced by market conditions as defined in the model. The market-economic simulation strategy, on the other hand, operates each energy production unit according to the electricity market in order to optimize the business economic profit. This strategy is highly influenced by market prices and conditions and typically relies on a higher degree of electricity exchange than the technical simulation strategy. For the analysis in this dissertation, the technical simulation strategy has been applied to quantify the impacts of optimizing energy

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[9] Page 3

system efficiency rather than the business economic optimization of each plant. For example, most current electricity markets are not particularly suitable for very large penetrations of wind power, since wind power has a marginal production price of zero. Given this situation, analysing the benefits of wind power within the existing market structure may lead to conclusions that are more related to the market rather than the technology. This is in line with the choice awareness theory concerning public regulation and the influence of markets.

EnergyPLAN has been used for the analyses in Papers 1, 2, 4 and 5 to evaluate the feasibility of various alternative technologies, cost methods and energy system designs.

The characteristics of the EnergyPLAN tool corresponds to some of the key features of the choice awareness theory by evaluating the economic feasibility of alternatives under different types of public regulation (electricity markets). Furthermore, it offers the ability to analyse radical technological changes when transitioning to 100% renewable energy systems.

3.8. EVALUATION FACTORS

The various energy system alternatives developed in this dissertation are evaluated using a variety of factors. These are usually defined by the EnergyPLAN user according to the objective of the analysis. The objective in this dissertation is related to 100% renewable energy and smart energy systems. Therefore, the selected evaluation factors are within the fields of Energy, Environment and Economy.

Energy is understood and quantified as 1) the annual primary energy supply for the entire energy system, 2) the flexibility in the energy system measured as excess electricity and district heating and 3) the balance between resource consumption and potentials with a particular focus on biomass resources, as previous studies have shown this resource to be critical.

Environment is measured in terms of the consequences for carbon dioxide emissions in the entire energy system. CO_2-emissions in EnergyPLAN are quantified based on the fuel consumption and the input data for emission coefficients for each fuel type. Only CO_2-emissions are quantified in EnergyPLAN, as opposed to CO_2-equivalents, which include other emissions as well.

Economy is measured in two different ways. 1) Firstly, and most importantly, are the entire energy system's costs, which might also be called socioeconomic costs. 2) Secondly, the levelized costs of different energy carriers are relevant and are analysed in Paper 3. Socio-economic costs are defined as the total energy system costs including investments, operations & maintenance, fuels, CO_2 costs and energy exchange. This entails that no taxes or subsidies are included in the cost calculations. This is in line with the definition in [137] for the choice awareness theory.

Finally, some factors are included qualitatively based on the smart energy systems approach. Some energy strategies aim to achieve 100% renewable energy by allowing net impacts over one year, i.e. producing more renewable electricity than is consumed to compensate for fossil consumption in the transport sector. This is not permitted in the present analysis, which identifies the impact for all hours of the year, i.e. the system analysed here would remain 100% renewable even without an exchange of e.g. electricity.

Measuring the impacts of a given system according to these evaluation factors can reveal both the type and scale of changes related to future energy efficiency solutions. This knowledge can subsequently highlight the relative importance of different decisions to policymakers and other key stakeholders in the energy system.

CHAPTER 4. RESULTS AND FINDINGS

The ambition of this dissertation is to contribute to the research topic of 100% renewable energy systems. However, this is a rather large research area so contributions are grouped into three different categories: methodologies, individual technologies and measures as well as energy system design alternatives (smart energy system). The following sections present examples of these contributions found in the associated papers.

4.1. METHODOLOGIES

One step in the choice awareness theory concerns economic feasibility studies. There is no clear consensus as to which methods should be used for feasibility studies; accordingly, they often differ between researchers and disciplines. Unsurprisingly, this can be problematic as it complicates the drawing of cross-study conclusions and reduces transparency among different methods. This section addresses this issue by analysing two different methods for assessing energy costs. The first is the Levelized cost of Energy (LCOE) approach, which forms the topic of Paper 3. Paper 4 then compares this method with the second alternative, the Energy system analysis cost method.

4.1.1. LEVELIZED COSTS OF ENERGY (PAPER 3)

This section investigates the LCOE method and discusses some of its advantages and weaknesses based on Paper 3 [3]. Firstly, a review is performed to identify a range of common evaluation factors that are typically included in LCOE calculations. Secondly, LCOE costs are compared for various energy carriers: electricity, heating and cooling. Finally, the significance of including or omitting certain evaluation factors is investigated.

The LCOE method has been critiqued in recent years for a lack of transparency, limited comparability and for not considering important factors such as the effects of variable and dispatchable energy production. However, the method is still used by e.g. the International Energy Agency (IEA) and the Danish Energy Agency (DEA) [145,146] to guide policy making and is featured in numerous research studies [147–152]. The LCOE method should therefore not be disregarded, despite its recent criticism.

The LCOE method is almost exclusively applied to estimate electricity generation costs. Very few studies focus on levelized energy costs for heating and no studies could be identified that apply LCOE for cooling.

As such, the ambition here is to compare levelized energy costs for multiple energy carriers (electricity, heating and cooling) and to highlight the value of each energy carrier as determined via the LCOE method. In addition, this analysis investigates some of the challenges related to the evaluation factors that might be included in the calculations.

Details regarding further definitions, data and results are available in Paper 3.

A review of typical evaluation factors for LCOE studies finds more than 25 commonly-used factors. The majority of these can be classified as technical or economic factors while a few are concerned with externalities (mainly environmental issues). The number of evaluation factors included in the reviewed studies varies considerably. This rather large number of evaluation factors hinders the comparison of LCOE calculations across studies as each factor represents different costs.

The term decentralized heating refers to heat supply in individual buildings (residential, services, etc.) rather than as district heat supply. This might also be called individual heating in this dissertation.

The present analysis calculates and compares LCOE costs for electricity, decentralized heating, district heating and cooling. The LCOE costs are calculated for 2015, 2020, 2030 and 2050 using the following formula:

$$\frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Energy generation in year t
R = Discount rate
N = Lifetime of the technology

LCOE electricity costs for a range of the most common technologies are illustrated in Figure 12 for 2015, 2020, 2030 and 2050. The 2015 electricity costs range from 40-90 €/MWh and are projected to decrease to 30-80 €/MWh in 2050, primarily because of decreasing renewable electricity production costs.

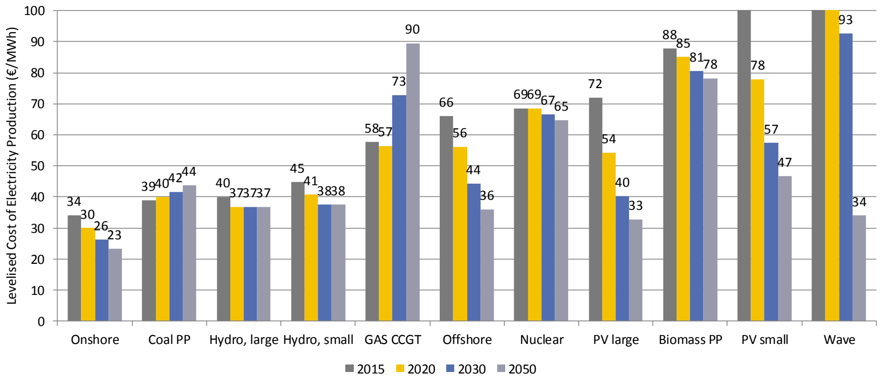

Figure 12: LCOE electricity costs for a range of technologies for 2015 and projections for 2020, 2030 and 2050. PP=power plant. PV=Photovoltaic. CCGT=combined Cycle Gas Turbine.

For LCOE decentralized heating costs, several technologies are expected to experience a small increase between 2015 and 2050, while slight reductions are anticipated for heat pumps and biomass. The outlier is solar thermal, for which costs are expected to drop considerably. Prices in 2015 range from 50-100 €/MWh and are projected to increase to 70-100 €/MWh in 2050.

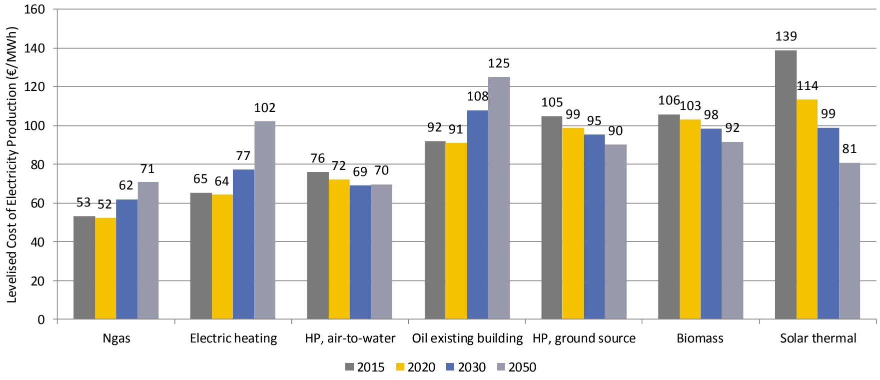

Figure 13: LCOE decentralized heating costs for a range of technologies for 2015 and projections for 2020, 2030 and 2050. HP=Heat pump.

Due to higher fuel and electricity prices in 2050, district heating LCOE costs are expected to grow. In 2015, these costs are between 25-40 €/MWh and are projected to increase to 25-50 €/MWh in 2050. Solar thermal is the only technology expected to have lower prices in 2050 than in 2015.

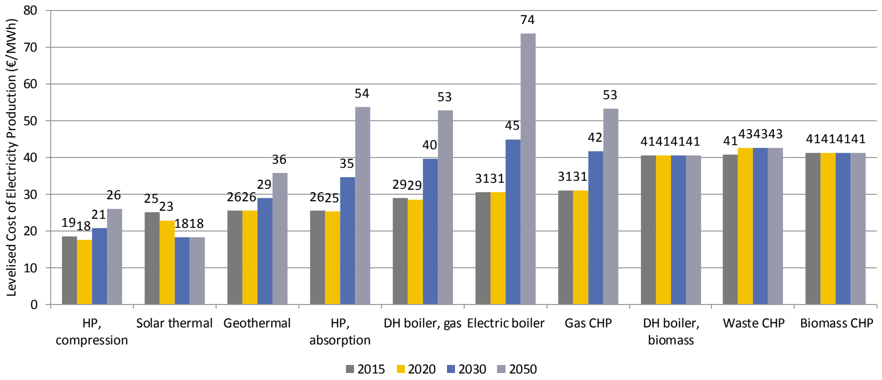

Figure 14: LCOE district heating costs for a range of technologies for 2015 and projections for 2020, 2030 and 2050. HP=Heat pump. DH=District heating. CHP=Combined Heat & Power.

The LCOE costs for cooling are also expected to increase towards 2050 due to higher electricity prices, which is the main energy source for these technologies. Costs are highly dependent on the efficiency of the technology.

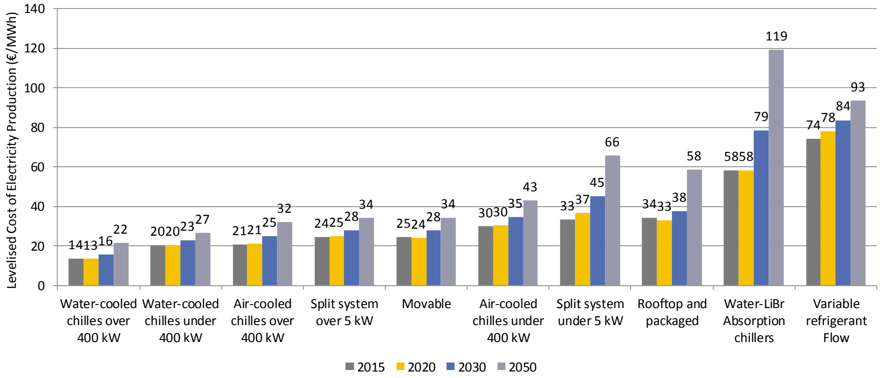

Figure 15: LCOE cooling costs for a range of technologies for 2015 and projections for 2020, 2030 and 2050.

When comparing the LCOE costs, as in Figure 16, the importance of planning for all energy carriers is clear since they each represent an economic value in the energy system. This contradicts the sole focus on electricity costs taken by the vast majority of studies identified in the literature review.

Moreover, LCOE costs only include the costs of energy production at the plant and exclude other costs such as transmission and distribution, which are usually considered when calculating consumer prices. It is therefore difficult to compare costs across different energy carriers, such as e.g. decentralized heating versus district heating, as the latter necessitates investments in distribution pipes that the former does not. The results of this analysis indicate that electricity costs will decrease slightly towards 2050 while district heating and cooling costs are expected to increase.

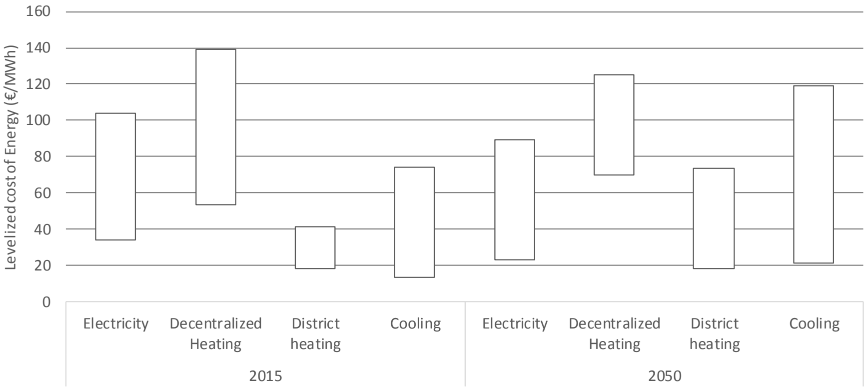

Figure 16: LCOE cost ranges for electricity, decentralized and district heating and cooling in both 2015 and 2050.

As previously described, several important parameters are not included in LCOE cost evaluations and it is therefore debatable just how realistic LCOE costs really are. For example, LCOE analyses due not consider the ability to operate in a dispatchable manner, which might be significant in future energy systems with high shares of variable renewable sources. Another example is for solar thermal energy, which is projected to experience cost reductions towards 2050, but is not expected to be able to meet the entire heat demand of a building or district heating network. Hence, additional production capacity is needed to supplement solar thermal plants; however, LCOE methods cannot account for this situation. Numerous other factors are also not included, such as a technology’s influence on other energy sectors (energy system dynamics), which could impact LCOE costs. For these reasons, it is unwise to rely solely on the LCOE method for policymaking. Instead, LCOE costs can provide first and general indications regarding cost developments for specific energy technologies.

This is crucial when discussing the choice awareness theory as it applies to feasibility studies and the design of technical alternatives. Feasibility studies that only apply the LCOE method are likely to produce different recommendations than those using other methods. The consequences of this are analysed in further detail in the next section.

4.1.2. LEVELIZED COSTS OF ENERGY OR ENERGY SYSTEM COSTS (PAPER 4)

This section presents the findings when comparing two different methods for conducting feasibility studies: the Levelized Cost of Energy (LCOE) approach and the Energy System Analysis (ESA) approach. The section is based on Paper 4 [4]. The comparison is carried out by ranking the technology costs when using each method and then comparing if the rankings are similar or not. The LCOE costs are estimated from a theoretical perspective while the Energy system costs are estimated based on an analysis of the German energy system. The latter approach uses two system configurations to evaluate potential system costs. The first configuration replaces all German nuclear power (which is already planned to be decommissioned) with a different electricity generating technology. The second configuration replaces all oil and coal boilers used for individual heating with either individual heating technologies or by expanding both district heating networks and supply. The author's design of the energy system clearly affects system costs but also provides a good framework for considering energy system dynamics, which is not possible when using the LCOE method.

The LCOE costs are based on the estimates in Paper 3 and only include the energy costs from each specific technology (e.g. €/MWh). The energy system costs, by contrast, include all costs from the energy system (investments, O&M, fuels, CO_2, energy exchange) and are measured as an aggregate for the entire energy system (e.g. B€/year).

The first comparison examines the cost rankings of electricity technologies derived by the two methods and is illustrated in Figure 17. As seen, the cost rankings are rather similar. The two exceptions are coal and gas power plants, which is caused by high CO_2 emission costs for coal plants and the consumption of expensive fuels such as gas. In general, the two methods are well aligned with respect to electricity technologies.

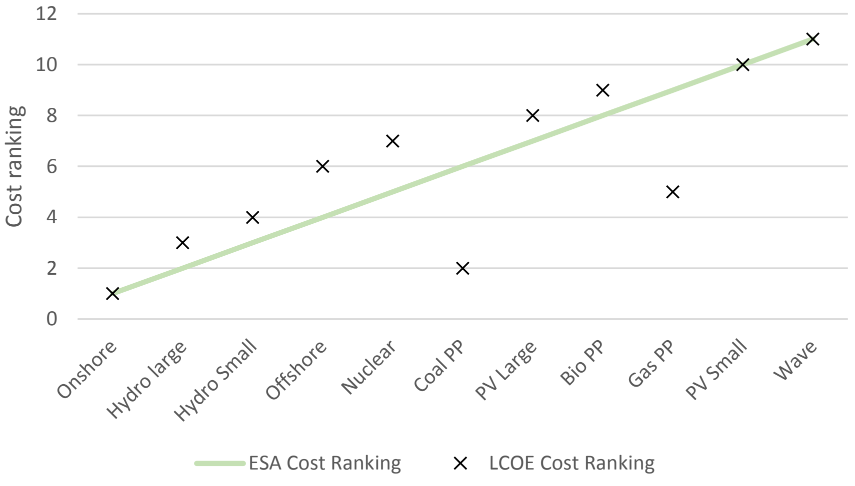

Figure 17: Cost ranking for electricity technologies using the LCOE and ESA methods.

The cost rankings between the two methods for decentralized heating technologies diverge significantly more than for electricity as seen in Figure 18. For example, electric heating has one of the lowest costs using the LCOE method while it has one of the highest costs using the ESA method. This difference is due to energy system dynamics that are included in the ESA method but not in the LCOE method. Concretely, electric heating production increases electricity demand, which in turn influences the technologies in the electricity sector. In this case, condensing power plants will operate significantly more to accommodate the higher electricity demand, which will affect the overall energy system costs (as well as fuel consumption and CO_2-emissions). Examples of these cross-sector energy system effects exist for most of the decentralized heating technologies.

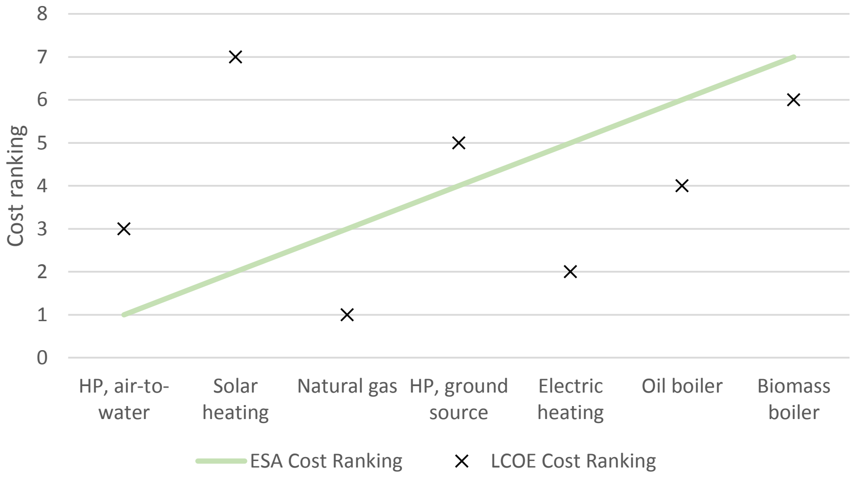

Figure 18: Cost ranking for decentralized technologies using the LCOE and ESA methods.

The two methods' cost rankings of district heating technologies are rather similar as seen in Figure 19. The extra investment costs for expanding district heating networks do not significantly affect the overall system costs because the associated technology investment costs when installing larger plants are lower (economy-of-scale). The operation of the heating system is greatly affected by the type of technology installed, as CHP plants and district heating boilers occupy different roles. This is caused by e.g. the overproduction of district heating when installing baseload technologies such as geothermal and waste CHP plants. Solar thermal technologies are one of the cheapest options in the LCOE method but are ranked lower in the ESA method. This is because solar thermal only supplies part of the demand and must therefore be supplemented by other technologies. This is considered in the ESA method but not in the LCOE method, which thus neglects potentially significant additional costs.

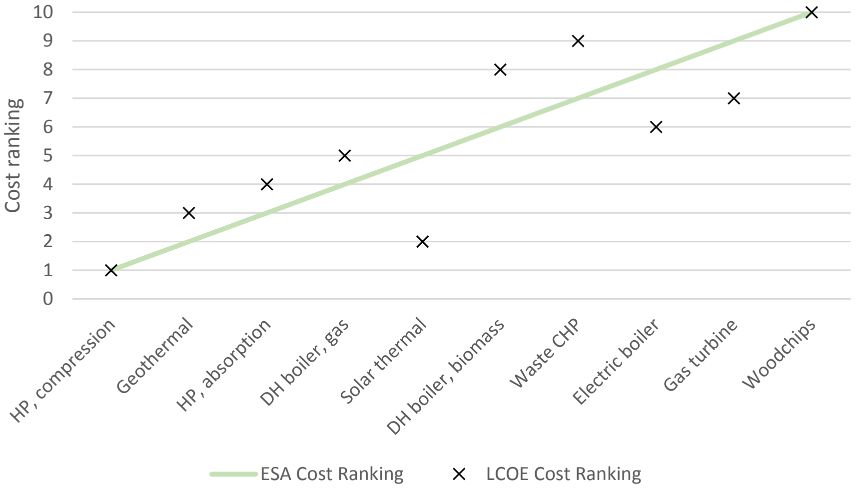

Figure 19: Cost ranking for district heating technologies using the LCOE and ESA methods.

The ESA method also permits one to analyse the significance of including other parameters, such as CO_2-emissions and fuel efficiency, into the decision-making process. This type of analysis is not possible using the LCOE method. Figure 20 shows the changes in CO_2-emissions, costs and primary energy supply for electricity technologies when replacing the nuclear power production. Some surprising findings arise regarding CO_2-emissions when examining the use of both small and large PV plants. When integrating larger shares these technologies the CO_2-emissions actually increase, despite the fact that the technologies themselves do not consume any fossil fuels. This increase is due to energy system effects that only become clear when analysing the entire energy system. The temporal mismatch between PV production and electricity demand requires other plants (e.g. thermal power plants consuming coal) to operate more, thereby affecting CO_2-emissions. It is therefore important to include the variability of PV generation in the analysis of both costs and emissions. Similar analyses are carried out for decentralized and district heating technologies and can be found in Paper 4. The LCOE method does not allow this type of analysis and thus incorrectly estimates some key projections.

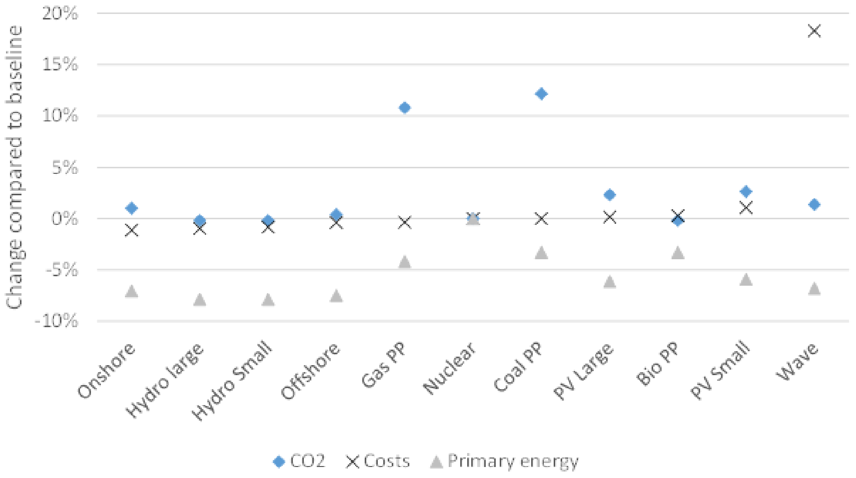

Figure 20: ESA changes in CO_2-emissions, costs and primary energy demand for electricity technologies compared to the baseline scenario with nuclear power.

Various system dynamics are ignored in the LCOE method such as the temporal alignment between demand and production. These effects might have implications for the cost rankings and are described and discussed in section 5.2.

This comparison proves the significance of selecting appropriate methods for conducting feasibility studies as the energy priorities diverge according to the method chosen. Furthermore, the parameters used for making decisions influence the resulting priorities. These findings correspond well with the choice awareness theory, which states that it is imperative to consider how feasibility studies are and should be carried out. Paper 4 demonstrates this clearly when it comes to the German energy system.

4.2. INDIVIDUAL TECHNOLOGIES TOWARDS 100% RENEWABLE ENERGY SYSTEMS

This section presents examples of comprehensive analyses of individual technologies and measures that may be influential in the transition towards 100% renewable energy systems. Concretely, two measures are presented, which show the importance of taking action on both the demand and supply sides. The demand side measure addresses heat savings and building refurbishment in some European countries; the supply side measure concerns solar thermal energy in other European countries.

These examples illustrate how and to what extent individual measures can contribute towards the target of 100% renewable energy systems in various European countries.

4.2.1. HEAT SAVINGS (PAPER 1)

Heat savings are analysed by evaluating the effects of building refurbishments on the energy system in the year 2050. The analysis and accompanying data are available in Paper 1 [1] while key findings are described here.

The purpose of the paper is to identify the feasible balance between saving heat and supplying heat on an aggregated national scale for Croatia, Czech Republic, Italy and Romania. The research was carried out in conjunction with the STRATEGO project [153], which selected the countries for analysis. In addition to identifying feasible heat savings, two different methods for assessing heat savings levels are compared using a similar approach as in Papers 3 and 4. These methods are the Levelized Costs of Energy approach (LCOE) and the Energy System Analysis (ESA) approach. Energy costs are applied as the main evaluation factor for identifying the feasible heat savings levels. This factor is chosen because other evaluation factors, such as primary energy supply, would indicate further savings potential, but at a much higher cost. Effects on primary energy and the environment are also considered in the analysis.

Heat savings are assessed using the LCOE approach by calculating the unit cost of saving heat and the unit cost of supplying heat. Figure 21 illustrates this; the x-axis displays the cost of saving heat per unit of energy (€/kWh) while the other axis displays the total amount of heat saved as a percentage of the total heat demand. By adding the cost of supplying heat per unit of energy to the figure, it is possible to identify the point at which the heat savings and the heat supply cost curves intersect. This intersection represents the optimal amount of heat savings from a levelized cost perspective.

However, some uncertainties exist when applying this method because a range of heat supply technologies with different costs are available. Moreover, these costs may differ across countries due to different labour and fuel prices. Furthermore, the cross-sector system effects of heat savings measures are not included in this type of analysis.

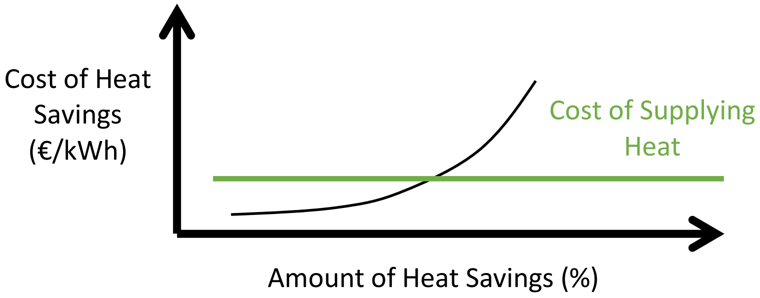

Figure 21: Theoretical illustration for identifying feasible heat savings levels based on the LCOE approach.

Figure 22 is created by calculating heat savings potentials in the four countries. The figure shows the unit cost of heat savings, the unit cost of heat supply technologies and the heat savings levels. As stated above, feasible heat savings levels are found by identifying the point at which heat savings and heat supply costs intersect.

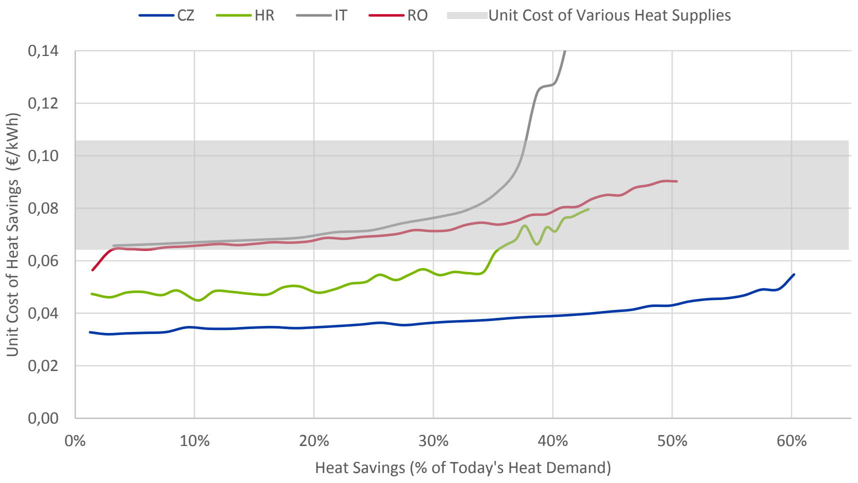

Figure 22: Feasible heat savings levels using the unit cost of heat savings and heat supply costs for various technologies. The point at which these intersect is identified as the feasible level of heat savings for this country.

The heat savings levels according to the levelized costs approach differ significantly between the countries. They vary from around 0% in Italy to 60% in the Czech Republic when assuming the lowest heat supply costs and around 40-60% across all four countries when assuming the highest heat supply costs. The heat savings levels for different heat supply costs are outlined in Table 5.

Table 5: Feasible levels of heat savings according to the assumed unit cost of heat supply for the Czech Republic, Croatia, Italy and Romania.

Heat Savings Feasible (% of Today's heat demand)	**Cost of Heat Supply €0.06/kWh**	**Cost of Heat Supply €0.11/kWh**
Czech Republic	60%	60%
Croatia	35%	45%
Italy	0%	40%
Romania	3%	50%

The comparative method applies an energy systems approach with the assumption that changes to heat demand also influence other parts of the energy system and hence the feasibility of heat savings. With this method, no unit cost of heat supply is calculated; instead, an energy system cost for supplying all energy demands is utilized. The levels of feasible heat savings differ between the two methods despite using similar heat savings costs. Applying the energy systems approach, the feasible heat savings levels range between 30-50% for the countries.

Table 6: Feasible levels of heat savings when applying the energy systems approach for the Czech Republic, Croatia, Italy and Romania.

Heat savings levels when applying the energy systems approach	**Heat savings level with lowest costs***
Czech Republic	40%
Croatia	40%
Italy	30%
Romania	50%

* Reduction as a percentage of the heat demand in the business-as-usual 2050 scenarios developed in the STRATEGO project.

These analyses demonstrate that different heat savings levels will be recommended depending on the method applied; this difference is due to a variety of reasons. Some of the reasons for this difference are outlined in Table 7 and further reasons are elaborated in the discussion of methods in Chapter 5.

Table 7: Characteristics of the two methods for balancing heat savings and heat supply.

Characteristics of the two methods	**Levelized Costs approach**	**Energy System Approach**
Calculation of heat supply unit cost	A heat supply unit costs range is calculated	Can potentially be calculated
Calculation of total energy system costs	Not possible	A total cost for the entire energy system
Identification of specific cut-off point	A cut-off range can be identified according to the heat supply unit cost assumed in the future	A specific cut-off point can be identified (in steps of 10%)
Impact on other sectors than heating	Not possible	Direct and indirect impacts across sectors
Ability to measure impacts on different metrics	Not possible	Measures impacts on both economy, energy and environment

The analysis in Paper 5 finds that heat savings from building refurbishments are crucial to remain within sustainable resource potentials in the analysed countries while also reducing CO_2-emissions. Furthermore, heat savings can also create improved conditions for the integration of low-temperature heating sources. Heat savings primarily influence the demand side of the energy system, but also indirectly influence the efficiency of the system as well as the energy production due to shifting peak demands. Heat savings are therefore vital in the pursuit of 100% renewable energy systems under the framework of the smart energy systems approach.

While heat savings via building refurbishments is clearly an important measure, it is only one solution out of many that must be implemented to achieve high renewable energy systems. Moreover, the methods applied when determining feasible savings levels are of crucial importance and greatly influence the research findings.

When relating these findings with the choice awareness theory and the smart energy systems concept, it can be argued that all three grids are critical to include in the assessment. If one only considers the thermal grid and heating production units, then critical aspects of the energy system dynamics are ignored, which in this case will alter the feasible heat savings levels.

4.2.2. SOLAR THERMAL ENERGY (PAPER 2)

The second type of individual technology analysed in this dissertation is solar thermal, specifically with respect to its feasibility and potentials in four European countries. The detailed results and data are outlined in Paper 2 [2] and in [154] while key findings are presented in this section.

The objective of this analysis is to identify the role of solar thermal energy in a range of future energy systems via an evaluation of the technical and economic energy system feasibility. This is done by quantifying the effects of installing further solar thermal energy in Germany, Austria, Italy and Denmark in energy systems representing the existing system (2010 scenario), a future business-as-usual system (2050 scenario) as well as systems with more heat savings (Heat savings), district heating expansions (District heating) and high shares of renewable energy integration (High-RES).

Solar thermal technologies for both individual heating and district heating areas are analysed with different heat production costs due to economy-of-scale effects. Thresholds of 5% are set for the maximum annual mismatch between heat production and demand to reduce the overproduction of energy. In addition, solar thermal potentials are analysed depending on the share of consumers connected to the solar thermal system (either in every building or through a district heating network).

The analysis shows that there is a technical limit to the solar thermal potential in each country due to the fluctuating nature of solar thermal energy. In Figure 23 and Figure 24, the solar thermal potentials are illustrated for individual and district heating technologies for the five energy system design variations in each country. The findings indicate that the solar thermal potential as a share of total heat production is higher in district heating networks (~8-12%) than in individual heating areas (~5-7%). This significant difference is due to the higher flexibility afforded by storage technologies to accommodate fluctuating energy in district heating networks. This emphasizes the importance of smart thermal grids as specified in the smart energy systems concept.

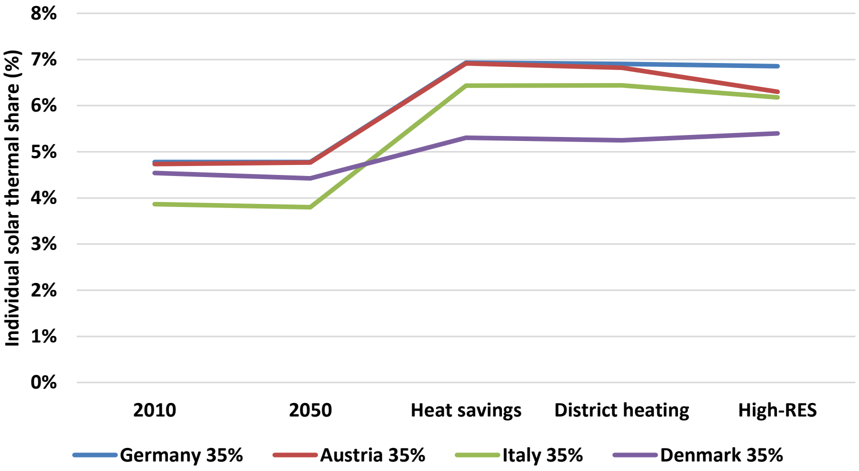

Figure 23: Solar thermal potentials for individual heat supply in the four countries assuming that 35% of all heat consumers are connected to the solar thermal systems.

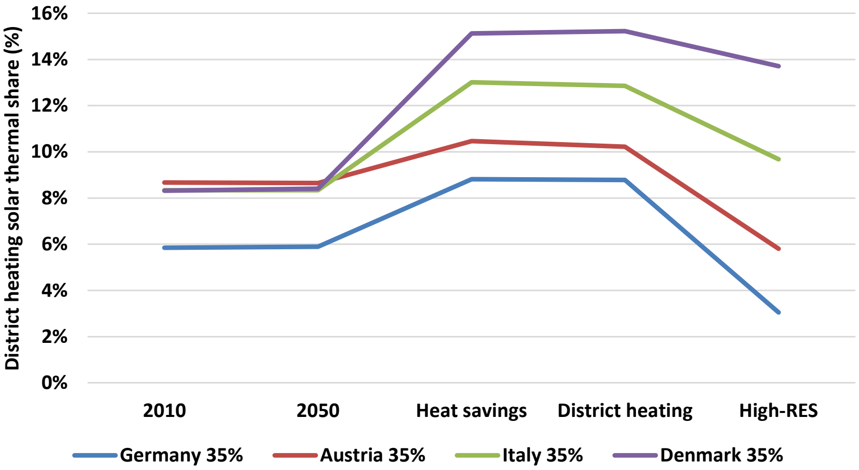

Figure 24: Solar thermal potentials for district heat supply in the four countries assuming that 35% of all heat consumers are connected to the solar thermal systems.

When installing solar thermal simultaneously in the individual and district heating areas, they accumulate to somewhere in the range of 4-10% of the total heat production depending on the country and scenario. This share increases or decreases slightly according to the share of heat consumers connected to the solar thermal systems.

The effects of installing these levels of solar thermal heating are quantified for fossil fuel and biomass consumption, CO_2-emissions and total energy system costs. Detailed results regarding fuel consumption and CO_2-emissions are available in Paper 2 while the economic feasibility is presented in Figure 25. Fossil fuel consumption primarily decreases in individual heating areas when installing solar thermal. However, installing solar thermal in district heating areas causes CHP plants to operate less, which leads to increased condensing power plant operation. This results in almost no changes to fossil fuel consumption in these areas, despite the installation of additional renewable energy production capacity. Overall, installing solar thermal in both individual and district heating areas results in a 1-2% reduction in total fossil fuel consumption. Similar energy system dynamics apply for biomass consumption, which decreases 1-3% of the total system demand. These changes in fuel usage are reflected in the system's CO_2-emissions, which primarily decrease in individual heating areas and remain rather unchanged in district heating areas or even experience small increases in some scenarios. This is counterintuitive, as one would expect CO_2-reductions when installing additional renewable energy production, but the reduction in CHP operation and increase in condensing power plant operation largely offset any associated benefits.

Figure 25 shows the marginal percentage change in socio-economic costs compared to the scenarios without any solar thermal energy. These effects are presented when considering individual heating, district heating and the combination of these potentials in the same system for the five scenarios in all four countries. Installing solar thermal in the individually supplied areas results in higher energy system costs because solar thermal replaces technologies with lower heat production costs. For district heating systems, some scenarios indicate cost reductions when installing solar thermal while other scenarios indicate small cost increases. Overall, the impacts from district heating areas are neutral on energy system costs. When considering both individual and district heating areas, the total energy system costs increase by up to 1%. The highest cost increases are found in situations that resemble the current energy system; this is due to larger fuel cost savings expected in the future (assuming higher fuel prices). In addition, high-renewable systems exhibit large cost increases because solar thermal energy in this scenario will compete with other renewable technologies that offer lower-cost energy.

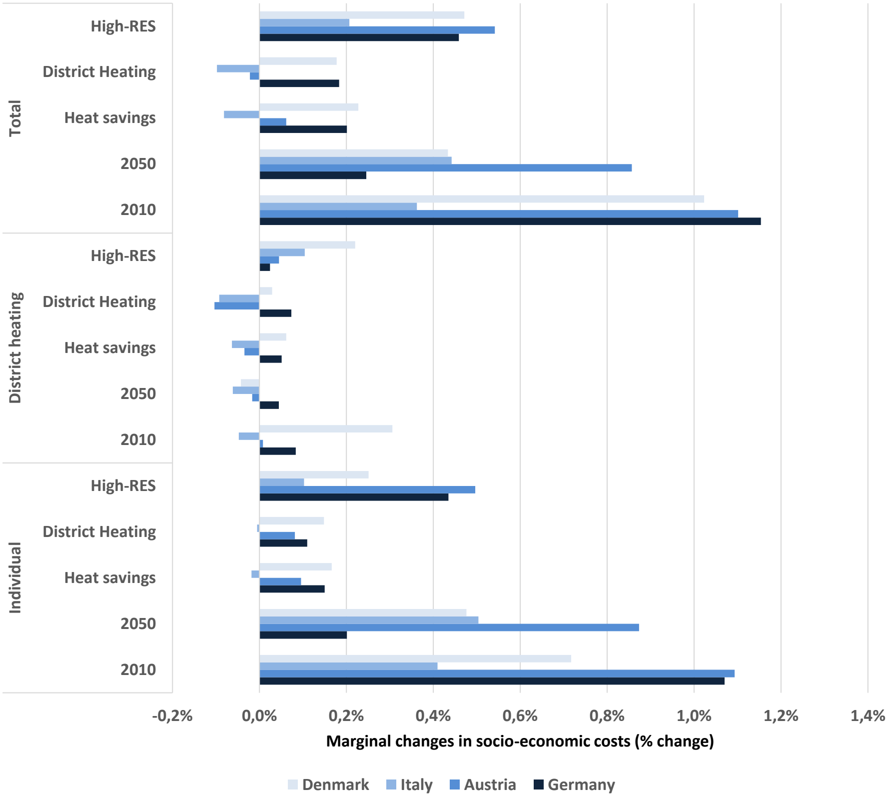

Figure 25: Energy system cost effects of installing the full solar thermal potential when 50% of all heat consumers are connected to the solar thermal systems.

This analysis demonstrates the importance of smart thermal grids for integrating renewable sources such as solar thermal energy. This is indicated through higher potentials and more beneficial costs in district heating areas than in individual areas. Large solar thermal plants can only be installed when district heating networks are established to connect centralized and decentralized plants with a large number of consumers.

The analysis further shows that no single technology can meet the ambition of creating a 100% renewable energy system. Moreover, the analysis reveals insights for energy system costs that are only available when using a full energy system perspective as advocated in the smart energy system concept.

4.3. ENERGY SYSTEM DESIGNS (PAPER 5)

This analysis presents a concrete alternative for the design of a 100% renewable energy system, including all sectors, for the German case. The purpose of the analysis is to apply the choice awareness theory and to demonstrate that there are various alternatives (especially in the transport sector) that warrant consideration and incur different consequences. The methodology for designing the alternatives is based on the smart energy systems concept, in which the integration of energy sectors is key to obtain feasible results. The energy system is modelled using the EnergyPLAN tool, see description in section 3.7. Detailed descriptions of the concrete initiatives and data are described in Paper 5 [5]; this section primarily focuses on the key findings.

The German energy system is used as an example because Germany 1) has ambitious policies in place to move towards a low-carbon energy system in 2050 (the Energiewende policies), 2) is familiar to a large audience, 3) has a large variety of energy sources and 4) has low biomass potentials compared to other countries, which makes the design of 100% renewable energy systems quite challenging.

The measures needed to create a 100% renewable energy system can be divided into the categories of heating, industry, transport and electricity. Figure 26 outlines the specific measures in each energy sector.

This analysis does not consider cooling in detail due to its low impact on the overall energy system (cooling demand is only 7 TWh/year compared to a total current PES of 3,200 TWh/year).

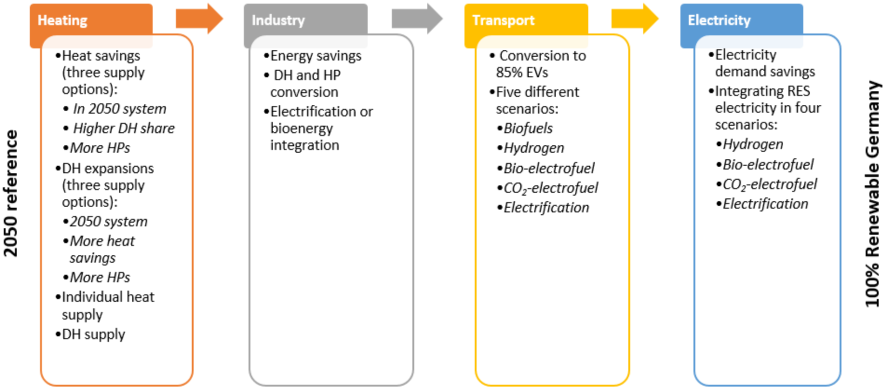

Figure 26: The measures needed to design a 100% renewable energy system in all sectors.

Designing a 100% renewable energy system in Germany requires three main types of actions as highlighted in the smart energy approach: changes to the demand side, system efficiency and resources. Hence, a literature study was conducted to estimate

Germany’s available renewable resources in terms of biomass, wind power and PV. The potentials are outlined in Table 8

Table 8: Assumptions about renewable energy potentials for the German energy system.

Renewable potentials (TWh/year)	**Range**	**Limit in this study**
Biomass	250-450	400
Onshore wind	360-3,000	526
Offshore wind power	180-300	242
PV	150-390	316
Total		1,484

The analysis demonstrates that it is challenging to remain within domestic biomass potentials. Resource availability is therefore used as an evaluation factor to prioritize the various measures along with their effects on energy system costs.

The focus in this chapter is on the overall system dynamics and the smart energy system approach; hence, only a few details about the individual measures in the separate energy sectors are included here. More details are available in Paper 5.

