The role of Solar thermal in Future Energy Systems

Country cases for Germany, Italy, Austria and Denmark

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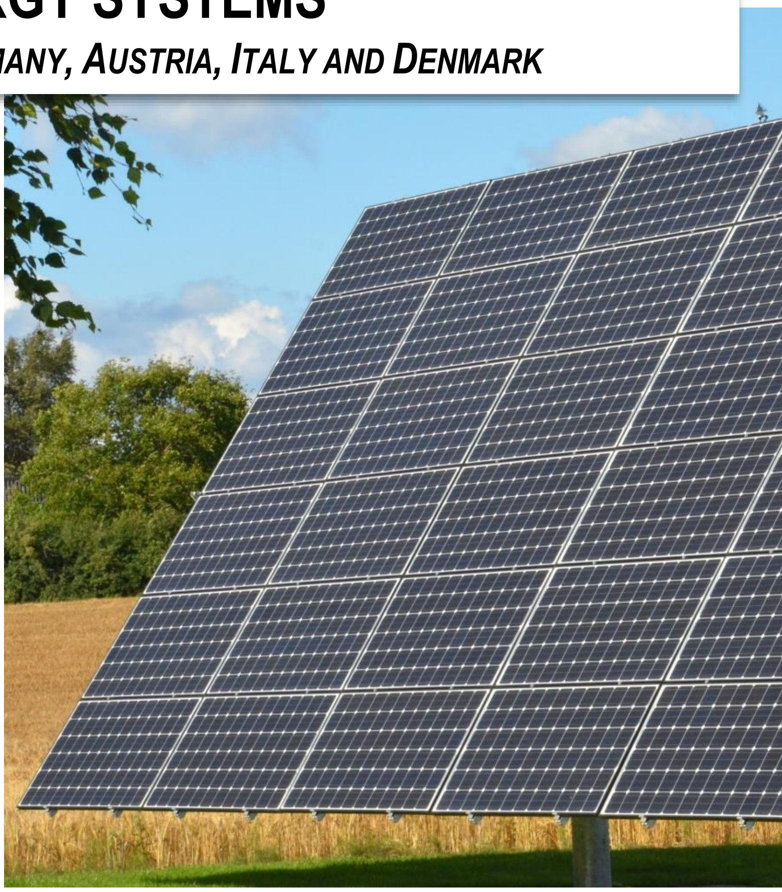
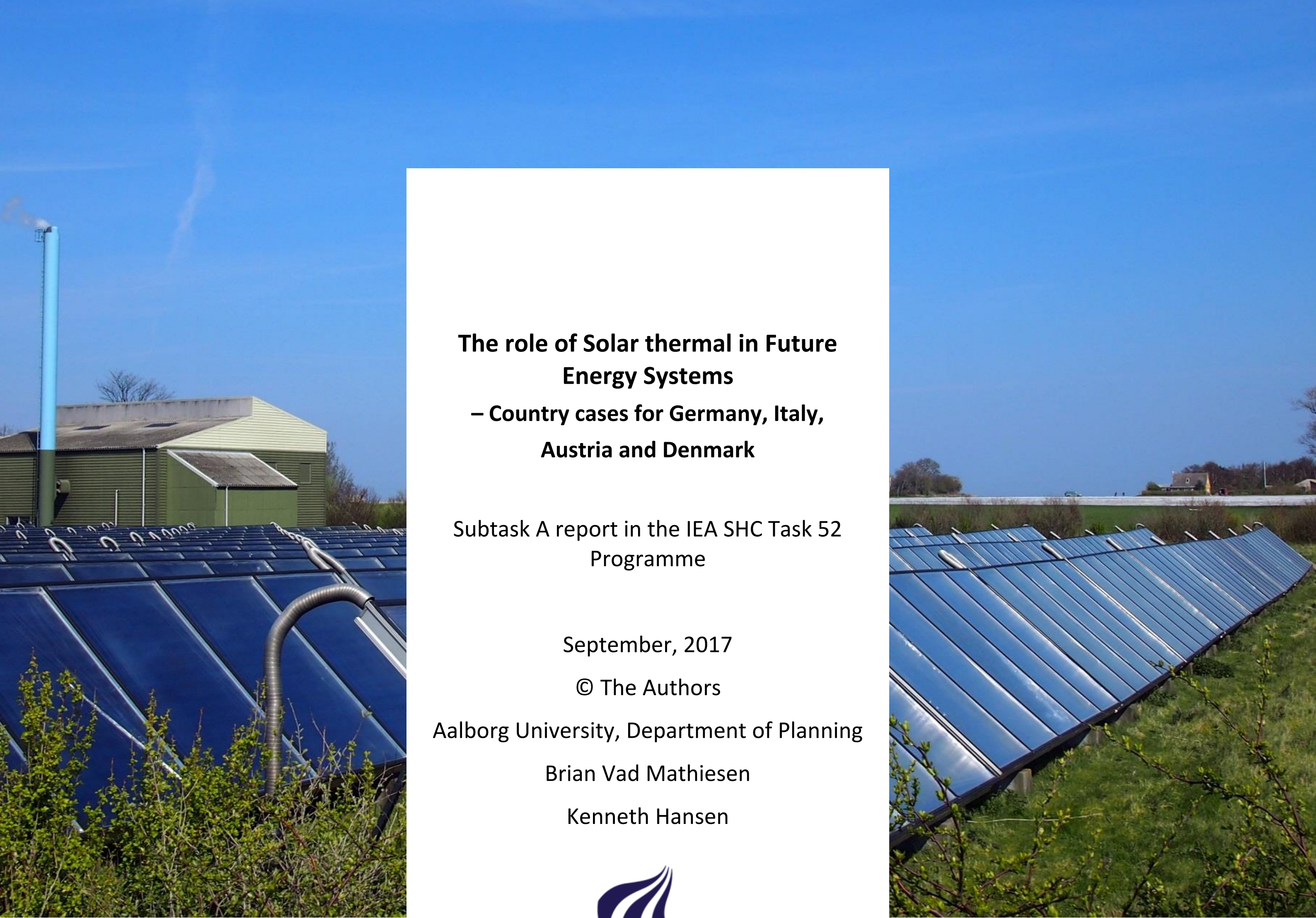
THE ROLE OF SOLAR THERMAL IN FUTURE ENERGY SYSTEMS

- *COUNTRY CASES FOR GERMANY, AUSTRIA, ITALY AND DENMARK*



SHC
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Task 52
Solar Heat and Energy Economics in Urban Environments



The role of Solar thermal in Future Energy Systems
– Country cases for Germany, Italy, Austria and Denmark

Subtask A report in the IEA SHC Task 52 Programme

September, 2017

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