In terms of the heating sector, one of the key measures is heat savings; energy system costs showed that 50% heat reductions were feasible compared to a 2050 reference scenario. This measure induces additional investments, but these are compensated for by reductions in fuel expenses. Another important measure is the expansion of district heating networks to cover 30% of the total heat production (from 18% in the 2050 reference). Next, the majority of heat production outside of district heating areas should be converted to individual compression heat pumps as this technology results in less PES while having reasonably similar costs to alternatives such as biomass boilers. Finally, further renewable and excess heat sources should be integrated into the district heating supply mix. These changes to the heat sector reduce the system’s overall PES by 14% compared to the 2050 reference scenario while energy system costs decrease by 6%, primarily due to heat savings.

The next broad category includes enhancements to the industrial sector. First, energy savings are carried out to the extent possible (30%) by improving technologies in production facilities, etc. Next, space heating and process heating below 100 °C are converted to either heat pumps or district heating with a 50/50 ratio between the two. Finally, two different options for converting the remaining fossil fuel consumption into renewable energy are considered. The first option involves converting the remaining fuels (excluding district heat and electricity) to bioenergy; this results in an additional biomass demand of 289 TWh/year. The other option converts half of the remaining fuels to electricity as described in [155] and the other half to bioenergy. The second approach places less stress on the availability of biomass resources, which are crucial for the later conversion of the transport and electricity sectors. This electrification scenario is thus used for further analysis due to the lower biomass demand (total of 238 TWh/year in this scenario).

The transport sector is typically the most challenging sector to convert to renewable energy as no obvious solution appears and because biomass limits do not allow for the direct conversion of fossil fuels to biofuels. Nonetheless, the first step is to convert 85% of all cars and vans to electricity powered transport due to the significant improvement in energy system efficiency (electric powertrain vehicles are assumed to be approximately three times as efficient as ICE vehicles) [156]. The conversion to electric vehicles proves to be one of the most vital measures for achieving a 100% renewable energy system. After this, five different paths are analysed for converting the remaining fuels, primarily in heavy-duty road transport as well as air and sea transport. These five alternative paths are defined as:

- 2nd generation biofuels
- Hydrogen
- Bio-electrofuels
- CO_2-electrofuels
- Electricity

These alternatives represent extreme scenarios in which all transport demands are converted into a single technology, which then affects the entire energy system in various ways. The specific details for each transport path are available in Paper 5 while the main findings are summarized here. The biofuel scenario relies on production of different types of biofuels for meeting transport demands. The hydrogen scenario assumes that all transport demands for both road, air and sea transport can be supplied by hydrogen production, including hydrogen storages. The two electrofuel scenarios utilize synthetic fuel production by boosting the energy content of a carbon source with hydrogen. Various fuels can be created via this process; the analysis assumes that the bio-electrofuel fuel type is methane and the CO_2-electrofuel type is DME. Further descriptions of production processes, advantages, etc. are available in [157,158]. Finally, the electricity scenario assumes that all transport modes can be 100% electrified, thereby improving engine efficiencies and allowing for using renewable electricity sources in a more direct way.

The effects of the various transport scenarios are illustrated in Figure 27, which shows that both the biofuel and bio-electrofuel scenarios require biomass resources that exceed the biomass potentials for the entire energy system. The overall energy system costs are similar, between 425-440 b€/year for most of the scenarios, but all are higher than the EV scenario (405 b€/year). The hydrogen scenario could potentially result in higher costs, but this is uncertain and depends on infrastructure and vehicle costs.

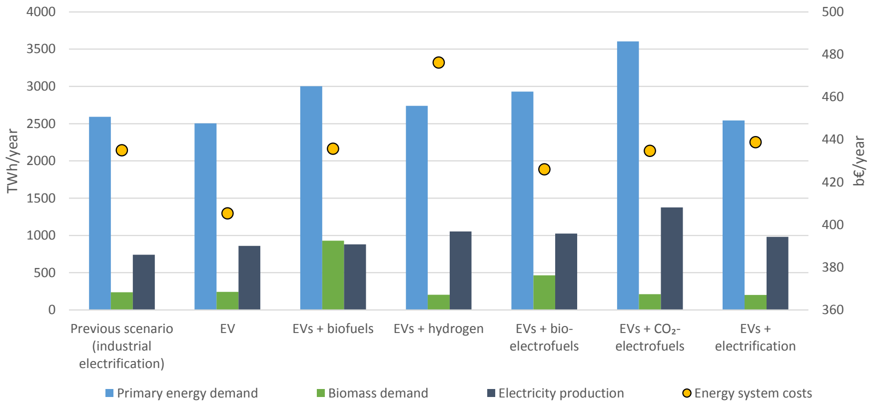

Figure 27: Energy system effects of the five transport alternatives and a comparison with the evaluation factors in the previous scenario (electrification of industry).

Due to the large variation in the results of the transport alternatives, four of these have been included in the final scenarios where the electricity sector is converted to renewable energy. The biofuel scenario is excluded due to its excessive biomass consumption.

In the electricity sector, the first step is to carry out electricity savings; it is assumed that 25% of the conventional electricity demand can be saved for an investment of ~90b€. Then, the thermal plants (PP and CHP) are converted from solid fuel technologies to gaseous generation units, thereby improving the plants' efficiencies. This is crucial for reducing fuel inputs. Finally, two variations of the scenarios are created to integrate more renewable variable electricity sources. The first variation assumes a maximum of 5% excess electricity production, which means a lower variable renewable production, compared to the second variation, in which all variable electricity sources are integrated in order to reduce the biomass demand.

Hence, eight different scenarios are ultimately created to represent a variety of alternatives for future 100% renewable energy systems in Germany. The eight alternatives are illustrated in Figure 28 in terms of PES; the scenario names refer to the primary technology path in the transport sector. The largest differences between the scenarios are related to biomass consumption and excess electricity generation. For the scenarios with full implementation of renewable resources, excess electricity is between 16-20% of total electricity production in three of the scenarios and 6% in the CO_2-electrofuel scenario. All the renewable scenarios are significantly more efficient compared to the 2050 reference scenario due to the integration of highly efficient technologies such as electric vehicles, heat pumps and wind and solar power as well as energy savings in the heating, electricity and industrial sectors.

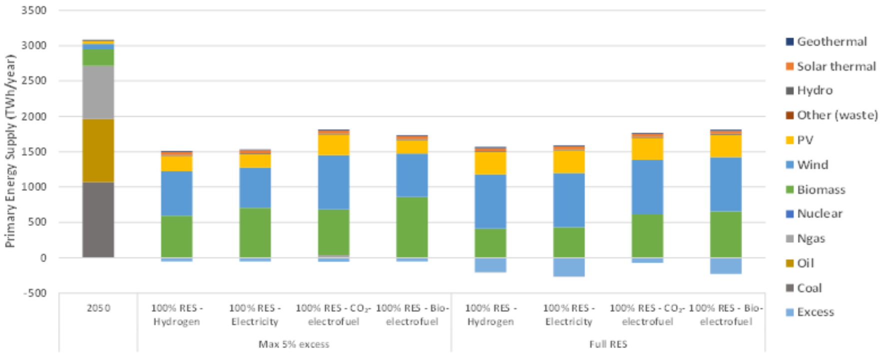

Figure 28: Primary energy supply for the 2050 scenario and the eight variations of a 100% renewable energy system.

As seen in Figure 29, the scenarios differ significantly in terms of biomass demands. The scenarios with full implementation of renewable resources have lower biomass demands than those in which only 5% excess electricity is allowed. The ranges change from 600-850 TWh/year when considering limited renewable production to 410-650 TWh/year when all renewable potentials are installed. However, even in the scenario with the lowest biomass demand and with all possible variable renewables installed, indications show that it will be challenging to remain within domestic biomass potentials.

Measures can be included to further reduce biomass demand and thereby avoid the import of biomass. Suggestions could include additional savings initiatives, particularly in the industrial sector, or measures to reduce thermal plant operation. [155] envisioned a situation in which all basic material industries are electrified, which would reduce biomass dependence in the German energy system. Additionally, further district heating expansions would most likely reduce biomass demand due to reduced electric heat pump demand. This would also allow for the increased integration of alternative heating resources such as excess heating, geothermal, solar thermal or waste-to-energy. However, this measure should be investigated from an energy system perspective with respect to its impact on excess district heat production. Finally, further renewable electricity resources could be integrated if future resource estimates change, to reduce thermal plant operation, even though this would also lead to higher levels of excess electricity production.

Further analysis of the biomass demand in 100% renewable scenarios is required because not only is it important to consider the total biomass potential but also the types of biomass. For example, some biomass resources could be in the form of wet biomass (manure, sludge, etc.), which can only be used for specific energy purposes and technologies. This is not considered in the present study.

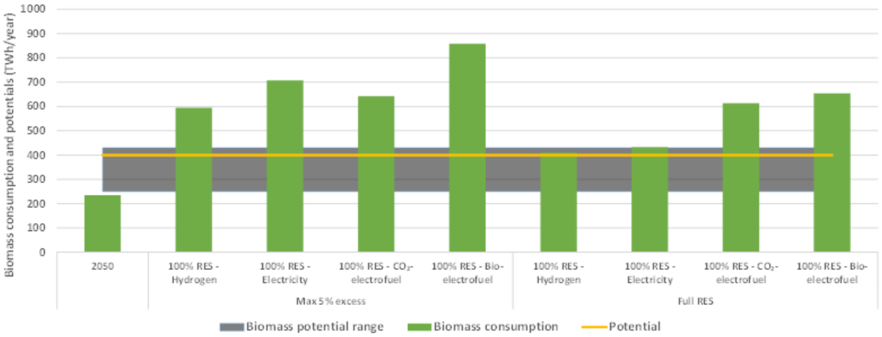

Figure 29: Biomass demand in the 2050 reference scenario and the eight 100% renewable scenarios.

The scenarios also influence energy system costs, with the largest changes showing up in the energy system cost proportions. In the 2050 reference scenario, fuel, O&M and investment costs represent almost equal shares. By contrast, in the 100% renewable scenarios, investments make up a higher share of the total costs. For instance, in the 2050 reference model, investment costs make up 36% of the total costs while this share is above 60% in all of the 100% renewable scenarios. This will have an indirect effect on societal perspectives such as job creation and balance of payment, which is discussed further in section 5.3.

In general, the largest cost proportions in all the energy system are for transport vehicles at more than half of the total system costs. Hence, changing these costs will have a substantial impact on the overall costs.

Overall, considering all the uncertainties for fuel prices, technology development and energy demand projections, the renewable energy scenarios are reasonably similar to the 2050 reference scenario in terms of costs. Hence, it can be concluded that future 100% renewable energy scenarios for Germany will incur costs that are comparable to a future reference system using large shares of fossil fuels.

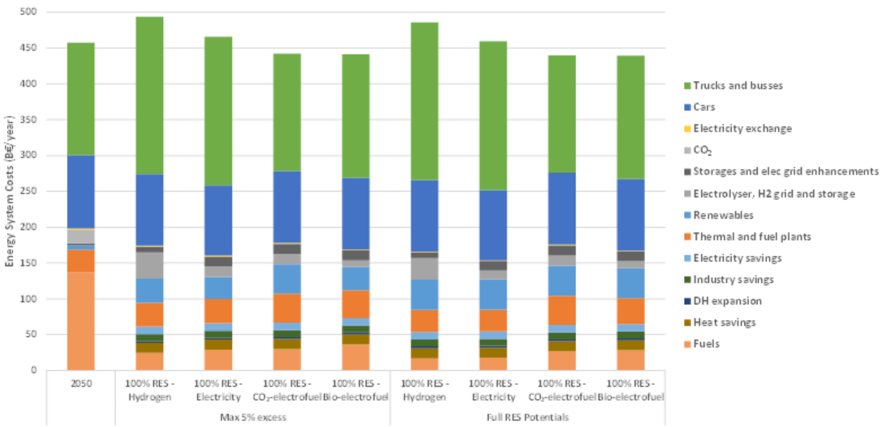

Figure 30: Energy system costs for the 2050 reference and the eight 100% renewable energy scenarios.

The majority of the technologies installed in the 100% renewable scenarios are currently available in large scales; however, some technologies, such as high-temperature solid oxide electrolysers, heavy-duty hydrogen vehicles and electric ships and planes for long distances, require further technological progress. Technological development is therefore required to achieve most of these 100% renewable energy scenarios.

The analysis proves the importance of applying the smart energy systems concept through the integration of sectors and the utilization of storages across energy carriers. Examples include the production of gaseous fuels for thermal plants from combining hydrogen with biomass sources. This enables the storing of electricity through the medium of hydrogen to increase the amount of integrated variable electricity, which in turn reduces biomass consumption. Another example is to harness excess heating from the numerous types of fuel production facilities for use in district heating systems. These facilities could be linked to either the transport sector to produce transport fuels or the industrial sector to produce materials. A third example is the electricity storage afforded by electric vehicles, whose main purpose is to meet the demands of the transport sector. The integration of large shares of electricity between the transport and electricity sectors is a key component in the 100% renewable energy system. Finally, heat pumps represent a vital example of integrating the electricity and heating sector to utilize excess electricity for heating purposes. Heat pumps can be located in both individual buildings and in district heating networks, which allows variable electricity sources to be used to fill low-cost large-scale thermal storages [159].

The analysis also proves that a wide variety of measures and technologies are necessary to achieve 100% renewable energy penetration. No single solution will suffice, which is also the conclusion in Papers 1 and 2. Furthermore, the design of 100% renewable energy systems has to be adjusted according to the local conditions and potentials. Germany offers an excellent case in comparison to other systems such as the Danish energy system. For example, the biomass share of total PES is ~25% in the final 100% energy system that uses hydrogen as the main solution for heavy-duty transport and installs the full renewable electricity potential. A similar study for Denmark, entitled IDAs Energy Vision 2050 [160], which also applies the smart energy systems concept, finds that a biomass share of ~40% is possible, accompanied by wind and solar power. Hence, the IDA study does not consider a hydrogen scenario for the transport sector because it is possible to remain within domestic biomass resource potentials using only electrofuels for the transport sector, thereby obtaining lower energy system costs. Furthermore, no electrofuels are used for thermal plants in the Danish case, only biomass gasification is utilized. This shows that even though the same methodological framework is applied (smart energy systems), the local conditions and resources determine which solutions will be recommended.

The next step after designing a national 100% renewable energy strategy could be to coordinate resources across national energy systems. Some countries might have excess biomass resources or greater capabilities to store energy while other countries might have excess variable electricity resources compared to what they require for a 100% renewable conversion. This type of approach would optimize the use of resources across countries and lead to better solutions on a regional or global scale.

CHAPTER 5. DISCUSSION

This chapter contains a discussion of the analysis results in connection with the energy system challenges, the suitability of the smart energy systems approach, the EnergyPLAN tool and other considerations that could influence the findings.

5.1. ENERGY SECTOR CHALLENGES

In Chapter 1, a number of challenges associated with the energy system were described including security of supply, resource availability, energy costs, access to energy, land use implications as well as impacts on the environment and climate. This section qualitatively contextualizes these challenges in relation to the analysis conducted in this dissertation.

Security of supply is a critical factor to be aware of from an energy system perspective. Paper 5 presents two options for managing the challenge of meeting energy demands for all hours when introducing higher levels of variable renewable energy sources that affect the energy system flexibility. The first involves integrating energy sectors to enable the sharing of excess energy across different sectors. Some examples of this cross-sector approach are to utilize variable electricity generation in the transport sector via electric vehicles, in the heating sector to drive heat pumps or to produce hydrogen. These integration technologies reduce the number of hours with excess electricity production and limit the need for electricity storage. Higher integration between sectors also provides access to more storage facilities, for example in the district heating and gas networks.

The second option to address security of supply regards the availability of resources as fossil fuel resources are limited and concentrated in relatively few regions of the world. By transitioning from fossil fuels to a high share of variable renewable sources, energy supply shifts from regions with high energy reserves to decentralized production units, which can be located in more varied parts of the world. This enhances security of supply because a system’s dependence on other countries or regions declines as it prioritizes local energy production. One exemption is for biomass reserves, which are country specific and may be traded in the future according to availability and demands.

Resource availability is improved when transitioning to renewable sources because most are infinite by definition and will not deplete in the same manner as fossil fuels. Biomass is the exemption as it could potentially be depleted if overconsumed. This issue is analysed in Paper 5, where a 100% renewable energy system design in Germany would require the use of all domestic biomass resources. The analysis in Paper 2 shows that even though there are abundant renewable resources, technical constraints may prohibit their integration into the energy system. Moreover, renewable resource potentials differ between countries; for example, hydropower is only available in regions with mountains or large rivers, while topology determines the resource potentials for e.g. tidal power.

Energy costs are a key concern and are addressed in all of the papers in this dissertation. Most of the papers include an evaluation of socio-economic costs to determine the feasibility of certain measures and system design changes and to prioritize future energy investments. The cost priorities change in some cases according to the cost methods applied, which in turn influences future energy decisions. The analyses also find that prioritizing costs over other evaluation factors could hamper certain measures such as reductions in energy demands (and biomass consumption). One example involves heat savings, where the socio-economic costs determine the optimal savings levels, even though additional savings would further reduce heat demands and primary energy supply. The analysis in Paper 3 shows that renewable prices are expected to decrease slightly in the future (especially for electricity technologies), which would accelerate the transition towards 100% renewable energy. In Paper 5, the analysis shows that transitioning to 100% renewable energy implies only small changes to the overall energy system costs as compared to a fossil fuel scenario. Finally, Paper 2 demonstrates that integrating renewable resources does not automatically benefit system costs as solar thermal is found to increase system costs under certain conditions.

Access to energy can also be improved by transitioning towards renewable energy sources. This is possible due to the decentralization of energy facilities from large power plants to smaller generation units such as wind and solar power plants and from local biomass production. This shift reduces the requirements for capital investments and could enable consumers to become energy suppliers as well (prosumers). In addition, some renewable energy sources will have lower costs than alternatives in the future, which is important when considering fuel poverty and consumers’ financial ability to meet their energy requirements.

Land use implications are critical to consider in the perspective of 100% renewable energy systems. In general, energy sources with low land use such as fossil fuels are replaced by renewable sources that might have higher land use requirements. The land use might change according to various factors, e.g. where PV systems are placed. PV plants can be installed in small or large scale in dedicated areas taking up land for energy purposes or they can be installed on building rooftops thereby not taking up additional land area. Similarly, wind turbines can be installed onshore with implications for land use or they might be installed offshore with no land use footprint. The most significant energy source for land use implications is however biomass, which can be highly influential on the land use for energy purposes. In the analysis in this dissertation biomass consumption increases and the implications for land use depends on the source of this biomass. If the biomass is solely from residual sources from e.g. industries, forestry and agriculture the implications are less severe while dedicated energy crops could have larger implications. This could conflict other land use priorities such as for food production or natural habitats.

Environmental and climate effects are improved by integrating additional renewable sources via reduced emissions of greenhouse gasses and other pollutants. This will help to minimize climate change and its associated impacts. Furthermore, renewables will most likely lead to a reduction in the amount of water used in large power plants as well as for the mining and refining of energy resources. However, uncertainties remain regarding the effects on biodiversity and deforestation since a heavier reliance on biomass could influence these factors. These effects have not been analysed in this dissertation. Biomass demands will most likely grow in the future (as described in Paper 5); depending on the production methods, standards and types of biomass used, these parameters could either improve or deteriorate

Other benefits related to a transition towards a 100% renewable energy system could include improvements in balance of payments for countries that previously imported large shares of their energy resources, technological and industrial developments as well as the development of rural areas.

5.2. SMART ENERGY SYSTEMS

Most of the analyses conducted in this study apply a full energy system analysis under the framework of the smart energy systems approach. This has a range of implications on the overall results.

The smart energy system approach provided perspectives that were of crucial importance in terms of capturing the full energy effects across sectors and technologies. This section contains a summary of the findings when applying the smart energy systems and full energy systems analysis approach. The findings differ between papers depending on the scope and extent of the respective analyses.

Paper 1 identifies some factors that might be accounted for when applying the full energy systems approach rather than the levelized costs approach. These factors relate specifically to the analysis of heat savings:

- Less heat capacity is required in the energy system when the heat demand in each building is reduced, which means that the investments in heating units in both individual and collective heating systems decline.
- Similarly, a lower heat demand reduces the required district heating piping dimensions, which also leads to lower investment expenses.
- It is necessary to alter the heat demand distributions when implementing heat savings because of lower peak demands. This affects the operation of heat production technologies across the energy system.

- Heat savings also influence electricity production technologies as less electricity production capacity is required due to the reduced demand for electric heating and heat pumps.
- In an energy system perspective, the operation of technologies can be optimised when implementing heat savings; this includes enhanced utilisation of storage technologies.
- The feasibility of integrating excess heat from sources such as industrial heat, waste incineration and transport fuel production is influenced by the flexibility and operation of the surrounding energy system.
- It is possible to identify impacts on the fuel demand of the complete energy system when implementing heat savings, thereby also considering reduced losses in conversion and transformation units not directly related to building refurbishments.

In Paper 2, important energy system dynamics are captured using the full energy system analysis perspective in relation to solar thermal energy, they are:

- The importance of considering what is replaced when installing a given technology. Under certain conditions and system designs, integrating renewable energy such as solar thermal may increase CO_2-emissions due to lower CHP operation, which would require increased use of condensing power plants. This shows how the integration of and changes in the heating sector could influence the operation of other sectors such as the electricity sector.
- Technologies might start competing with each other in a future high-renewable energy system. The analysis supports this idea as solar thermal feasibility dropped when installing other renewable baseload heating sources such as geothermal, industrial excess heating and waste incineration. Integrating these other heating sources led to a decline in the technical potential for solar thermal because of an increased overproduction of heating. This is primarily applicable for district heating networks though also to a lesser degree in individually heated buildings.

Paper 4 identifies crucial energy system dynamics in relation to cost estimations and priorities depending on whether a full energy system analysis or LCOE estimation is applied:

- A crucial system dynamic is the temporal hour-by-hour alignment between production and demand patterns and the effect of this alignment on over- or underproduction of energy as well as the need for back-up capacity in the system. This factor is not considered in the LCOE method, even though it can have a substantial impact on the overall costs and feasibility of a given technology in an energy system.
- The ESA method allows for optimizing the operation of an energy system as well as individual technologies by aligning production patterns including storages. This affects a given technology’s overall energy system costs.

- Another system dynamic is the technologies' ability to enhance flexibility in the energy system due to e.g. fast ramping rates, use of excess energy or the ability to balance heat and electricity production. Such technologies include heat pumps, electric heating or CHP plants, and this benefit is typically not monetized in the LCOE method.
- The opposite case also occurs for some technologies, where the system's flexibility is reduced, leading to more excess energy; such excess is wasted if it cannot be stored or exported. These technologies are primarily baseload technologies such as nuclear power, waste incineration plants and geothermal heating as well as technologies with variable production patterns (solar thermal, wind and solar power).
- One of the key benefits of the ESA method is its ability to account for synergies across sectors. For example, installing either gas CHP plants with high electric efficiencies or woodchip CHP plants with high thermal efficiencies induces a significant difference in how the energy system will operate.
- In the ESA method, "free" energy can be utilized by capturing excess electricity or district heating to reduce fuel consumption in alternative energy production units. This reduces costs and improves overall energy system efficiency.
- The LCOE method calculates the costs to produce one unit of energy at the site of generation. However, fuel and energy losses occur in various phases of the energy system including fuel extraction, energy conversion and transmission and distribution. These losses can be important when estimating energy technology costs.
- The ESA method allows for the assessment of parameters other than costs, such as primary energy demand and CO_2-emissions, which is not possible in the LCOE method (unless using simple and generic calculations). This provides a more comprehensive overview of the impacts of prioritizing certain technologies.
- The evaluation method applied has a significant impact on the cost rankings of individual heating technologies. For example, solar thermal cannot supply the entire heat demand of a building and thus needs to be supplemented by another technology, which should be included in the cost assessments. Another example is for electric heating that necessitates additional electricity production (power plant operation in this case), which likewise leads to additional costs.
- CO_2-emissions might increase when replacing nuclear power with variable renewable electricity sources because more power plant operation becomes necessary, which is currently (and in the short-term horizon) supplied by coal and other fossil fuels.

Paper 5 highlights the following crucial energy system dynamics for achieving a 100% renewable energy share:

- Biomass resources are crucial in a 100% renewable energy system. They play an important role in parts of the industrial sector, in the creation of transport fuels and in providing fuels for thermal plants to ensure balancing is achieved during hours with low variable energy production.
- Reducing energy demands is crucial to ensure that system consumption remains within sustainable energy potentials. These reductions could occur within the heating sector but could also include industrial and electricity demands and, if possible, the transport sector. Altering the demands in any sector has a significant effect on the entire energy system.
- Electric vehicles are critical to obtain a higher renewable energy share because they act as electricity storages, even in the absence of V2G technologies. Furthermore, electric vehicles are significantly more efficient than ICE vehicles, thereby improving the system's overall energy efficiency and positively influencing biomass demands. Installing electric vehicles in the transport sector necessitates further electricity production and influences demand patterns in multiple energy sectors.
- Thermal power production should be reduced to the greatest extent possible, as these plants will require some form of biomass consumption. However, the future need for thermal plants is only clear when looking at the hour-by-hour analysis of the entire system as their main role is for balancing the system.
- Production of hydrogen allows for the integration of more renewable electricity sources and reduces excess energy production. Without hydrogen production for electrofuels or hydrogen vehicles, significantly more excess electricity is produced, which in turn slightly increases biomass demand. Again, this is only clear from the hour-by-hour analysis.
- Producing hydrogen to make bio-electrofuels for thermal plants might also reduce biomass requirements. This permits the integration of electricity production with gas storages, which are significantly cheaper than electricity storages.
- Many technologies in a future 100% renewable energy system will produce excess heating (bio refineries, synthetic fuel plants, electrolysers, etc.) and are thus important to consider as part of the overall resource potential. The extent to which this excess heat is feasible can only be quantified by analysing the full energy system. It is necessary to determine how these baseload sources influence excess energy generation to the extent that it cannot be utilized in the system.
- Installing and expanding district heating networks allows for the use of energy that would otherwise be unavailable or wasted. These sources include e.g. large geothermal and solar thermal, industrial excess heat and waste incineration. Without these, the demand for other resources, such as biomass, would increase even further. In addition, district heating networks allow for the integration of renewable electricity sources with low cost energy storages in the district heating network.

When considering all five papers, it can be concluded that no single solution is able to deliver the required energy system changes needed to achieve 100% renewable energy. Instead, a multitude of technologies and measures are required, and even then, it might be challenging to remain within the limits of sustainable resource potentials at acceptable costs. This is clear from Papers 1, 2, and 5. Moreover, it is vital to apply a full energy system perspective guided by the smart energy systems approach in order to pursue feasible strategies for 100% renewable energy. This section made this point clear by identifying a wide range of system dynamics that could be neglected if a full energy system perspective is not applied.

It should be noted that there are a few aspects that might be considered disadvantages when applying a full energy system analysis as suggested in the smart energy systems approach. For example, many data inputs are necessary in relation to energy demands, generation units, distributions, cost data, etc., which are not always available or can be time consuming to collect. This must be considered when planning studies that utilise this approach. Furthermore, by focusing on the entire energy system, there is less opportunity to conduct detailed, specific analyses than when analysing single technologies or sectors. This is, however, only a minor downside, since the study can be scoped to accommodate for this drawback as done in Papers 1 and 2.

5.2.1. THE ENERGYPLAN TOOL

The EnergyPLAN tool was used for the analyses in Papers 1, 2, 4 and 5 and therefore had a significant influence on this dissertation’s findings. It is thus critical to evaluate the benefits and drawbacks of the tool.

The EnergyPLAN tool proved suitable for applying the smart energy system approach for the energy system analysis since it includes all energy sectors, considers current and future technologies and conducts analysis on an hourly resolution. The latter is particularly significant when analysing the integration of large amounts of variable renewable resources in future systems. Several of the papers find that the excess energy produced limits the integration of variable renewable sources; this could only be identified using a tool with high temporal resolution such as the EnergyPLAN tool.

Furthermore, the EnergyPLAN tool aided in the design of technical and economic alternatives to achieve a 100% renewable energy future. It did so by allowing for the development of multiple scenarios that can be compared and discussed in terms of their feasibility. The tool also enables the evaluation of socio-economic costs on a system-wide scale rather than solely for individual technologies or plants. This corresponds to the choice awareness theory, which highlights the importance of putting forward multiple alternatives and making clear that several choices exist.

Some shortcomings of the model were, however, also identified during the analysis. One of these is the lack of grid constraints in the tool since grids are modelled as copperplates. It could be relevant to analyse this concept further, particularly when considering a future with significantly larger shares of variable renewable energy, where the grid's capacity might be challenged by the many fluctuations in energy production. However, this is primarily an economic issue, since enhancing grids is not a technical challenge. The present analysis compensates for this issue to some degree by adding external costs for grid enhancements, but these are uncertain and may differ from cost requirements in reality.

The EnergyPLAN tool works by aggregating demands and supply for a large area, such as a country, and thereby neglects local scale differences and impacts. This is important since strategies that are feasible for an entire country might not be equally feasible for all local communities when considering the individual local contexts and challenges. However, this goes beyond the scope and purpose of the EnergyPLAN tool and should thus be addressed in additional analyses that utilize other tools more appropriate for this objective.

Finally, the EnergyPLAN tool optimizes the operation of an energy system based on a given simulation strategy (technical or market-economic). Numerous other tools work as investment optimization solvers to identify optimal investments for a system given certain constraints and targets [133]. This difference between models can be seen when examining the EnergyPLAN scenarios that might not find optimal solutions from an investment perspective. Hence, further cost reductions could be possible for the scenarios in this analysis. This situation arises due to the objective of the EnergyPLAN tool, which is intended to develop a range of alternatives (choice awareness perspective) and identify consequences of such a range of choices for the future energy system. Developing a similar number of alternatives would most likely not be possible when using an investment optimization tool that finds one solution, possibly accompanied by sensitivity analysis of that optimal solution [134]. The tool type is important to consider because this affects the choice of research methodology. In this work, a simulation tool was chosen to describe possible futures given a range of user inputs and the importance placed on various evaluation factors. This requires more of the user in terms of interpreting the outputs and the influence of various priorities. An optimization tool, on the other hand, provides one optimal solution from typically an economic perspective and hence requires less user interpretation.

Given the purpose of this dissertation, an optimization tool would not have allowed for the generation of a similar number of alternatives for 100% renewable energy systems nor the evaluation of individual technologies. For example, proposing only one optimal solution in Paper 5 would not have revealed the importance of choosing between either high biomass demand or overproduction of excess electricity. Moreover, the methodology applied in Paper 2 about solar thermal feasibility highlighted the significance of developing a range of alternatives. For example, some of the scenarios indicate that solar thermal will be less desirable when other renewable energy sources are integrated or when replacing CHP operation. These findings were only possible due to the simulation methodology, which allowed for the development of a large range of alternatives with different implications. The simulation approach in EnergyPLAN thus encourages further debate about how to prioritize the future energy system, rather than just proposing one “optimal” solution as suggested by the optimization tools. The “this one or none” argument described in the choice awareness theory is present when using optimization tools in this context. Hence, the use of such tools does not follow the second choice awareness theorem about putting forth a range of alternatives to make it clear that more than one option exists.

5.3. ALTERNATIVE EVALUATION FACTORS

Certain factors were used in the analysis to determine feasibility as specified in section 3.8. However, other relevant factors could also have been applied, which may have influenced the findings.

One such factor could be material consumption by technologies in future energy systems. Technologies like electrical vehicles and wind turbines require certain materials to produce (lithium for the batteries, rare earth minerals such as neodymium for wind turbine production). Studies have investigated whether these material reserves are sufficient to support a transition towards 100% renewable energy. For example, [161] and [20] find that this transition will not be constrained by the availability of these materials, but that some rare earth materials will have to be recycled or eventually replaced by other materials.

Another important issue is the inclusion of bioenergy as a renewable resource. This has been heavily debated in recent years [162,163] due to factors such as short and long term carbon cycles and political definitions of whether the carbon emissions should be included in the energy sector or the agricultural (LULUCF) sector. The sustainability of biomass combustion can therefore be debated and should be taken into account when considering limitations on CO_2-content in the atmosphere. If biomass was excluded from the analysis in this study, other energy sources or additional energy saving measures would be required. In Paper 5, all available renewable electricity sources are utilized and it is therefore difficult to find additional renewable sources to replace biomass. Despite this concern, possible solutions could involve further expansion of renewable sources, harnessing excess heat from district heating network expansions, additional hydropower production or importing excess energy from other regions. Furthermore, nuclear and CCS technologies could be options if going beyond the renewable energy definition in this study.

Some studies have developed strategies for converting to 100% renewable energy without any fuel combustion (i.e. no bioenergy) [164]. However, when examining the proposed solutions for Germany in the referenced study, the total load annually supplied from electricity sources is 1,982 TWh. Of this load, 99% is supplied by wind power and PV, meaning that the production from these technologies is 1,962 TWh, which significantly exceeds the available potentials found in Germany in Paper 5

(1,084 TWh). This naturally influences the biomass consumption in a future 100% renewable energy system.

Job creation is important to consider within the context of high renewable energy systems. Paper 5 proves that the energy system cost proportions change considerably when transitioning from the current system with high fuel costs to a future energy system with a larger proportion of investments. These investments are typically made in the areas where energy production facilities are located, which increases the demand for local workers and labour. Hence, transferring system costs from fossil fuel imports to investments in renewable energy facilities is expected to increase local job creation (see e.g. [160]). IRENA estimates that on average 8.6, 18.1 and 17.9 jobs are created per installed MW of onshore wind, offshore wind and PV plants in OECD countries, respectively [165]. Applying this to the German renewable energy systems analysed in Paper 5, achieving full renewable potential suggests that 1,800,000 jobs would be created due to onshore wind power expansions, 1,130,000 from offshore wind power and 4,650,000 from PV installations. The total job creation potential could thus be 7,500,000 from only these technologies. This number should be viewed across the entire time horizon towards 2050 and compensates for the number of jobs lost in the energy industries that will decline.

5.4. CHOICE AWARENESS AND 100% RENEWABLE ENERGY SYSTEMS

The choice awareness theory was used as the theoretical framework in this work for the analysis of 100% renewable energy. The theoretical findings are discussed in this section.

The choice awareness aspects included in this dissertation are the creation of technical alternatives and the execution of feasibility studies, see section 3.3. Paper 1 and 2 are examples of creating alternatives for specific technologies in the perspective of high-renewable energy systems. The creation of alternatives revealed the importance of the energy system context and the choices that are made for the energy system. It was demonstrated that in some scenarios the specific technology (i.e. solar thermal) was beneficial while under other conditions the effects on the energy system were less advantageous. These findings can be used for debating and planning for the role of this technology and whether it should be given priority above other technologies.

In Paper 3 and 4 methods for feasibility studies were analysed. By comparing two different methods the importance of selecting appropriate feasibility methods were demonstrated. This is vital to consider when making long-term energy policies based on cost-efficiency.

Finally, in Paper 5, alternatives were developed for a national energy system for achieving 100% renewable energy. The alternatives vary in terms of the biomass consumption and variable renewable energy constraints. By creating these alternatives it was shown that trade-offs must be made between either exceeding biomass potentials or accepting high excess electricity production. These only became clear from the creation of multiple alternative scenarios that might afterwards be debated for priority making in the energy transition policies. The feasibility of the alternatives are influenced by the energy system context and the creation of alternatives is the method for demonstrating this.

This dissertation does not include a detailed analysis on the implementation of the proposed renewable energy alternatives. However, by employing the choice awareness theory, valuable insights can be gleaned regarding some key considerations for future implementation. The theory emphasizes the radical technological change that will occur when transitioning from a fossil fuel to a renewable energy system. The change can be considered radical when more than one of the four defining elements of a technology changes: technique, knowledge, organization and product.

In the transition discussed here, the element of technique will change as fossil fuel power plants are replaced by smaller plants utilizing e.g. wind or solar energy. These new power facilities will require new organization. This will cause a shift in the existing structure in which typically large companies produce energy centrally at only a few locations, to a more distributed system in which energy is produced at many locations. This will have a significant influence on the ownership of energy technologies. Furthermore, knowledge of the energy system and technologies will be altered because new technologies are required to harvest local resources rather than importing fossil fuels from abroad. This necessitates new ways of distributing knowledge, possibly also because consumers can become co-owners of energy plants such as wind turbines and other local energy technologies. Hence, multiple elements of the technology will change; this transition can therefore be defined as a radical technological change.

Barriers to implementation of the renewable alternatives include issues related to the time horizon needed to carry out the measures. One critical measure is the refurbishment of buildings to achieve the heat savings suggested in the analysis (30-50% of the heat demand in 2050). These savings require that existing buildings be refurbished throughout the entire period, starting today and continuing all the way to 2050, as refurbishment rates are often around 1% per year. New buildings typically have lower energy demands, but the new build rate is also too low to accommodate the necessary energy savings. Hence, it is imperative that refurbishments start in earnest today and that the rate of refurbishment be increased considerably in the future. Otherwise, energy savings will not reach target levels and the system will experience higher energy demands. This would put even further pressure on scarce resources such as biomass.

5.5. ORIGINALITY AND BENCHMARKING

This dissertation has contributed to the research area of 100% renewable energy systems in various aspects. These contributions include creating an overview of existing research to outline main tendencies in the literature and for defining areas where further research is required. The literature review showed that research for certain regions of the world is scarce and that the majority of studies focus on the electricity sector solely or in combination with more energy sectors. In addition, the most common energy system analysis tools are based on investment optimization approaches. The work in this study has moved beyond these tendencies by focusing on all energy sectors from a simulation approach.

A different contribution regards the analysis of the role of technologies and solutions that have not previously been analysed in the perspective of 100% renewable energy systems. The influence of variable heat production from solar thermal facilities is analysed in a range of alternative scenarios, which has previously not been analysed. Furthermore, novelty is also demonstrated by analysing heat savings with two different methods and comparing these.

This dissertation also analysed energy costs for energy carriers that are not usually analysed as heating and cooling costs have only been analysed in few studies previously. In addition, two methods for estimating energy costs have been compared in a manner that is new to the research field. The LCOE method has been analysed in great detail previously, but comparing it with another method brings new evidence to an old issue.

This dissertation has conducted systematic analysis and testing of the smart energy system concept by applying it to the case of Germany. This demonstrates the use of an existing approach in a new area or for a new case where it has not been used before. From these analyses, it was found that the use of the smart energy system method also affects the results. For example, in relation to the order of implementing certain measures (heat savings and district heating expansions) and the need for boosting biomass resources with hydrogen according to the available biomass resources.

These contributions demonstrate originality through looking at areas that people in the discipline did not investigate previously.

The main solutions and findings in Paper 5 are in some ways similar to the general findings in the existing literature and are in other ways different. The literature review showed that a large share of the current research primarily focuses on solutions within one of the following areas: the supply side (RES integration), conversion, exchange and storage (electricity storages, electric vehicles, heat pumps, etc.) and to a lesser degree on changing energy demands. By contrast, Paper 5 finds that all three types of solutions are crucial and, in particular, changes to the demand side are vital if the ambition is to achieve a 100% renewable energy system using only domestic resources. Some recent studies focus on the importance of interconnections between countries to share excess energy production in an effort to optimize resource use. Electricity storage is likewise seen as a key solution in some studies to integrate large shares of variable electricity production. These two solutions are not supported by the analysis in Paper 5. Interconnections are found to have only a minor influence on a system's ability to integrate large amounts of variable renewable electricity, with other solutions proving more important. Similarly, electricity storages are not found to be crucial due to their effect on energy system costs and because other solutions are more feasible. The smart energy systems approach of integrating energy sectors is seen as more significant than the inclusion of these measures When integrating sectors, there is less need for electricity storages as energy is stored in other energy carriers such as heating.

In general, Paper 5 supports the overall trend in the literature demonstrating that it is possible to design 100% renewable energy systems for the future. The existing literature is less clear about the effect of this transition on energy system costs, while the analysis in this dissertation indicates that costs will be on par with the fossil fuel alternatives.

CHAPTER 6. CONCLUSIONS AND FURTHER WORK

The work in this dissertation answered the following research question:

How can the analysis of technical and economic alternatives for energy systems and technologies support the design of 100% renewable energy systems?

The conclusions from this work can be divided into three categories: theoretical, methodological and analytical conclusions. The theoretical conclusions reflect on the appropriateness of the choice awareness theory in relation to 100% renewable energy systems. The methodological conclusions are concerned with using the smart energy system approach and the suitability of the EnergyPLAN tool. Finally, the analytical conclusions summarize the key findings from the analyses of technologies, methods and energy system design alternatives for 100% renewable energy systems.

6.1. THEORETICAL CONCLUSIONS

The choice awareness theory was applied as the theoretical framework for this dissertation. It was used to guide the methodological approach by developing a range of alternatives to show that more options are available for the development of future energy systems. A simulations approach was applied in the analysis to support the development of alternatives. In Paper 1 and 2 alternatives for specific technologies were created in the perspective of high-renewable energy systems. The alternatives were used to discuss under which conditions these technologies perform best and which role they might have in a 100% renewable energy system. Moreover, alternatives were created for the German energy system varying in terms of certain key parameters related to energy supply. By creating these alternatives it was shown that trade-offs must be made between e.g. exceeding biomass potentials or accepting high excess electricity production. These only became clear from the creation of multiple alternative scenarios that might afterwards be debated for priority making in the energy transition policies. The feasibility of the alternatives are influenced by the energy system context and the creation of alternatives is the method for demonstrating this.

In addition, other analytical methods were scrutinized in terms of how they facilitate the analysis and how they influence the results of feasibility studies. The choice of feasibility evaluation method significantly affects the choices of future energy priorities as demonstrated in Paper 4, which used costs as the primary indicator of feasibility. Other evaluation factors will influence the energy priorities in a different direction.

The energy systems proposed in this analysis require radical technological changes as defined by the need to alter multiple technological elements. For example, the technologies in the energy system will shift from large centralized (fossil fuel) plants to a higher share of decentralized generation units, which necessitates a new organizational framework.

6.2. METHODOLOGICAL CONCLUSIONS

The methodological conclusions relate to 1) the smart energy systems approach used to guide the methods in the analyses and 2) the concrete methods applied.

From a methodological perspective, applying the smart energy systems approach to analyse the full energy system was concluded to be vital to the dissertation. Numerous aspects that might have been ignored or neglected when using a single-sector/technology approach were instead highlighted and discussed. Concretely, a variety of energy system dynamics spanning across energy sectors, such as the heating and electricity sectors, could have large effects on overall system feasibility. This approach was supported by using a simulation tool for the development of alternative scenarios.

The literature review showed that a large share of the current research primarily focuses on solutions related to just one of the following areas: the supply side (RES integration), conversion, exchange and storage (electricity storages, electric vehicles, heat pumps, etc.) and to a lesser degree on changing energy demands. In this dissertation, all three types of solutions were found to be crucial and, in particular, changes to the demand side are of vital importance if the ambition is to achieve a 100% renewable energy system within available renewable resources.

The EnergyPLAN energy system analysis tool was applied for the majority of the analytical work and therefore had a major influence on the constraints and possibilities of the analysis. The tool proved valuable in designing a large range of alternatives to analyse both individual technologies and entire energy system designs. The greatest advantages of the tool are its ability to evaluate a range of factors, its short computation time, its inclusion of all energy sectors and technologies and its ability to design alternatives for radical technological changes. However, some drawbacks were also identified including the minimal focus on grid constraints and the limited possibility to integrate variable renewables on a more disaggregated level.

6.3. ANALYTICAL CONCLUSIONS

The overall conclusion of the analysis in this dissertation is that the design of 100% renewable energy systems is possible and that no single solution or technology will enable this. Various 100% renewable energy system alternatives were designed for the German energy system in 2050; these indicate that the most significant challenges include energy demands on one the side and renewable energy potentials on the other, especially biomass potentials. There will be substantial pressure on future renewable energy potentials, even when considering lower energy demands due to savings and system efficiency enhancements. Paper 5 demonstrated that the overproduction of variable electricity reduces the overall biomass requirements without increasing energy system costs.

Uncertainties were identified as part of this analysis when considering future energy systems towards 2050; for example, uncertainties exist in relation to energy technology developments, fuel prices, and technology prices. These will affect the overall energy system costs as well as the preferences for different technology paths within e.g. the transport sector.

Future technologies in a 100% renewable energy system will play different roles; some will enable higher rates of renewable energy penetration, some will enhance and support system flexibility while others will improve system efficiency and reduce energy losses. These roles are to a large degree determined by the context in which technologies are installed as exemplified in Paper 2, where installing more solar thermal energy influenced the overall energy system in various ways depending on the scenario. For example, solar thermal energy was less feasible in scenarios where other renewable heating sources were also integrated because this reduced the flexibility of the system and thereby increased the overproduction of heating. Furthermore, one example showed that installing more solar thermal energy could actually increase CO_2-emissions due to the interaction with CHP plant operation. Hence, the system design and context are both crucial for developing 100% renewable energy system alternatives and there is no one-size-fits-all solution.

Future 100% renewable energy systems will be more efficient in terms of primary energy supply compared to existing systems due to energy savings and the integration of technologies with less energy losses. Moreover, the analysis showed that the overall energy system costs in the proposed alternatives remain similar to the current system, but a high proportion of fuel expenses is shifted to a larger share of investments and O&M costs.

All energy carriers are valuable in the energy system as witnessed in Paper 3, despite the dominating trend in the literature of analysing primarily the electricity sector. Utilizing a combination of energy carriers grants the ability to store and convert energy to the benefit of each individual sector as well as the overall energy system.

6.4. FURTHER WORK

This dissertation contains important aspects that will advance the research field of 100% renewable energy systems. However, one study cannot cover all necessary aspects within a given field and further work is thus required. Such work could concern:

- Application to additional energy system types

Other types of energy systems should be analysed using the smart energy systems approach, as this has not been sufficiently done to date (see 0). Future studies could evaluate systems outside of Europe, which is the most frequent geographical scope of the smart energy systems approach. These systems could be located in developing countries, on a more local scale, such as for cities, and in different energy system configurations such as island systems and larger regional or global systems.

- Further refinement of data inputs

A large portion of the data used in this work, including costs, efficiencies and future technology development, comes from Danish references. This is because of data availability, especially when considering heating technologies. However, it would be relevant to investigate whether other data, such as for labour costs, would influence the results.

- Saving potentials for industries and electricity

The savings potentials for the industrial and electricity sector in this work are mostly based on estimates; hence, deeper analysis could be beneficial. This would also provide further details about costs for these types of measures.

- Further analysis of transport sector measures

Two types of further analyses should be carried out with respect to the transport sector. Firstly, further analysis of possible transport technology pathways could be included concerning, for example, eRoads and the production of nitrogen based transport fuels rather than carbohydrate based electrofuels. Secondly, measures for reducing transport demand could be implemented such as modal shifts, changing driving patterns, urban planning, etc.

- Further analysis in the cooling sector

The cooling sector was not analysed in sufficient detail in this work due to its insignificant influence on the overall energy system. However, this could change when investigating other energy systems where heating is less important and cooling is more significant, for example in the Middle East and Africa. In general, district cooling as a possible measure should be further analysed.

- Further analysis of grid constraints

Due to the lack of focus on grid constraints in the EnergyPLAN tool, it could be interesting to analyse this aspect using other tools that are better suited to this task. This would provide further insights about how future energy grids should be designed.

- Full choice awareness analysis

This dissertation only applies the first two steps of a full choice awareness methodology; hence, further studies could analyse the remaining two steps, which address market structures and democratic infrastructures.

- Implementation of 100% renewable energy alternatives

Limited attention has been paid to the implementation of the suggested 100% renewable energy system alternatives in this dissertation. This is, however, an imperative consideration because the implementation process could favour some alternatives over others and it must be ensured that changes would actually be initiated towards 100% renewable energy systems. Appropriate topics to study could include policy, regulation, relevant actors, etc.

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APPENDICES - PUBLICATIONS

This appendix includes the publications that form this dissertation. The supplementary material and appendices to the papers are not included here, but can be found in their full version in the publisher databases.

The original sources for the papers are:

Primary publications:

- Paper 1: Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat, Energy, 2016, doi:10.1016/j.energy.2016.06.033 [1]
- Paper 2: Comprehensive assessment of the role and potential for solar thermal in future energy systems, Solar Energy, 2018, 169:144–52. doi:10.1016/J.SOLENER.2018.04.039. [2]
- Paper 3: Comparison of Levelized cost of Energy across electricity, cooling and heating, Working Paper, 2018 [3]
- Paper 4: Decision-making based on energy costs: Comparing Levelized Cost of Energy and Energy System costs, Submitted to Energy Strategy Reviews, 2018 [4]
- Paper 5: Full energy system transition towards 100% renewable energy in Germany in 2050, Submitted to Sustainable and Renewable Energy Reviews, 2018 [5]

Secondary publications:

- Beyond sensitivity analysis: A methodology to handle fuel and electricity prices when designing energy scenarios, Energy Research & Social Science, 2018;39. doi:10.1016/j.erss.2017.11.013 [6]

PAPER 1

1

Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat

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Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat

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ABSTRACT

The cost of heat savings in buildings increase as more heat savings are achieved and hence, alternatives other than savings typically become more economically feasible at a certain level of heat reductions. The challenge addressed in this paper is to identify when the cost of heat savings become more expensive than the cost of sustainable heat supply, so society does not overinvest in heat saving measures. This study first investigates the heat saving potentials for different countries in Europe, along with their associated costs, followed by a comparison with alternative ways of supplying sustainable heating. Furthermore, the levelised cost of supplying sustainable heat is estimated for both a single technology and from an energy system perspective. The results are analysed by assessing various parameters such as socio-economic costs and energy efficiency improvements in the national energy systems. The results demonstrate the economically feasible levels of heat savings and heat production for various European countries, highlighting differences in their national conditions and energy systems. The findings in this paper indicate that overinvestments in heat savings can be avoided by saving heat until a level around 30–50% of projected heat demands and supplying the remaining heat demand with sustainable heat sources.

1. Introduction

This paper presents two distinct methods and analyses for assessing the balance between heat savings and heat supply for various European countries. The purpose is to shed light on the debate about feasible levels of heat savings and the different methods that can be used to analyse this. If this balance is not identified societal overinvestments could be the outcome. Currently little knowledge is available about feasible levels of heat savings and how these are impacted by local conditions and settings. This paper therefore contributes with possible methods for analysing the relation between heat savings and heat supply and presents the findings when applying these methods.

The European Union targets of achieving 27% energy efficiency improvements by 2030 compared to projections will be a challenge to meet. Therefore, it is important to identify the balance between heat savings and heat supply as both of these might have a role in achieving these efficiency targets [1]. Similarly, the affordability to achieve this target will be vital. Energy efficiency and renovation of buildings is recognised as beneficial in the European Commission: "*Investments in this area [building renovations] can provide great returns in terms of growth and jobs*" [1], page 13.

All EU member states are obliged to "*… carry out and notify to the Commission a comprehensive assessment of the potential for the application of high-efficiency cogeneration and efficient district heating and cooling*" [2], page 20. It is therefore relevant to analyse for each member state the feasible level of heat supply in order to accommodate feasible heat production through the potentials for cogeneration and district heating and cooling [3]. This paper contributes with analyses of the roles of heat savings and heat supply and how these are both crucial for a future low-carbon society.

The hypothesis in this paper is that there is a certain level where it becomes more economical to supply heat rather than continuing to save heat, see Fig. 1.

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If this hypothesis is valid it means that it will not be possible to simply use savings as the only measure to improve the future energy systems. The three questions that will be answered are:

- What are the heat savings potential for various European countries?
- What is the unit cost of heat supply for various heat supply technologies in the future?
- At which point does it become more economical to supply heat rather than saving heat for various European countries applying two different methods?

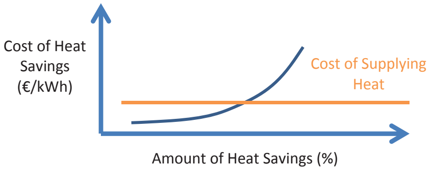

Fig. 1. Theoretical illustration of the relation between cost of heat savings, the amount of heat savings and the cost of heat supply.

Heat saving strategies have recently been described in a number of studies focusing on decarbonising the European heating and cooling sectors through a combination of heat savings and district heating [4] and by implementing energy efficiency in buildings across Europe [5] [6]. Other studies focus on similar research areas, but on a national scale for Denmark [7], including potential barriers for renovating buildings such as tariff systems and the need for a financial reform in a Danish context [8]. Studies also focus on different ways and strategies of achieving heat savings in multi-storey buildings [9] and for specific energy sectors such as the paper industry [10]. Some of these strategies relate to improving single technologies such as industrial heating technologies [10] while others focus on energy savings through improved efficiency in buildings across EU-27 [11]. These studies show that heat savings are vital if a future low-carbon energy system is to be achieved.

Several studies also conclude that heat savings cannot stand alone and that heat supply in the future will also be necessary through efficient heating technologies such as district heating [12] to avoid unfeasible investments in building refurbishments [13] [14]. This is in particular the case since there is a mismatch between the consumption in net zero-emission buildings and the production in the energy system [15]. Heat savings is therefore not the only measure required for achieving a low-carbon energy system and research therefore focus on sustainable heating technologies such as expansion of district heating in both Denmark [16,17] and in Germany [18], integration of electricity in the heating sector [19,20] and improved storage options [21]. Other studies find that net zero energy buildings must be coordinated with the heat supply networks in order to integrate excess heat from solar thermal into the remaining energy system [22].

However, only few attempts of quantifying the balance between heat savings and heat supply have been developed so far and only for national systems such as Denmark [7] [23] and the UK [24] or on urban district scale [25]. In Ref. [26] optimal private investments are considered for both heat demand and heat supply and an additional focus is on health damage costs of particle emission from heat supply technologies. The balance between heat demand and supply is considered for a community near San Francisco in Ref. [25] focusing on costs, carbon dioxide emissions and system efficiency while [24] emphasises the role of domestic energy efficiency in the United Kingdom without further assessment of feasible saving levels. Single-country assessments are also part of [7,23] while [27] analyses Europe as a single entity.

These studies therefore only present single-country assessments and do not draw comparisons between multiple countries or comparisons between different methods.

This paper therefore contributes with new types of analyses in more detail applying two different methods for quantifying the balance between heat savings and heat supply for various countries. The findings presented here provides the first attempts of quantifying this balance between heat savings and heat supply in multiple national energy systems. In addition, this is the first time a comparison is carried out for two different methods of assessing the balance between heat savings and supply.

The background for this paper is the research project called STRATEGO, financed by the Intelligent Energy Europe, with the aim of supporting the development of enhanced heating and cooling plans for national authorities in European countries. The STRATEGO project combines research from a number of universities and private partners in order to develop future energy efficient Heat Roadmap scenarios with low-carbon heating and cooling sectors for the Czech Republic, Croatia, Italy, Romania and the United Kingdom and builds on top of the previous Heat Roadmap Europe pre-studies [28–31]. Focus in the STRATEGO project is on energy efficiency on both the demand and supply side of the heating sector, while the focus in this paper solely is on energy efficiency improvements on the demand side.

This paper is structured with a description of the methods applied in Chapter 2 for heat savings potentials and associated costs followed by a description of the two methods that are compared for assessing feasible balances between heat savings and heat supply. Chapter 3 then presents the main results and findings for both of these two methods and finally, the conclusions are summarised in Chapter 4.

2. Methods

This paper compares heat savings to heat supply by comparing different heat saving levels and the impacts on the Economy (socio-economic costs), Energy (Primary Energy Supply) and Environment (Carbon Dioxide Emissions). This allows for considering a variety of metrics when identifying heat saving levels and ensuring that for example reductions in energy demand is accompanied by acceptable changes to the socio-economic costs. If only considering a single metric such as the energy demand the maximum technical saving potential should be implemented regardless of costs and would then only be limited by implementation concerns.

First, the heat saving potentials and costs are presented followed by two different methods for balancing heat savings and heat supply: a Levelised Costs approach and an Energy Systems approach.

2.1. Heat saving potentials and costs

Heat savings will play an integral part of a future decarbonized energy system as previously described, but the question is how much is feasible and how it differs between different countries according to the conditions of the local energy systems. A method is developed in Ref. [32] to assess heat saving potentials along with the associated costs of implementing these for different countries using the BEAM (Built Environment Analysis Model) tool [33]. Further documentation of the BEAM tool as well as the input data used to calculate the energy saving costs are available from Ref. [32]. The tool focuses solely on the buildings in a country and is used to project respectively a future reference and energy efficiency

Table 1
Retrofit, New building and Demolition rates assumed for Czech Republic, Croatia, Italy and Romania for the modelling of heat savings potentials using the BEAM tool. *SFH = Single-family houses.** MFH = Multi-family houses.

Rates	Retrofit	New building	Demolition
Czech Republic	For all components of the building envelope increasing from 1.0% p.a. to 1.5% p.a. (0.1% p.a. increase per year)	0.95% p.a. for SFH* and 0.65% p.a. for MFH** and non-residential buildings	0.2% p.a. for all buildings
Croatia	1.0% p.a. for all buildings	1.0% p.a. for all buildings	0.5% p.a. for all buildings
Italy	3.0% p.a. for all buildings	1.0% p.a. for all buildings	0.35% p.a. for all buildings
Romania	For all components of the building envelope 1.7% p.a.	0.64% p.a. for residential buildings 2.0% p.a. for non-residential buildings	0.2% p.a. for all buildings

path for each country including the development of the building stock as a function of demolition rate, new building activity, refurbishments and energy efficiency measures in retrofits. The investment costs applied are based on [13] while the assumed retrofit, new building and demolition rates are presented in Table 1 below.

The output from the BEAM modelling resulted in data illustrating the potential heat demand savings as well as the associated costs split between wall, roof & cellar and windows as illustrated in Fig. 2 and Fig. 3. It is noteworthy that it is only the space heating demand that is reduced while the hot water demand increases due to the assumptions related to growing population and floor area and that the analysis only included residential and services buildings. The heat saving costs are assumed to be carried out as other renovations take place, hence making the costs lower than if they are implemented without other renovations [34].

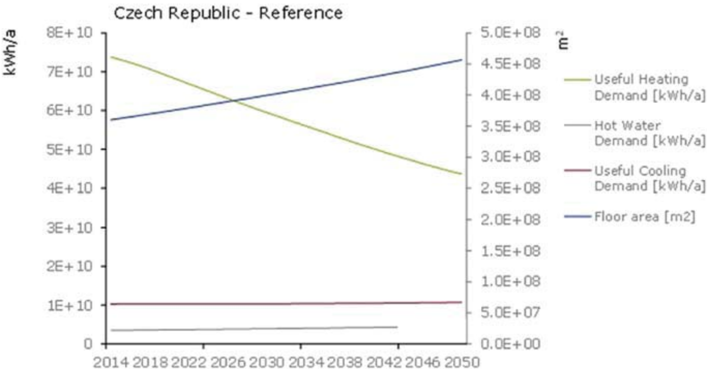

Fig. 2. Development in space- and hot water demand in the efficiency paths along with the changes in cooling demand and floor area. The figure illustrates the changes in the Czech Republic as an example [32].

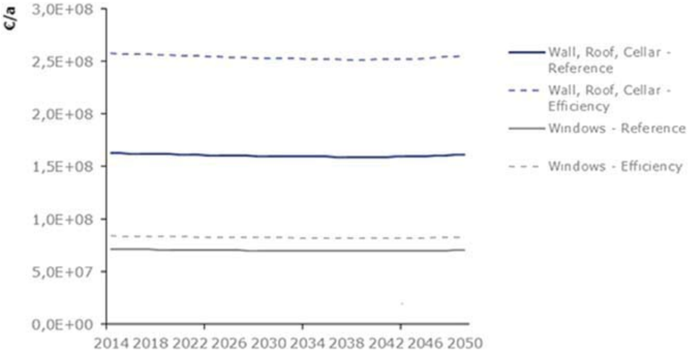

Fig. 3. The investments for Wall, Roof, Cellar and Windows in respectively the reference path and the efficiency path for obtaining heat savings in the Czech Republic as an example [32].

These heat saving potentials and costs are subsequently annualised applying an interest rate of 3% and a lifetime of 25 years for windows and 40 years for walls and roofs. The accumulated annualised costs are then compared to heat savings as a share of the heat demand in 2014, see Fig. 4.

The slope of the curve for the Italian annualised costs increases faster than for the other countries when achieving similar heat saving shares because the Italian building stock today has a lower kWh/m^2 demand than in the other countries and hence the benefits from new windows and insulation measures are smaller. These heat saving potentials and costs form the foundation for the analysis of feasible levels of heat supply that are presented in the next sections.

2.2. Two methods for balancing heat savings and heat supply

In order to identify the balance between heat savings and heat supply two different methods for assessing the feasible amount of heat savings are compared.

Firstly, a Levelised Costs approach calculates the future costs of various heat supply technologies in order to develop a heat supply unit cost range in both 2010 and 2050. This approach calculates a theoretical heat supply cost that will be compared with the heat saving curves presented previously.

Secondly, an Energy Systems approach where the feasible level of heat savings is analysed when implementing heat savings in a complete energy system perspective. This approach also accounts for all the potential impacts and synergies that the heating sector may impose on other sectors and that other sectors might impose on the heating sector.

Fig. 4. The accumulated annualised costs for heat savings in relation to today's heat demands for Romania, Czech Republic, Italy and Croatia [35].

The characteristics of the two methods to identify the balance between heat savings and heat supply are described in Table 2.

2.2.1. Levelised costs approach

The first approach, the Levelised Costs approach calculates a future heat supply unit cost that is then compared to the heat savings costs. In this way it will be possible to identify cut-off points by developing a graph showing the heat saving costs on one axis and the unit costs of heat supply on the other axis and finding the point where the two curves intersect.

The unit cost of heat supply is calculated based on the assumption in Table 3 below.

The heat production costs for the various technologies are depicted in Fig. 5 indicating the unit heat production costs for both 2010 and 2050. The lowest unit heat supply costs are in 2010 for district heating around 0.06 €/kWh while heat pumps are expected to have the lowest production costs in 2050 around 0.07–0.08 €/kWh. On the other hand, electric heating and oil boilers have the

Table 2
Characteristics of the two methods for balancing heat savings and heat supply, respectively the Levelised costs approach and the Energy System approach.

Characteristics of the two methods	Levelised costs approach	Energy system approach
Calculation of heat supply unit cost	A heat supply unit costs range is calculated	Can potentially be calculated
Calculation of total energy system costs	Not possible	A total cost for the entire energy system
Identification of specific cut-off point	A cut-off range can be identified according to the heat supply unit cost assumed in the future	A specific cut-off point can be identified (in steps of 10%)
Impact on other sectors than heating	Not possible	Direct and indirect impacts across sectors
Ability to measure impacts on metrics	Not possible	Measures impacts on both economy, energy and environment

Table 3
Assumptions applied for calculating levelised costs for a number of heat supply technologies for the years 2010 and 2050.

Heating system	Oil boiler	Natural gas boiler	Biomass boiler	Heat pump air source	Heat pump ground source	Electric heating	District heating
Specific investment (1000€/unit)	6.6	5	6.75	12	16	8	2.5
Technical lifetime (years)	20	22	20	20	20	30	20
Annual Investment[a] (€/year)	444	251	454	672	874	408	202
Fixed O&M (€/unit/year)	270	46	25	135	135	80	150
Efficiency	100%	102%	87%	330%	350%	100%	98%
Annual Fuel Consumption[b] (MWh/year)	15	15	17	4.5	4.3	15	15
2010 Fuel Cost[e] (€/MWh)	32	36	32	65[d]	65[d]	65[d]	36[d]
2050 Fuel Cost[e] (€/MWh)	65	54	41	83[d]	83[d]	83[d]	51[d]
Annual District Heating Pipe Costs (€/MWh)[c]							4

[a] Assuming an interest rate of 3%.
[b] Annual heat demand of 15 MWh/year.
[c] Based on the cost of conventional district heating networks in existing areas [38].
[d] Assuming the electricity/heat is produced from a combined cycle gas turbine and based on the cost assumptions in the EnergyPLAN Cost Database [37].
[e] Based on the cost from the European Commission [36], with the addition of fuel handling costs [37]. Carbon dioxide costs are not included here.

highest unit costs for heat production in both 2010 and 2050 at around 0.10–0.13 €/kWh. These extremes are used to define a range for the future unit heat supply costs based on the Levelised costs approach and is represented as the grey band in Fig. 5.

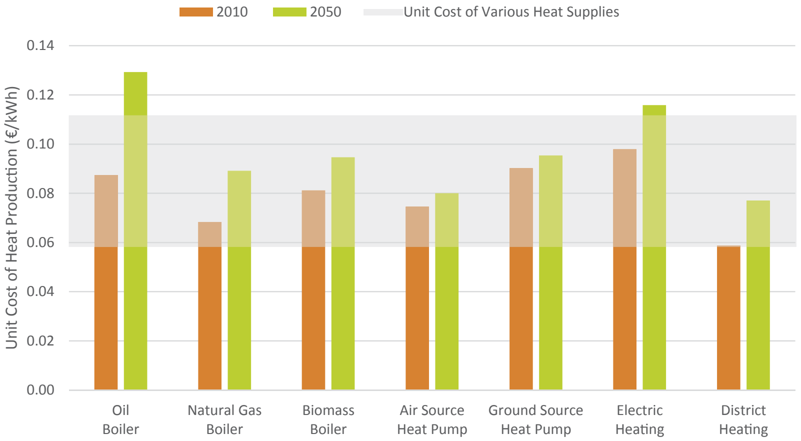

Fig. 5. Unit cost of heat production for various heat supply technologies in the years 2010 and 2050. The grey band represents the highest and lowest unit cost for heat supply when selecting the lowest unit cost of any supply technology (district heating in 2010) and the highest unit cost of heat supply in 2050 (electric heating/oil boiler in 2050). This grey band is used for estimating the unit cost range of heating technologies and is compared to the costs of heat savings for identifying a feasible balance between the two measures.

2.2.2. *Energy system approach*

For the second approach, the Energy System approach, the heat production costs are determined based on the supply mix in the national energy systems and it is therefore not necessary to calculate a unit cost for heat production for the different countries. Instead, the socio-economic costs are calculated for the entire energy system applying the comprehensive energy system analysis tool called EnergyPLAN that hour-by-hour models the national energy systems over a full year, see Fig. 6. The socio-economic costs for the energy system are calculated based on a cost database compiled over a number of years and applying an interest rate of 3% and no taxes are included in the socio-economic costs calculations [37]. The EnergyPLAN model as well as the accompanying models and cost assumptions are available online from Refs. [40], which allows for replication of the modelling results. EnergyPLAN therefore focuses on the dynamics in the energy system while the BEAM tool is buildings focused and is used to develop inputs for the EnergyPLAN tool.

EnergyPLAN is a deterministic model that simulates the operation of a national energy system and is used by many researchers, consultancies and policymakers worldwide. The model is designed so that it can accommodate radical technological changes in the energy system with high shares of renewable energy and is therefore able to model future low-carbon scenarios. The EnergyPLAN model has been applied in numerous studies of national energy systems such as Denmark [41–43], Hungary [44], Croatia [45], Serbia [46], Ireland [47] and China [48] for different purposes such as integration of fluctuating renewable energy, energy efficiency improvements in the heating sector and integration of renewable energy in the transport sector. The EnergyPLAN model includes all sectors in the energy system (Heating, Cooling, Electricity, Transport, and Industry) and it is therefore possible to measure the indirect impacts that energy efficiency measures in the heating sector causes on the other sectors and thereby to identify possible synergies and dynamics across sectors [39,49]. The model is based on a full energy sector approach in opposition to alternative models that investigate individual sectors of the energy system [50].

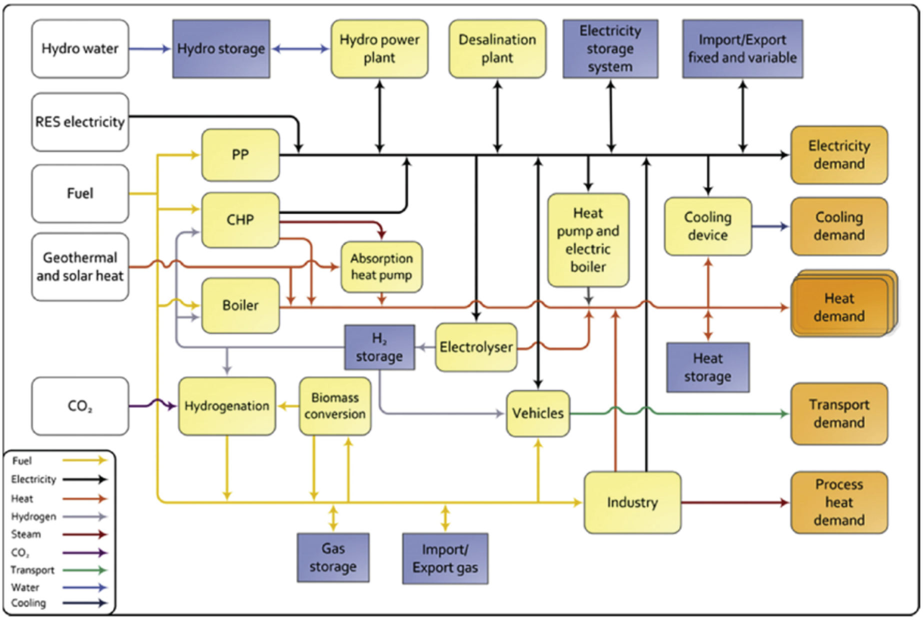

Fig. 6. The structure of the EnergyPLAN tool that analyses changes in all sectors of the energy system [49] [39].

The specific method for the Energy System approach includes a reduction of the heat demand in intervals of 10% and for each interval the corresponding costs of achieving those heat savings are identified in a total energy system perspective. The least cost level of heat savings is identified where more or less heat savings will increase the overall costs. This allows for finding a specific feasible level of heat savings in each country along with the impacts on socio-economic costs, energy demand and carbon dioxide emissions for the heat saving levels.

3. Results and discussion

The results are presented for the Levelised Costs approach and the Energy System approach respectively.

3.1. Levelised costs approach

The results applying the Levelised Costs approach combining the unit costs for heat supply and the heat savings potentials and costs are illustrated in Fig. 7 indicating the feasible levels of heat savings before heat supply become more economical.

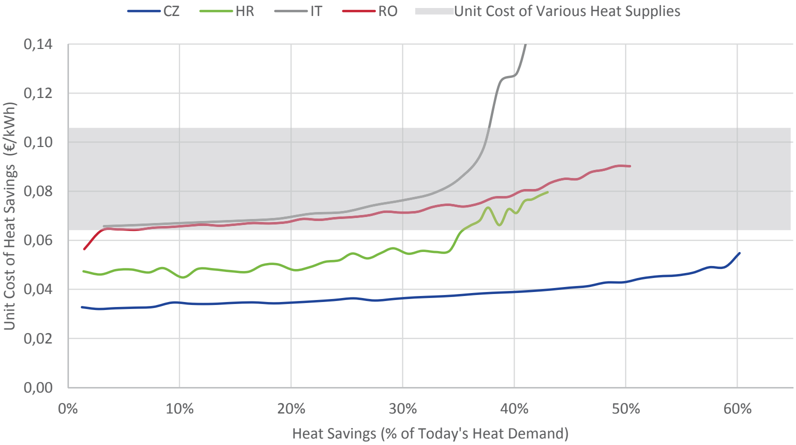

Fig. 7. Unit cost of heat savings compared to the unit cost of heat supply and the heat savings levels shares of today's heat demand. The figure can be used to identify feasible levels of heat savings before it becomes more economical to supply heat according to the assumed unit cost of heat supply. Heat savings are assessed for each country while the heat supply is generic for all countries.

Table 4
Feasible levels of heat savings according to the assumed unit cost heat supply for the Czech Republic, Croatia, Italy and Romania as well as the heat intensities for the different heat supply costs.

Heat savings feasible (% of today's	Cost of heat supply €0.06/kWh	Heat intensity kWh/m^2	Cost of heat supply €0.11/kWh	Heat intensity kWh/m^2
Czech Republic	60%	66	60%	66
Croatia	35%	70	45%	60
Italy	0%	100	40%	55
Romania	3%	120	50%	50

The figure shows the heat savings unit costs versus the heat saving levels and the range of heat supply unit costs.

Assuming the heat supply technology with the lowest heat supply unit cost can cover the entire heat demand, the heat savings levels should be between 0 and 60% of today's heat demand (0% for Italy and up to 60% for the Czech Republic), see Fig. 7. The highest heat supply cost indicates that the heat savings should be between 40 and 60% of today's heat demand for the different countries (around 40% for Italy and up to 60% for the Czech Republic). The heat intensity with the low heat supply unit cost is in the range of 65–120 kW h/m^2 (lowest in Czech Republic and highest in Romania) while the high heat supply unit costs leads to higher heat savings and hence a lower heat intensity around 50–65 kW h/m^2, see Table 4. It is however unrealistic to believe that the future heat production mix will consist of only one type of technology and a mix of low and high unit cost technologies is therefore to be expected. It is therefore not clear exactly where the cut-off point for each country should be as this is somewhere in between these two extreme heat supply unit costs.

3.2. Energy system approach

When applying the Energy System approach no heat supply unit cost is calculated since the heat savings also impact other sectors and types of investments than in the heating sector.

The results when applying the Energy System approach shows that the feasible levels of heat savings are between 30 and 50% for the four countries, see Table 5.

The heat intensities for the countries after heat savings with the Energy System approach is between 60 and 110 kW h/m^2 (with the lowest heat intensity in Romania and the highest in the Czech Republic).

Another benefit from applying an Energy System approach is that it is possible to quantify the impacts for the energy system on economy, energy and environment when implementing heat savings, see Table 6.

This means that for e.g. Romania 50% heat savings leads to socio-economic cost reductions of 13% in the heating, cooling and electricity sectors combined compared to the business-as-usual scenario where no additional actions are implemented.

The results applying the Energy Systems approach proves that feasible heat saving levels across all four countries can reduce socio-economic costs, primary energy demands and carbon dioxide emissions.

4. Discussion

The results for the Levelised Costs approach suggests that the heat savings levels could vary between 0 and 60% for the different countries with the cheapest unit cost of heat supply as the cut-off point. This may suggest that the heat saving levels in countries such as Italy and Romania should be close to 0% and up to 60% in countries such as the Czech Republic. However, when analysing the heat saving levels from an Energy System approach the heat saving levels with the least costs were between 30 and 50% for the different countries. These differences are most likely due to the synergies and dynamics that occur across the different sectors in the energy system when applying the Energy System approach

Table 5
Feasible levels of heat savings and the associated investments when applying the energy system approach for the Czech Republic, Croatia, Italy and Romania.

Heat saving levels and costs applying the energy systems approach	Heat saving level with lowest costs	Heat intensities	Annualised investment cost for the heat savings	Unit investment cost for the heat savings
	Reduction as % of the BAU 2050 heat demand[a]	kWh/m^2	M€/year	M€/TWh
Czech Republic	40%	110	2350	70
Croatia	40%	65	535	69
Italy	30%	71	8500	77
Romania	50%	61	3700	78

[a] The BAU (Business-as-usual) demands are established according to projections from Ref. [36].

Table 6
Heat savings impacts in the Heating, Cooling and Electricity sectors compared to the business-as-usual scenarios for Czech Republic, Croatia, Italy and Romania when applying an energy system approach.

Heat saving impacts compared to the Heating, Cooling and Electricity sectors in the Business-as-usual scenarios	Economy	Energy	Environment
	% change in socio-economic costs	% change in Primary Energy Demand	% change in Carbon Dioxide emissions
Czech Republic	−9%	−12%	−15%
Croatia	−8%	−8%	−7%
Italy	−5%	−9%	−8%
Romania	−13%	−16%	−16%

which are not accounted for in the Levelised Costs approach.

Some of the factors that can be accounted for when applying the energy systems approach and not when applying the levelised costs approach are:

- Less heat capacity is required in the energy system when the heat demand in each building is reduced, which means that the investments in heating units both in individual and collective heating systems decline.
- Similarly, a lower heat demand reduces the required district heating piping dimensions, which also lead to lower investment expenses.
- It is necessary to alter the heat demand distributions when implementing heat savings as these lead to lower peak demands. This affects the operation of heat production technologies installed in the energy system.
- Heat savings influence electricity production technologies as less electricity production capacity is required due to the reduced electricity demand from electric heating and heat pumps.
- In an energy system perspective, the operation of technologies can be optimised when implementing heat savings, including an enhanced utilisation of storage technologies.
- The feasibility of integrating excess heat from other sectors such as industrial heat, waste incineration and transport fuel production can change with a different heat demand and distribution.
- It is possible to identify impacts on the fuel demand of the complete energy system when implementing heat savings when applying the energy systems approach.

When applying the Levelised Costs approach it is therefore important to assess whether some dynamics and synergies are overlooked and whether it would be more beneficial to apply an Energy System approach. Furthermore, these cross-sector dynamics should be included in all studies where heat savings are investigated to avoid the exclusion of heat saving benefits that occurs across energy sectors.

Based on the analysis and the comparison of the energy system and building characteristics of the countries analysed in this paper some determining factors for feasible levels of heat savings across the countries were identified:

- The state of the building stock, i.e. the building standards implemented in the country and whether the buildings have already undergone refurbishments
- The specific heat demand impacts the feasible heat savings as indicated by the Italian example in this study, see Fig. 4. The specific heat demand (kWh/m^2/year) in Italy is lower than in the other countries and hence the heat saved compared to the heat saving investments in Italy is accordingly lower.
- The heat supply cost has a large impact on the degree of heat savings feasible and changes the balance between savings and supply in a system, see Fig. 7.
- The technical heat saving potentials possible to implement in a country within the next 35 years as indicated on the first axis of Fig. 4.

The heat savings that can be carried out each year is restricted by the share of buildings that either undergo other renovations (where energy efficiency renovations should take place) or the amount of new buildings that are constructed, and these combined usually account for around 2% of the building stock every year (Table 1). Hence, implementation of heat savings should begin today to avoid that all the heat savings must be implemented in the final stages before 2050.

5. Conclusion

This paper has presented two different methods for assessing feasible balances between heat savings and heat supply in the Czech Republic, Croatia, Italy and Romania. Based on a Levelised Costs approach and an Energy Systems approach feasible levels have been identified finding different levels for the two methods. This is the first time two methods have been applied to multiple countries thereby allowing for comparisons across countries.

The analysis proved that energy efficiency in the heating sector is a balance between demand side and supply measures and in this study results of quantifying this balance for multiple countries was presented for the first time.

When applying the Levelised Costs approach the results indicate heat saving levels between 0 and 60% for the different countries with the lowest heat supply unit costs and 40–60% with the highest costs. Using this method, the determining factor is therefore the unit cost of heat supply. For the Energy System approach where dynamics across sectors and technologies are accounted for the saving levels are between 30 and 50% for the four countries analysed.

An important finding is therefore that the two methods result in relatively different saving levels due to the inclusion of synergies across sectors in the Energy Systems approach, e.g. reductions in electricity production capacities with a reduced electric heating demand. It is therefore recommended to apply a full Energy System perspective as this approach also accounts for impacts and synergies across sectors. Furthermore, the energy system approach also allows for assessing impacts on socio-economy, energy demand and environment, which is not possible applying the Levelised Costs approach.

When comparing the heating sectors and building characteristics of the countries analysed in this study some factors for determining feasible heat saving levels in a country were found. These factors are the state of the building stock, the specific heat demand, the heat supply costs and the technical heat saving potentials that are possible to implement within the given time period.

Heat savings should be carried out while other renovations take place to reduce the costs and ease the implementation. The major implementation challenge is that with the current retrofit and new build rates it will most likely not be possible to reach these heat saving levels without further actions. Examples from Denmark has shown that even with an active building refurbishment policy over a 40 years period only 20% heat savings have been achieved [7]. It is therefore necessary to build an active policy to encourage investments in refurbishments and to develop energy efficiency measures in the supply of heat.

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PAPER 2

Comprehensive assessment of the role and potential for solar thermal in future energy systems

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Comprehensive assessment of the role and potential for solar thermal in future energy systems

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ABSTRACT

The European Union has set targets to increase the share of renewable energy in the coming years. Solar thermal energy is currently expanding and could possibly contribute to achieving the European targets. This paper evaluates the potentials of solar thermal energy from an energy system perspective along with the impacts of installing these potential for four European national energy systems; Germany, Austria, Italy and Denmark. The potentials are evaluated by applying energy system analysis of existing and future energy systems under different conditions such as substantial heat savings, expansion of district heating networks and with high-renewable electricity and heating sectors. The findings in this paper indicate that the national solar thermal potentials are in the range of 3–12% of the total heat supply and that installing the potentials will impact the energy system according to the energy system configurations. Solar thermal benefits reduce when moving towards a high-renewable energy system as other renewable energy sources start competing with solar thermal on energy prices and energy system flexibility. The findings can be applied to a diversity of energy systems also beyond the country cases of the study. The role of solar thermal should be to reduce the pressure on scarce renewable resources and to supply renewable energy in conditions where no alternatives are available.

1. Introduction

Solar thermal technologies have expanded rapidly in Europe in the last five years, more than doubling in production (Eurostat, 2017). This has primarily taken place in individual buildings, but solar thermal for district heating is also growing, particularly in Denmark. The question is however how large the potential is for installing solar thermal and whether solar thermal is a viable solution for Europe to achieve its energy targets, or if better alternatives exist. These questions are thoroughly examined in this study for four European national energy systems; Germany, Austria, Italy and Denmark.

The objective of this paper is to:

- Enhance the knowledge about the role of solar thermal in future energy systems
- Assess the potentials for installing solar thermal from a national energy system perspective
- Quantify the impacts of installing these potentials

Previous studies evaluating the feasibility of solar thermal have researched the integration of solar thermal in residential buildings in Norway (Good et al., 2015), Greece (Tsalikis and Martinopoulos, 2015), Tunisia (Hazami et al., 2013) and for North European housing (Ampatzi et al., 2013). Other studies analyse the potentials for integrating solar thermal in industrial processes such as breweries (Eiholzer et al., 2017), dairy processes (Quijera et al., 2011) or for tuna fish canning factories (Quijera et al., 2014). These studies find potentials for integrating solar thermal on a building scale, but do not reach any conclusions regarding the solar thermal feasibility in a broader scale such as from a national energy system perspective.

Solar thermal has also been analysed for geographical regions such as the Geneva Region (Quiquerez et al., 2015) and the Canary Islands (Gils and Simon, 2017) finding significant solar thermal potentials in these areas. However, these studies focus on the local scale and do not include the national perspective.

Some studies analysed the role of solar thermal from a national energy system perspective such as for Taiwan (Chang et al., 2013), for the United Kingdom (Greening and Azapagic, 2014), for Turkey (Benli, 2016) and more generally as a renewable resource for the future (Seyboth et al., 2008). Common for these studies are that no energy system analyses and quantification of the solar thermal potentials were conducted and that these studies apply more generic arguments for the integration of solar thermal resources.

Only few studies previously quantified the potential of solar thermal

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from a national energy system perspective. For the Danish energy system, a study found that 15% of the heating demand ought to be supplied by solar thermal (Lund and Mathiesen, 2009) while (Palzer and Henning, 2014) found that the solar thermal potential in Germany might be 125–165 GW_{th} capacity. These studies analysed solar thermal in a high-renewable situation where a variety of other renewable sources also influence the solar thermal feasibility. Finally, (Weiss and Biermayr, 2009) analysed the solar thermal potentials for all of Europe as well as for some individual countries (including Austria, Germany and Denmark). Here, it was found that solar thermal fractions could increase to 6–40% in Austria, 6–34% in Germany and 5–32% in Denmark as a share of the low-temperature heat demand.

This demonstrates that solar thermal potentials previously have been evaluated for selected regions and countries. This paper adds to this knowledge by applying a different methodology and by quantifying the impacts of installing the solar thermal potentials.

Hence, this paper adds to the current knowledge through:

- The development of a novel methodology for analyzing solar thermal potentials
- Comparing solar thermal potentials across national energy system
- Quantifying the impacts of installing these solar thermal potentials

This paper contains a description of the methods and materials applied for the analysis of the solar thermal potentials and is followed by a presentation of the main results, including the solar thermal potentials for each country and the impacts of installing the potentials. The subsequent chapter entails a discussion of the methods applied and the possible role of solar thermal in a future energy system while the conclusions are summarized in the end.

2. Methods and materials

The approach for evaluating the role of solar thermal technologies in this paper is founded on an energy systems approach. This implies that solar thermal is analysed in terms of the impact on the energy system rather than on the individual building level and the study differentiates itself by not relying on a levelized cost of heat approach as in other studies (Baez et al., 2016). Hence, aspects such as dynamics across energy sectors, various storage types, the influence of other technologies as well as the energy system flexibility impact the feasibility of integrating solar thermal.

The novelty of this paper is demonstrated by assessing the solar thermal potentials in an energy system context encompassing all energy system dynamics rather than for individual energy sectors or users. Part of this approach is evaluating solar thermal against other renewable alternative technologies such as renewable heating from geothermal and excess heating. The energy systems approach necessitates an energy system analysis tool which includes all energy sectors (heating, cooling, electricity, transport and industry), operates on an hourly scale to accommodate for the variations of solar thermal generation, and is able to quantify the impacts for the indicators selected. For these reasons, the energy system analysis tool EnergyPLAN is applied for this study (Aalborg University, 2014). The main purpose of the model is to assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments. EnergyPLAN has been used in numerous papers (Østergaard, 2015) for multiple purposes such as the design of 100% renewable energy systems on a municipal, national and European level (Lund and Mathiesen, 2009; Mathiesen et al., 2015; Connolly et al., 2016).

The indicators for the analysis are based on an energy system perspective and does not consider the individual consumer, as well as the allocation of benefits within society. The indicators are energy system costs (investments, O&M, fuels, CO_2 and electricity exchange costs, excluding all subsidies and taxes and using a 3% discount rate), energy consumption (primary energy supply with a focus on biomass), environment (CO_2-emissions) as well as the flexibility of the energy system (overproduction of electricity and district heating due to a temporal mismatch between demand and production).

The role and potential of solar thermal is analysed in a variety of energy system types. Firstly, four European countries are part of the study; Germany, Austria, Italy and Denmark. These countries vary in terms of climatic conditions with both Southern, Central and Northern European climates, the solar irradiation varies between the countries and they differentiate in terms of energy system design and available resources where some countries have a high share of hydropower (Austria) while others rely on natural gas (Italy) or wind power and district heating (Denmark). Secondly, these four national energy systems are modified by designing five alternative future energy systems for each country. These alternative future energy systems are called; 2010, 2050, Heat savings, District heating and High-RES. These are briefly presented below while further details can be found in Mathiesen and Hansen (2017).

Firstly, a 2010 model of each national energy system replicating the current energy systems is designed. In the 2010 models the solar thermal production is insignificant. Secondly, the 2010 model is projected towards 2050 in terms of energy demands and renewable energy capacities as anticipated by the European Commission when no further policies are implemented (Capros et al., 2014). This model is called the 2050 model and no solar thermal is installed in these models in order to identify the full impact of installing additional solar thermal energy. Next, a scenario is designed based on the 2050 model where substantial heat savings are implemented to analyze whether this factor is significant for the solar thermal integration. The heat savings correspond to 40–50% of the total heat demand in the 2050 models. After implementing heat savings, scenarios are designed with significant district heating expansions reaching heat shares of 40–70% in each country (Denmark already has above 50% district heating share today). This model is entitled District heating. The final model includes a transition to a high-renewable energy system (called High-RES) in the heating and electricity sectors. In this scenario, the measures include a shift of heat supply outside of district heating areas to mainly compression heat pumps and a further integration of renewable sources for district heating (geothermal, waste incineration, industrial excess heat and large heat pumps). Wind and solar power is implemented to meet the majority of the electricity demand while the remaining fossil energy demand is converted to biofuels. In this scenario, all energy demands are supplied by renewable resources, except for heavy-duty-transport. The purpose of these scenarios is to enable the analysis of solar thermal potentials in future high-renewable energy systems rather than designing optimized high-renewable energy systems. An elaborate description of these scenarios is available in Mathiesen and Hansen, 2017.

In each of these energy system types the role and potential of solar thermal is analysed in terms of the maximum solar thermal potential the energy system can accommodate given certain assumptions and thresholds. The first threshold regards the overproduction of solar thermal due to the hour-by-hour mismatch between solar thermal production and heating demands. This overproduction threshold is selected as 5% annually and applies to both solar thermal in district heating areas and in individual buildings. This threshold is based on dialogues between project partners and a sensitivity analysis is performed in Mathiesen and Hansen (2017) indicating that this value only has minor influence on the overall impact of solar thermal. The second threshold is regarding the imbalance of the district heating system supply and demand, also impacted by other technologies than solar thermal (solar thermal can indirectly impact this). This threshold is also selected to be 5% on an annual basis. The amount of baseload technologies installed in the energy system is crucial impacting the energy system ability to integrate solar thermal. The final assumption regards the solar thermal penetration, which is defined as the share of heat consumers that are connected to a solar thermal system, i.e. a solar

Table 1
Key characteristics of the solar thermal technologies based on inputs from Mauthner (2016).

Solar concept characteristics	Unit	Technology 1 (CS-SFH)	Technology 2 (SDH-DK Diurnal)
		Single-Family-House Combined system	District Heating system with diurnal storage
Type of solar collector		FPC	FPC
Solar fraction (annual)	% of heating demand covered	20%	12%
Type of storage		TTES[a] (pressurized)	TTES[a] (non-pressurized)
Peak capacity per unit	kW	13	7000
Production per unit	MWh/year	5.9	4100
Solar energy yield[b]	kWh/year/m^2 gross	330	410
Specific cost (ready installed, excl. VAT/subsidies)	1000 €/m^2 gross	0.76	0.24
Fixed O&M	€/m^2 gross/year	6.1	1.7
Variable O&M	€/m^2 gross/year	1.2	1.5

[a] TTES = Tank Thermal Energy Storage, PTES = Pit Thermal Energy Storage.

[b] The solar yields are based on the countries where these solar concepts are typically installed. For example, are the solar district heating plants based on yields for Denmark while the block heating plants are based on German yields.

penetration share of 20% means that 20% of all heat consumers are connected to a solar thermal plant, either directly in the building or via a district heating system. The solar thermal penetration is analysed for shares between 20 and 50% for the national energy system where 50% represents an extreme case, while 20% represents a moderate and implementable penetration level. It should be noted, that the penetration level is hard to determine and impacts the results significantly and instead of trying to identify one penetration level a wide range has been chosen. The 20–50% penetration shares are not based on scientific evidence, as no current solar thermal markets are sufficiently developed to provide actual data for this. Hence, the 20–50% penetration levels are based on expert estimates from the IEA SHC Task 52 project team.

Many types of solar thermal technologies exist and to summarize these a review of existing solar thermal plants has been performed in connection with this study (Mauthner, 2016). In order to limit the magnitude of analyses and scenarios two of these solar thermal technologies are prioritized for analysis in this paper, see characteristics in Table 1. The first type is a representative of a solar thermal installation in a single-family house providing both space heating and domestic hot water. The second type is a district heating solar thermal system with a ground-mounted solar collector field and diurnal storage. Examples of the latter system can be found in Denmark, Austria and Germany. In the analyses, it is assumed that these technologies are installed in residential and commercial buildings, but not for industrial buildings. Since the solar thermal plants are not able to cover the entire heat demand other technologies are installed as supplementing heat production. Findings for the German energy system is presented in this paper while additional findings for the Italian, Austrian and Danish energy systems are available in Mathiesen and Hansen (2017).

Solar thermal production costs are outlined in Table 2 for individual and district heating solar thermal plants.

3. Results

This section is divided into two parts; assessment of the solar thermal potentials in each scenario and secondly, an analysis of the impact of installing these solar thermal potentials.

3.1. Solar thermal potentials

For each scenario, the technical solar thermal potential is identified for buildings with solar thermal installed directly in the building (individual heating), district heating areas and the combination of these. Fig. 1a and b illustrates the solar thermal potentials in the German energy system with a solar thermal penetration rate of 20–50%. If assuming a higher or lower solar thermal penetration rate, the solar thermal potentials will change accordingly. The German case indicates that the combined solar thermal potential for individual heating and district heating is in the order of magnitude 15–60 TWh/year, equivalent to a solar thermal share of 3–10% of the total energy system heat production. The widespread solar thermal potential is caused by the different energy system configurations. The solar thermal potential in terms of annual production is highest in the 2010 scenario where the heat demand is highest and the renewable share is lowest influencing the energy system ability to integrate solar thermal. In the Heat savings scenario, the annual solar thermal production drops as the heat demand decreases, however the solar thermal share increases simultaneously. This is caused by the fact that heat savings reduces the variation of the heat demand over the year and especially reduces demands during winter. This causes the actual solar thermal production to drop while increasing the solar thermal share. Finally, in the High-RES scenario the solar thermal potential is the lowest, both in terms of annual production and as a share of the heat production. This is a consequence of energy savings and because more renewable heat and waste energy is installed. Solar thermal competes with other renewable resources such as base-load heat production from geothermal heating, waste-to-energy, industrial excess heat and to some extent large-scale heat pumps supplied by renewable electricity. The influence of other renewable sources is especially significant in the summer periods when solar thermal peaks. Further analyses have been performed for the other three national energy systems showing rather similar trends in terms of solar thermal share potentials in the various scenarios (Mathiesen and Hansen, 2017).

Some interesting findings across the countries are for the solar thermal shares in the individual and district heating sectors. In Fig. 2 the individual solar thermal shares are illustrated indicating rather similar potentials across the countries, with Denmark having slightly lower potentials after heat savings. This is due to a high district heating share already in the 2010 scenario.

Table 2
Solar heating unit costs in 2010 and 2050 for the solar technologies.

Solar thermal heating unit costs (million €/TWh annual yield)		Germany	Austria	Italy	Denmark
2015	Technology 1 (CS-SFH)	2303	1888	1686	2421
	Technology 2 (SDH-DK Diurnal)	559	458	409	588
2050	Technology 1 (CS-SFH)	1515	1242	1109	1593
	Technology 2 (SDH-DK Diurnal)	419	344	307	441

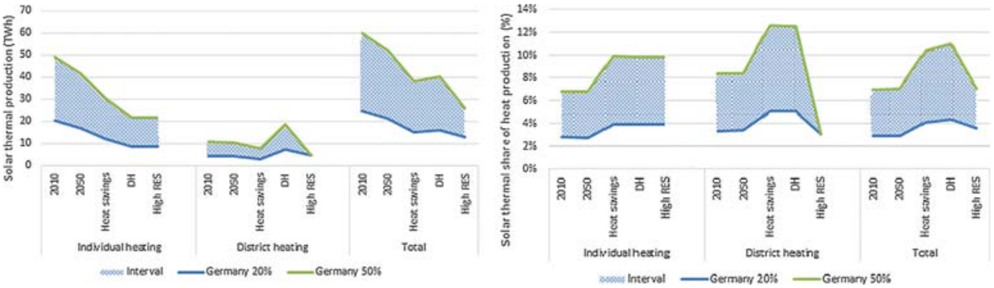

Fig. 1. (a) and (b): The solar thermal potential in the German energy system for buildings with individual heating and for district heating. (a) shows the annual solar thermal production while (b) illustrates the solar thermal production as a share of the total heat production in the energy system. The potentials are illustrated for five different energy system types to assess the solar thermal potentials in various energy system configurations.

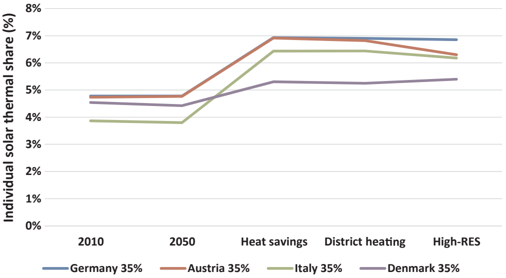

Fig. 2. The individual solar thermal potentials for Germany, Austria, Italy and Denmark as a share of the total heat production in the energy system. These potentials are based on a solar thermal penetration rate of 35%.

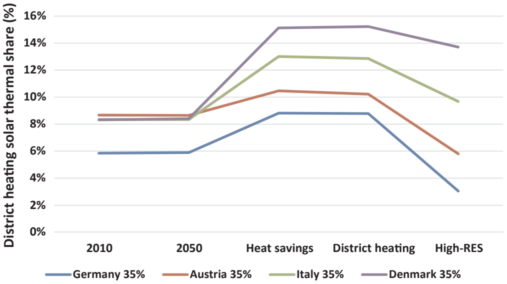

Fig. 3. The solar district heating potentials for Germany, Austria, Italy and Denmark as a share of the total heat production in the energy system. These potentials are based on a solar thermal penetration rate of 35%.

For solar thermal district heating shares Denmark has the highest potential with lower potentials in for example the German energy system (see Fig. 3). This difference is caused by the higher flexibility in the Danish energy system due to a higher share of CHP plants that are better suited for accommodating fluctuating solar thermal production. Implementing further renewable sources such as geothermal heating and excess heating from industries and waste incineration causes a rather large reduction for solar thermal potentials in the High-RES scenario.

The solar thermal potentials for the four national energy systems are presented in Fig. 4 assuming a solar thermal penetration rate of 35% (average of 20% and 50% penetration rate). The solar thermal potentials are rather similar across the countries with the lowest solar thermal shares in the 2010 and 2050 scenarios as well as in the scenario with a high share of renewable energy. The solar thermal share increases after heat savings are implemented. The Italian solar thermal share potential differs in the district heating scenario compared to the other countries because of higher district heating expansion potential. This allows for installing more flexible technologies such as CHP plants, large heat pumps and heat storages, which can accommodate the integration of further solar thermal in the district heating sector. The overall solar thermal potential across the national energy systems are between 4 and 10% with a 35% solar thermal penetration rate and increases to 6–12% with a solar thermal penetration rate of 50%. If higher penetration rates can be realized in the future, then the solar thermal potential might also increase accordingly.

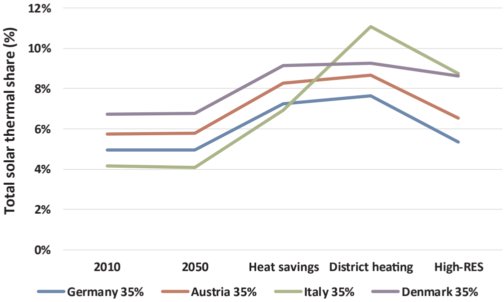

Fig. 4. The solar thermal potentials for Germany, Austria, Italy and Denmark as a share of the total heat production in the energy system. These potentials are based on a solar thermal penetration rate of 35%.

3.2. *Impact of installing solar thermal potentials*

This section presents the impact on the energy system of installing the solar thermal potentials with 50% solar thermal penetration rate for the selected indicators; fossil fuel consumption, biomass consumption, CO_2 emissions and energy system costs. The 50% penetration rate is chosen as the impacts are more significant than with lower penetration rates.

Installing the solar thermal potentials decreases the fossil fuel consumption, however mainly in the individually supplied buildings. In the district heating areas, the technologies replaced by solar thermal are to a large extent CHP plants co-producing heating and electricity. When the electricity production from CHP units decrease other thermal condensing power plants conversely has to produce more, thereby impacting the fossil fuel consumption. As a result of this the district heating solar thermal integration has almost no impact on the fossil fuel consumption.

Overall, the combined energy system fossil fuel reduction is 1–2% and differs between the national energy systems according to the fuel mixes and technologies installed (see Fig. 5).

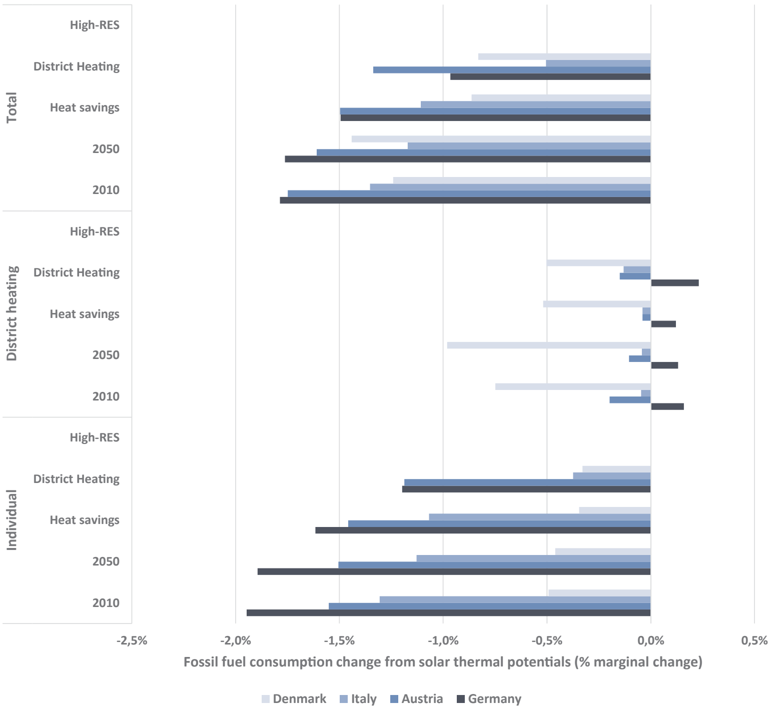

Fig. 5. Impacts on energy system fossil fuel consumption when installing the solar thermal potentials with 50% solar thermal penetration in Germany, Austria, Italy and Denmark. The figure illustrates the impacts for both individual solar thermal, district heating solar thermal and both of them combined.

The largest improvements in terms of biomass consumption are gained in the individual buildings compared to district heating solar thermal. This is due to the fact that solar thermal in district heating areas replace CHP plants with a high overall conversion efficiency (70–85%) and is replaced by condensing power plants with lower conversion efficiencies (40–45%). Solar thermal integration reduces biomass consumption in all scenarios and contributes to reducing the reliance on this scarce resource that will be in high demand in the future. Overall, the biomass consumption reduction is 1–3% of the energy system consumption (see Fig. 6).

Solar thermal impacts on CO_2-emissions is a result of the technologies and fuels displaced and can be explained by the fossil fuel impacts presented in Fig. 4. It is assumed that biomass has no CO_2-emissions in the energy sector according to the IEA and EU guidelines (Bourguig, 2015; International Energy Agency, 2007), despite recent critiques about this assumption (Bracmort, 2016; Brack, 2018). CO_2-emission reductions occur in all scenarios where the solar thermal potentials are installed directly in the buildings because energy sources such as natural gas, electricity or oil is replaced (see Fig. 7). The impacts are more diverse for solar thermal district heating due to the technologies replaced. District heating networks are supplied by a higher share of renewable energy than individual supply while the technologies replaced, as previously explained, often are CHP plants consuming coal, natural gas or biomass. The reduced electricity production from CHP plants has to be produced at condensing power plants typically fueled by coal and with an overall lower conversion efficiency. Hence, installing a renewable energy source such as solar thermal in district heating networks could in some cases result in reduced thermal plant efficiency and an increase in coal consumption leading to no changes in CO_2-emissions. This highlights the importance of the hour-by-hour energy system approach as intuitively one would expect that installing solar thermal would benefit the CO_2-balance.

Finally, the impacts on energy system costs are quantified and presented in Fig. 8. The results indicate that for all scenarios the costs increase when installing solar thermal directly in the individual buildings. The overall energy system costs might increase by up to 1% (0.9b €/year in Germany) and for the heating, cooling and electricity sectors alone this corresponds to an 3% increase. The main reason for the increasing costs are the additional investment costs exceeding the savings in fuel expenditures. For buildings in district heating areas, the solar thermal investments are lower per heat delivered resulting in overall better economy compared to the individual buildings. The impact of installing the district heating solar thermal potentials are cost-neutral compared to a system with no solar thermal plants. Sensitivity analyses proved that the solar thermal investment prices for individual buildings have to decrease by extreme rates (65% compared to today) in the future to become cost-competitive.

4. Discussion

The findings in this study highlight the importance of approaching renewable integration from an energy systems perspective, including all sectors on an hourly resolution. The methodology allowed for capturing the dynamics across energy sectors such as the operation of CHP plants and how this impacts the electricity sector. Furthermore, the feasibility of energy storages could be analysed as well as the integration of renewable electricity such as wind power connected to the heat sector through the use of heat pumps. If the entire energy system is not analysed at once a variety of important dynamics cannot be identified thereby overlooking the indirect impacts of solar thermal on the energy system. The analyses proved the importance of certain key assumptions such as the solar thermal penetration rate, which had a significant effect

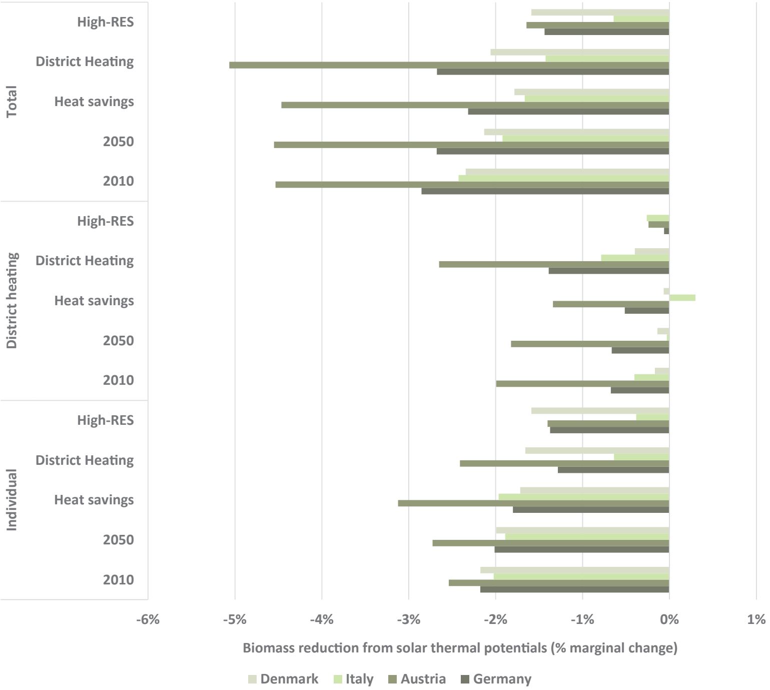

Fig. 6. Impacts on energy system biomass consumption when installing the solar thermal potentials with 50% solar thermal penetration in Germany, Austria, Italy and Denmark. The figure illustrates the impacts for both individual solar thermal, district heating solar thermal and both of them combined.

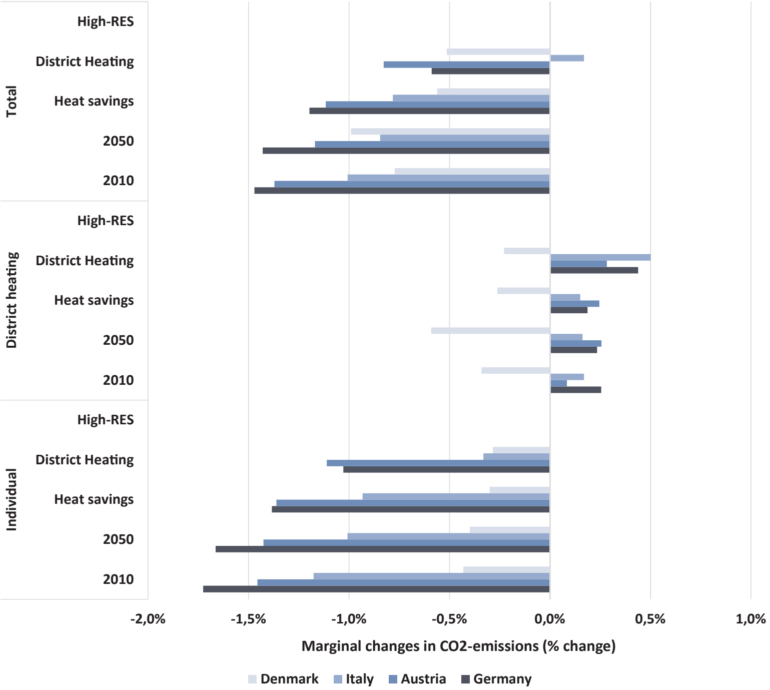

Fig. 7. Impacts on carbon dioxide emissions when installing the solar thermal potentials with 50% solar thermal penetration in Germany, Austria, Italy and Denmark. The figure illustrates the impacts for both individual solar thermal, district heating solar thermal and both of them combined.

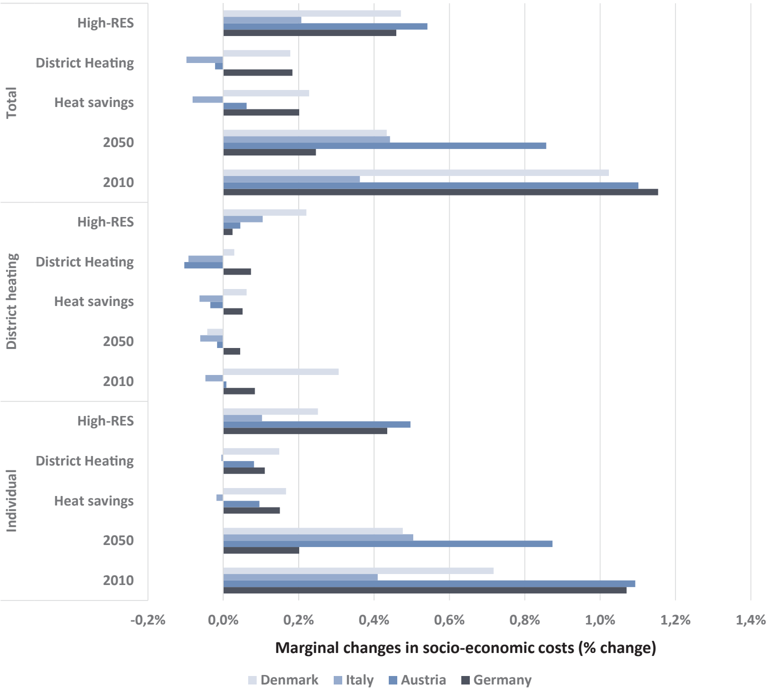

Fig. 8. Impacts on energy system costs when installing the solar thermal potentials with 50% solar thermal penetration in Germany, Austria, Italy and Denmark. The figure illustrates the impacts for both individual solar thermal, district heating solar thermal and both of them combined.

on the overall solar thermal potentials. If the aim is to exploit the full solar thermal, it is therefore vital to distribute the solar thermal energy to a large number of consumers and not solely to ensure a high solar thermal production.

The solar thermal potentials identified proved strong consistency across the countries despite the different characteristics of the energy systems. The findings therefore apply to a variety of energy system types, regardless of whether these are dominated by natural gas, hydro power or wind power.

The impact of installing solar thermal directly in the buildings or via a district heating network is different for a number of reasons. Firstly, (1) the heat delivery costs are significantly lower when larger scale technologies for district heating are utilized (approximately 1/4 of the costs), (2) the solar thermal production can be distributed over a larger number of consumers in a district heating network (peak shaving), (3) larger and cheaper heat stores are available in the district heating network, (4) installing the district heating solar thermal potentials proved better energy system economy than in the individually heated areas, (5) in a district heating network solar thermal can to a higher degree benefit from the energy system flexibility through technologies such as CHP and large heat pumps. However, (6) it is also noteworthy that the results indicated that the fossil fuel displacement (and CO_2) was better for individual solar thermal than in district heating areas.

Installing the solar thermal potentials lowered the biomass demand in the heating and electricity sectors, which will be crucial in the future as this resource will be in high demand in the transport and industrial sectors, where fewer renewable alternatives exist. The role of solar thermal should therefore be to reduce the reliance on scarce resources such as biomass and renewable electricity resources in cases where the potentials are limited. Similarly, solar thermal is a viable option in situations where the access to energy from network systems is restricted (i.e. electricity grids, gas networks, district heating). Finally, solar thermal technologies might have a geopolitical dimension as it could contribute to enhancing the security of supply, along with a mix of other technologies, by replacing imported fossil fuels or bioenergy such as natural gas from Russia and oil from Saudi Arabia.

In a high-renewable energy system solar thermal will no longer displace fossil fuels and thereby improve CO_2-emissions, but will instead start competing with other renewable technologies on parameters such as costs, flexibility and contribution to energy system efficiency (fuel consumption). In such a situation, solar thermal might have less advantageous characteristics than other renewable resources that can supply the same heat for lower costs (e.g. geothermal, waste-to-energy, excess heat from industries and condensing power plants converted to CHP operation). Furthermore, more renewable baseload sources will most likely be integrated impacting the energy system capability to integrate fluctuating resources such as solar thermal. In addition, solar thermal will compete for available spaces with other technologies such as PV. This dynamic regarding the competition with PV may prove to be crucial for future solar thermal disbursement, as examples have proven that PV developments have eroded solar thermal markets. This was studied in Good et al. (2015) analyzing stand-alone PV and solar thermal systems as well as a combined PV/T system. Here, the most desirable energy balance for a net zero energy building was found to be a stand-alone PV system indicating that competing alternatives to solar thermal could impact the share of the solar thermal potential that will eventually be installed. Similar trends were found in Meyers et al. (2016) that analysed the competition between solar thermal and PV for industrial process heat generation. One of the key factors in that study was the temperature requirements as lower temperatures favored solar thermal while higher temperatures benefitted PV for heat generation.

In addition, a proportion of the solar thermal potentials identified in this paper depend on the presence of district heating networks, which currently is rather limited (10–15% of the EU heat supply). Other alternatives such as PV combined with heat pumps or electric boilers do not depend on district heating infrastructure. Finally, PV prices have declined rapidly in recent years suggesting improved economy for installing PV systems compared to solar thermal systems in situations with limited space.

This creates a challenge and necessitates long-term planning for the integration of renewable resources given the specific energy system characteristics.

In this paper, solar thermal is considered as a stand-alone technology, but other solutions exist where solar thermal is developed in combination with other renewable technologies. For example, hybrid PV/solar thermal technologies have been developed as well as systems where solar thermal is combined with heat pumps (Good et al., 2015). Moreover, the development of low-temperature district heating networks will contribute to improving the solar thermal efficiency while other sectors such as industrial processes or cooling might also use solar thermal energy thereby increasing the solar thermal potentials (Mathiesen and Hansen, 2017; Platzer et al., 2015; Montagnino, 2017; Eicker et al., 2015). Furthermore, seasonal heat storages are currently expanding and could store solar thermal peak production during summer periods to winter periods (Tulus et al., 2016; Paiho et al., 2017). These elements would however not increase the technical potential for solar thermal significantly. Hybrid systems and heat pumps do not change the fact that solar thermal is producing mostly in parts of the year where the heat demand is low and larger seasonal storages can only contribute in smaller settlements and not in larger district heating areas due to space requirements and land prices.

Several barriers hinder the achievement of the technical potentials for each country. As part of the SHC Task 52 project trends and possibilities for solar district heating have been analysed based on the Danish experiences (Trier et al., 2018). Here, a spatial analysis using GIS tools for identifying suitable areas in Europe proved that there is sufficient suitable land to establish more than 2500 networks in Europe, primarily in smaller towns, and the total solar district heating supply could be around 100 TWh. The spatial analysis therefore supports the technical energy system analysis about large unused solar thermal potentials. The spatial analysis can be used for finding specific locations and areas suitable for solar district heating and for raising awareness about these potentials among the appropriate actors. Furthermore, it was concluded that economy of scale outweigh the additional network costs associated with solar district heating removing the barrier associated with the additional investments in district heating pipes. Some of the main barriers for achieving these potentials are financing options as this technology is capital intensive and requires large up-front costs while the operation, maintenance and fuel costs are lower compared to fossil fuel technologies. Previous examples from Denmark have shown that consumer or publicly owned district heating networks might be better equipped for making these large up-front investments due to the large number of consumers connected to the networks. In addition, alternative heat supply costs is a key to creating a more desirable trajectory for solar thermal and in particular fossil fuel taxation can play a role in this regard. Finally, also the economy of other renewable energy technologies will influence the future solar thermal potentials along with fuel price developments and political priorities.

The findings in this paper can be used for assisting in future planning of energy resources for policy-makers and energy planners. The findings also reveal business potentials for solar thermal and can aid in the design of subsidy and tax schemes.

5. Conclusions

This paper focused on the role of solar thermal in future national energy systems by identifying solar thermal potentials and quantifying the impacts of installing these potentials. The technical solar thermal potentials with a solar thermal penetration rate of 20–50% are:

- Germany: 15–60 TWh/year or 3–11% of the total heat production
- Austria: 2–7 TWh/year or 4–12% of the total heat production
- Italy: 8–24 TWh/year or 2–10% of the total heat production
- Denmark: 2–5 TWh/year or 3–10% of the total heat production

The district heating solar thermal potentials proved to be slightly higher than for individual buildings due to the larger variety of flexibility options in connection with the district heating network.

The overall conclusion from the study is that solar thermal has a role to play in a future energy system by (1) easing the pressure on scarce resources and (2) supplying heat where no alternative heating sources are available. Installing solar thermal could increase the socio-economic costs, but this is highly impacted by the energy system configuration. The advantages of solar thermal energy reduce in terms of fossil fuel and CO_2-emission reductions when transitioning towards a high-renewable energy system. The findings apply to a diversity of national energy systems, also beyond the cases analysed in the study, proven by the large variety in terms of climate, population and energy resources.

Further research is required to enhance the knowledge about the role of solar thermal even more, for example regarding the influence of local variations within the national energy systems. Additionally, the space availability should be studied while private-economic consequences is also of importance.

Acknowledgements

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PAPER 3

Comparison of Levelized cost of Energy across electricity, cooling and heating

Working paper, 2018

3

Comparison of Levelized cost of Energy across electricity, cooling and heating

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Highlights:

- Numerous evaluation factors for calculating LCOE are identified
- LCOE is calculated for electricity, cooling and heating
- LCOE values are compared across energy carriers
- The impact of central evaluation factors is evaluated for LCOE costs

Abstract:

Levelized cost of energy (LCOE) is a measure for comparing energy technologies in terms of costs. Previously, LCOE has been used for prioritizing between energy technologies in aid for decision making, but the assumptions and evaluation factors included in the calculations differ significantly. Furthermore, LCOE has primarily been used for evaluating electricity technologies. This paper presents and compares LCOE costs ab plant across different energy carriers: electricity, decentralized and district heating and cooling. The results show that all energy carriers have value in the energy system and that heating costs to a large degree are comparable to electricity costs. The central evaluation factors for LCOE are interest rate, investment prices and fuel prices as these might alter the LCOE costs significantly. Finally, the paper discusses risks of relying solely on LCOE calculations for decision making as numerous aspects are not included in these calculations.

Keywords: Levelized cost of energy, electricity, cooling, decentralized heating, district heating

Declarations of interest: none.

1. Introduction

The need for comparing costs for different energy technologies has fostered the development of the Levelized cost of energy concept. This concept might also be referred to as the electricity generation or production costs, but the idea behind the concept is similar [1]. The LCOE method is used for estimating the full life-cycle costs of an energy generating technology per unit of energy and is often used for benchmarking purposes across various technologies. The concept allows for comparison between technologies despite of scales of operation, time periods and investments [2]. Included in the LCOE costs are typically factors such as the capital initial investments, operation and maintenance and fuel costs and these costs are discounted over the lifetime of the technology.

LCOE has previously been used for various purposes such as for inputs to energy modelling, for benchmarking between technologies and ultimately for aiding in decision making and designing of policies. For example, electricity generation costs are used as inputs to energy models such as the MARKAL/TIMES and other cost-optimizing energy system models in order to create future scenarios for the energy system. Examples of these might be the IEA's World Energy outlook and technology perspective papers [3]. [4] also concludes that: "it [LCOE] has become the de facto standard for cost comparisons among the general public and many stakeholders such as policymakers, analysts, and advocacy groups". The LCOE methodology is therefore used for multiple purposes all contributing to setting the direction of future policy making.

A typical criticism of the LCOE methodology is the difference between the average lifetime cost of producing electricity from a technology and the system cost of a technology. Some of the factors that cannot be captured in the LCOE methodology are the lack of comparability between variable production and dispatchable generation technologies [5,6]. Here, no monetary value is assigned to the value of electricity in terms of timing, i.e. the possible mismatch between electricity production and demand. This is not reflected in the LCOE methodology, but is to a higher degree normally valued in electricity prices based on market conditions. Others highlight the differences in LCOE methodologies according to regional conditions, economy-of-scale, capacity factors and efficiencies, heating and electricity crediting, overnight costs, availability of resources, opportunity costs as well as balancing and backup costs [7,8]. It is also pointed out in the literature that the LCOE methodology is “a static measure that looks at a snapshot in deriving the price per generated energy, while true market prices are dynamic” [9]. Because of this, comparing LCOE costs across different methodologies has several times been referred to as “comparing apples with oranges” [5,10]. Due to the differences in methodologies some studies suggest to use alternative measures than solely the LCOE and instead also focus on the Levelized avoided cost of electricity [8]. The LCOE concept is used in this paper for assessing the value of energy across energy carriers and because LCOE to a large degree is still used for decision making.

In the vast majority of studies, the LCOE methodology has been used for assessing electricity generation costs and to a lesser degree heating and cooling generation costs. In some studies the LCOE methodology is used for single technologies such as the development of generation costs for PV [9,11–13], wind power [14] and nuclear technologies [15]. In other cases, focus lie on electricity generation costs within a single country or region [16,17] while only few studies apply a general or global perspective to the LCOE costs [8,10,18–23].

The efforts within LCOE heat generation costs are sparse, but include the development of a solar thermal unit cost methodology [24] and determining pricing mechanisms for heating markets with CHP plants [25]. Finally, [26,27] developed an overview of heating unit costs for district heating and decentralized heating technologies. According to the knowledge of this paper’s authors no studies have evaluated the levelized cost of cooling.

Putting this into context, approximately 50% of the European final energy demand is either heating or cooling (cooling is only 2%) while the remainder is electricity, transportation or industrial demands [28]. Of the heating demand 12% is district heating and the remainder is supplied by decentralized heating technologies or for industrial process heating. In other regions such as the Middle East larger shares of the energy demands are for cooling.

In this paper novelty is demonstrated through comparing levelized cost of energy across multiple energy carriers such as electricity, decentralized and district heating as well as cooling technologies. No similar studies were identified during the literature review. In addition, LCOE data for cooling technologies are provided, which is first of its kind. This allows for a discussion of the value of energy across energy carriers and a quantification of the most significant LCOE evaluation factors for a variety of energy technologies.

The contents of this paper include a description of the methodology applied and the evaluation factors that might be used in LCOE calculations. Next, the LCOE costs for electricity, decentralized heating, district heating and cooling technologies are presented along with the impact of the central evaluation factors. Finally, a discussion and conclusion complete the paper.

2. Material and methods

The LCOE methodology in this paper applies a simple approach for three reasons:

- Comparability across energy carriers
- Uncertainty about the impact of various evaluation factors
- Analysis of the impact of central evaluation factors

The simplified LCOE methodology is calculated as follows [29].

$$\frac{\sum_{t=1}^{n}\frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Energy generation in year t
R = Discount rate
N = Lifetime of the technology

The LCOE concept in this paper is based on a societal approach calculating the costs ab plant dissimilar to a consumer approach (an consumer). This entails that the costs are cleaned from taxes and subsidies and that energy grid costs are not included, which will usually impact the consumer costs for energy services. These grids include electricity grids, gas networks as well as district heating networks. For more information about grid and network costs see [30–32].

The results are based on cost projections for each technology for 2015, 2020, 2030 and 2050 when available and otherwise closest projections have been applied (i.e. if no 2050 data is available then 2030 data has been used). The calculations are based on technical lifetimes, except for hydropower which is based on the economic lifetime. Comparisons are drawn for new plants and do not take sunk costs from existing plants into account.

The data collection is based on a top-down approach relying primarily on the technology data sheets developed by the Danish Energy Agency presenting best available technologies for electricity and heating technologies commissioned in Denmark at publication [32,33]. This data source provides the benefit of a consistent data set across the majority of the energy technologies analysed. For cooling technology data [34] is the main source while further sources have been utilized when necessary [35,36]. The data is based on Danish experiences and might diverge compared to other countries due to differences in labor costs, technology maturity, etc. Furthermore, the costs are based on aggregated data, which might fluctuate on a local scale. The heat and electricity values from CHP plants are calculated in line with the cost allocation method described in [20].

A societal interest rate of 4% is applied to all calculations based on recommendations from the Danish Ministry of Finance while current and future fuel prices are in line with the IEA World Energy Outlook [37]. Further input details are specified in the Appendix.

Numerous evaluation factors can be included as part of the LCOE costs. Table 1 shows some of the evaluation factors that have been used in previous LCOE calculations grouped into categories of technical, economic and externalities. More than 25 evaluation factors have been identified in this non-exhaustive list. Most of these are excluded in this paper, but the impact of central evaluation factors is subsequently analysed.

Table 1: Possible evaluation factors for LCOE costs [1,3,4,8,20,22,38,39]*. Most of these are excluded in the LCOE costs in this paper for simplicity reasons.*

Technical factors	**Economic factors**	**Externalities (mainly environmental)**
Technology efficiencies/ Capacity factors (Full-load hours)	Interest rate	CO_2, air pollution and climate costs
Costs for existing and/or for additional transmission/ distribution costs	Investment and O&M costs (current and future, learning curves/rates)	Radioactivity costs**
Backup capacity	Fuel prices	Decommissioning costs
Construction time	Opportunity costs/interest during construction	Use of water
Minimum load operation	Land area and costs	Damage to natural environment
Ramping rate	Job creation	
Quality of energy*	Financing (capital requirements)	
Technical/economic lifetimes (scrap/residual values)	Economy of scale	
System costs	Taxes and direct/indirect subsidies	
Installations in existing/new buildings (energy demand)	Price variations between countries (labour costs, materials, etc.)	
	Profile costs (relative value of generation to the market)	
	Sunk costs and forced retirements	

* Electricity can be used for multiple purposes while other energy carriers such as low-temperature heat cannot.

** These include accidents, emissions from mine-tailings, storage of waste and decommissioning.

3. Comparing LCOE costs across energy carriers

This chapter presents the LCOE costs for electricity, decentralized heating, district heating and cooling, as well as a benchmark of LCOE electricity costs and an assessment of the impact of central evaluation factors.

3.1. Electricity

LCOE electricity costs generally decrease for most technologies between 2015 and 2050 as investments are expected to decrease. The exception is for natural gas plants, where increasing natural gas prices has a significant impact on the overall LCOE. Onshore wind power is the least cost technology option in 2015 and 2050 while other renewable technology costs such as offshore wind power and large-scale PV also decrease significantly towards 2050. Coal-fired power plants is the second lowest cost technology in 2015, but has only the sixth lowest costs in 2050 surpassed by a number of renewable technologies. The overall trend is that renewable technologies achieve lower LCOE costs towards 2050 while other technologies remain on similar cost levels between 2015 and 2050. The overall electricity LCOE cost is in the range of 40-90 €/MWh in 2015 and 30-80 €/MWh in 2050.

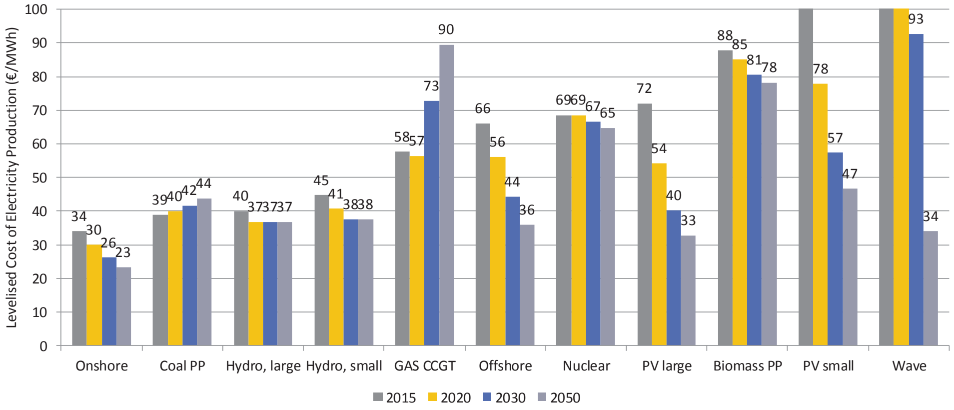

Figure 1: LCOE electricity costs for a variety of technologies in 2015, 2020, 2030 and 2050 sorted according to 2015 costs. All thermal plants are assumed to be operating in condensing mode while the Gas CCGT plant has the capability of operating in cogeneration mode, but with a lower electric efficiency. PP=power plant. PV=Photovoltaic. CCGT=combined Cycle Gas Turbine.

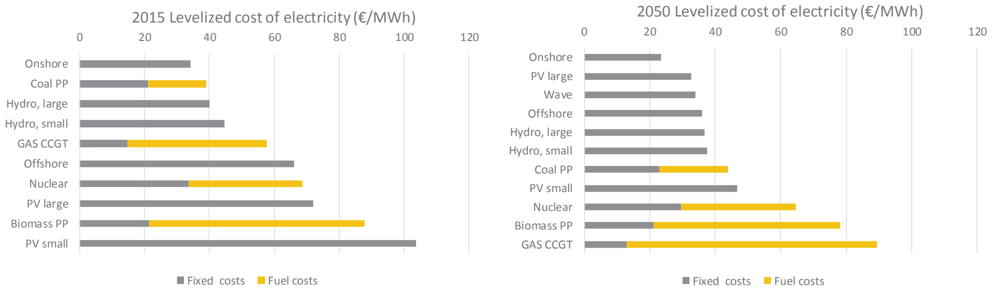

Figure 2: LCOE electricity costs sorted from lowest to highest costs in 2015 and with technology projections for 2050.

3.2. Decentralized heating

The decentralized heating technologies do not decline in costs in the same way as the electricity technologies. In fact, the costs are generally expected to increase slightly going towards 2050 with price levels around 50-100 €/MWh in 2015 and 70-100 €/MWh in 2050. Natural gas boilers, oil boilers and electric resistance heating costs increase while solar thermal technologies decrease. Natural gas boilers are in the low end of the LCOE costs in both 2015 and 2050 while heat pumps become more cost competitive in 2050 despite higher electricity prices. Due to the low efficiency of electric resistance heating this technology moves from the second lowest technology in 2015 to the second highest in 2050.

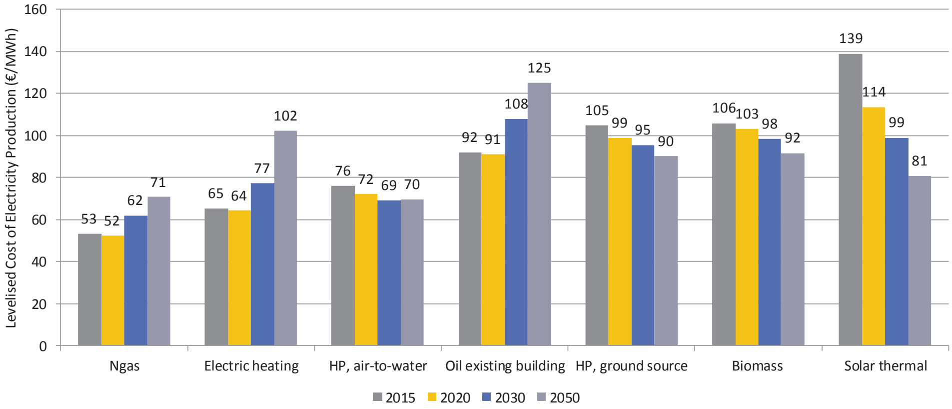

Figure 3: LCOE decentralized heating costs for a variety of technologies in 2015, 2020, 2030 and 2050 sorted according to 2015 costs. HP=Heat pump.

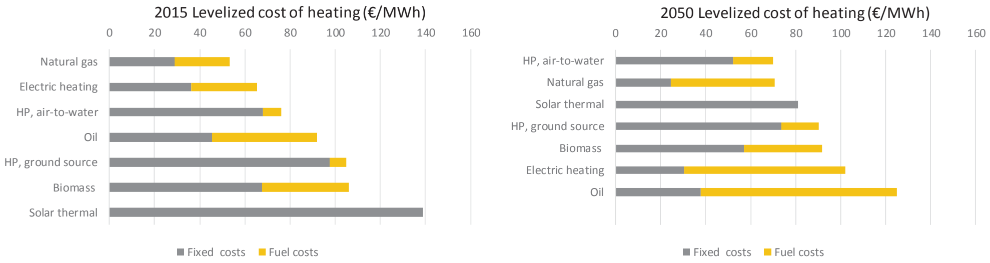

Figure 4: LCOE decentralized heating costs sorted from lowest to highest costs in 2015 and with technology projections for 2050.

3.3. District Heating

For LCOE district heating costs prices generally increase between 2015 and 2050 due to increasing electricity and fuel prices and because only minor investment cost reductions are expected. Only solar thermal has lower costs in 2050 than in 2015. Technologies with lowest costs are solar thermal, compression heat pumps and geothermal technologies. The district heating costs in 2015 are between 25-40 €/MWh and 25-50 €/MWh in 2050. The electricity prices are assumed to increase towards 2050, which has a significant impact on the costs for electric boilers and absorption heat pumps.

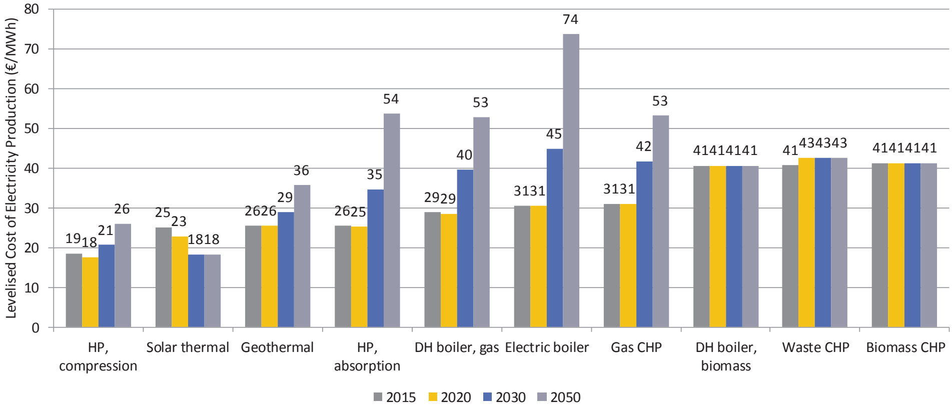

Figure 5: LCOE district heating costs for a variety of technologies in 2015, 2020, 2030 and 2050 sorted according to 2015 costs. HP=Heat pump. DH=District heating. CHP=Combined Heat & Power.

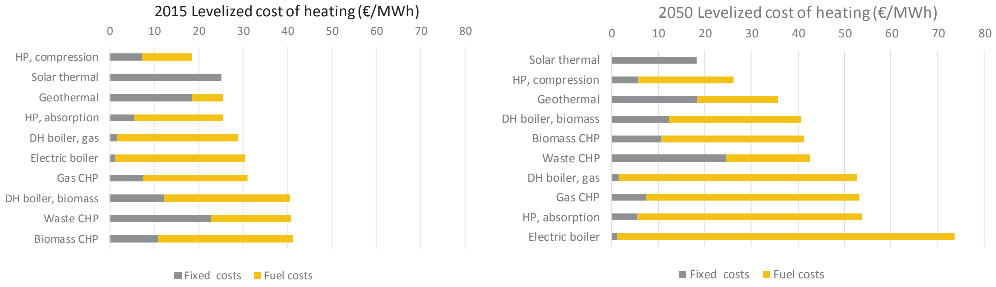

Figure 6: LCOE district heating costs sorted from lowest to highest costs in 2015 and with technology projections for 2050.

3.4. Cooling

Cooling costs are only for decentralized technologies as no district cooling data could be identified for this study. The LCOE costs to a large degree depend on the efficiency of the technology and the electricity price. LCOE costs in 2015 are between 15-50 €/MWh and they increase to 20-70 €/MWh in 2050. The technologies with lowest costs are water-cooled chillers followed by larger air-cooled technologies. The ranking of the cooling technologies does not change significantly between 2015 and 2050.

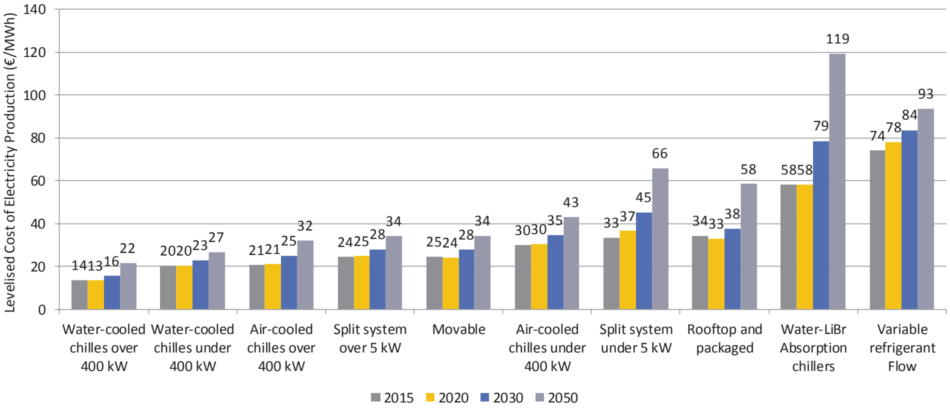

Figure 7: LCOE decentralized cooling costs for a variety of technologies in 2015, 2020, 2030 and 2050 sorted according to 2015 costs.

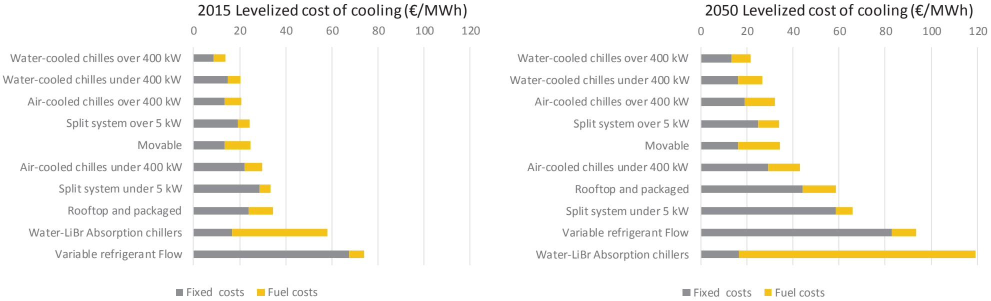

Figure 8: LCOE cooling costs sorted from lowest to highest costs in 2015 and with technology projections for 2050.

3.5. Comparison of costs across energy carriers

Different cost levels can be observed in Figure 9 when plotting the LCOE cost ranges for each energy carrier for 2015 and 2050. Decentralized heating solutions have the highest cost range in both 2015 and 2050 while the lowest costs are for some cooling and district heating technologies. Electricity costs decrease slightly towards 2050 while district heating and cooling ranges increase, primarily due to the assumptions about higher electricity prices in 2050.

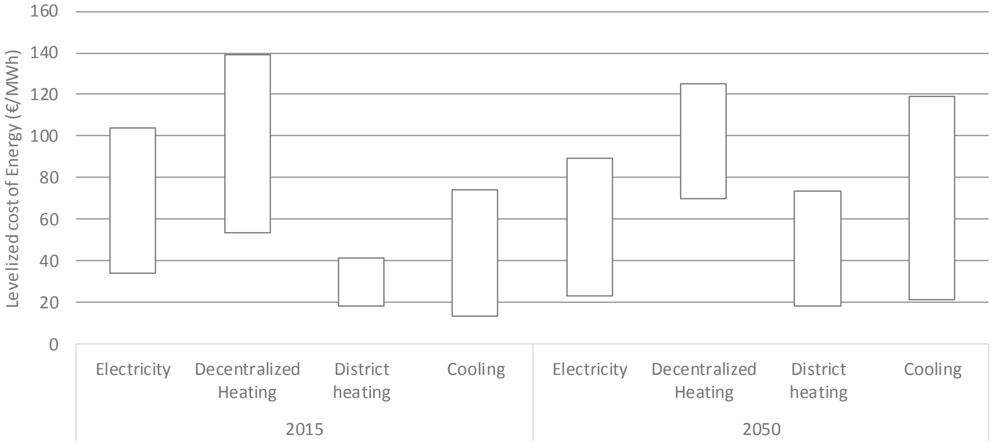

Figure 9: Levelized cost of energy ranges in 2015 and 2050 for the different energy carriers. Notice, that it is not recommended to compare decentralized heating costs directly with district heating costs as district heating networks also require additional investments in piping, substations, etc.

3.6. Benchmarking of LCOE electricity costs

Benchmarking of 2015 LCOE electricity costs are presented in Figure 10. A direct comparison across these references is not advised since the methods and assumptions differ significantly. Instead, the technology cost ranking is more appropriate to compare across the sources. Overall, onshore wind power and natural gas combined cycle plants are ranked as the lowest LCOE costs. These are followed by geothermal and hydropower. Some difference do occur for coal power plants, which are ranked as one of the lowest LCOE costs in present paper and in some other studies [20,21,23], but conversely rank as one of the highest LCOE costs in other studies [8][18,19]. This indicate differences in terms of methodologies and the evaluation factors included. The technologies with highest LCOE costs are nuclear, PV, biomass, natural gas turbines and offshore wind power. If considering 2050 costs this ranking might be altered. The benchmarking underlines the point about differences in evaluation factors causing the large range of LCOE costs across the studies. Overall, there is a satisfactory alignment between the LCOE ranking of this study and the LCOE cost ranking in the literature.

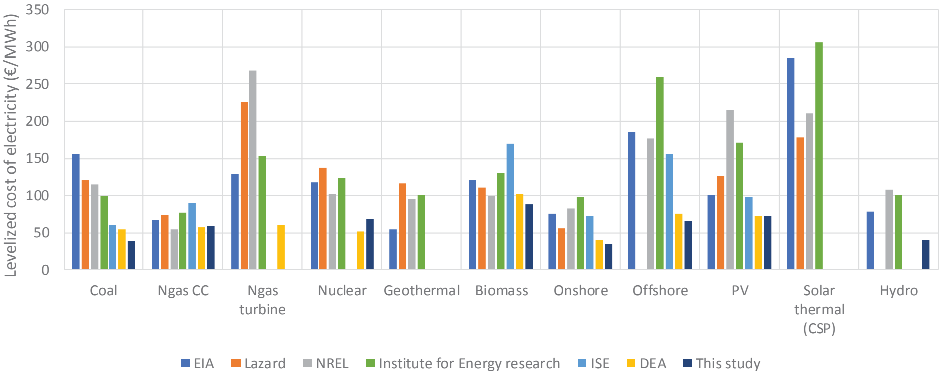

Figure 10: LCOE costs for various electricity generating technologies. Based on [8,18–21,23].

No benchmarking is performed for LCOE heat costs due to lack of other studies. Few sources were identified [26,27], but these are based on significantly different price assumptions and methodologies. Same argument applies for LCOE cooling costs where no other studies were identified.

3.7. Evaluation factors

As outlined in Table 1 a diversity of evaluation factors might be included in LCOE cost calculations. The evaluation factors analysed here apply to all technologies and include: increasing the interest rate to 7%, 25% higher fuel prices, 25% higher investment prices and inclusion of CO_2 damage costs. These changes do not reflect future projections, but are used as indications regarding the factors' influence on the LCOE costs. The impacts are illustrated in Figure 11 as the relative change compared to the 2015 LCOE costs. Impacts on LCOE costs in 2015 and 2050 are rather similar, but smaller differences occur as some technologies decline in investment costs thereby influencing the impact of changing the interest rate and investments. Furthermore, fuel consuming technologies are impacted by higher fuel prices in 2050 compared to 2015.

The most significant impacts vary between the energy carriers as interest rate and investment costs are key for electricity technologies while fuel costs have less influence. For cooling and decentralized heating, the interest rate and investment prices have highest impact while the fuel prices have the largest impact for district heating technologies. CO_2 damage costs only marginally impact the LCOE costs and only for the CO_2-emitting technologies. Overall, electricity generating technologies are most sensitive to changes in the evaluation factors while cooling technologies are least sensitive.

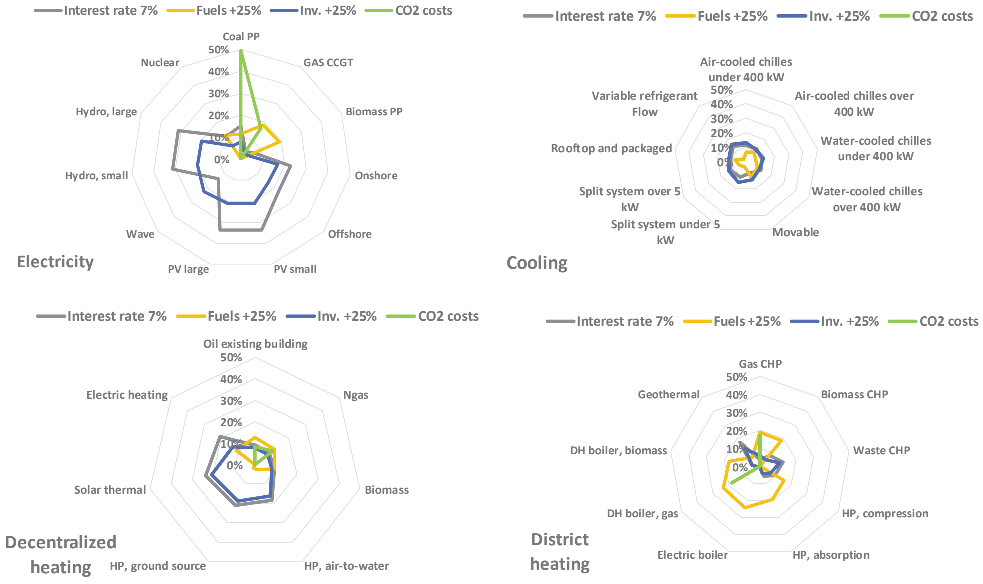

Figure 11: Impact of central evaluation factors on the LCOE costs in 2015 for electricity, cooling, decentralized heating and district heating (excluding substations and network costs). The impacts are presented relative to the 2015 LCOE costs. No CO_2 costs are assumed for electricity consumption as these are already part of the electricity price.

Changing the capacity factors and technology efficiencies mostly impact electricity and district heating technologies, but is not crucial for the total costs. The impact of other evaluation factors such as balancing costs for renewable electricity sources (2 €/MWh [20]) has less impact than the evaluation factors presented in Figure 11.

4. Discussion

The results proved the value of all the energy carriers and suggested that the highest levelized costs are for decentralized heating followed by electricity and district heating technologies. The energy carrier with the lowest LCOE costs are decentralized cooling technologies. This proves that all the energy carriers have a significant impact on the energy system costs and should be regarded in the future energy planning. This is in contrast to the fact that most LCOE studies and data are for electricity technologies.

The results also proved that the majority of the renewable technologies are expected to reach lower LCOE costs towards 2050 compared to today while fossil fuel sourced technologies will remain at similar costs or increase due to higher fuel prices. The largest cost improvements are for renewable electricity sources such as wind power, PV, solar thermal and wave power.

The LCOE calculations are a simplified way of comparing energy technologies and energy carriers and the question is whether this method is too simple and generic. For example, this approach does not encompass the challenges related to integrating variable and baseload sources and the value of dispatchable sources. If these factors are included in a full energy system perspective the LCOE values might change. For example, flexible technologies such as heat pumps might aid in integrating variable renewables like wind power and PV, which would otherwise be curtailed, which is not reflected in the LCOE costs. Another example is regarding solar thermal technologies that is expected to be among the lowest heating cost technologies in 2050, but is not able to supply the entire heat demand of a building or district heating network. Consequently, additional costs must be expected for technologies to generate in periods with no solar thermal production. Furthermore, numerous other factors such as local availability, energy resource potentials, political ambitions and energy efficiency also impact the feasibility of installing a technology.

The most influential evaluation factors for the LCOE costs are the interest rate, investment prices and fuel prices. Hence, the assumptions for these factors are crucial for the LCOE calculations and could ultimately alter the prioritization between energy technologies in the future. This is critical to have in mind during decision making as studies do not reach similar cost levels, as witnessed in Figure 10, and certain evaluation factors therefore indirectly influence the energy technology priorities. The consequence of this can be a lack of comparability with alternative energy solutions such as energy savings. Concretely, the feasibility of measures such as building retrofits and other heat saving measures can be impacted by the LCOE calculations as discussed in [40].

5. Conclusion

This paper has presented a methodology to compare levelized cost of energy across different energy carriers with the purpose of demonstrating the value of technologies within electricity, heating and cooling. More than 25 different evaluation factors were identified in a literature review highlighting the differences and the lack of comparability across levelized cost of energy studies.

The analysis showed that the highest LCOE costs are for decentralized heating technologies followed by electricity and district heating sources while cooling technologies have the lowest LCOE costs. The societal LCOE costs range between 50-120 €/MWh for decentralized heating in 2015 and 2050, 20-100 €/MWh for electricity, 20-70 €/MWh for district heating and 20-120 €/MWh for cooling. These costs exclude grids and are calculated ab plant.

The LCOE electricity costs in this study differ somewhat from cost levels in other studies in terms of absolute costs, but have higher similarity when considering the LCOE ranking of the technologies. This proves the significance of the evaluation factor assumptions and the influence of including or omitting certain factors. It was found that the most influential evaluation factors are interest rate, investment prices and fuel costs, which might significantly change the LCOE costs. The influence of these factors highlights the importance of creating transparency about assumptions and methods across studies. Otherwise, energy policies might change according to the LCOE costs supporting the decision making.

It is questionable how appropriate the LCOE method is for decision making since important aspects are ignored. The LCOE concept can provide an overview of how technology costs are expected to develop in the future, but does not encompass the full energy system impacts due to factors such as system dynamics and synergies.

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6. Appendix

Fuel prices

€/GJ	Coal	Oil	Natural gas (Europe)	Biomass (Wood chips)	Electricity	Uranium	Waste
2020	2.3	11.9	6.5	8.5	8	3.1	5
2030	2.7	16.8	9.5	8.5	12	3.1	5
2050	3.1	22.2	12.7	8.5	20	3.1	5

CO_2 prices

CO_2 prices	€/t
2020	26
2030	44
2050	59

Investment costs

	Technology	Unit	2015	2020	2030	2050
Electricity	400-700 MW Coal Steam PP	M€/MW	2	2.2	2.2	2.2
	100-500 MW Gas turbine CCGT, condensing mode	M€/MW	0.9	0.9	0.8	0.8
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	M€/MW	2	2	2	1.9
	Wind farm large onshore	M€/MW	1.1	1	0.9	0.8
	Wind farm large offshore	M€/MW	2.9	2.6	2.2	1.9
	PV small (residential)	M€/MW	1.5	1.3	1	0.9
	PV Large (utility)	M€/MW	1.2	1	0.8	0.7
	Wave	M€/MW	7.8	6.4	3.4	1.6
	Hydro, large (above 10 MW)	M€/MW	4.7	4.3	4.3	4.3
	Nuclear	M€/MW	3	3	2.7	2.4

Decentralized heating	Oil burner, One-family house, existing building	1,000 €/unit	6	5.9	5.6	5
	Natural gas boiler, one-family house, existing and energy renovated building	1,000 €/unit	3.2	3.1	3	2.7
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	1,000 €/unit	7	6.8	6.5	5.9
	Electrical heat pump, air-to-water, one-family house, existing building	1,000 €/unit	10	9.4	8.5	7.6
	Electrical heat pump, ground source, one-family house, existing building	1,000 €/unit	16	15	14	12
	Solar heating system, one-family house, existing building	1,000 €/unit	4	3.6	3.4	2.7
	Electric heating, one-family house, new building	1,000 €/unit	9	8.7	8.4	7.5
District heating	Gas turbine (combined cycle), back-pressure	M€/MW	0.9	0.9	0.8	0.8
	Medium steam turbine, woodchips	M€/MW	4	4	4	4
	Waste-to-energy CHP plant	M€/MW	8.5	8.5	8.5	8.5
	Electrical compression heat pumps	M€/MW	0.7	0.66	0.59	0.53
	Absorption compression heat pumps	M€/MW	0.6	0.56	0.51	0.46
	Electric boilers	M€/MW	0.06	0.06	0.06	0.06
	District Heating boiler, gas-fired	M€/MW	0.06	0.06	0.05	0.05
	District Heating boiler, wood chips	M€/MW	0.8	0.8	0.8	0.8
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	M€/MW	1.8	1.8	1.8	1.8
	Solar district heating	€/MWh	425	386	307	307
Cooling	Air-cooled chillers under 400 kW, Residential and service	1,000 €/10 kW capacity	2.6	2.7	2.9	3.4
	Air-cooled chillers over 400 kW, Service	1,000 €/10 kW capacity	1.8	2	2.2	2.5
	Water-cooled chillers under 400 kW, Residential and service	1,000 €/10 kW capacity	1.7	1.8	1.8	1.9
	Water-cooled chillers over 400 kW, Service	1,000 €/10 kW capacity	1.2	1.2	1.3	1.8
	Movable, Residential and services	1,000 €/10 kW capacity	1.6	1.7	1.7	2
	Split system under 5 kW, Residential and services	1,000 €/10 kW capacity	2.9	3.3	4.1	6
	Split system over 5 kW, Residential and services	1,000 €/10 kW capacity	2.2	2.3	2.5	2.9
	Rooftop and packaged, Services	1,000 €/10 kW capacity	2.8	2.9	3.2	5.1
	Variable Refrigerant Flow, Services and Residential	1,000 €/10 kW capacity	7.8	8.4	8.8	9.6
	Water-LiBr Absorption chillers (steam heated), Industry and District cooling	1,000 €/10 kW capacity	1.7	1.7	1.7	1.7

Lifetimes

	Technology lifetime in years	2015	2020	2030	2050
Electricity	400-700 MW Coal Steam PP	40	40	40	40
	100-500 MW Gas turbine CCGT, condensing mode	25	25	25	25
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	40	40	40	40
	Wind farm large onshore	25	27	30	30
	Wind farm large offshore	25	27	30	30
	PV small (residential)	30	35	40	40
	PV Large (utility)	30	35	40	40
	Wave	10	20	25	30
	Hydro, large (above 10 MW)	30	30	30	30
	Nuclear	35	35	35	35
Decentralized heating	Oil burner, One-family house, existing building	20	20	20	20
	Natural gas boiler, one-family house, existing and energy renovated building	20	20	20	20
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	20	20	20	20
	Electrical heat pump, air-to-water, one-family house, existing building	20	20	20	20
	Electrical heat pump, ground source, one-family house, existing building	20	20	20	20
	Solar heating system, one-family house, existing building	20	25	30	30
	Electric heating, one-family house, new building	30	30	30	30
District heating	Gas turbine (combined cycle), back-pressure	25	25	25	25
	Medium steam turbine, woodchips	30	30	30	30
	Waste-to-energy CHP plant	20	20	20	20
	Electrical compression heat pumps	25	25	25	25
	Absorption compression heat pumps	25	25	25	25
	Electric boilers	20	20	20	20
	District Heating boiler, gas-fired	25	25	25	25
	District Heating boiler, wood chips	20	20	20	20
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	25	25	25	25
	Solar district heating	30	30	30	30
Cooling	Air-cooled chillers under 400 kW, Residential and service	15	15	15	15
	Air-cooled chillers over 400 kW, Service	20	20	20	20
	Water-cooled chillers under 400 kW, Residential and service	15	15	15	15
	Water-cooled chillers over 400 kW, Service	20	20	20	20
	Movable, Residential and services	10	10	10	10
	Split system under 5 kW, Residential and services	12	12	12	12
	Split system over 5 kW, Residential and services	15	15	15	15
	Rooftop and packaged, Services	15	15	15	15
	Variable Refrigerant Flow, Services and Residential	15	15	15	15
	Water-LiBr Absorption chillers (steam heated), Industry and District cooling	12	12	12	12

Fixed O&M

	Technology fixed O&M (% of investment)	2015	2020	2030	2050
Electricity	400-700 MW Coal Steam PP	2.9	2.8	2.8	2.8
	100-500 MW Gas turbine CCGT, condensing mode	3.3	3.3	3.4	3.3
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	2.8	3.0	3.1	3.3
	Wind farm large onshore	2.4	2.4	2.5	2.6
	Wind farm large offshore	2.5	2.5	2.5	2.5
	PV small (residential)	1.0	1.0	1.0	1.0
	PV Large (utility)	1.0	1.0	1.0	1.0
	Wave	1.1	1.3	2.5	3.0
	Hydro, large (above 10 MW)	1.5	1.7	1.7	1.7
	Nuclear*	0	0	0	0
Decentralized heating	Oil burner, One-family house, existing building	4.0	4.0	4.0	4.0
	Natural gas boiler, one-family house, existing and energy renovated building	6.3	6.3	6.2	6.23
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	7.1	7.2	7.1	7.1
	Electrical heat pump, air-to-water, one-family house, existing building	2.9	2.9	2.9	2.9
	Electrical heat pump, ground source, one-family house, existing building	1.8	1.8	1.8	1.8
	Solar heating system, one-family house, existing building	1.5	1.6	1.7	1.9
	Electric heating, one-family house, new building	0.3	0.3	0.3	0.3
District heating	Gas turbine (combined cycle), back-pressure	3.3	3.3	3.3	3.3
	Medium steam turbine, woodchips	0.7	0.7	0.7	0.7
	Waste-to-energy CHP plant	1.7	1.7	1.7	1.7
	Electrical compression heat pumps	0.3	0.3	0.3	0.4
	Absorption compression heat pumps	0.3	0.4	0.4	0.4
	Electric boilers	1.8	1.8	1.8	1.8
	District Heating boiler, gas-fired	3.3	3.3	3.8	3.4
	District Heating boiler, wood chips	0.0	0.0	0.0	0.0
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	2.6	2.6	2.6	2.6
	Solar district heating	0.0	0.0	0.0	0.0
Cooling	Air-cooled chillers under 400 kW, Residential and service	4.0	4.0	4.0	4.0
	Air-cooled chillers over 400 kW, Service	4.0	4.0	4.0	4.0
	Water-cooled chillers under 400 kW, Residential and service	4.0	4.0	4.0	4.0
	Water-cooled chillers over 400 kW, Service	4.0	4.0	4.0	4.0
	Movable, Residential and services	4.0	4.0	4.0	4.0
	Split system under 5 kW, Residential and services	4.0	4.0	4.0	4.0
	Split system over 5 kW, Residential and services	4.0	4.0	4.0	4.0
	Rooftop and packaged, Services	4.0	4.0	4.0	4.0
	Variable Refrigerant Flow, Services and Residential	4.0	4.0	4.0	4.0
	Water-LiBr Absorption chillers (steam heated), Industry and District cooling	4.0	4.0	4.0	4.0

* All nuclear O&M included as variable

Variable O&M

	Technology variable O&M (€/MWh)	2015	2020	2030	2050
Electricity	400-700 MW Coal Steam PP	2	2.2	2.2	2.2
	100-500 MW Gas turbine CCGT, condensing mode	4.5	4.4	4.2	4.0
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	2.0	2.2	2.2	2.2
	Wind farm large onshore	2.8	2.5	2.3	2.1
	Wind farm large offshore	5.5	4.8	3.9	3.2
	PV small (residential)	0.0	0.0	0.0	0.0
	PV Large (utility)	0.0	0.0	0.0	0.0
	Wave	20	15	10	7
	Hydro, large (above 10 MW)	0.0	0.0	0.0	0.0
	Nuclear*	14.5	14.5	14.5	14.5
Decentralized heating	Oil burner, One-family house, existing building	0.0	0.0	0.0	0.0
	Natural gas boiler, one-family house, existing and energy renovated building	0.0	0.0	0.0	0.0
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	0.0	0.0	0.0	0.0
	Electrical heat pump, air-to-water, one-family house, existing building	0.0	0.0	0.0	0.0
	Electrical heat pump, ground source, one-family house, existing building	0.0	0.0	0.0	0.0
	Solar heating system, one-family house, existing building	0.0	0.0	0.0	0.0
	Electric heating, one-family house, new building	0.0	0.0	0.0	0.0
District heating	Gas turbine (combined cycle), back-pressure	4.5	4.4	4.2	4.0
	Medium steam turbine, woodchips	3.9	3.9	3.9	3.9
	Waste-to-energy CHP plant	0.0	0.0	0.0	0.0
	Electrical compression heat pumps	2	1.8	1.7	1.6
	Absorption compression heat pumps	1.0	1.0	1.3	1.9
	Electric boilers	0.5	0.5	0.5	0.5
	District Heating boiler, gas-fired	1.0	1.0	0.9	0.9
	District Heating boiler, wood chips	5.4	5.4	5.4	5.4
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	0.0	0.0	0.0	0.0
	Solar district heating	0.6	0.6	0.6	0.6
Cooling	Air-cooled chillers under 400 kW, Residential and service	0.0	0.0	0.0	0.0
	Air-cooled chillers over 400 kW, Service	0.0	0.0	0.0	0.0
	Water-cooled chillers under 400 kW, Residential and service	0.0	0.0	0.0	0.0
	Water-cooled chillers over 400 kW, Service	0.0	0.0	0.0	0.0
	Movable, Residential and services	0.0	0.0	0.0	0.0
	Split system under 5 kW, Residential and services	0.0	0.0	0.0	0.0
	Split system over 5 kW, Residential and services	0.0	0.0	0.0	0.0
	Rooftop and packaged, Services	0.0	0.0	0.0	0.0
	Variable Refrigerant Flow, Services and Residential	0.0	0.0	0.0	0.0
	Water-LiBr Absorption chillers (steam heated), Industry and District cooling	0.0	0.0	0.0	0.0

Efficiencies/capacity factors (Lower heating value)

	Technology efficiencies/capacity factors (%)	Unit	2015	2020	2030	2050
Electricity	400-700 MW Coal Steam PP	Elec.	46.0	48.5	52.0	53.5
	100-500 MW Gas turbine CCGT, condensing mode	Elec.	55.0	56.0	58.0	60.0
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	Elec.	46.0	48.5	52.0	53.5
	Wind farm large onshore	CF	35	36	37	38
	Wind farm large offshore	CF	50	51	53	56
	PV small (residential)	CF	11	12	12	13
	PV Large (utility)	CF	13	14	14	15
	Wave	CF	17	29	40	51
	Hydro, large (above 10 MW)	Elec.	45	45	45	45
	Nuclear	Elec.	32	32	32	32
Decentralized heating	Oil burner, One-family house, existing building	Thermal	92	92	92	92
	Natural gas boiler, one-family house, existing and energy renovated building	Thermal	97	97	98	99
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	Thermal	80	82	86	88
	Electrical heat pump, air-to-water, one-family house, existing building	Thermal	358	368	388	405
	Electrical heat pump, ground source, one-family house, existing building	Thermal	395	405	415	435
	Solar heating system, one-family house, existing building	Thermal	-	-	-	-
	Electric heating, one-family house, new building	Thermal	100	100	100	100
District heating	Gas turbine (combined cycle), back-pressure	Thermal	30	30	31	32
	Medium steam turbine, woodchips	Thermal	64	64	64	64
	Waste-to-energy CHP plant	Thermal	74	71	71	71
	Electrical compression heat pumps	Thermal	350	360	380	410
	Absorption compression heat pumps	Thermal	170	171	173	175
	Electric boilers	Thermal	99	99	99	99
	District Heating boiler, gas-fired	Thermal	103	103	104	104
	District Heating boiler, wood chips	Thermal	108	108	108	108
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	Thermal	100	100	100	100
	Solar district heating	Thermal	100	100	100	100
Cooling	Air-cooled chillers under 400 kW, Residential and service	Thermal	380	420	460	520
	Air-cooled chillers over 400 kW, Service	Thermal	400	460	500	560
	Water-cooled chillers under 400 kW, Residential and service	Thermal	520	550	590	680
	Water-cooled chillers over 400 kW, Service	Thermal	590	660	740	880
	Movable, Residential and services	Thermal	260	280	320	400
	Split system under 5 kW, Residential and services	Thermal	610	660	780	1000
	Split system over 5 kW, Residential and services	Thermal	580	610	680	800
	Rooftop and packaged, Services	Thermal	280	360	420	500
	Variable Refrigerant Flow, Services and Residential	Thermal	430	520	570	490

PAPER 4

Decision-making based on energy costs: Comparing Levelized Cost of Energy and Energy System costs

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Highlights:

- Evaluation of energy costs based on two different cost estimation methods.
- The comparison of the levelized cost of Energy and the Energy System Analysis costs.
- The analysis of Energy costs using the German energy system.
- The change of priorities depending on the energy cost method used.

Abstract:
Some energy policies aim to increase the share of renewable energy in the most cost-effective way, but the challenge is how to assess the costs of integrating these technologies into an energy system. This article analyzes two cost estimation methods, the Levelized Cost of Energy (LCOE) and the Energy System Analysis (ESA) methods. These methods are compared for electricity, decentralized heating and district heating technologies for two system configurations of the German energy system. The Advanced Energy System Analysis Tool EnergyPLAN is used to model a situation where nuclear power is decommissioned and a situation without coal and oil boilers for heating. The results indicate that priorities differ according to the applied method. The results also show that looking beyond costs and including other parameters such as energy system efficiency and CO_2 emissions will significantly change energy priorities. Various system dynamics that are not captured in the LCOE method are highlighted and discussed.

Keywords: Levelized Cost of Energy, Energy System Analysis, Energy Costs, Germany.

Declarations of Interest: None.

1. Introduction

Energy and Climate Policy aims to increase the share of renewable energy in the future energy system through the 2015 Paris Agreement [1], the U.S. energy targets [2] and the European Union defined targets [3]. The challenge is how to achieve these targets in the most cost-effective way. Energy system costs can be evaluated in various ways influencing future energy system decisions. Precisely, this article examines two different methods of evaluating energy costs: the levelized cost of energy (LCOE) method and the energy system analysis (ESA) method. The purpose of this paper is to analyze how different costing methods support decision-making within the energy system and may change future energy technology priorities. The emphasis is not on actual costs, but how the priority may change when using two different methods.

The levelized cost of energy is used to assess the energy production costs of energy technologies. This method is mainly used to assess the cost of electricity generation, and only a few studies investigated heating and cooling technologies [4]. The purpose of the LCOE method is to compare and benchmark energy technologies across scale, geography and type in order to find the costs of energy supply throughout its lifetime. The LCOE method has been used for numerous purposes of cost evaluation such as photovoltaic solar energy and electrical energy storage [5,6], nuclear energy [7], wind energy [8,9], wave and tidal energy [10], biomass technologies [11,12] and for hybrid systems that combine PV, batteries and cogeneration [13].

Examples show that this method is used to help in political decision making in the past, as well as in current research [14–18]. The LCOE costs have supported decision-making by the European Union to justify the subsidy schemes for renewable technologies and establish adequate CO_2 emission fees in accordance with the gap between renewable and fossil resources [15]. Another example is the change in UK energy policies in the early 2000s towards a greater focus on nuclear energy solutions due to improved assessments of the economics of nuclear energy [19]. Here, it was concluded that nuclear technology no longer needed subsidies and could contribute to the fulfillment of future energy objectives.

The criticism of the LCOE method arose due to the lack of comparability and transparency for calculating costs as different assumptions and methods are used [15,16,20–22]. These differences are related to the cost assumptions for environmental damage, dispatchable production, interest rates and various other factors. Improvements have been suggested in the LCOE method by adding a correction factor to internalize the missing aspects of costs, such as the cost of renewable technology by intermittency [23]. Others suggest that the LCOE method is too static and does not take uncertainties into account, which is why improved methods have been discussed to include the costs of uncertainty through a probabilistic model [24], Monte Carlo simulations [25] or by comparing different methods for probabilistic life-cycle costs for power plants [26]. In addition, the return on investment factor is lacking in the LCOE method and [16] therefore suggests using policies for this purpose. Finally, methods to incorporate externalities into the LCOE method have also been suggested [27]. These studies focus on refining the LCOE method through new parameters instead of suggesting a different method to evaluate energy costs.

An alternative method is the ESA method that relies on analyzing the whole energy system instead of the individual technologies, which can be more cumbersome and requires an additional effort to complete the cost calculations. Unlike the LCOE method, the ESA method normally does not generate unit costs of energy production (for example, €/kWh), but rather a total cost of the energy system (for example, M€). In addition to evaluating costs, the ESA method has the ability to evaluate other parameters at the same time, such as fuel consumption and CO_2 emissions, which will also be analyzed in this article.

The ESA method has been used in numerous studies, mainly to assess the costs of national energy systems. [28] analyzed the costs of the Danish energy system costs in a future 100% renewable energy scenario compared to the costs in the current system and a business-as-usual scenario. A similar study was carried out for the German energy system that identifies feasible paths towards a highly renewable future that evaluates the costs of the energy system and other indicators [29]. The ESA method has also been used for techno-economic assessments across the EU [30,31], and in a global analysis for small islands [32]. A comparison and discussion of the different characteristics of multi-energy systems (multiple energy sectors) are provided by [33], concluding that multi-energy systems work better than separate energy systems. Finally, a framework was created to develop beyond the cost perspective solely to assess the scenarios of sustainability (environmental, economic, social) of energy [34].

According to the knowledge of the authors of this article, there have been no comparisons of these methods previously to evaluate priorities based on different cost calculation methods. In addition, this article provides new insights for heating technologies, which are often not included in cost calculations. The novelty in this article is presented through methodological advances on the importance of ESA with respect to LCOE.

2. Methods and materials

The LCOE and ESA methods include different energy system elements in the analysis, which are illustrated in Figure 1 and Figure 2. In the ESA method, all the elements of the energy system are evaluated, such as resources, conversion, exchange, demand and storage technologies. Hence, an aggregate system cost is obtained for system synergies when carrying out changes in one part of the energy system. The costs are usually calculated as B€/year or a different unit that aggregates the total costs of the system into a single number.

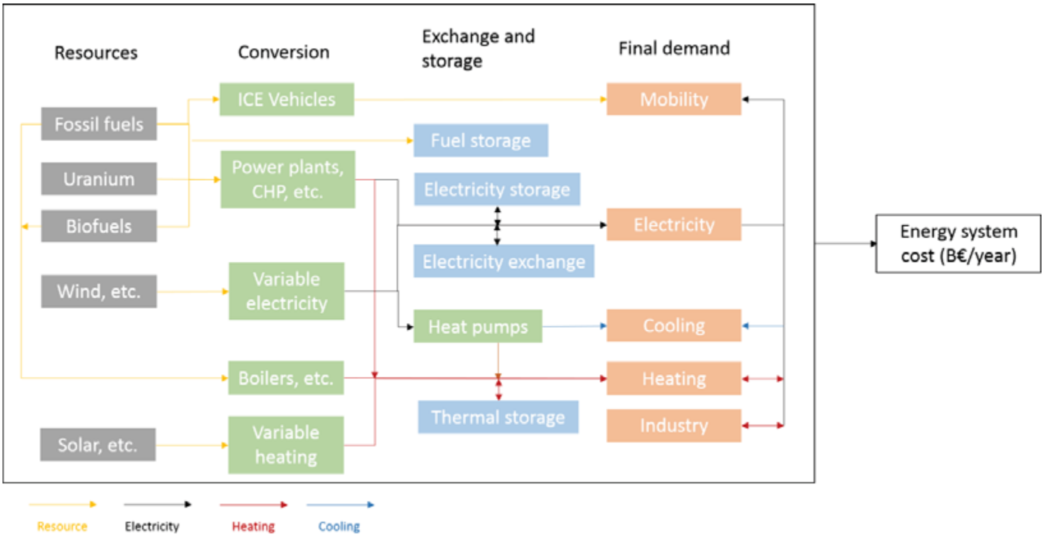

Figure 1: Illustration of energy system elements included in the ESA method for cost assessments.

The LCOE method has a narrower focus on the energy system that evaluates the costs of producing energy from a single technology. In this method, resources and elements of conversion of the energy system are included. This method usually calculates costs in €/MWh or a different unit that represents the cost of energy production.

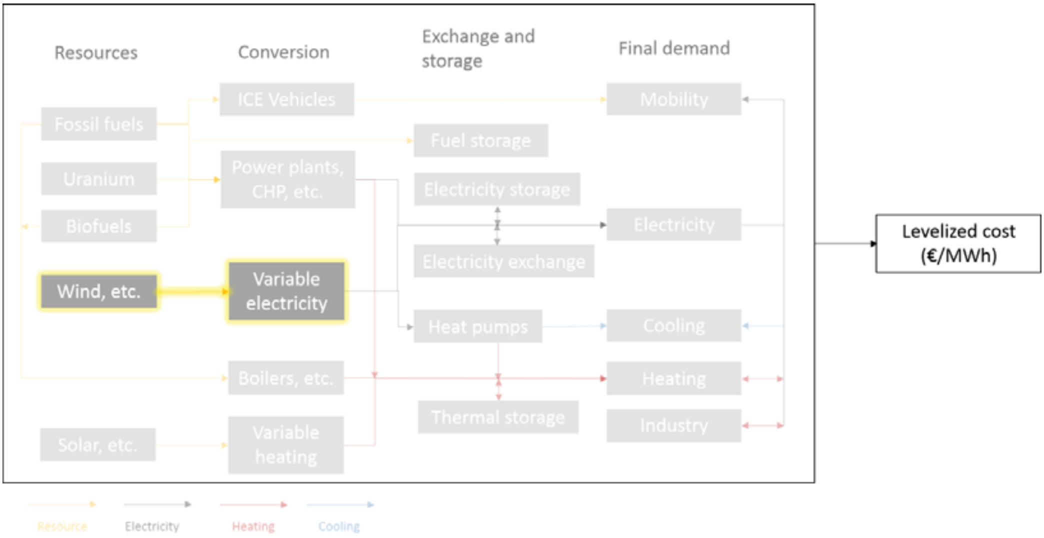

Figure 2: Illustration of energy system elements included in the LCOE method where individual technology costs are analysed.

The purpose of this article is to investigate the influence of different cost calculation methods on the energy priorities for the future.

The LCOE costs are calculated according to these inputs and the data are presented in the appendix.

$$\frac{\sum_{t=1}^{n}\frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Energy generation in year t
R = Discount rate
N = Lifetime of the technology

The energy technologies included for cost comparisons are grouped into electricity, decentralized heating and district heating technologies. Decentralized heating technologies are installed in individual buildings instead of collective solutions. All LCOE technology costs are presented in Table 1, Table 2 and Table 3.

Grid and network costs are not included in LCOE cost calculations, which makes it difficult to compare energy costs across energy carriers. For example, district heating and electricity grid costs should be included in order to get the consumer costs while for decentralized heating technologies, it is not necessary to include additional grid costs.

The costs of ESA apply a complete analysis of the energy system to cover all the direct and indirect energy system dynamics, that is, the effects on the entire energy system of the installation of a technology. For example, the installation of additional electrical heat demand in the heating sector also affects the generation of electricity and the capacities required in the electricity sector. The ESA costs are based on a model of the German energy system in 2015 available on [35], which is selected because the German energy system has a wide range of installed technologies needed for the comparison. The German energy system of 2015 is based on a model developed jointly with the projects IEA SHC Task 52 and IEA ECES Annex 28 projects [36,37].

The ESA costs are aggregated for the entire system, including all technologies, fuels, etc. They are measured in billions of Euros/year and consist of investments, operation and maintenance, fuel costs and CO_2 emission costs. A detailed description of the input data is available in the appendix. The ESA cost ranking is evaluated based on the total costs of the energy system to install each technology in the system, that is, the technology with the lowest energy system cost is classified as number one and so on. For both methods, an interest rate of 4% is assumed. All cost assumptions for both methods are based largely on the continuously updated technology data sheets published by the Danish Energy Agency [38,39]. This source is used as data is provided for almost all technologies through electricity, decentralized and district heating, and provides a consistent framework for comparing technologies. Most other cost databases focus on electricity costs, while only a few sources include heating technologies. It is assumed that the possible price differences between Danish and German energy systems are insignificant and that data from the Danish Energy Agency apply to both energy systems. Fuel prices are from [40] and are generally in the high range, which should be taken into account when comparing the costs of the technologies. All costs are from a social perspective, excluding technology and fuel subsidies, taxes, etc.

The energy system models are developed using the advanced energy system analysis tool EnergyPLAN, which has been previously used for numerous studies and multiple purposes, such as the development of national energy strategies and the evaluation of the feasibility of a variety of technologies [28,36,41–43]. EnergyPLAN is a simulation tool that simulates all energy sectors (electricity, heating, cooling, industry, transport) for a full year with an hourly resolution [44]. This allows covering all the direct and indirect dynamics in the energy system, such as the synergies between heating and electricity technologies when new technologies are installed. In addition, EnergyPLAN can analyze factors beyond costs, such as CO_2 emissions and primary energy supply, as well as the temporal balance between supply and demand for electricity and heating. The use of the EnergyPLAN tool allows the evaluation of the energy system analysis costs for the entire energy system.

Two separate energy system configurations are created with changes in the German energy system to compare the technological ranking in the two methods. These classifications are ordered from the most feasible technology using the LCOE method (technology generation costs) and the ESA method (aggregate energy system costs).

The first configuration of the system compares the technologies in the German electrical system by dismantling nuclear power capacity and installing a different technology to replace it. There are no changes in the final energy demands. The nuclear power capacity is 21,500 MW with a production of 141 TWh / year in the 2015 model, equivalent to 23% of the total electricity production. By installing other technologies to replace nuclear energy, thermal plants (condensing power plants and CHP plants) are installed with a capacity similar to nuclear capacity, while other technologies are expanded to produce a similar electricity production. The existing German nuclear energy is expected to be eliminated in the early 2020s and this case, therefore, analyzes the technological priorities for short-term developments in the German electricity sector.

The second energy system configuration compares the heating technologies if all decentralized coal and oil boilers are replaced with another technology. The coal and oil boilers deliver 229 TWh of heating in 2015, which is equivalent to 26.7% of the total heat demand, and most of it is produced in oil boilers. Decentralized heating technologies replace coal and oil boilers considering changes in investments, efficiencies, etc. For district heating technologies, an expansion of the

German district heating network with a network loss of 17.9% is assumed and is based on the approach used in [36]. The expanded supply of district heating produces the same amount of heat as coal and oil boilers in decentralized heating and expands to a heat demand proportion of 42% of all heating in Germany (15% before expansion) . The additional costs of this expansion include district heating pipes (transmission, distribution and branch pipes) and amount to an investment of € 26,788 million, while operation and maintenance (O & M) represents 1.25% of the investment and lifespan is 40 years [36]. When the district heating share increases, the cost of the network per unit of energy also increases due to the lower density of heat demand in the new urban heating areas. This is considered in the calculations of network costs based on geographic data developed in the STRATEGO project [45]. In addition, the costs of installing district heating substations are included depending on the number of homes converted to district heating. This investment is 8,982 M€ with a lifetime of 25 years and an O&M of 2.27% of the investment [39].

The two configurations of the energy system are extreme where only one technology is installed in each scenario to allow the exploration of the effects of the system for each technology. These scenarios are not realistic, since a range of technologies would be complemented in a future energy system, but this method is suitable for this article for comparison with LCOE costs, which also calculate the installation costs of a single technology. Considerations on the potential of resources are not included, although technologies such as wave power probably can not produce this amount of energy.

The main parameter for the comparison is the energy costs because the LCOE method does not allow comparing other factors. However, other factors such as primary energy supply and CO_2 emissions are considered in later chapters.

3. Results

The technology cost rankings are carried out in accordance with Table 1, Table 2 and Table 3 and the analysis of the energy system of the German energy system configurations. The classifications illustrate the order of the lowest cost to the highest, but do not specify the cost differences between the technologies.

3.1. Electricity technologies

The synergies in the energy system are visualized in Figure 3 and Figure 4 for the first week of the year when the production of nuclear energy is replaced with more variable onshore wind power production. The electricity production per hour is illustrated to indicate how the electricity demands and the type of production profile for each technology are met. With less nuclear production, other technologies in the system operate more, while the excess production of electricity increases after implementing more wind power. This type of synergies affects the energy system costs and fuel consumption and are not visible when the LCOE method is applied.

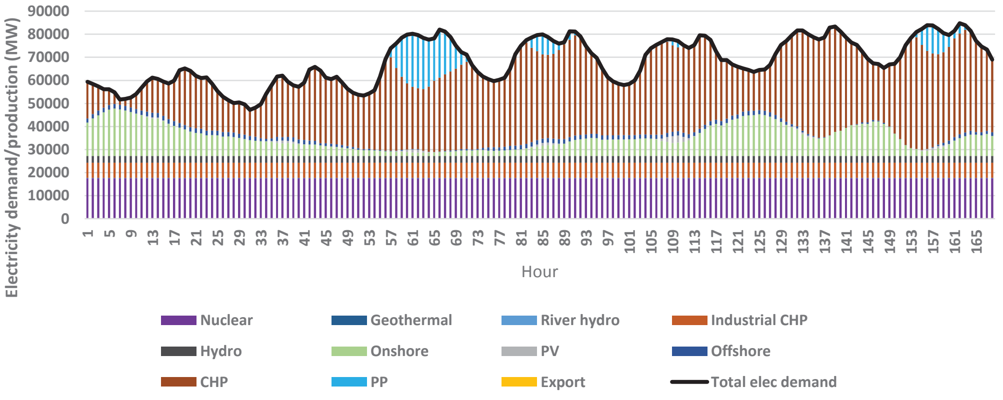

Figure 3: Hour-by-hour baseline electricity demand and production in the first week of the year.

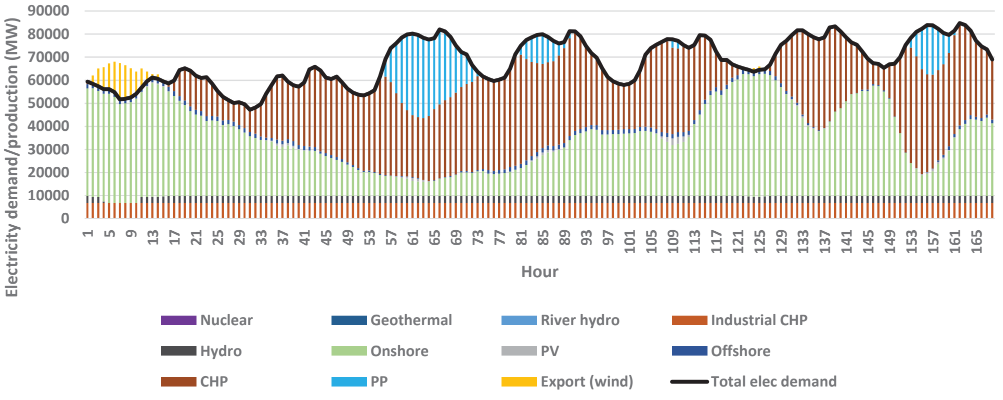

Figure 4: Hour-by-hour electricity demand and production in the first week of the year after replacing the nuclear power with onshore wind power.

There is some alignment between the cost ranking of electric technologies using the LCOE method and the ESA method as illustrated in Figure 5. The ranking is a measure of the order of the lowest to the highest costs when evaluating the technologies, which can be seen in Table 1. The technology ranking only differs in up to two locations, except in coal and gas power plants. This difference is mainly caused by the increase in CO_2 costs, which strongly influences the costs of the condensing coal power plants. The gas-consuming power plants use more expensive fuels, which overall results in high energy system costs.

Table 1: Energy costs for electricity technologies using the LCOE method and the ESA method for the German energy system. PP=Power plants.

	Onshore	Coal PP	Hydro-power, large	Hydro-power, small	CCGT^a	Offshore	Nuclear	PV, large	Biomass PP	PV, small	Wave

LCOE costs (€/MWh)	34	39	40	45	58	66	69	72	88	104	798
ESA costs (b€/year)	484.7	490.2	485.5	486.2	494.8	488.4	490.1	491.0	491.5	495.5	579.7

[a] Excess heat might also be generated from these plants while producing electricity.

Replacing the production of nuclear power with thermal plants in condensing mode improves the flexibility of the system. This is demonstrated by the increased production of electricity from CHP plants in cogeneration mode, although the capacity of the condensing plants also increases. CHP's electricity production grows by 24% when baseload nuclear power plants are replaced by more flexible coal and gas thermal plants. Simultaneously, this reduces the district heating boiler production, which shows that adjustments in the electricity sector also affect the heating sector. The CHP and condensing power plants have a fairly similar fuel mixture in the model resulting in lower effects on fuel costs. The conversion of nuclear plants to thermal plants reduces the primary energy supply by 3.3% caused by increasing cogeneration CHP operation and because the conversion efficiencies are improved (the efficiencies of the nuclear plant are 33% while the coal and gas plants have electrical efficiencies of 39% and 41%).

Compared to the nuclear baseline scenario, the installation of additional variable renewable capacities such as wind and solar power, does not lead to changes in CHP production. This indicates that the flexibility of the energy system is not modified due to the low capability of variable technologies to meet the demands, which also causes an increase in the export of electricity and an excess of production at certain times of the year. In particular, installing more photovoltaic capacity leads to a greater excess of electricity production (20-25 TWh/year or 3.5% of total annual electricity production). This is caused by the lack of correspondence between production patterns and electricity demand, which is greater than for other variable technologies.

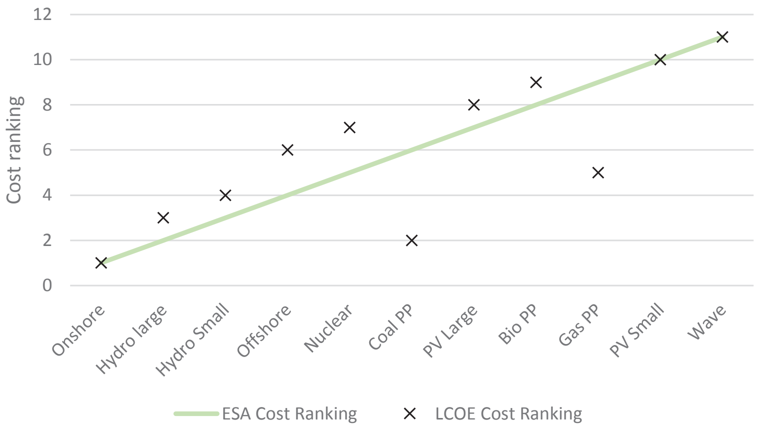

Figure 5: Cost ranking for electricity technologies using the LCOE and ESA cost methods. PP=power plants. PV=photovoltaics.

3.2. Decentralized heating

When converting from decentralized coal and oil boilers to other technologies such as ground-source heat pumps, changes occur in the heating sector, as illustrated in Figure 6 and Figure 7. The installation of new heat pumps causes a greater demand for electricity, which requires more power from condensing power plants and CHP plants. This additional heat production from CHP plants reduces the demand for the production of district heating boilers. This is an example of the synergies between decentralized and district heating sectors that can only be identified using the ESA method.

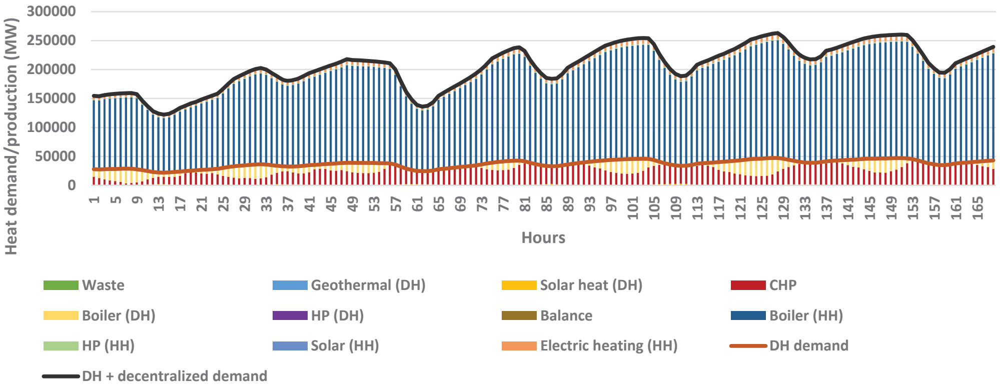

Figure 6: Hour-by-hour baseline heat demand and production in the first week of the year.

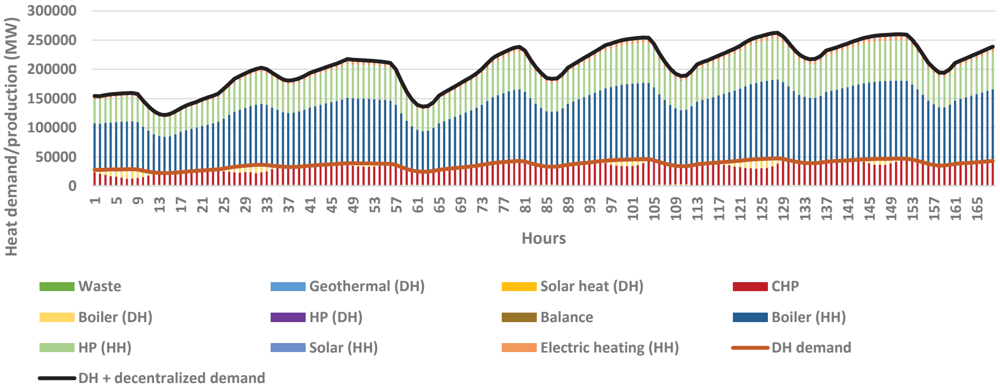

Figure 7: Hour-by-hour baseline heat demand and production in the first week of the year after replacing coal and oil boilers with ground-source heat pumps.

The rankings of the decentralized heating technology diverge significantly between the two methods. For example, in the ESA calculations, solar heating is considered the second lowest cost technology and the highest cost in LCOE calculations. In the ESA method, the fuel savings are greater than the increase in investments, which results in a reduction of the energy system costs by 2.1% compared to the scenario with high fuel costs for oil boilers. Almost all decentralized heating technologies lead to a general reduction in system costs when the ESA method is applied, with the exception of biomass boilers due to increasing O&M costs.

Table 2: Energy costs for decentralized technologies using the LCOE method and the ESA method for the German energy system. HP=Heat pump.

	Ngas boiler	Electric heating	HP, air-to-water	Oil boiler	HP, ground source	Biomass boiler	Solar heating
LCOE costs (€/MWh)	53	65	76	92	105	106	139
ESA costs (b€/year)	480.6	486.6	479.2	490.1	485.7	495.0	480.1

The energy system is affected beyond the decentralized heating sector when more technologies that consume electricity are installed, since this leads to an additional operation of the CHP plant, which reduces the production of district heating boilers. More significantly, this takes place for electric heating. The increased demand for electricity also increases the operation of condensing power plants that generally consume coal. In fact, the coal consumption of the energy system grows by more than 400 TWh/year (about 50% increase) in the electric heating scenario, which results in an increase in CO_2 emissions, despite replacing the oil boilers. Electric heating is also the only technology that causes an increase in the demand for primary energy. The higher technological efficiency of heat pumps means that CO_2 emissions decreases in the heat pump scenarios due to the lower electricity production of thermal power plants that consume coal compared to the electric heating scenario.

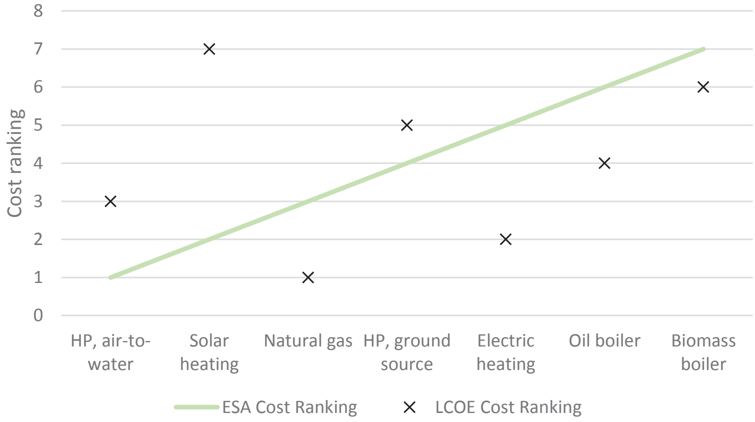

Figure 8: Cost ranking for decentralized heating technologies using the LCOE and ESA cost methods.

3.3. District heating

The hour-by-hour district heating production is illustrated for the baseline situation in Figure 9 and after converting to additional compression heat pumps in Figure 10. Despite installing heat pumps and increasing the demand for electricity, the operation of the condensing power plant decreases compared to the baseline because the higher district heating demand allows for more CHP operation. The dynamics of the energy system again encompass the various energy sectors, in this case, the district heating and electricity sectors.

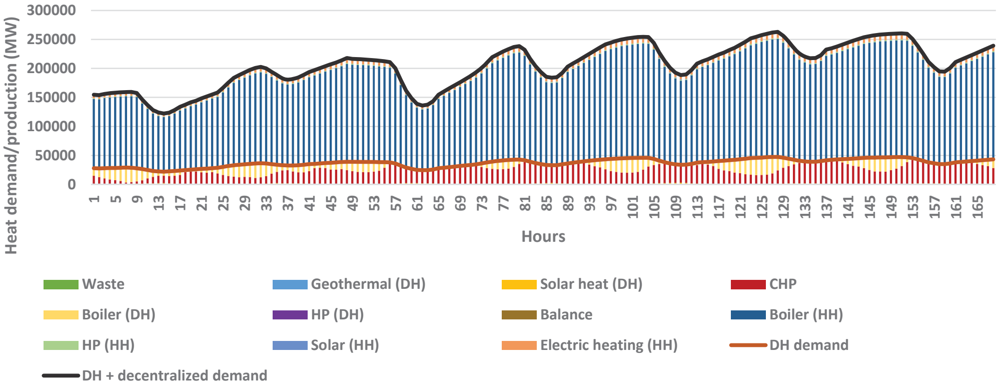

Figure 9: Hour-by-hour baseline heat demand and production in the first week of the year.

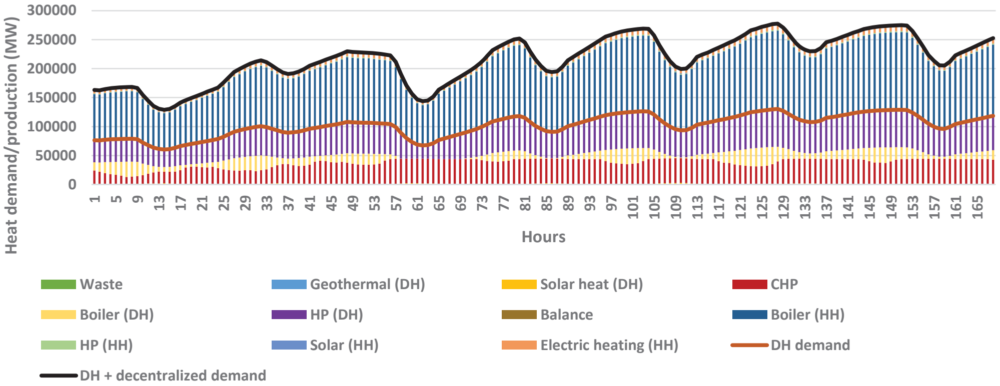

Figure 10: Hour-by-hour baseline heat demand and production in the first week of the year after district heating expansion and installing further compression heat pumps for district heat supply.

The cost rankings of LCOE and ESA are quite similar for district heating technologies, as shown in Figure 3, where some technologies are lower and others are higher. This is surprising considering all the system dynamics when considering the district heating sector. In general, the largest cost reductions are for lower fuel costs due to oil savings. Investment costs are maintained at a similar or slightly higher level, even when the additional costs of the district heating network and the substations are included. However, there are large differences in the operation of the technologies in the system. The biggest differences are for CHP plants and district heating boilers, where the boiler production varies from 4 TWh/year (electric boiler scenario) to 263 TWh (DH boiler scenarios) while CHP production is as low as 63 TWh/year (thermal solar scenario) up to 249 TWh/year (CHP woodchips scenario). These changes also affect the electricity sector since the production of CHP influences the operation of the condensing power plants.

Table 3: Energy costs for district heating technologies using the LCOE method and the ESA method for the German energy system. HP=Heat pump.

	HP, compression	Solar thermal	Geo-thermal	HP, absorption	DH boiler, gas	Electric boiler	Gas turbine	DH boiler, biomass	Waste CHP	Wood-chips
LCOE costs (€/MWh)	19	25	26	26	29	31	31	41	41	41
ESA costs (b€/year)	468.3	473.7	470.5	472.4	473.0	479.6	480.0	474.7	476.4	481.3

The temporal alignment between the demand for district heating and production also influences the costs of the energy system. Some technologies are inflexible, such as geothermal, waste CHP and solar thermal, and generate either constant baseload heating or fluctuates according to the sun. This results in an overproduction of district heating, which must be wasted, since there is no demand or possibilities to store it. The geothermal scenario has the highest overproduction of district heating of 65 TWh/year, equivalent to 12% of the total district heating production. The total fuel consumption is affected by the flexibility inflicted by technology in the energy system, where technologies such as district heating boilers must guarantee a balance between heat demand and production every hour of the year. This can be observed in the solar thermal, geothermal and CHP waste scenarios, where the consumption of natural gas increases due to the increased production of district heating boilers.

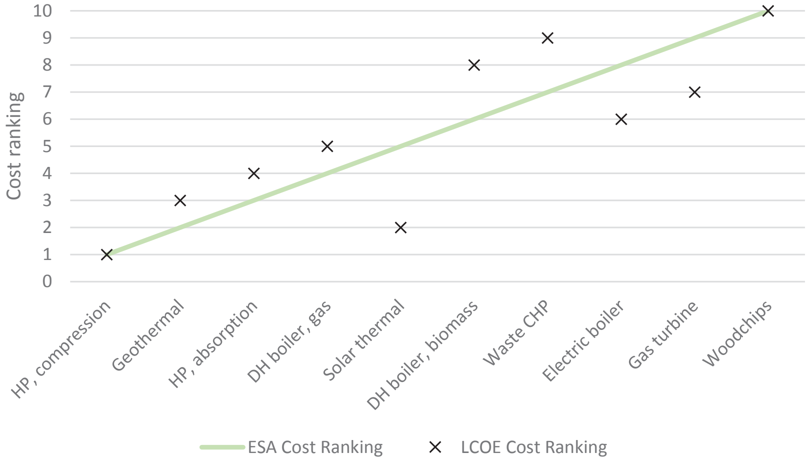

Figure 11: Cost ranking for district heating technologies using the LCOE and ESA cost methods. No grid costs are included for LCOE costs and it is not recommended to compare directly with decentralized heating costs.

3.4. CO_2-emissions and fuel efficiency parameters

The ESA method has the ability to quantify the effects on other factors besides costs. These are analyzed for primary energy and CO_2 emissions to assess whether these should support in the decision-making priorities.

For electricity technologies, some surprising results are found when analyzing CO_2 emissions for the energy system. For example, both small and large photovoltaic systems increase the total CO_2 emissions of the system when nuclear power plants are replaced. This occurs due to a temporal mismatch between the production of PV and the demand for electricity that causes overproduction that can not be used, stored or exported to other systems. Consequently, thermal plants have to operate more consuming fossil fuels that affect the CO_2 emissions of the system. Priority should be given to hydroelectric power, biomass power plants (assuming that biomass does not have CO_2 emissions in the energy system) and wind energy if CO_2 reductions are the central parameter for policy formulation.

For fuel efficiency of the energy system, all technologies result in primary energy reductions, since the low efficiency of nuclear power plants (33%) is replaced by more efficient or fuel-free technologies.

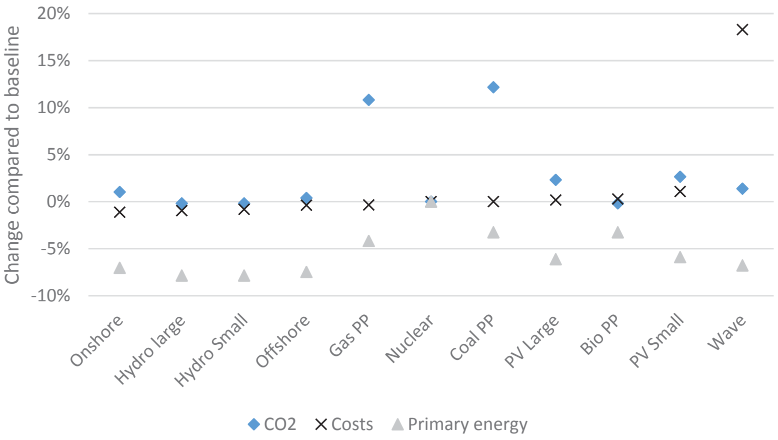

Figure 12: ESA changes in CO_2-emissions, costs and primary energy demand for electricity technologies compared to the baseline scenario with nuclear power.

The decentralized heating technologies show less surprising results and indicate that the installation of biomass boilers and thermal solar energy produce the lowest CO_2 emissions. However, biomass boilers are among the technologies with the highest energy system costs, which shows that the priorities change significantly according to the parameters. In addition, the supply of electric heating leads to an increase in CO_2 emissions caused by the growing demand for electricity, which is supplied by coal plants. This type of energy system dynamic is difficult to anticipate with the LCOE method.

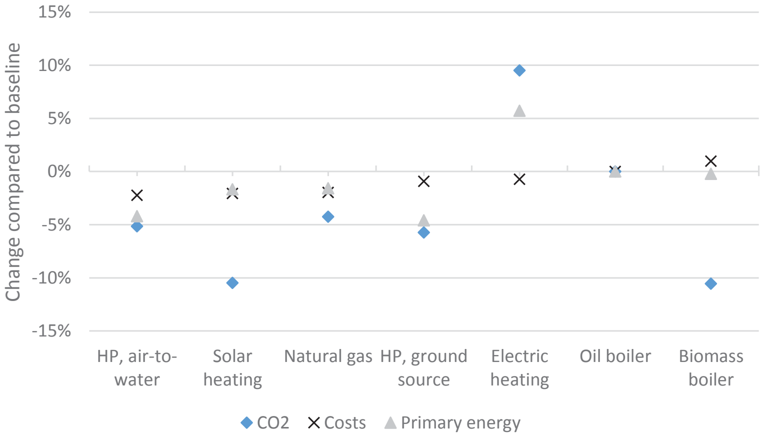

Figure 13: ESA changes in CO_2-emissions, costs and primary energy demand for decentralized heating technologies compared to the baseline scenario with oil and coal boilers.

All district heating technologies, except electric boilers, reduce CO_2 emissions compared to the scenario with more decentralized oil and coal boilers. Similar to the decentralized electric heating installment, the demand for electricity for electric boilers to supply district heating increases, leading to a higher consumption of coal that affects CO_2 emissions in general. The compression and absorption heat pumps also increase the production of thermal plants (mainly CHP plants), but the increase is much lower than that of electric boilers due to their higher efficiency.

Technologies that consume biomass generate the lowest CO_2 emissions for electricity and decentralized heating technologies. This is not the case of district heating technologies, exemplified by CHP woodchip plants, as these plants can not meet all the additional demand for district heating. Therefore, natural gas boilers for district heating must operate more, which affects CO_2 emissions. In general, woodchip CHP plants reduce the CO_2 emissions of the energy system, but at a lower level than other technologies. A similar situation occurs in the solar thermal scenario where district heating boilers must operate in periods without solar thermal generation.

Surprisingly, the combined cycle gas turbine scenario leads to lower CO_2 emissions than the renewable technology scenarios with solar thermal and woodchip CHP plants. This is related to the conversion efficiencies since the combined cycle fuel turbines have a high electrical efficiency (almost 50%), which reduces the operation of the condensing coal power plant, thus replacing some demand for coal with the consumption of natural gas. CHP woodchip plants have a lower electrical efficiency (around 30%) while the thermal efficiency is much higher (62%) compared to gas turbines (30%). This leads to a greater need for condensing coal power plants. Despite the fact that woodchip CHP plants have a higher total efficiency (92%) than gas fueled plants (80%), the electrical efficiencies of the plants are more influential in the overall operation of the energy system. The dynamics of this system is impossible to discover without a complete analysis of the energy system.

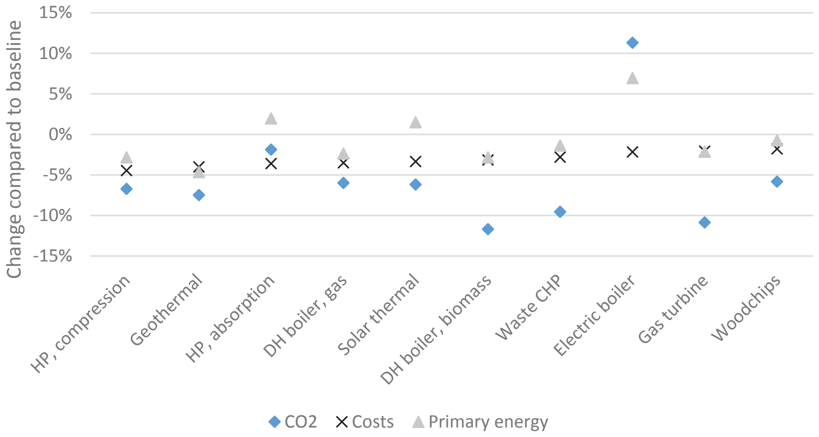

Figure 14: ESA changes in CO_2-emissions, costs and primary energy demand for district heating technologies compared to the baseline scenario with oil and coal boilers.

Other factors of ESA that could also be part of an evaluation of technological priorities could be the renewable energy share, the reduction of biomass consumption, the health impacts, the creation of employment, etc.

4. Discussion

The analysis showed that the priorities change according to the cost method and the parameters included in the evaluation of feasible technologies. The main examples include the decentralized electric heating scenario, which has the second lowest costs using the LCOE method, the fifth lowest cost using the ESA method and the worst impact on CO_2 emissions that increased by 10% despite replacing oil and coal boilers. The model of the German energy system even favors scenarios with high demands for electricity, since the capacity of the installed thermal plant is sufficient to supply this growing demand for electricity, while in other systems it might be necessary to increase the electrical capacity. In addition, the analysis showed that CO_2 emissions could increase by replacing nuclear power with variable renewable sources such as wind and solar energy because the demand and production profiles do not match all hours of the year, leading to more dispatchable fossil fuel production. These aspects are only recognized with the ESA method and will not be anticipated with the LCOE method.

Some of the system dynamic aspects that are not captured in the LCOE method, but could be in the ESA method are described below.

A crucial system dynamics is the hour-by-hour time alignment between production and demand patterns and the effect on energy over- or underproduction, as well as the need for backup capacity in the system. This factor is not considered in the LCOE method, but it can be substantial and have a large impact on the overall costs and viability of a given technology in an energy system.

Another system dynamic is the ability of technologies to contribute to improving flexibility in the energy system due to: e.g. ramping rates increases, use of excess energy or the ability to balance the production of heat and electricity. These technologies could be heat pumps, electric heating or CHP plants and this benefit is not normally monetized in the LCOE method.

The opposite case also occurs for some technologies where the flexibility of the energy system is reduced, which leads to an excess of energy, which is wasted if it can not be stored or exported. These technologies are mainly baseload technologies such as nuclear energy, waste incineration plants, geothermal heating or technologies with fluctuating production patterns (solar thermal, wind and solar power).

One of the key benefits of the ESA method is the ability to embrace synergies in sectors such as the electricity and heating sectors. The example of installing either CHP gas plants with high electrical efficiencies or woodchip CHP plants with high thermal efficiencies illustrates the significant difference for the operation of the energy system.

In the LCOE method, it is difficult to assess the costs of the additional demand for electricity in the heating sector through the installation of electric heating or heat pumps. Electricity costs change significantly depending on whether this electricity is supplied by excess renewable electricity or whether electricity has to be generated from thermal plants.

In the LCOE method, considerations for heating temperatures and possible mismatches between the temperatures required for district heating networks and the supply temperatures of solar thermal or other low temperature sources are not included. Heating temperatures may need to be boosted before they are distributed to consumers, which increases energy consumption and costs. Temperatures can be considered in the ESA method according to the energy system analysis tool.

Some technologies can not meet the total heat demand and additional production capacity may be necessary. This applies to, for example, solar thermal technologies that rarely produce enough energy to meet all the energy demands of a building or a district heating network, unless the system is accompanied by large storages.

The ESA method allows optimizing the operation of an energy system and individual technologies by aligning production patterns, including storages, etc. This affects the overall costs of the energy system.

In the ESA method, "free" energy can be used from excess electricity or district heating to reduce the fuel consumption from alternative energy production. This reduces costs and improves the efficiency of the energy system.

The LCOE method calculates the production costs of a unit of energy at the generation site. However, fuel and energy losses occur in several phases of the energy system such as fuel extraction, energy conversion and energy transmission and distribution. These losses may be important to include in estimating the costs of energy technologies.

Finally, the ESA method allows for the evaluation of other parameters besides costs, such as primary energy demand and CO_2 emissions, which is not possible in the LCOE method (unless it is with simple and generic calculations). This provides a more complete description of the impacts of prioritizing certain technologies.

4.1. Limitations and further work

The models developed for this article are for the German energy system, which is characterized by a specific energy system design that is different from other national or local energy systems. For example, one can speculate whether the design of the system configuration examples of the German energy system influences the priorities of energy technology since oil boilers with high fuel costs are replaced by technologies with lower or no fuel costs. In a different situation where these technologies replace a low-cost fuel technology, the ranking of the technologies could change. Similarly, the assumptions included in the models with respect to efficiencies, fuel prices, investment prices, etc., also influence the findings. However, this is valid for all analyzes and applies to both the ESA method and the LCOE method. In addition, the design of the models influences the costs and priorities of the ESA that could be altered if a different energy system or a future highly renewable energy system is analyzed. The priorities change according to the context in which the technologies are installed and it is necessary to carry out a complete analysis of the energy system for each energy system, which contrasts the LCOE method that implies one optimal technology.

In addition, the costs of the scenarios could be improved if they are combined so that more renewable resources are installed as demands increases, but this is not comparable to the LCOE method.

The costs in this article are considered from a societal perspective and the priorities can change if they are considered from an individual perspective of the consumer or plant, since other aspects such as subsidies and taxes would influence the costs.

Further work should improve the knowledge of the differences between the application of the LCOE and ESA methods through the investigation of other types of energy systems and technologies. This will allow greater documentation of the methodological differences between the methods and the impact on energy priorities.

5. Conclusions

The priorities of energy technologies can be evaluated using different cost calculation methods with variable results. In fact, it was found that the LCOE and ESA rankings showed some alignment for the costs of electricity and district heating technologies, while decentralized heating technologies demonstrated significantly different priorities. In addition, the ESA method demonstrated that priorities change for technologies such as condensing coal power plants, electric heating and solar thermal energy when other parameters are taken into account, such as primary energy supply and CO_2 emissions.

A range of system dynamics were highlighted by its exclusion in the LCOE method despite having an impact on the costs of the energy system. These system dynamics include the mismatch between demand and production, the influence on the flexibility of the energy system, the synergies across the energy carriers, the optimized operation of the energy system and the energy losses. Several studies apply the LCOE method to support the formulation of energy policies despite the shortcomings of this method, which could affect the final priorities.

The analysis showed that the priorities diverge between the two methods of estimating costs, which is important to take into account for the formulation of policies on the future energy system. Policies affect a wide range of cost factors for energy technologies such as CO_2 prices, subsidies and (fuel) taxes, long-term price guarantees, discounting, support for technology development, climate strategies, etc. Therefore, it is imperative to establish the right political priorities to achieve the most cost-effective energy system.

However, as demonstrated in this article, decision makers may have to change their priorities according to 1) the cost calculation method and 2) the parameters included in the evaluation. It is crucial for decision makers to take this into account.

Policymakers are advised to use a complete analysis of the energy system to support decision-making on future energy priorities to ensure that all dynamics of the energy system are taken into account.

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Appendix

The appendix contains model input data in terms of demands and cost data.

Table 4: Baseline German 2015 model energy demands and capacities from [36,37]. *MWe refers to MW installed capacity.*

			Baseline 2015 model
Energy demands	Electricity	TWh/year	621.5
	Decentralized heating	TWh/year	725
	District heating	TWh/year	131
Energy generation inputs	Condensing power plants	MWe	35,545
	Wind turbines	MWe	45,050
	PV	MWe	39,591
	Hydropower	TWh/year	25,9
	Nuclear power	MWe	21,500
	CHP plants*	MWe/MWth	50,055
	Industrial CHP	TWh/year	53
	Waste CHP	TWh/year (elec/th)	4.8/7.3
	Boilers (DH)	MWth	56,000
	Solar thermal (DH)	TWh/year	5.6
	Geothermal (DH)	TWh/year	6.9
	Heat Pumps (DH)	MWe	0
	Solar thermal (decentralized)	TWh/year	4.3
	Coal boiler (decentralized)	TWh/year	18.4
	Oil boiler (decentralized)	TWh/year	210.6
	Natural gas boiler (decentralized)	TWh/year	396.1
	Biomass boiler (decentralized)	TWh/year	59
	Electric heating (decentralized)	TWh/year	36.6
	Heat pumps (decentralized)	TWh/year	6.7

* Some of these plants can also operate in condensing mode

Table 5: Fuel prices assumed for the analysis

€/GJ	Coal	Oil	Natural gas (Europe)	Biomass (Wood chips)	Uranium
2015	3.2	17	10.2	6.8	1.75

Table 6: CO_2 costs

CO_2 prices	€/t
2015	34.6

All technology data are based on a combination of the costs of the already installed technologies and installing the additional capacity in the scenarios.

Table 7-Table 10 are based on data from the Danish Energy Agency [38,39] providing data for both heating and electricity.

Table 7: Technology data for installed capacities

	Technology	Unit	2015
Electricity	400-700 MW Coal Steam PP	M€/MW	1.18
	100-500 MW Gas turbine CCGT, condensing mode	M€/MW	0.96
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	M€/MW	1.19
	Wind farm large onshore	M€/MW	1.07
	Wind farm large offshore	M€/MW	2.86
	PV small (residential)	M€/MW	1.33
	PV Large (utility)	M€/MW	1.11
	Wave	M€/MW	7.8
	Hydro, large (above 10 MW)	M€/MW	4.72
	Nuclear	M€/MW	2.95
Decentralized heating	Oil burner, One-family house, existing building	1,000 €/unit	5.8
	Natural gas boiler, one-family house, existing and energy renovated building	1,000 €/unit	4.85
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	1,000 €/unit	6.75
	Electrical heat pump, air-to-water, one-family house, existing building	1,000 €/unit	10.02
	Electrical heat pump, ground source, one-family house, existing building	1,000 €/unit	15.94
	Solar heating system, one-family house, existing building	1,000 €/unit	4
	Electric heating, one-family house, new building	1,000 €/unit	8.87
District heating	Gas turbine (combined cycle), back-pressure	M€/MW	0.89
	Medium steam turbine, woodchips	M€/MW	3.76
	Waste-to-energy CHP plant	M€/TWh	215.6
	Electrical compression heat pumps	M€/MW	0.7
	Absorption compression heat pumps	M€/MW	0.6
	Electric boilers	M€/MW	0.06
	District Heating boiler, gas-fired	M€/MW	0.06
	District Heating boiler, wood chips	M€/MW	0.8
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	M€/TWh	118.92
	Solar district heating	M€/TWh	422.17

Table 8: Technology lifetimes

	Technology lifetime in years	2015
Electrici	400-700 MW Coal Steam PP	29.6
	100-500 MW Gas turbine CCGT, condensing mode	26.6
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	29.6

	Wind farm large onshore	25
	Wind farm large offshore	25
	PV small (residential)	32.2
	PV Large (utility)	32.4
	Wave	10
	Hydro, large (above 10 MW)	30
	Nuclear	35
Decentralized heating	Oil burner, One-family house, existing building	20
	Natural gas boiler, one-family house, existing and energy renovated building	20.6
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	20.2
	Electrical heat pump, air-to-water, one-family house, existing building	20
	Electrical heat pump, ground source, one-family house, existing building	20
	Solar heating system, one-family house, existing building	20.2
	Electric heating, one-family house, new building	30
District heating	Gas turbine (combined cycle), back-pressure	25
	Medium steam turbine, woodchips	29.6
	Waste-to-energy CHP plant	20
	Electrical compression heat pumps	25
	Absorption compression heat pumps	25
	Electric boilers	20
	District Heating boiler, gas-fired	26.2
	District Heating boiler, wood chips	20.1
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	25
	Solar district heating	30

Table 9: Technology operation and maintenance

	Technology fixed O&M (% of investment)	2015
Electricity	400-700 MW Coal Steam PP	3.1
	100-500 MW Gas turbine CCGT, condensing mode	3.2
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	3.1
	Wind farm large onshore	2.4
	Wind farm large offshore	2.5
	PV small (residential)	1.0
	PV Large (utility)	1.0
	Wave	1.1
	Hydro, large (above 10 MW)	1.5
	Nuclear	1.6
Decentraliz	Oil burner, One-family house, existing building	4.0
	Natural gas boiler, one-family house, existing and energy renovated building	3.9
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	6.2

	Electrical heat pump, air-to-water, one-family house, existing building	2.8
	Electrical heat pump, ground source, one-family house, existing building	1.8
	Solar heating system, one-family house, existing building	1.5
	Electric heating, one-family house, new building	0.4
District heating	Gas turbine (combined cycle), back-pressure	3.4
	Medium steam turbine, woodchips	1.0
	Waste-to-energy CHP plant	1.9
	Electrical compression heat pumps	0.3
	Absorption compression heat pumps	0.3
	Electric boilers	1.8
	District Heating boiler, gas-fired	3.1
	District Heating boiler, wood chips	0.1
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	2.6
	Solar district heating	0.0

Table 10: Technology efficiencies/capacity factors (Lower heating value)

	Technology efficiencies/capacity factors (%)	Unit	2015
Electricity	400-700 MW Coal Steam PP	Electrical	46
	100-500 MW Gas turbine CCGT, condensing mode	Electrical	55
	250-400 MW Steam Turbine, fired by wood pellets, advanced steam process	Electrical	46
	Wind farm large onshore	Capacity factor	35
	Wind farm large offshore	Capacity factor	50
	PV small (residential)	Capacity factor	11
	PV Large (utility)	Capacity factor	13
	Wave	Capacity factor	17
	Hydro, large (above 10 MW)	Electrical	45
	Nuclear	Electrical	32
Decentralized heating	Oil burner, One-family house, existing building	Thermal	92
	Natural gas boiler, one-family house, existing and energy renovated building	Thermal	97
	Biomass boiler (automatic stocking) - wood pellets or wood chips, existing and energy renovated building	Thermal	80
	Electrical heat pump, air-to-water, one-family house, existing building	Thermal	358
	Electrical heat pump, ground source, one-family house, existing building	Thermal	395
	Solar heating system, one-family house, existing building	Thermal	-
	Electric heating, one-family house, new building	Thermal	100

District heating	Gas turbine (combined cycle), back-pressure	Elec/Thermal	51/30
	Medium steam turbine, woodchips	Elec/Thermal	29/64
	Waste-to-energy CHP plant	Elec/Thermal	24/74
	Electrical compression heat pumps	Thermal	350
	Absorption compression heat pumps	Thermal	170
	Electric boilers	Thermal	99
	District Heating boiler, gas-fired	Thermal	103
	District Heating boiler, wood chips	Thermal	108
	Geothermal heat-only plant with steam-driven absorption heat pump - 70 C, Denmark	Thermal	100
	Solar district heating	Thermal	100

PAPER 5

Full energy system transition towards 100% renewable energy in Germany in 2050

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Full energy system transition towards 100% renewable energy in Germany in 2050

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Abstract
Germany has set ambitious policies for increasing renewable energy shares and decommissioning nuclear energy, but there are certain scientific gaps on how this transition should occur, especially when considering all energy sectors. The purpose of this study is to advance the knowledge of transitioning the German energy system to 100% renewable energy towards 2050. Taking into consideration renewable resource potentials, energy system costs and primary energy supply this study develops a path for transitioning the German energy system within the heating, industrial, transport and electricity sectors. The analysis demonstrates that it is possible to carry out this transition from a technical and economic perspective with some measures being vital for achieving this ambition in a cost-effective manner. The most significant challenge in this transition is regarding resource potentials where especially biomass resources are constrained and under pressure. Finally, the most influential measures for achieving the renewable transition are discussed.

Keywords
100% Renewable energy systems, Germany, Biomass, Energy potentials

1. Introduction

In the past years, ambitious climate policies have been agreed such as for the German energy transition (Energiewende) in the early 2010's and the Paris agreement in 2015 for reducing the CO_2-emissions and global temperature increase [1,2]. The challenge is how to achieve these targets while also considering other factors such as costs of energy, resource availability and cross-country collaborations. This paper addresses the German energy transition by developing a strategy for achieving 100% renewable energy in the entire energy system.

The Energiewende was formed in the early 2010's, based on decades of energy policy discussions in Germany affected by numerous events and key drivers leading to ambitious climate targets and a phase-out of nuclear power [3]. It is crucial to understand that it has been a long process, which highlights the importance of long-term planning in the energy sector with complex infrastructure [4]. The Energiewende targets aim at reducing the GHG emissions by 80-95% in 2050 compared to 1990 while increasing the renewable share of final energy to at least 60% and the renewable share of electricity demands to 80%. In addition, targets are stated for reducing primary energy demands, as well as for electricity, heat and transport demands [5].

Previous solutions for the German energy transition has focused on the Energiewende policy development and less on the actual energy infrastructure design to achieve the emission targets. Examples show that policies are key in determining the future energy development [4] and that the current legislation does not support a transition towards the Energiewende targets, especially when focusing on the current and future

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heating market [6]. Several studies focus on the implementation of the Energiewende by regional implementation of renewable energy in Germany [7] or on how wind power auctions should be designed in the future [8]. Other studies discuss the importance of including institutions and actors in defining the future system simultaneously with introducing technologies to the energy system [9].

Numerous studies focus on individual sectors within the energy system such as transportation and electric vehicles [10–12], the heating market [6] or the future development in the German electricity market given the current policies [13]. Schmid *et al* [14] provides a review of five studies for achieving the Energiewende in Germany, but primarily within the electricity sector and excludes other energy sectors. Similarly, Lehmann and Nowakowski focus on the electricity sector by analyzing three different scenarios for structuring the future renewable electricity sector [15]. These scenarios focus on a decentralized, a centralized and a pan-European approach for integrating further renewables. Along these lines, Gullberg *et al* [16] evaluate benefits of a stronger connection between the Norwegian and German energy systems in order to use the Norwegian hydropower capacities as reserves for storing electricity. Other technical challenges are defined qualitatively in [17] by highlighting which bottlenecks need to be overcome before a transition is possible. Furthermore, in [18] authors investigate the need for transmission grid expansions when reaching higher levels of renewable energy.

This shows that numerous studies analyse the Energiewende and its role on the German energy system, but most of these focus on particular aspects of a sector or on the institutions, markets and actors surrounding the energy system. Few studies have applied a technical multi-sector approach for suggesting solutions for a future low-carbon energy system in Germany [5,19]. Palzer and Henning [19] present a conversion to 100% renewable energy in the heating and electricity sectors while keeping energy system costs at a level similar to the current system costs. Furthermore, they show that it is possible to do this with restrictions on the renewable electricity and biomass resources. Similarly, Pregger *et al* [5] found that fuel cost savings and lower fuel imports are crucial in relation to the overall energy system costs. Both studies draw attention to the importance of reducing energy demands in order to obtain the climate targets where especially the heating sector has a great potential for energy savings (e.g. 60% heat demand reductions in [19]).

When looking beyond the solutions suggested for Germany, numerous studies present strategies for achieving 100% renewable energy at a national level, including all sectors. Examples exist for Europe [20], Denmark [21], Croatia [22], Sweden [23], Macedonia [24] and Ireland [25]. Furthermore, reviews are carried out for high-renewable studies focusing on the electricity sectors [26,27]. Possible solutions have been suggested, but as mentioned here only few full energy system analyses exist for Germany.

The objective of this paper is therefore to design a 100% renewable energy strategy of the whole German energy system while evaluating which measures are most important for achieving the targets within reasonable costs and resource potentials. The strategy goes further than the Energiewende targets in terms of renewable energy share and aims for a net 100% renewable energy share over one year in 2050. Inspiration from previous strategies is utilized, but this study enhances and extends the methods by investigating the importance of multiple measures and the order in which they are implemented in the energy system. Furthermore, the paper discusses limiting factors of the suggested scenarios.

2. Methodology and evaluation criteria

The overall ambition of the scenarios is to achieve a 100% renewable German energy system in 2050. Renewable energy in this paper excludes nuclear energy (which is already planned to be phased out) and carbon capture and storage (CCS) technologies [28]. In accordance with national, EU and UN definitions, biomass is assumed to be CO_2-neutral in the energy sector, even though this has been heavily debated recently [29,30]. Scenarios are developed with a view towards 2050 as this time period corresponds with energy policies and leaves sufficient time for implementing the suggested measures. This is crucial as changes in buildings and energy infrastructure with long lifetimes are difficult to implement in a short period of time.

One of the possible approaches for transitioning to a 100% renewable energy system is the Smart Energy System concept. This concept emphasizes the importance of utilizing cross-sectoral measures for harvesting the benefits for each measure and across different energy sectors. The concept has been defined in [28,31] and described in relation to markets in [32]. In this paper, the concept is applied to the German energy system for the first time.

First, a model of the German 2015 energy system based on recent data from [33] was created as a representation of the current German energy system. From this model, a 2050 reference model is developed where all nuclear power is decommissioned, development improvements for renewable energy technologies have been applied and projected 2050 technology and fuel costs are used. In order to create 100% renewable scenario for Germany, a set of measures have been applied in each energy sector (see Figure 1).

The first measures are related to the future heating market in terms of demands and network solutions and include heat savings and district heating expansions. Next, different options for supplying the remaining heat demand outside of district heating areas is investigated, including electric heating, heat pumps and biomass boilers. Finally, different district heating supply mixes are analyzed to obtain a high-renewable heating sector. Measures within the industrial sector include energy savings and conversion of low-temperature heat demands to district heating or heat pumps. Next, two options for converting the industrial sector to only renewables are analysed including a high reliance on bioenergy or electrification to the extent possible. In the transport sector, the first measure is a conversion of 85% of all cars and vans to electric vehicles followed by five different scenarios for achieving 100% renewables for heavy-duty transport as well. Finally, the electricity sector is transformed through savings and integration of renewable resources.

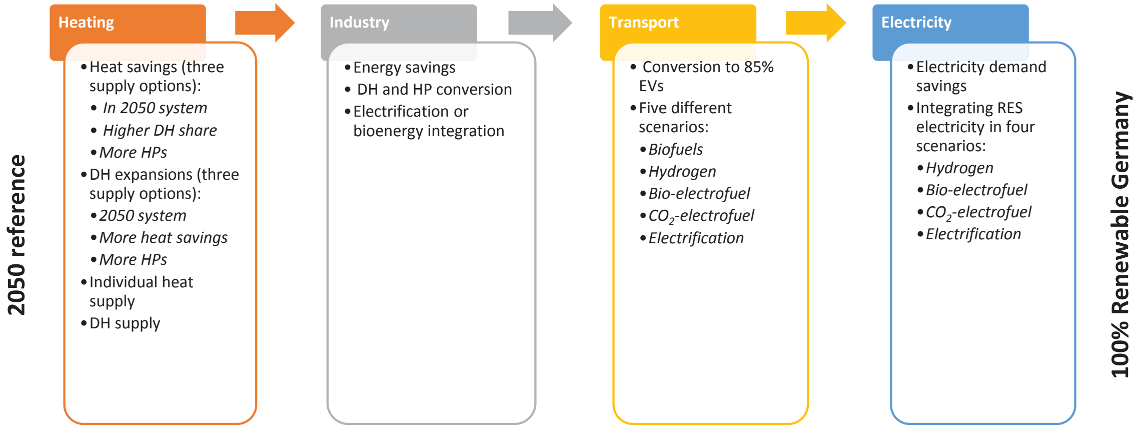

Figure 1: The measures for converting towards 100% renewable energy in all sectors.

The step-by-step methodology applied for reaching 100% renewable energy penetration, makes it possible to identify the impact of each measure rather than the impact of all measures at once. This allows for discussing the importance of each measure.

Throughout the scenarios electricity demands increase due to electrification in other sectors while the electricity supply is only changed as the final step. This modelling approach was selected as the electricity demand is affected numerous times and it would not be worthwhile to optimize the renewable electricity integration for each measure. Hence, the system is converted to renewable electricity sources as the final step when all changes to electricity demands have been conducted.

The parameters used for assessing the scenarios rely on three indicators; energy system costs, CO_2-emissions and primary energy supply. Energy system costs are seen from societal perspective excluding taxes and subsidies and applying an interest rate of 3%. In addition, special attention is given to biomass demands and the balance between energy demands and resource potentials. Finally, the impact on energy system flexibility is also assessed in terms of excess energy for electricity and heating production. A combination of these measures is used to evaluate the feasibility of the energy system scenarios.

Furthermore, costs are included for enhancing electricity grids in scenarios with larger electricity demands or renewable energy production. A value of 165 €/kW is applied based on [34].

2.1. Scenario resources and limitations

A literature review is conducted to estimate renewable energy potentials for Germany in order to specify available resources for a future 100% renewable energy system. The resource potentials differ between the studies indicating either theoretic, technical, economic or restricted potentials (limitations from environmental areas, etc.). Biomass, wind power and PV resources are reviewed, as these are the main resources in a future system with high shares of renewable energy.

The biomass potentials are aggregate potentials for the entire country, but potentials differ across studies, for example between dry and wet biomass. The biomass range is specified as 250-450 TWh/year with a potential of 400 TWh/year used as the limit for the scenarios in this study (see Table 1). In the 2015 reference model, the biomass demand is 235 TWh/year and the total fossil fuel consumption is more than 2500 TWh/year. The biomass resources can therefore only replace a small fraction of the fossil fuel consumption and should be prioritized for areas of the energy system where few alternatives to bioenergy exist.

Table 1: Biomass potentials in Germany based on a literature review

Biomass resources (TWh/year)	Ruiz, et al [35]	Pregger, et al [5]	Palzer, Henning [19]	Brosowski, et al [36]	Majer, et al [37]	Edel et al [38]	Benndorf et al [39]	This study
	400	431	300	299	246	396	364	400

In Table 2 wind power resources potentials are specified for both onshore and offshore resources in terms of capacities, annual production and capacity factors. Based on the review, an onshore wind power capacity of 250 GW is assumed as the limit in this study (526 TWh/year and capacity factor of 24%) while the offshore wind power capacity is assumed to be 65 GW (242 TWh/year and capacity factor of 42.5%).

Table 2: Wind power potentials in Germany for onshore and offshore resources.

Wind power resources		Palzer, Henning [19]*	Lütkehus, Salecker [40]**	EEA [41] ***	Mckenna, Hollnaicher, Fichtner [42] ****	Hossain, et al [43]	Benndorf et al [39]	This study
Onshore	Capacity (GW)	200	1188					250
	Production (TWh/year)	360	2898	2467	600	4017	1000	526

	Capacity factor (%)	20.5	27.8					24
Offshore	Capacity (GW)	85					45	65
	Production (TWh/year)	298					180	242
	Capacity factor (%)	39.9					45.6	42.5

* Constrained potential reduced by economic viability and soft factors such as aesthetics, military, environment, etc.

** Maximum potentials based on a GIS analysis and does not consider limitations from environmental reasons, etc.

*** Competitive potentials for Germany in 2030.

**** Economic potential (technical potential of 860 TWh).

For PV resources, this study assumes a capacity of 300 GW (316 TWh/year and capacity factor of 12%), see Table 3.

Table 3: Photovoltaic potentials in Germany.

PV resources	Palzer, Henning [19]*	Mainzer, et al [44]**	Lödl, et al [45]	Benndorf et al [39]	Danish Energy Agency [58]***	This study
Capacity (GW)	400	208	161	275		300
Production (TWh)	390	148		248		316
Capacity factor (%)	11.1	8.1		10.3	26	12

* Constrained potential reduced by economic viability and soft factors such as aesthetics, military, environment, etc.

** Includes only residential-roof-mounted technical PV potential

*** Capacity factor for PV technologies in 2050

The total wind and PV potential in this study is approximately 1,000 TWh/year (1,084 TWh/year), which is in line with [46]. Hydropower potentials are assumed to be constant between 2015 and 2050 as the majority of these potentials have already been utilized.

Limitations also apply for electricity and district heating excess energy production caused by temporal mismatches between production and demand. For example, the electricity production might exceed the demand in a given hour without the option of exporting or storing the energy, which creates critical excess electricity production in the system. In this study, the ambition is to keep these levels as low as possible to avoid overproduction of energy, but this might be challenging considering the limited potentials for storable energy such as biomass in a 100% renewable energy system.

2.2. Modelling tool

The energy system scenarios are developed using the advanced energy system analysis tool EnergyPLAN, which has been used for numerous studies such as developing national energy strategies and evaluating the feasibility of a variety of technologies [31,47–50]. The EnergyPLAN tool is a simulation tool that simulates all energy sectors (electricity, heating, cooling, industry, transport) for one full year on an hourly resolution [51]. This allows for encompassing all direct and indirect dynamics in the energy system such as the synergies across heating and electricity technologies. In addition, EnergyPLAN is capable of analyzing a variety of parameters such as energy system costs, CO_2-emissions and primary energy supply as well as the temporal balance between supply and demand for gas, hydrogen, electricity and heating. The EnergyPLAN tool does not factor in constraints on electricity grids and the models are simulated as copperplates scenarios while costs for grid enhancements are added based on peak electricity demands.

The deterministic nature of the EnergyPLAN tool optimizes the operation of the system rather than the investment decision in the system, which could possibly influence the findings considering that the user defines the scenarios and the order of the measures. This is discussed further in Discussion chapter.

Key assumptions for data is provided in the Supplementary data for factors such as fuel prices, energy technology prices as well as grid expansion costs.

3. Results

The scenario results of the German energy system are presented in this chapter for each sector and summarized for the 100% renewable German energy system.

3.1. 2050 reference

The 2050 reference scenario resembles the 2015 model to a large degree with updated fuel and CO_2 prices as well as technology costs for onshore/offshore wind and PV technologies. The effect of updating other technology prices is negligible. Furthermore, all nuclear power plants are phased out and replaced by thermal production. Other types of energy demands and production capacities are similar to the 2015 energy system. This 2050 scenario is used as the starting point for comparison with the alternative scenarios and for creating the alternative measures by implementing changes to one energy sector at a time.

3.2. Heating

The key measures to transform the heat sector are: heat savings, district heating expansion and changes in the individual and district heating supply. These are investigated in order to determine the levels of heat savings, district heating expansions and supply mix that should be applied. The parameters for determining the appropriate levels are system costs, biomass levels and CO_2 emission level. The results below are presented for energy system costs.

First, the heat savings are investigated for three different systems where the only difference is the heat supply mix. The heat demands are the same (672 TWh/year) before heat savings are conducted. This will provide insights regarding the feasibility of heat savings in systems with different heat supply mixes:

- In the 2050 Reference system
- In a scenario with higher district heating (30%)
- In a scenario with the majority of heating supplied by individual heat pumps (80%)

The heat saving costs are based on heat saving cost curves developed in [52] indicating the investments required for reducing heat demands by improving the building envelopes. Feasible heat savings levels have previously been analysed in details in [53]. The feasibility of various heat saving levels from 0-60% compared to the reference model are illustrated in Figure 2 showing the total energy system costs. The figure presents costs for heat savings in the 2050 reference model, a scenario where district heating has been expanded from 16.3% to 30% of the heat demand and a scenario with 80% of all heating supplied by individual heat pumps. The feasible saving levels are highest in the 2050 reference model (50-60% savings) followed by the model with expanded district heating (50% savings) and finally the model with more heat pumps (40-50%). Based on these results, 50% savings are used for the 100% renewable German model.

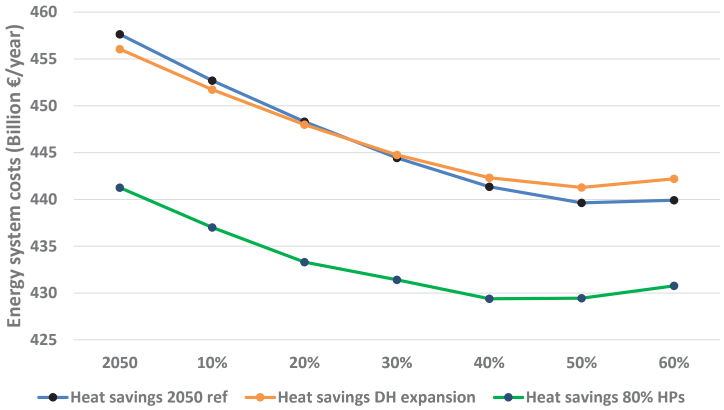

Figure 2: Energy system costs when implementing heat savings in the 2050 reference model, a scenario with expanded district heating supply (30%) and a scenario with 80% individual heat pumps.

Secondly, in order to determine levels of district heating network expansions the analysis looked into going beyond the 16% district heating share of the total heat demand in the 2050 reference model. The analysis considers the 2050 reference model, a system with 50% heat savings and a system with 80% individual heat pumps. District heating expansion costs for piping investments are based on district heating cost curves from [54], indicating increasing costs when heat densities decrease.

Based on the energy system costs, Figure 3 indicates that the district heating level should be 30% in the 2050 reference model and 20% in the system with a 50% lower heat demand. District heating shares of 10-40% have similar cost levels when expanding district heating in a system with a high share of individual heat pumps. The recommended district heating level is therefore 30% of the heat demand. It is concluded, that the overall heat demand influences the feasibility of district heating expansions. District heating feasibility is slightly influenced by factors such as network losses and lifetimes of district heating substations and pipes, but not to a degree that influences the overall recommendable district heating levels.

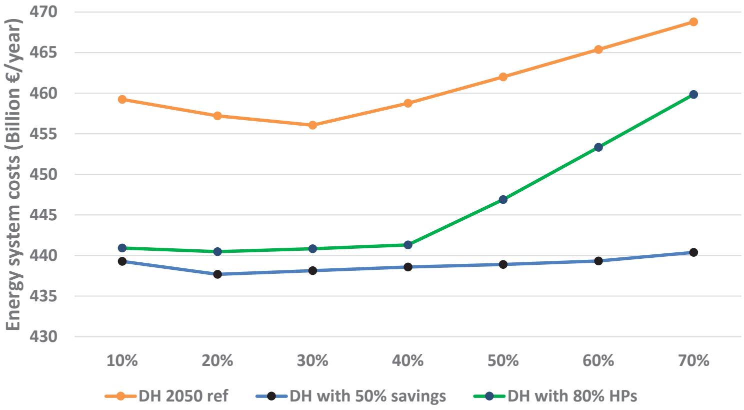

Figure 3: Energy system costs when expanding district heating networks in the 2050 reference model, in a scenario with 50% heat savings and in a scenario supplied by 80% individual heat pumps.

The following analyses are carried out in a German energy system with 50% reductions in heat demands and a 30% district heating share as these levels proved most feasible from the first set of analyses considering first of all energy system costs, but also primary energy and CO_2-emissions.

Thirdly, the changes in the supply mix for individual heat supply technologies in areas outside of district heating networks (~70% of heat demand) are analysed. Three options are considered for their effects on the evaluation parameters; electric heating, heat pumps and biomass boilers to supply 95% of the individual heat demand. These are rather extreme scenarios, but indicate which technology is preferable in the longer term. Heat pumps are divided 50/50 between air- and ground source heat pumps.

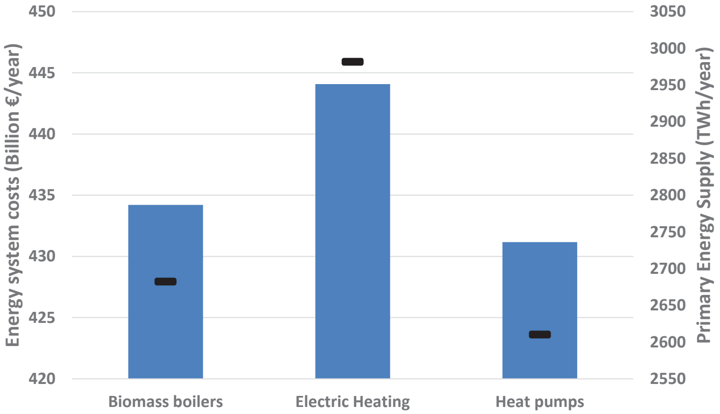

Figure 4: Energy system costs and primary energy supply for three individual heat supply technologies. Blue bars indicate costs while black markers indicate primary energy supply for the German energy system.

The results in Figure 4 indicate that the primary energy supply is highest for electric boilers followed by biomass boilers and heat pumps. A large share of the fuel demand is met by fossil fuels (coal) for electric heating and heat pumps due to a growing electricity demand, which is produced by coal power plants in this scenario (before integrating further renewable electricity resources). This also affects CO_2-emissions, which are lowest for biomass boilers. The lowest energy system costs are in the heat pump scenario decreasing them by 1.6% compared to the scenario with 50% heat savings and 30% district heating supply. The biomass boiler scenario decreases costs by 0.9% while the biomass boiler scenario causes energy system cost increases of 1.2%. Heat pumps are therefore recommended outside of district heating areas due to best performance on energy system costs and energy system efficiency (lowest primary energy supply). However, the heat pump scenario increases CO_2-emissions, but this will change with further installation of renewable electricity sources.

The final measure in the heating sector concerns the district heating supply technology mix. Four different scenarios are considered in this analysis: large shares of either industrial excess heating, solar thermal, large heat pumps or a combination of these. In these scenarios, it is assumed that maximum 1/3 of the district heating production can be baseload production as further baseload production significantly influences the temporal mismatch between demand and production. It is assumed, that solar thermal plants have seasonal storages to be able to supply 1/3 of the district heating demand, even though this for practical and space reasons is rather unlikely in reality. Solar thermal integration in Germany has previously been analysed in details in [55]. Waste incineration and geothermal energy is assumed to affect the energy system similarly to the scenario with a high share of industrial excess heating as all these technologies produce baseload heating.

All these scenarios result in higher CO_2 emissions compared to the previous system because these technologies cause less CHP plants operation, which means that other technologies have to supply electricity that was previously produced from CHP plants in cogeneration mode. In these scenarios, condensing power plants supply this electricity, primarily based on coal consumption. This also results in reduced overall energy system fuel efficiency with higher primary energy demands. Furthermore, the district heating imbalance (temporal mismatch between supply and demand) is increased when installing industrial excess heating with constant baseload production. The energy system cost effect is negligible as the changes are below 0.5% compared to the previous scenario. The lowest energy system costs are in the scenario with industrial excess heating, but this scenario also influences security of supply as this heat source could close or move to another country. The reliance on industrial excess heating should therefore be kept in mind. For this reason, a combination of district heating supply technologies is recommended for the German energy system as specified in Figure 5. The majority of the district heating supply is from CHP plants due to the system effects previously mentioned regarding the necessity for electricity production.

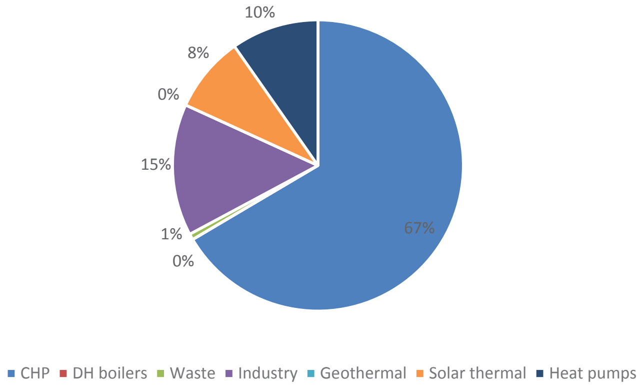

Figure 5: District heating supply mix in the recommended DH supply scenario for the German system

The heat sector modifications (heat savings, district heating expansion, individual heat pumps, district heating supply) significantly affect the energy system operation. For example, the operation of CHP plants influences the electricity sector and the integration of renewable electricity sources.

Compared to the 2050 reference model primary energy supply is reduced by 440 TWh/year equal to 14% after implementing these measures in the heating sector. Additionally, electricity production is increased by 55 TWh/year equal to 10% while heat production is decreased by 334 TWh/year equal to 49%. Furthermore, CO_2-emissions are reduced by 62 Mt/year equal to 8% and the energy system costs decreased by 27 b€/year equal to 6%.

No measures are analysed for changes in the cooling supply as this energy demand is negligible (7.4 TWh/year) compared to other demands such as heating (672.4 TWh/year in the 2050 reference scenario).

3.3. Industry

For the industrial sector, two scenarios are developed for converting towards 100% renewable energy. The first scenario is primarily focusing on bioenergy while the second scenario focus on electrification. Following measures are carried out for both scenarios:

- Improvements in industrial energy intensity resulting in a lower fuel demand. Based on saving potentials in previous studies [19,56–58] this fuel reduction in industries equals 30% of the 2050 reference model consumption. The savings costs are assumed to be 872 M€/TWh with a lifetime of 20 years.
- Space heating and process heating under 100 °C to is converted to district heating and heat pumps with a 50/50 split between these sources. This energy share equals 25% of the industrial heat demand and is based on a detailed industrial energy demand breakdown for various temperature levels for space and process heating [59]. The district heating and heat pump demands increase by 49 TWh/year. District heating network costs are assumed to be 20,000 €/TJ [34].
- Next, different measures are implemented for the bioenergy and electrification scenarios. In the bioenergy scenario, all remaining fuel consumption, which is not district heating or electricity, is converted to solid biomass, corresponding to a biomass demand of 289 TWh/year.
- In the electrification scenario, it is assumed that 50% of the remaining fuel consumption after savings and conversion to district heating and heat pumps can be electrified. This conversion to electricity driven technologies leads to efficiency improvements of 20%. The electricity demand increases by 133 TWh/year, which necessitates reinforcements of the electrical grid and additional thermal power plant capacity that increases by 25 GW. The industrial biomass demand in this scenario is 144 TWh/year.

The scenario results indicate that the electrification scenario has higher primary energy supply, CO_2-emissions and energy system costs compared to the bioenergy scenario. This is due to a higher electricity demand, which is met by condensing coal and natural gas power plant production. However, the biomass demand differs significantly between the two scenarios and challenges the biomass resource limit of 400 TWh/year. The total biomass demand in the bioenergy scenario is 379 TWh/year while the electrification scenario has a demand of 238 TWh/year. The bioenergy scenario therefore leaves no room for further biomass consumption before carrying out changes in the transport sector. For this reason, the industrial electrification scenario is prioritized, despite higher fuel, CO_2 and energy system costs. These factors will improve when more renewable electricity is integrated in the system, which is conducted as the final step of the conversion towards 100% renewable energy. The excess industrial district heating potentials are significantly higher than the installed quantity and no changes are therefore conducted for this.

3.4. Transport

The transport sector scenarios continues from the scenarios developed for the heating and industrial sectors. Six scenarios are developed within the transport sector for converting to renewable energy. The first scenario, which is part of all the subsequent scenarios, is a significant conversion to electric vehicles and vans. Next, five alternatives are analysed for converting the remaining cars and vans as well as heavy duty transport (air, sea, rail, trucks and busses) to renewable energy. The six scenarios are:

- Conversion of 85% of cars and vans to electric vehicles (EVs)
- Conversion of the rest of the transport demand to:
    - 2nd generation biofuels
    - Hydrogen
    - Bio-electrofuels
    - CO_2-electrofuels
    - Electricity

The EV conversion scenario assumes that 85% of all transport fuel demand that was previously based in oil-based products can be converted to electricity powered transport in cars and vans. The remaining transport demands is supplied from fossil fuel sources as the purpose of this scenario is to investigate the importance of EVs. Electric vehicles have significantly higher well-to-wheel efficiencies compared to internal combustion engine (ICE) vehicles, which reduces the energy demand of the transport sector. Electric vehicle efficiencies in 2050 are 78% while diesel engine efficiencies are 23% and petrol engines 21.6% [60]. The electricity demand increases by 118 TWh/year and the oil demand reduces by 404 TWh/year compared to the previous scenario. One charging station is assumed per electric vehicle and every vehicle is assumed to have a battery storage capacity of 25 kWh and a power capacity of 5 kW. Details about investment prices and transport fuel demands are listed in Supplementary data. The conversion to electric driven vehicles reduces the overall primary energy supply by 3% (oil decreases and coal increases), while CO_2-emissions remain similar and energy system costs decrease by approximately 7%.

The five subsequent scenarios differ significantly in their approach towards converting the remaining transport demand to renewable energy sources. The scenarios are rather extreme versions as all remaining transport demand is converted to a single fuel type or technology, which is unrealistic in reality where a combination of these alternatives is more likely. However, this approach indicates which technologies are preferable for converting towards 100% renewable energy in the transport sector.

The biofuel scenario converts all remaining oil consumption to 2nd generation biofuel products assuming that diesel vehicles are converted to biodiesel, petrol vehicles to bioethanol while aviation is converted to bio-jetfuel. The vehicle efficiencies are unchanged in this scenario compared to the previous fossil fuel scenarios [60]. Biodiesel production is assumed to be 39.3% efficient from input of biomass to biodiesel output, while bioethanol production has an efficiency of 41.1% [60]. The total biofuel demand grows by 245 TWh/year, which equals a biomass increase of 685 TWh/year compared to the EV scenario. The biomass demand solely in the transport sector for this scenario significantly exceeds the total biomass potential for all sectors of 400 TWh/year.

In the hydrogen scenario, all remaining transport demand is converted to transport modes supplied by hydrogen via fuel cell powertrain technologies. Hydrogen cars are assumed to have an efficiency of 41% in 2050 while trucks are 47.3% efficient, buses 53.5% and sea and air transport 38.5% efficient [60–63]. The annual hydrogen demand for transportation in this scenario is 143 TWh/year, which is equal to an electricity demand increase of 194 TWh/year in addition to the electricity demand in the EV scenario. As a result, an expansion of the thermal power plant capacity by 10 GW is necessary to cover the additional electricity demand. This increase is optimistic assuming that SOEC electrolysers can produce the hydrogen demand with an electrolysis efficiency of 73% [64]. The total electrolysis capacity is 45 GW with a 1-week hydrogen storage of 7.500 GWh. Moreover, costs are also included for enhancing the electricity grid as well as infrastructure costs for establishing hydrogen fuel stations. It is assumed that these costs equal conversion of half of all current petrol stations in Germany (~14,500) and a similar cost for hydrogen transmission and distribution infrastructure are included. The total investment in hydrogen infrastructure is 54 b€ with a lifetime of 20 year. The biomass demand in this scenario is 203 TWh/year, but the coal consumption increases significantly due to the higher electricity demand, which at this point to a large degree is supplied by condensing coal power plants.

The bio-electrofuel concept relies on production of renewable gasses (methane) to supply the remaining transport demand and is further described in [65–67]. Briefly described, bio-electrofuels boost the energy content of the fuels through the addition of hydrogen with the purpose of reducing the biomass consumption. In this case, gasified biomass is produced and boosted by hydrogen from SOEC electrolysis. Vehicle efficiencies and costs are the same as for gas vehicles. The hydrogen demand in this scenario is 120 TWh/year while the biomass input for producing methane is 265 TWh/year. Electrolysis capacity is 40 GW with a hydrogen storage of approximately 3,150 GWh and additional power plant capacity of 5 GW. The total biomass demand in this scenario is 465 TWh/year, which is slightly above the German biomass potential.

The next transport scenario is based on CO_2-electrofuel production. This scenario relies on methanol/DME production through CO_2 hydrogenation and boosting of the energy content in the fuels through hydrogen addition. A total of 361 TWh/year hydrogen is required due to the vehicle efficiencies that are similar to ICE vehicles. In addition, 79 Mton of CO_2 is required, which has to be recovered from fuel combustion in thermal plants, industries or other sources. The electrolysis capacity in this scenario is 115 GW with approximately 9,500 GWh hydrogen storage and 45 GW of additional power plant capacity compared to the EV scenario. The electricity demand increases by 516 TWh/year, even higher than in the hydrogen scenario. The biomass demand is however rather low at 212 TWh/year, which is actually lower than in the EV scenario, but this might increase once converting the electricity sector to renewables. The CO_2-emissions are higher in this scenario compared to the alternative scenarios due to the significantly increased electricity demand. This will however change when more renewable electricity sources are integrated into the energy system.

The final transport scenario analyses the consequences of electrifying all transport modes through full electrification of the transport sector. This entails that remaining cars and vans (15%) are converted to electricity-powered vehicles, while heavy-duty transport and ships and planes are also electrified. These technologies are not commercialized today and might never be, but the scenario shows the consequences of aiming at electrification of all transport modes. Truck efficiencies are assumed to be 73.7%, airplanes are assumed to be 83.6% and ships have an efficiency of 71.5% [62,63]. These are highly uncertain and discussed in Chapter 4, but for the purpose of developing this scenario best estimates have been applied. The total transport electricity demand in this scenario is 261 TWh/year, which necessitates additional power plant capacity of 20 GW to cover peak demands. Additional costs are included for enhancing the electricity grids. The biomass demand in this scenario is 201 TWh/year, rather similar to the hydrogen and CO_2-electrofuel scenarios.

Figure 6 summarizes the results for transport sector scenarios. Overall, the energy system costs are rather similar between the scenarios at 425-440 b€/year with the exception of the hydrogen scenario. The hydrogen scenario costs are highly affected by the O&M costs for trucks and two variants of this value has been analysed and can be found in section 3.6. Biomass demands exceed available resources in Germany in the biofuels and bio-electrofuels scenarios, which is not feasible considering that further conversions to renewable energy could result in additional biomass demand in the electricity sector.

The assumptions regarding operation and maintenance costs for the transport vehicles influences the overall energy system costs. These costs are highly uncertain when considering technologies that are not fully commercialized and will develop towards 2050 and the cost comparisons should therefore take this into account.

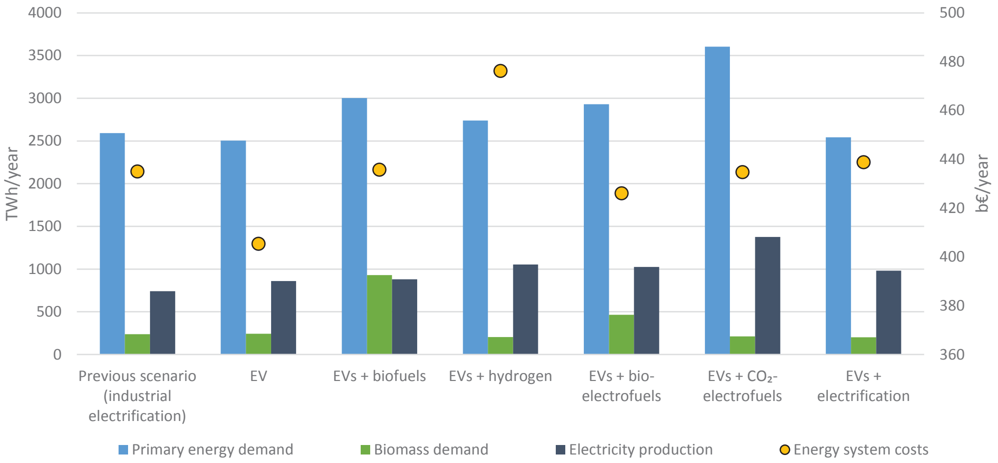

Figure 6: Evaluation factors for the five transport scenarios and the previous scenario.

3.5. Electricity

The non-renewable primary energy remaining in the system at this stage is within the electricity sector, which is the final sector to be converted. This order is selected from a modelling perspective due to the increasing electrification in other sectors thereby influencing the need for additional renewable electricity production. Following measures are taken for converting to 100% renewable Germany:

- Energy savings in the conventional electricity demand
- Integration of intermittent renewable sources wind and PV
- Improvements of thermal plant efficiencies

The first measure in the electricity sector consists of savings in the conventional electricity demand by 25% with costs of 613 M€/TWh and a lifetime of 10 years. The saving potentials and costs are based on [58] and correspond to estimates from [19] and the ambitions of the Energiewende policies [5]. The conventional electricity demand is hereby reduced by 147 TWh/year with a total investment of 89,855 M€.

Four transport scenarios enable the integration of renewable electricity from wind power and PV, with an exception of the biofuel transport scenario. Two variations of integrating variable electricity sources is analysed with the major difference being the allowed excess electricity generation. Firstly, a variation is analysed with a maximum of 5% excess electricity generation allowed while the second variation implements all the variable renewable electricity potentials identified in section 2.1 thereby reducing the need for thermal plant generation and the associated biomass consumption. The combined wind and PV potential is 1,084 TWh/year while the remaining electricity supply is based on thermal production from condensing power plants and CHP plants and small shares of hydropower and industrial electricity production. If the thermal plants are converted to solid biomass the total energy system biomass demand would exceed the biomass potentials significantly and it is therefore necessary to convert the thermal plants to gas as this allows for more efficient use of fuels. This increases condensing power plant efficiencies to 61% and CHP efficiencies to 52% electric and 39% thermal [34]. However, this also requires production of renewable gasses in order to obtain a 100% renewable energy system, which can be accommodated through either gasification of biomass or production of bio-electrofuels by boosting some of the gasified biomass. It was found that the latter was necessary to reduce the biomass input for gasification despite adding further losses from the production of hydrogen. However, a large share of excess electricity is available, which can be integrated into the bio-electrofuel production, thereby reducing biomass demands and using electricity that would otherwise be wasted.

The results from integrating further renewable electricity is described in the following section.

3.6. 100% Renewable German energy system

In addition to integrating renewable electricity, few other measures are adjusted to reduce biomass demands. These include installing additional 20 TWh/year individual and district heating solar thermal, increasing DH heat pump capacity by a factor 10 to 7 GW and integrating further industrial excess heat by 13 TWh/year. This increases the DH imbalance but reduces the annual biomass demand.

During the modelling of the conversion to 100% renewable energy it was realized that staying within biomass potentials would become the most critical and challenging threshold and the last stages of the modelling are therefore prioritized from a biomass reduction perspective.

Figure 7 displays the primary energy supply in the 2050 scenario and the four 100% renewable energy scenarios named after the main solution for the transport sector; hydrogen vehicles, electrification of all transport modes, CO_2-electrofuels and bio-electrofuels. The 100% renewable scenarios are presented in two variations; allowing only 5% excess electricity and when installing the full renewable variable electricity potentials in order to reduce biomass demands. All the 100% renewable energy scenarios are significantly more efficient in terms of primary energy demand than the 2050 scenario as variable electricity sources replace fossil fuel consumption associated with large losses in thermal conversion technologies. The hydrogen scenario has the lowest fuel consumption despite additional losses from hydrogen production compared to the electrification scenario. This difference is due to the utilization of excess electricity as the hydrogen scenario is better able to integrate and store this energy while there are less storage options in the electrification scenario. There are only small differences for overall primary energy demand between the scenarios with maximum 5% excess electricity and the scenarios with full renewable potentials installed.

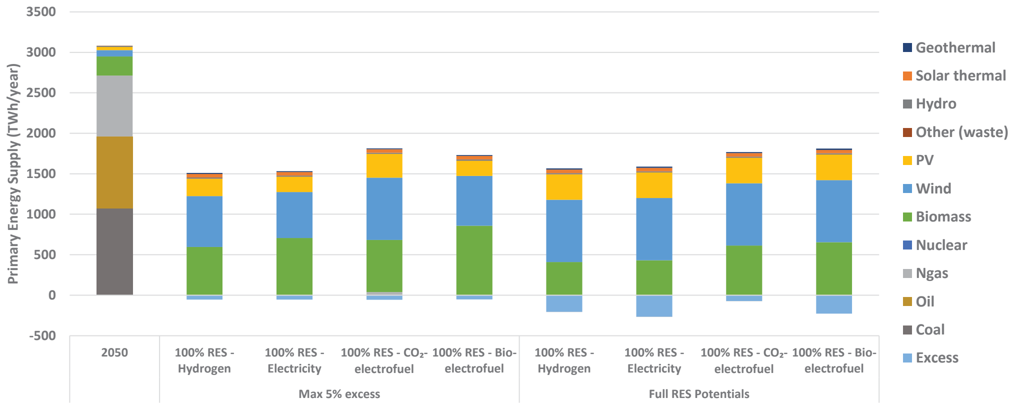

Figure 7: Primary energy supply in the 2050 and the four 100% renewable energy scenarios for Germany in a situation with maximum 5% excess electricity and when the full renewable variable potentials are installed. Hydrogen, Electricity, CO_2-electrofuel and Bio-electrofuel refers to the key technology in the transport sector.

As it can be seen in Figure 8, the hydrogen scenario has the lowest biomass demand in both of the situations, decreasing to 410 TWh/year with all the renewable electricity potentials installed, which is rather close to the biomass potential of 400 TWh/year. Similarly, the electrification scenario with full renewable potentials have a low biomass demand around 430 TWh/year. Even with all the renewable electricity potentials, the two electrofuel scenarios significantly exceed the biomass potentials either because of higher electricity demands (CO_2-electrofuel) or relying on biomass consumption for fuel production (Bio-electrofuel). In the situation where only 5% excess electricity is allowed none of the scenarios remain within biomass potentials, as the lowest demand here is almost 600 TWh/year.

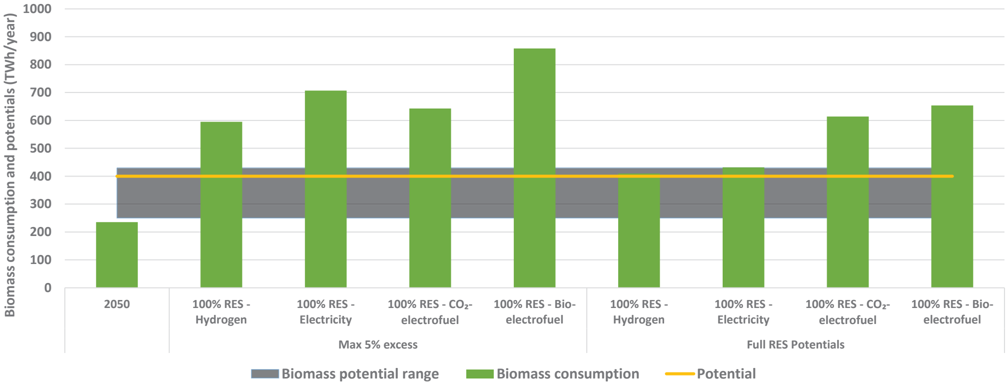

Figure 8: Biomass consumption in the 2050 and the four 100% renewable energy scenarios for Germany in a situation with maximum 5% excess electricity and when the full renewable variable potentials are installed. Hydrogen, Electricity, CO_2-electrofuel and Bio-electrofuel refers to the key technology in the transport sector.

The electricity production significantly increases in all the 100% renewable scenario from around 580 TWh/year in the 2050 scenario to between 1100-1300 TWh/year, i.e. a doubling of the total production (see Figure 9). This occurs because all sectors are electrified through e.g. heat pumps, electric vehicles and hydrogen production. The largest electricity production is from onshore wind power, followed by PV and offshore wind power production. In the renewable energy scenarios, the excess electricity production increases compared to the 2050 scenario due to production of significantly higher amounts of variable renewable electricity (from 116 TWh/year to 1084 TWh/year in the full renewable scenarios) and more periods with mismatches between electricity demand and production. The largest excess production occurs in the electrification scenario with the full renewable potentials where approximately 20% of all electricity production is wasted, as it is not possible to utilize or store it. In the hydrogen and bio-electrofuel scenarios, more storage opportunities are available for storing the excess electricity as hydrogen for other periods (16-18% excess electricity). The lowest excess electricity production (6%) is in the CO_2-electrofuel scenario due to higher electricity demands and the largest electrolyser capacity and hydrogen storages.

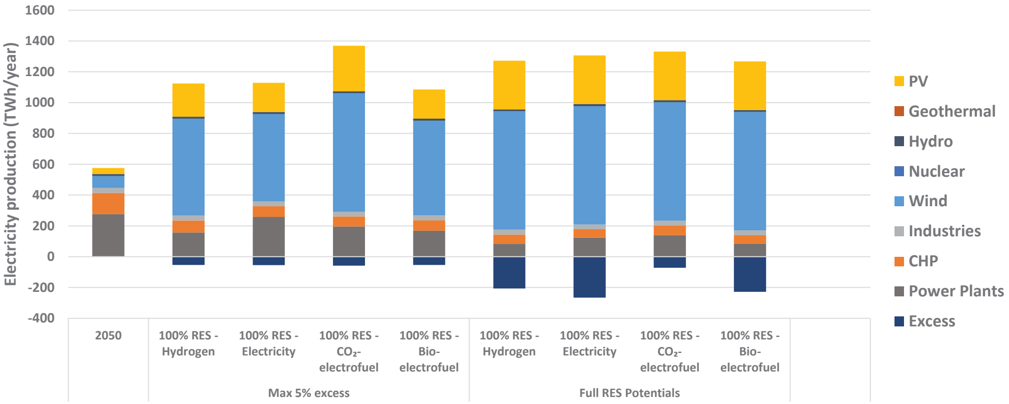

Figure 9: Electricity production in the 2050 and the four 100% renewable energy scenarios for Germany in a situation with maximum 5% excess electricity and when the full renewable variable potentials are installed. Hydrogen, Electricity, CO_2-electrofuel and Bio-electrofuel refers to the key technology in the transport sector.

Significant changes have been implemented in the heating sector for both the heat demands and supply. Firstly, heat savings are implemented to reduce demands whilst replacing the remaining heat demand in individual areas with compression heat pumps. Significant reductions in heating production are obtained after applying the measures mentioned above, with ~50% lower heating production in comparison to reference 2050. The four 100% renewable scenarios are rather similar within the heating sector only affected by the amount of excess heat production from electrolysers and gasification plants (Figure 10). Furthermore, no significant differences occur between the scenarios with full renewable electricity potentials and the scenarios with a cap on excess electricity.

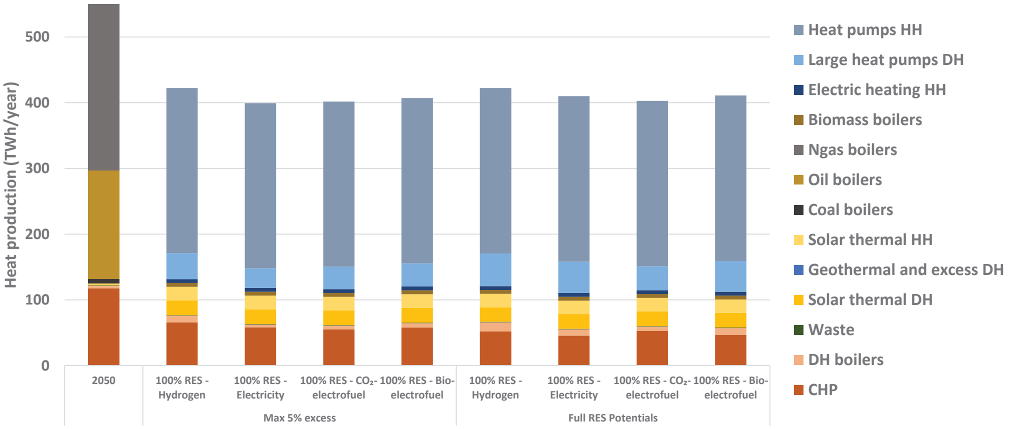

Figure 10: Heat production in the 2050 and the four 100% renewable energy scenarios for Germany in a situation with maximum 5% excess electricity and when the full renewable variable potentials are installed. Hydrogen, Electricity, CO_2-electrofuel and Bio-electrofuel refers to the key technology in the transport sector.

The energy system costs changes from being equal proportions of investments, O&M and fuel costs in the 2050 scenario to becoming significantly more investment and O&M dominated in the 100% renewable scenarios. The 2050 scenario energy system costs are 455 b€/year, which is quite similar to the energy system costs of the renewable scenarios that have costs between 435-485 b€/year when the full renewable potentials are installed (Figure 11). Overall, the 100% renewable scenarios are at a level similar to the 2050 scenario considering the large uncertainties for some technologies, fuel prices and demands in a 2050 energy system. The measures causing the largest cost reductions from the 2050 to the 100% RES scenarios are heat savings and integration of electric vehicles, while costs increase when a high share of thermal coal production is substituted by variable electricity generation. The transport vehicles are responsible for a large share of the overall costs (55-65%) and these costs therefore highly influence the overall costs. This is further discussed in the next chapter.

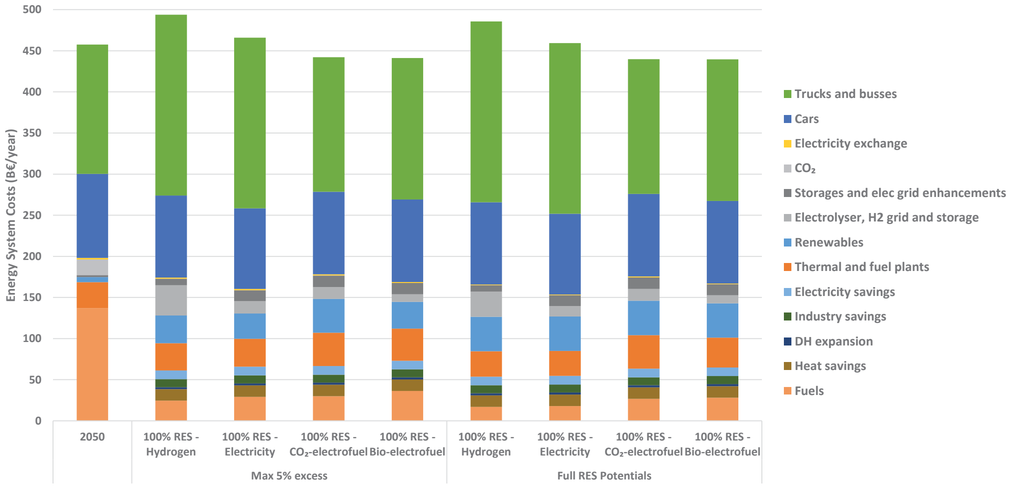

Figure 11: Energy system costs in the 2050 and the four 100% renewable energy scenarios for Germany in a situation with maximum 5% excess electricity and when the full renewable variable potentials are installed. Hydrogen, Electricity, CO_2-electrofuel and Bio-electrofuel refers to the key technology in the transport sector.

4. Discussion

Some measures are decisive for achieving 100% renewable energy in Germany. However, additional measures could be integrated for further reduction of biomass demand to stay within sustainable domestic biomass resources. The biomass demand is primarily consumed in industries and for gasification, biofuel and electrofuel production. Hence, it is crucial to reduce the demand of these technologies as much as possible. Particularly, the thermal power plant operation has a large impact on the biomass demand and rather it should be pursued to integrate as much of the excess electricity as possible. For this purpose, the electrolyser capacity is important as a higher capacity (also implying lower operation hours) enables integrating and storing further variable electricity.

Furthermore, all variable renewable electricity resources should be integrated as otherwise the biomass demand will increase even further and necessitate biomass import. Some bio-electrofuel production is beneficial for supplying renewable gasses to thermal plants thereby integrating excess electricity rather than solely supplying gasified biomass to the thermal plants. The ratio between gasified biomass and bio-electrofuels for thermal plants differ depending on the specific scenario. It might seem counterintuitive to introduce additional losses to the system by producing more hydrogen and to use a high-value product such as electrofuels for thermal energy production, but in the case of the German energy system, it makes sense after integrating all the renewable electricity potentials. The bio-electrofuel production integrates electricity, which otherwise would be wasted and the energy is therefore readily available at low costs. The energy system costs however increase slightly when installing further electrolyser capacity, but still at an acceptable level compared to the 2050 reference scenario.

Some ways of reducing the biomass demand further is through additional demand savings in the heating, industrial, transport and electricity sectors. These will either directly reduce the biomass demand or the electricity demand, which indirectly influences the biomass consumption. Direct reductions of biomass demand are preferable and the industrial sector could therefore be beneficial if further savings or electrification is possible. Lechtenböhmer *et al* [56] even suggests to electrify all basic material industries for EU28 in order to decarbonize this sector, which would also reduce the biomass demand in the present study. In the transport sector, energy efficiency improvements could be gained from modal shifts converting individual transport to collective transport modes thereby reducing the demand for transport energy. Moreover, further expansions of the district heating network would enable the integration of heating resources that are not fully exploited rather than the need for electricity for individual heat pumps. This would also ease the pressure on biomass and variable renewable electricity sources.

Some measures are crucial for achieving a high share of renewable energy including the introduction of electric vehicles to replace ICE vehicles. This allows for the integration of renewable electricity, adds electric storage to the energy system and vastly increases the energy efficiency of the transport sector. Another important measure is the conversion of thermal plants from burning solid fuels to using gaseous fuels thereby allowing for more efficient plants. This ensures as low a biomass consumption for thermal plants as possible. The most critical measure of all are energy demand savings, which have a significant impact on both the primary energy requirements and the energy system costs. Savings in the heating, industrial and electricity (conventional demands) sectors are necessary unless further renewable resources are available for integration in the German energy system, for example through import of additional biomass. The largest saving demands were found for the heating sector. As Heard *et al* [26] suggests it can be debated whether "energy demands must be adjusted to the realistic amounts of renewable sources" or if "supply options must be scalable to realistic projections of future demand".

In the analysis, it was found that the order of implementing certain measures such as heat savings and district heat expansions influence the evaluation parameters. For example, heat demands (i.e. level of heat savings) effect the feasibility of district heating and it should therefore be considered in which order certain measures are implemented into the energy system.

The measures proposed in this study for 100% renewable energy in Germany requires a long time period for implementation and should be integrated once existing technology and plant lifetimes expire. Especially building refurbishments for achieving the suggested heat savings can be difficult to obtain as current refurbishment rates often are not adequate for renovating a sufficient proportion of the existing building stock. Lock-in situations should also be considered since energy infrastructure investments often last for decades (e.g. power plants) delaying further developments in the energy system.

Some of the findings apply only to the German energy system, for example the resource potentials, the ratio between onshore, offshore and PV potentials as well as the energy demands. Despite these differences, many of the findings could be used for designing 100% renewable energy systems in other national systems as most of the key technologies will also be crucial in other systems.

4.1. Uncertainties of scenarios

Converting the transport sector to 100% renewable energy imposes certain challenges. As presented in Figure 6 biomass demands exceed resource potentials for some of the analyzed transport scenarios (biofuel and bio-electrofuel), even before converting the electricity sector to 100% renewable energy. Other challenges relate to technology development, as some of the transport technologies are not fully commercialized. For example, hydrogen vehicles for heavy-duty transport such as trucks and planes are still generally under development and significant technology improvements are required for this scenario to be possible in the future. As previously mentioned, the total system costs are sensitive to the changes in the vehicle prices, particularly changes in the O&M costs. To the best of our knowledge, there is no data in the literature regarding costs for fuel cell electric trucks, and the authors have therefore assumed that the O&M costs are similar the costs for electric trucks, due to the nature of these vehicles. In case these costs decrease in the future, which the authors find rather unlikely, the costs of the scenarios with hydrogen driven transport could be affected.

Similarly, high temperature solid oxide electrolysers are currently only demonstrated on kW scale and need further development in order to replicate the 2050 transport scenarios in reality. Finally, the electrification scenario also necessitates technology development as long-distance driving and air traffic currently cannot be supplied by electricity-only technologies (e.g. batteries). Some of the transport vehicle technology efficiencies such as electric ships and planes as well as certain types of hydrogen-based vehicles are also uncertain. No reliable data was available and hence best estimates are applied for these technologies. If the efficiencies and costs of these transport vehicles are not reliable then energy system costs and primary energy could be significantly affected. Current research also focuses on concepts such as electric roads (e-Roads) to facilitate a larger electrification of all road transport in the future, however these were not applied in our modelling [68].

Additionally, large infrastructure changes are needed if the entire transport sector is supplied by hydrogen or electricity as current infrastructure (e.g. refilling stations) do not support this.

5. Conclusion

Numerous technologies exist for increasing the renewable energy share in the German energy system. This study provides a feasible transition strategy for achieving 100% renewable energy considering all energy sectors. It was found that savings are vital in order to remain within sustainable resource potentials for renewable electricity and biomass. Especially within the heating sector are large energy saving potentials viable while additional savings are also possible in the industrial and electricity sectors. Furthermore, some technologies such as electric vehicles, heat pumps and electrolysers improve the energy system efficiency while enhancing the system flexibility and allowing for integrating further renewable electricity. Finally, all renewable electricity resources should be installed due to significant electrification of all energy sectors.

The largest challenges for achieving this transition are not related to energy system costs, but rather to biomass resources that will be pushed to the maximum of the defined constraints. The 100% renewable energy scenario with the lowest biomass demand relies on hydrogen for transport, gasification and electrofuel production for thermal plants, but is still slightly above the defined biomass threshold of 400 TWh/year when all variable electricity potentials are installed. Other scenarios supplying all transport demands by electricity, 2nd generation biofuels, bio-electrofuels or CO_2-electrofuels have higher biomass demands either because of higher electricity demands, large biomass consumption for fuel production or from the lack of storage capabilities. The biomass demands increase significantly when constraining the scenarios to only 5% excess electricity generation. The compromise is therefore whether to accept either a high biomass consumption or high excess electricity production from variable sources. Some of these scenarios are highly uncertain and require additional technology development and infrastructure changes to be attainable in a future energy system. Challenges therefore remain with the present knowledge for designing 100% renewable energy in Germany.

Despite the challenges, the findings demonstrate that it is possible to transition the German energy system to 100% renewable energy supply within sustainable domestic renewable resources and keeping costs at an acceptable level similar to the energy system costs of a 2050 system.

Key policies should be introduced to support energy savings in all energy sectors, technology development for critical technologies such as electrolysers and some transport technologies and to increase the renewable energy generation.

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PAPER 6

Beyond sensitivity analysis: A methodology to handle fuel and electricity prices when designing energy scenarios

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Original research article

Beyond sensitivity analysis: A methodology to handle fuel and electricity prices when designing energy scenarios

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ABSTRACT

World market fuel prices vary and have historically been very difficult to predict. Especially the price of oil has shown remarkable and unexpected increases and decreases throughout the past 5 decades. The same kind of uncertainty can be seen in many of the new cross-border markets for the trade of electricity, which have been introduced in recent decades. These uncertainties pose a challenge to the design and assessment of future energy strategies and investments, especially in the economic assessment of renewable energy versus business-as-usual scenarios based on fossil fuels. From a methodological point of view, the typical way of handling this challenge has been to predict future prices as accurately as possible and then conduct a sensitivity analysis. This paper includes a historical analysis of such predictions, leading to the conclusion that they are almost always wrong. Not only are they wrong in their prediction of price levels, but also in the sense that they always seem to predict a smooth growth or decrease. This paper introduces a new method and reports the results of applying it on the case of energy scenarios for Denmark. The method implies the expectation of fluctuating fuel and external electricity prices.

1. Introduction

In recent years, many countries and regions around the world have formulated policies with the aim of decarbonizing current energy supplies. Such policies are often driven by a desire to deal with the threat of climate change. However, other reasons such as energy security, job creation and industrial development often also play an important role [1–3]. These aims call for the design and assessment of long-term future energy strategies meant to help determine how to implement such objectives in the best way, including identifying least-cost strategies and calculating the cost of such strategies compared to business-as-usual policies based on fossil fuels.

An essential part of these efforts is to decide what expectations one should have with respect to future world market fuel prices, because such expectations, by nature, have huge impacts on the results. Furthermore, the introduction of international electricity markets means that the exchange of electricity also plays an important role. As such, the same challenge arises when determining expectations for future electricity exchange prices as for fuel prices.

The choice of expectations for future fuel and electricity prices has an important influence on the results in at least two aspects:

- Firstly, on the design of the desired solution, especially if optimisation models or similar methodologies are used to identify the optimal investment strategy. For obvious reasons, high or low fuel and/or electricity prices will influence the identification of the optimal or best solution.
- Secondly, on the assessment of the cost of choosing one strategy against another, especially when a renewable energy strategy is compared to a fossil fuel strategy, or if a renewable energy strategy with little flexibility in terms of integrating fluctuating productions from wind, etc. is compared with a smart energy systems [4–6] strategy that includes a high degree of flexibility.

Since the design and assessment of future sustainable energy strategies involves quite time consuming and complex calculations, it often calls for the use of advanced energy system analysis tools and models. Many such models have been developed, described and applied in the academic literature. Review papers listing and comparing these models find that they are both numerous and difficult to compare [7]. Some models focus on specific aspects such as e.g. forecasting [8], buildings [9] or a shift towards distributed generation [10]. Some have a national approach [1], while others have a regional focus [11]. In [12], different types of models such as energy planning models, energy supply-demand

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models, forecasting models, renewable energy models, emission reduction models and optimization models have been reviewed and presented.

The typical purpose of using such models is to assist in the design, planning and implementation of future energy systems by comparing different scenarios and/or identifying best strategies, often referred to as optimal solutions. Many creators of widely used energy system models identify their models as optimization models such as e.g. the HOMER [13,14] or the BALMOREL [15,16] models. Other models use the term simulation, such as e.g. the EnergyPLAN model [17] or models within district heating [18,19], building design [20] or policy design in the electricity sector [21]. Some models combine the two terms, either by discussing optimization algorithms as part of simulation models [22], or by comparing and/or combining the two types of models [23,24]. Yet another method can be seen in approaches such as exergoeconomics [25,26] and emergy [27,28], in which the idea is to combine thermodynamic optimization with economics. Some also add extensions to existing optimisation models in order to include the effect of limited foresight [29] or adds stochastic elements to include uncertainties [30].

When attempting to identify least-cost scenarios or solutions – no matter whether one uses an optimization or a simulation model – the fuel and electricity exchange cost assumptions become essential, especially if only one future price development is utilised. However, as will be discussed in this paper, there is a fundamental difference between using a specific set of future price level prognoses and assuming that the price level will go up and down from year to year. It is important to realise that fuel and electricity prices are to some extent interlinked, and hence, here the term “price level” refers to an overall price level across different types of fuel and electricity.

For example, if one assumes that future electricity prices will increase or remain at a constantly high level then the optimal solution will typically be to invest in wind turbines and power plants. By contrast, assuming decreasing or constantly low electricity prices will lead to optimal investments in heat pumps and electrolysers. But, if one assumes that future prices will go both up and down then the best solution will likely be a flexible combination of the two. From an energy system analysis model and tool perspective, the key point is that investment optimization models are typically not as well suited to do the latter as models that use a simulation approach, a point which is also argued in this paper. Consequently, the method discussed in this paper also has model and tool implications. For a more detailed discussion on how the choice of models influence the making and use of scenarios please see more in the following paper [31].

The aim of this paper is to raise awareness on the problems related to the typical approach of prices prediction, and demonstrate how to go beyond sensitivity analysis in the handling of fuel and electricity prices when designing energy scenarios.

2. Examples of historic fuel price predictions

Historically, fuel prices have gone up and down and have been affected by economic, geopolitical or natural events [32]. Fig. 1 is a well-known diagram that shows the historic development in the yearly average crude oil price in 2016-USD/barrel.

As seen in Fig. 1, the crude oil price has fluctuated significantly since 1970, with a price peak in 1979–1980 due to the two oil crises in the 70s, and two additional peaks in 2008 and again after 2009. The price drop in 2009 is related to the 2008 financial crisis. The recent price drop seen at the end of the graph has taken prices down to a level of 40–50 USD/barrel.

Outside the USD area, another important aspect of price development is the currency exchange rate. In Fig. 2 the historical development of the monthly price of crude oil in Denmark since 1991 is presented as an example.

As seen in Fig. 2, the price of oil in Denmark has seen a development similar to that presented in Fig. 1, though here the cost is also influenced by the USD to DKK/EUR exchange rate. The price fluctuations seen in both figures underline the challenge involved in predicting the crude oil price, with international events potentially having huge effects. Moreover, the crude oil price influences the price of other fuels such as coal.

These fluctuating fuel prices form the basis for future price predictions at both the country and international levels. As such, predicting the oil price has also received attention within research [35–39]. The International Energy Agency’s (IEA) price predictions often play an important role at the international level, since similar predictions made by national authorities such as the Danish [40] often refer to IEA’s reports. In practice, the same predictions are used by a variety of organizations, since authorities, NGOs, industries and lobbyists all typically prefer to rely on and refer to official projections and predictions.

As currency exchange rates, handling costs, etc. affects the energy market prices it is relevant to focus on a specific geographical case. In this paper, the case of Denmark is used, as predictions based on IEA predications are made and published by the Danish Energy Agency (DEA) on a regular basis [40]. Typically, these predictions refer to the IEA and are used by many different parties in Denmark [41,42]. These predictions are used in the application of Danish law when permissions for new energy investments are granted as well as by many different parties during energy policy discussions.

Fig. 3 shows the actual historic crude oil price development together with DEA’s price forecast for crude oil in an eleven-year period from 2005 to 2016 alongside three of IEA’s price forecasts from 2010 and one from 2015.

As shown in Fig. 3, price predictions by DEA show significant changes. There is a nearly four-fold gap between the lowest and highest oil price expectations in 2030, ranging from 5 to 19 EUR/GJ. During the period from 2005 to 2008, which saw relatively low but increasing oil prices, DEA expected that the crude oil price would decrease in the coming years and thereafter increase slowly. The forecasts after 2008, when actual prices had begun to decrease, predict that the crude oil price would continually increase. Liao et al. [44] found that IEA’s expectations to GDP has been the leading source of energy demand forecast errors.

However, what may be the most characteristic about all the predictions is that they involve smooth curves with smooth increases or decreases over many years. But, historically, as shown in Fig. 3, Figs. 1 and 2, the crude oil price has fluctuated through the years, and has not seen a continuous increase or decrease during any prolonged period.

3. Examples of historic electricity price predictions

As previously mentioned, electricity price predictions have recently become equally important as fuel prices in the design and assessment of suitable energy scenarios and investments. In Denmark, such predictions relate to the Nord Pool Spot market. As part of their fuel price predictions, DEA also makes predictions for electricity prices. Fig. 4 shows a number of DEA price forecasts compared to the actual historic yearly average system prices on Nord Pool Spot.

As seen in Fig. 4, expectations of future system prices on Nord Pool Spot vary significantly between the different DEA price forecasts. For example, the predictions for price in 2030 vary by a factor of almost 2, i.e. between 42 and 78 EUR/MWh. However, DEA has always expected that the Nord Pool System price (in fixed prices) will increase in the long-term. As the actual historical prices show, the system price on Nord Pool Spot varies significantly from year to year and in the last couple of years it has seen a significant decrease, reaching prices considerably below any of the predictions. Unger et al. [45] found that decisions made in individual countries historically have shown to potentially have a large consequence on the electricity prices on Nord Pool Spot.

The electricity price predictions are not as smooth as the fuel price

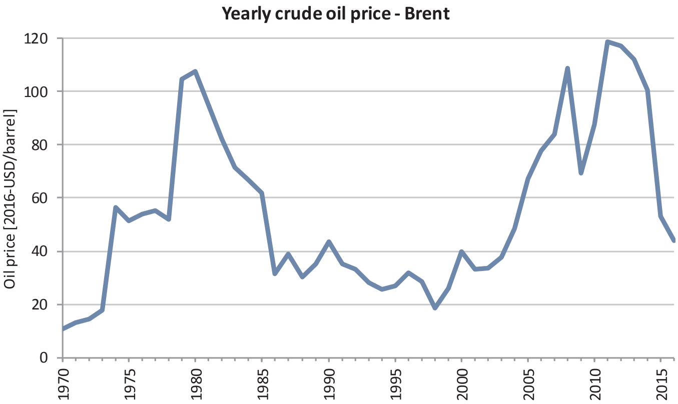

Fig. 1. Yearly Brent crude oil price in 2016USD/barrel [33].

predictions. However, they hardly reflect the actual fluctuations in annual average prices, as illustrated in Fig. 4.

In general, one may conclude that none of the many predictions have been correct so far, not in predicting the current price level, nor, more importantly, in predicting the significant price fluctuations between the individual years.

4. A new method

As illustrated above, both the world market oil price and the electricity exchange price on international markets have shown remarkable and unexpected (not predicted) fluctuations throughout the past decades. Both the price fluctuations and the uncertainties pose a challenge to the design and assessment of future energy strategies, especially in the economic assessment of renewable energy against business-as-usual scenarios based on fossil fuels. From a methodological point of view, the typical way of handling this challenge has been to predict future prices as accurately as possible and then conduct a sensitivity analysis. However, as illustrated above, such long-term predictions are almost always wrong. They are not only wrong in their prediction of price levels, but also in the sense that they always seem to predict a relatively smooth growth or decrease, while historical prices have typically fluctuated up and down, e.g. due to changing economic activity, shifting political goals and changes in technology.

In this paper it is argued that instead of assuming smooth developments of future prices or trying to estimate one specific future price level, when doing long-term energy system analyses one should instead aim to replicate a future price environment in which the prices level vary between the years. From a practical point of view, one can do that by considering a range of different potential future price levels, as this will provide a better framework for estimating how a proposed energy system handles the fluctuating nature of energy prices, especially with respect to fuel and electricity prices.

This method has been used in (among others) a series of three studies of national energy strategies for Denmark, all made in a collaboration between the authors of this paper and the Danish Association of Engineers (IDA). These studies were conducted and published in 2006 [47,48], 2009 [49,50] and 2015 [51]. In addition to the expectations of shifting fuel and electricity prices, these studies also assumed shifting CO_2-emission taxes/payments.

In all three studies, a method is used in which fuel prices are expected to fluctuate between three different price levels: low, medium and high. The same goes for expectations of the prices on the international electricity markets. The three studies are here presented as examples of how this method can be implemented in specific studies, and as the details of these studies are extensive, please refer to the source listed above for further information.

4.1. Fuel prices

For example, the study from 2015 (IDA's Energy Vision 2050) refers to the most recent DEA fuel price assumptions from December 2014 [40], which are based on inputs from the IEA World Energy Outlook from November 2013. In DEA's update, the crude oil price is expected

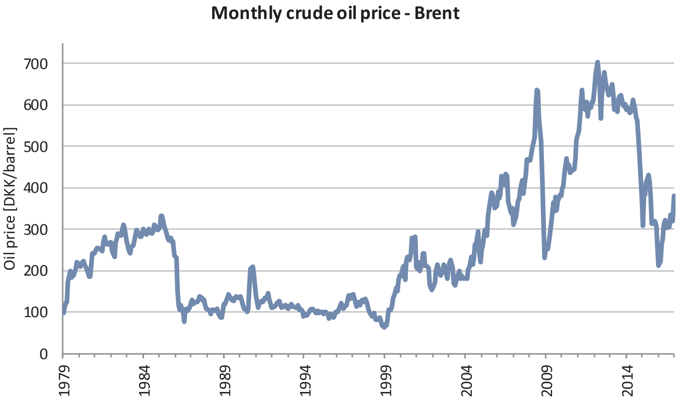

Fig. 2. Monthly market prices for Brent crude oil in current prices [34].

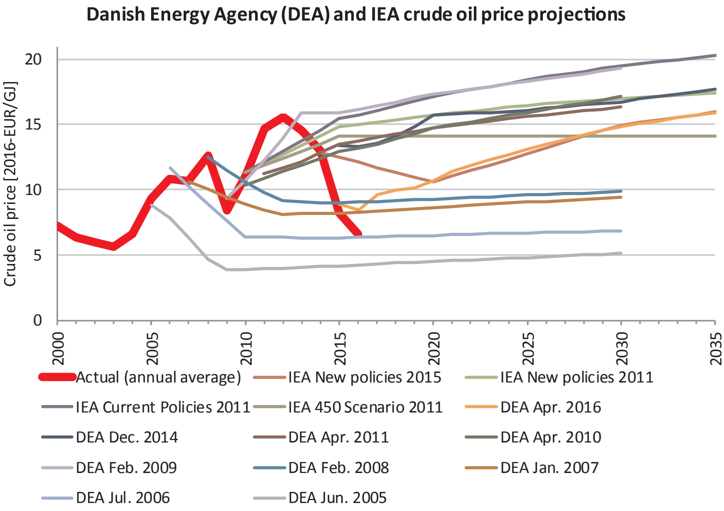

Fig. 3. Comparison of different crude oil price forecasts from DEA and IEA alongside the historic annual Brent crude oil price [43].

to increase to 148 2015-USD/barrel in 2035. However, based on the historical crude oil price development shown in Fig. 1, which shows that the yearly crude oil price has never exceeded 120 2015-USD/barrel, a crude oil price of 148 2015-USD/barrel must be considered high. As such, in IDA's Energy Vision 2050, DEA forecasts from December 2014 are seen as high price forecasts.

In IDA's Energy Vision 2050, three different cost scenarios for 2035 are used:

- Low fuel cost: Based on the fuel prices in 2015, where the crude oil price is about 62 USD/barrel [52,43,53].
- Medium fuel cost: The average between the low and high cost scenarios, where the crude oil price corresponds to about 105 2015-USD/barrel.
- High fuel cost: DEA's fuel price forecast for 2035 from December 2014, where the crude oil price is expected to be about 148 2015-USD/barrel [40].

Similar methods and price level variations were used in the two previous studies, though with slightly different price fluctuations. For example, the prices used in the study from 2006 were 40, 68 and 96 2005-USD/barrel in 2030, while the numbers in the 2009 study were 60, 122 and 132 2008-USD/barrel in 2030 and onwards. Differences in the exchange rate between DKK and USD makes it difficult to compare these three studies. However, the method used in each study is the same and the prices are in the same order of magnitude.

4.2. Electricity exchange prices

The idea of expecting significant fluctuations in the annual average electricity price on the Nord pool market was already used in a study from 2004 [54] and is described in more detail in [55]. At that time, the method was closely linked to the observation that Nord Pool prices were highly dependent on the water content in the reservoirs of the hydro power systems in Sweden and Norway. Consequently, the assumption distinguishes between years with lots of rain (wet years),

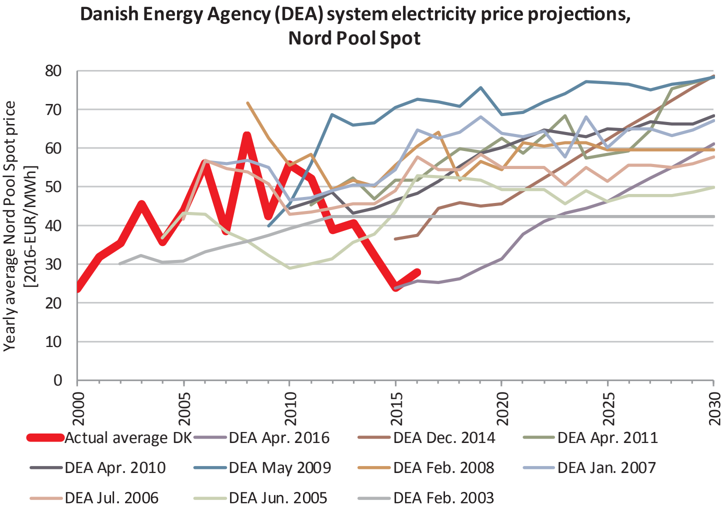

Fig. 4. Comparison of different Nord Pool Spot system price forecasts for Denmark by DEA alongside the historic unweighted yearly average Nord Pool Spot price for the two Danish price areas [46].

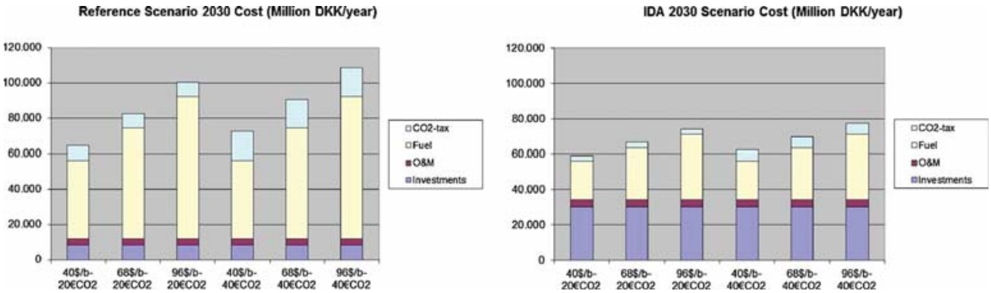

Fig. 5. Total Cost of the IDA 2030 energy scenario for Denmark compared to a Business-As-Usual reference under different fuel price and CO_2-tax assumptions. The diagram shows a shift in cost structure in the direction away from fuel towards investment costs. Source [1,47].

years with normal rain (normal years) and years with very little rain (dry years). Historical data show that out of 7 years, typically one is a dry year, three are wet years and three are normal years. Thus, a 7 year period is made up of one dry year and three wet and normal years [54,55].

In the study from 2004, the average electricity exchange price at Nord Pool over the 7 year period was adjusted to DEA's expectations from 2003 (see Fig. 5). At that time, the prices were heavily influenced by severe surplus power capacity. For this reason, the previous historical prices were, in many situations, considered to be close to the short-term marginal costs, not including investment. In the future (after 2003), when new capacity would be needed, the prices were expected to increase to the long-term marginal costs of the new units (i.e. including investment costs of new capacity). DEA expected the average price in 2010 to be 32 EUR/MWh, set by the long-term marginal price of new combined cycle units in Norway, which, at that time, were considered the most cost-effective option for expanding the system (the price shown in Fig. 4 is a little higher since it is shown in 2015 prices), and the DEA assumed that the average market price would be able to cover the costs of this type of unit.

Based on such expectations about the average price, the three types of years were defined as follows:

- Wet year average price: 19 EUR/MWh.
- Normal year average price: 35 EUR/MWh.
- Dry year average price: 64 EUR/MWh.

The average price of the 7-year period thus becomes 32 EUR/MWh, equal to DEA's expectations.

It should be noted that in the detailed calculations of the above-mentioned studies, such prices levels are average prices, which, in the simulation and modelling process, were assumed to be subject to significant hourly price variations, as is typically observed in electricity markets.

4.3. CO_2 taxes/costs

In addition to the variations in fuel and electricity prices, the IDA study from 2006 included an assumption of fluctuations in CO_2 taxes, which then further influenced the electricity price assumptions. In the IDA 2006 study, two CO_2 taxes were included, namely 20 and 40 EUR/tonne.

In the fuel price forecast from December 2014, DEA uses three estimates for the CO_2 quota price in 2035; a low price of 24 2015-EUR/tonne, a medium price of 42 2015-EUR/tonne and a high price of 60 2015-EUR/tonne. In the IDA 2015 study, only one CO_2 quota price forecast for 2035 of 42 2015-EUR/tonne was used.

5. The case of Denmark: IDA 2006 study and IDA 2015 study

To illustrate the implications of using the method described in this paper, a few results from two of the mentioned cases are highlighted, namely the IDA study from 2006 and the most recent one from 2015. In these studies, detailed hourly calculations were conducted for the different scenarios using the energy systems analysis tool and model, EnergyPLAN [56]. EnergyPLAN has been used in a number of studies around the world over the past couple of decades [17].

In the IDA 2006 study, a proposed increase in the use of renewable energy was compared to a Business-As-Usual scenario that described the current official energy policy of 2005. The socio-economic feasibility was calculated in terms of annual costs, including fuel and operation, as well as annual investment costs based on lifetimes of the investments and an interest rate (in this case 3%). A feasibility study was carried out using three different oil prices for setting three different price levels (as mentioned previously), and the IDA 2030 alternative was compared with the Business-As-Usual reference scenario (Ref 2030). It was assumed that price level based on the average oil price is applicable 40 percent of the time, while the price levels based on low and high oil prices are each applicable 30 percent of the time.

The results are shown in Fig. 5. Compared to Ref 2030, the IDA 2030 alternative has lower fuel costs but higher investment costs and has lower total annual costs. Thus, the IDA 2030 scenario is more robust to fluctuating fuel prices in comparison to the Ref 2030 scenario, as also shown in Fig. 5.

The IDA 2006 study also used EnergyPLAN to calculate net revenues for the Danish energy system from the exchange of electricity with other countries. This was done by comparing the results of a closed system with no exchange of electricity with other countries to the results of an open system, where exchange of electricity is possible. As such, the open system benefits from the exchange by selling electricity when the price on the relevant international electricity markets exceeds the Danish energy system's marginal production costs and by buying electricity when the price on the relevant international electricity markets is lower than the marginal production costs within the Danish energy system. The modeling takes into consideration transmission bottlenecks between the exchanging countries. The whole calculation procedure is based on the assumption that each of the electricity production units optimizes its business-economic revenues. This was then carried out for all the different price levels for fuel and electricity prices as well as the two CO_2 taxes described above; the results are shown in Fig. 6.

As seen in Fig. 6, the net revenue for the system (in this case Denmark) is typically on the order of between 500 and 1000 million DKK/year. In years with low fuel prices and high electricity prices on the international electricity markets, revenues are primarily earned from exporting, while in years with high fuel prices and low electricity prices, revenues are earned from importing electricity. It should be

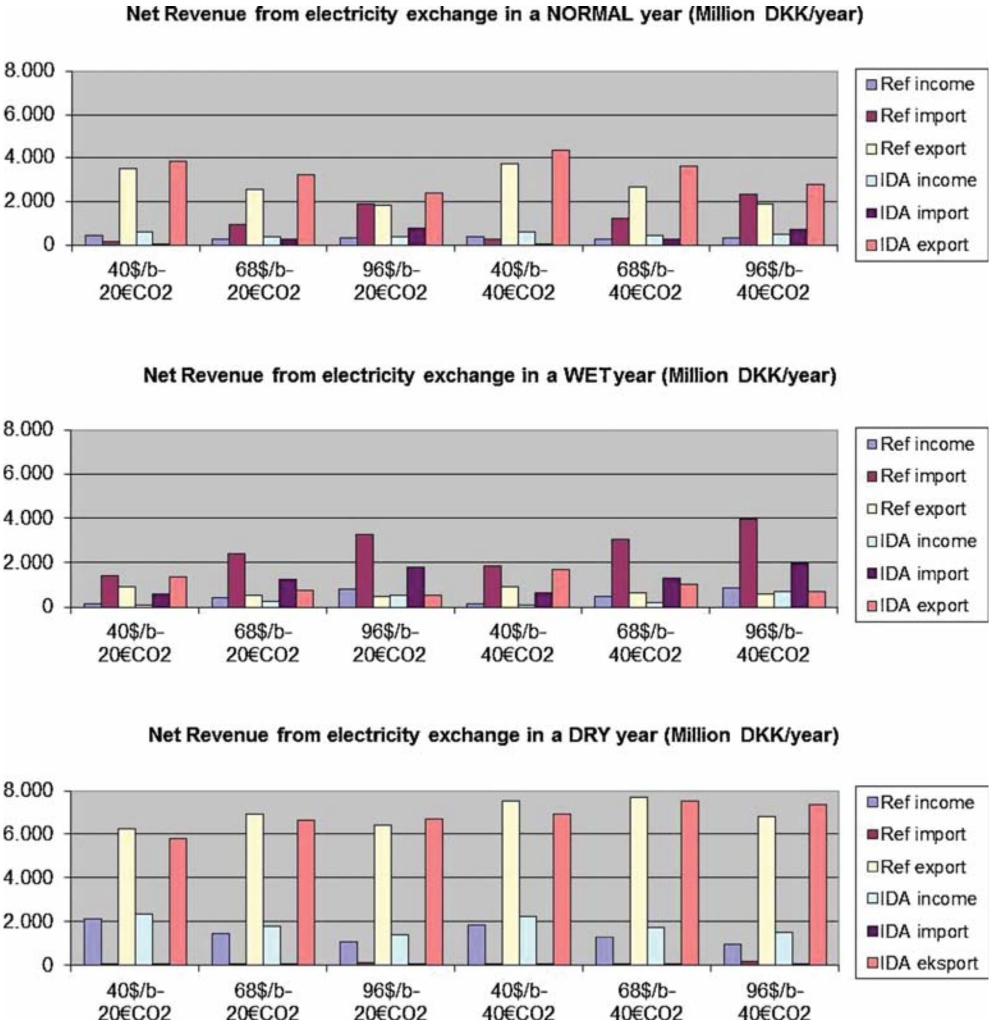

Fig. 6. Net Revenue from exchange of electricity under different CO_2-taxes and fuel and electricity prices. Import and export shows the turnover while the Income is the Net Revenue calculated in comparison to a situation with no exchange of electricity. Source [1,47].

mentioned that not all combinations are equally probable. The electricity market price will, to some extent, follow the changes in fuel prices. It should also be noted that the revenue (shown in Fig. 6) is calculated not including the investment costs.

In order to compare the Ref 2030 and the IDA 2030 scenarios the average net revenue was calculated for each scenario using the following occurrences that were deemed relevant for the net revenue of the Danish energy system:

- Wet, normal, and dry years appear in the ratio 3:3:1
- Low, medium, and high fuel prices appear in the ratio 3:4:3
- Low and high CO_2 emission trading prices appear in the ratio 1:1

Based on these ratios, the average net revenues of the IDA 2030 system are 585 million DKK/year compared to 542 million DKK/year in the Ref 2030 scenario. Based on this analysis, the two systems were found to benefit equally from the exchange of electricity on the Nord Pool Spot market. The important economic benefits come from the fuel savings achieved by changing the system from the one described in Ref 2030 to the one described in IDA 2030, as shown in Fig. 5.

Fig. 7 shows a final calculation of the total annual system cost using the same ratios as listed above. As seen, the average annual cost under these assumptions is lower for the IDA 2030 scenario than for the reference. It should be emphasized that the resulting numbers differ from those that would be produced using the traditional method, in that these numbers represent an average cost based on the assumption of fluctuating fuel and electricity prices as well as different CO_2 emissions costs. Moreover, it is important to notice that the two alternatives have been analysed on their ability to adjust to such shifting circumstance from one year to another. Consequently, the results presented in this paper include the benefits of having a flexible energy system that are able to change production and consumption based on the fluctuation of prices, rather than considering them only via an external sensitivity analysis, as the traditional method does.

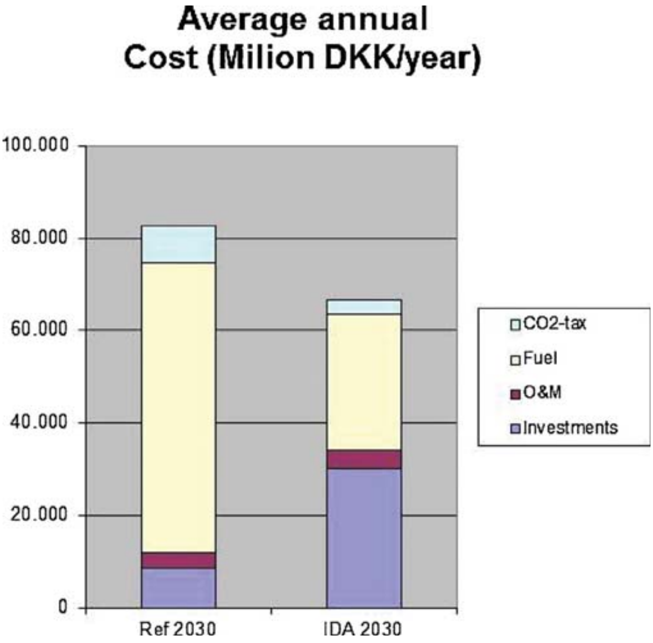

Fig. 7. Total average annual cost of the IDA 2030 energy scenario for Denmark compared to a Business-As-Usual reference, assuming fluctuating fuel prices, electricity prices and CO_2 taxes. Source [1,47].

In the IDA 2015 study, use of the new method was taken a step further: the number of price correlations was expanded even more to include 10 different average electricity prices on the international electricity markets in combination with three fuel price levels. In addition, comparisons were made regarding the socio-economic feasibility of implementing two scenarios suggested by DEA: a fossil fuel scenario continuing the trends of the current system (DEA Fossil 2050) and a system dominated by wind power (DEA Wind 2050).

In Fig. 8, the socio-economic consequences of various external electricity prices as well as three fuel price levels are illustrated. The results suggest that the fossil fuel scenario is impacted more by varying fuel prices than the other scenarios. Each trend line represents impacts on import or export as well as electricity bottleneck earnings.

As before, it is important to emphasize that each calculation has been made for the same energy system; however, a shift in operational setup was considered. When world market fuel prices are low and external electricity prices high then the system is operated to consume fuel and export electricity, and vice versa when fuel prices are high and

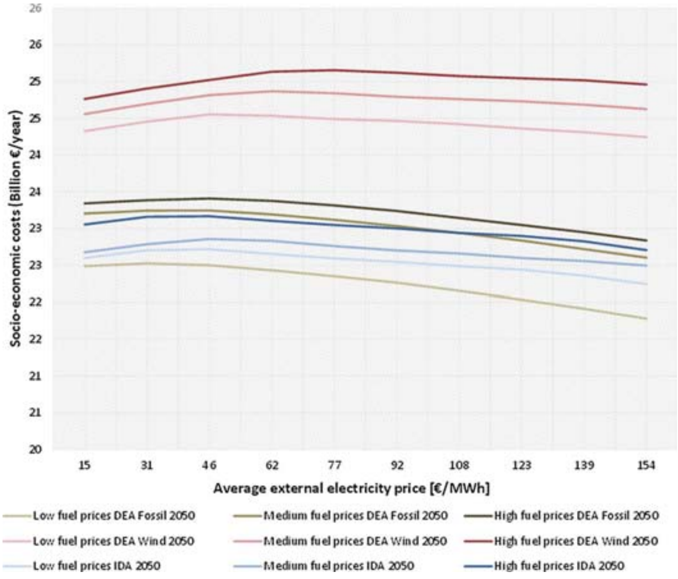

Fig. 8. Total socio-economic costs of the 2050 energy systems with three levels of fuel prices and 10 different levels of electricity prices. Source [51].

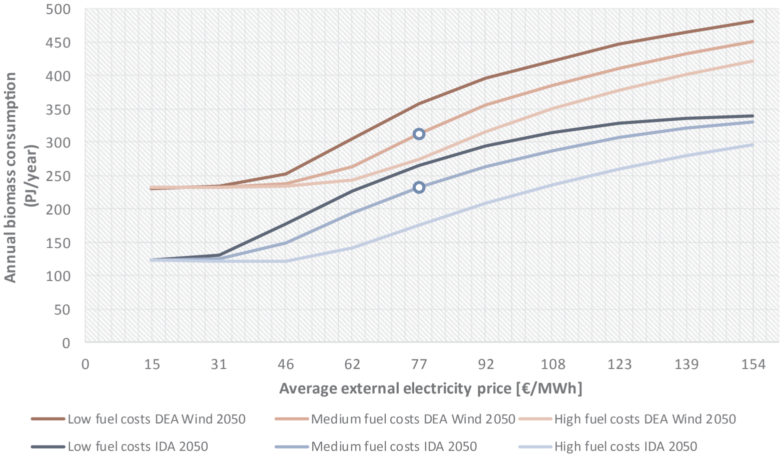

Fig. 9. Annual biomass consumption in DEA Wind 2050 and IDA 2050 for three different fuel price levels and 10 different price levels for electricity on the internal electricity markets. The central scenarios for DEA Wind 2050 and IDA 2050 are marked in the diagram. Source [51].

electricity prices low.

The IDA 2015 study also includes an analysis regarding the impact of varying electricity and fuel prices on overall biomass consumption in the wind scenario as suggested by DEA and in the IDA 2050 scenario (see Fig. 9). Biomass demand was a key concern in the study, which had a goal of ensuring a sustainable level of biomass consumption in a future energy system, and as such, it was important to analyse the effect of electricity exchange on the biomass consumption within Denmark. Based on these analyses, it was quantified how a lower fuel price leads to higher biomass consumption and also how a higher electricity price will increase the consumption of biomass.

Also in the IDA 2015 study, it is important to notice that the alternatives were analysed on their ability to adjust to shifting circumstance from one year to another. Consequently, these results include the benefits of flexible energy systems, rather than considering them only via an external sensitivity analysis. This approach can therefore be used to create a robust energy system that stays within sustainable biomass limits, regardless of varying electricity and fuel prices.

6. Discussion

The idea underlying the method described above is to acknowledge that:

- Historic fuel and electricity prices demonstrate significant fluctuations in their yearly averages.
- There is an essential element of uncertainty as to whether next year's prices will be high or low, but there is an element of likelihood that the long-term development will be fluctuating rather than smooth.
- Fuel prices influence electricity prices but there is a huge element of decoupling between the two since the former depends mostly on geopolitical events while the latter depends on weather conditions and similar.

Thus, the prediction of future oil and electricity prices is difficult to capture using "smooth curve" predictions, even if they are combined with sensitivity analyses. Consequently, this paper has described an alternative method in which both the design and the assessment of future energy solutions and scenarios are based on the expectation of shifting fuel and external electricity prices. The core idea is to include the essential elements of price fluctuations and uncertainties into the design and assessment of future energy systems and strategies.

The cases described above illustrate how such a focus leads to the design of flexible smart energy systems rather than "optimal" systems, which are calculated under strict assumptions and therefore are only "optimal" under specific circumstances. And again, such circumstances may only occur in one or a few years out of the coming decades, if at all.

Regarding the use of energy system analysis tools and models, the nature of development in fuel and electricity prices calls for an approach in which different scenarios and designs are compared and assessed rather than embarking on a search for the one and only optimal solution. Therefore, as discussed further in [57], an analytical simulation and alternative assessments approach seems more suitable than a prescriptive investment optimizations approach.

7. Conclusions

From a methodological point of view, the typical way of handling the challenge of fluctuating and shifting prices has been to predict future prices as accurately as possible and then conduct a sensitivity analysis. However, a historical analysis of such predictions has shown that they are almost always wrong. Not only are they wrong in their prediction of the price level, but also in the sense that they always seem to predict a smooth growth or decrease, while historical prices have typically fluctuated up and down.

Consequently, this paper has described an alternative method in which both the design and the assessment of future energy solutions and scenarios are based on the expectation of shifting fuel and external electricity prices. Results of applying this method on the case of energy scenarios for Denmark have been described. In general, the cases illustrate that such a methodological approach has been able to influence not only the assessment but also the design of the scenario.

The core difference between the two methodologies is that the new method determines the desired solution based on an assumption of uncertain and fluctuating fuel and electricity prices; this is not the case in the traditional method. The traditional method has a tendency to underestimate the economic benefits of flexible and agile energy systems as well as systems that are equipped to tackle uncertainties related to when prices will be low or high.

For example, if one assumes that future electricity prices will be high then the optimal solution will typically be to invest in wind turbines and power plants, while low electricity prices will lead to optimal investments in heat pumps and electrolysers. But, if one assumes that future prices will go up and down then the best solution will likely be a flexible combination of the two.

In terms of assessment, the new method can incorporate the economic consequences of different price combinations, in this case fuel prices, electricity prices and CO_2 taxes. And in terms of design, the new method can promote flexible solutions, rather than solutions that are optimized against a certain high or low-price prediction. In real life, the flexible solution will be much more likely to survive in an economically feasible way.

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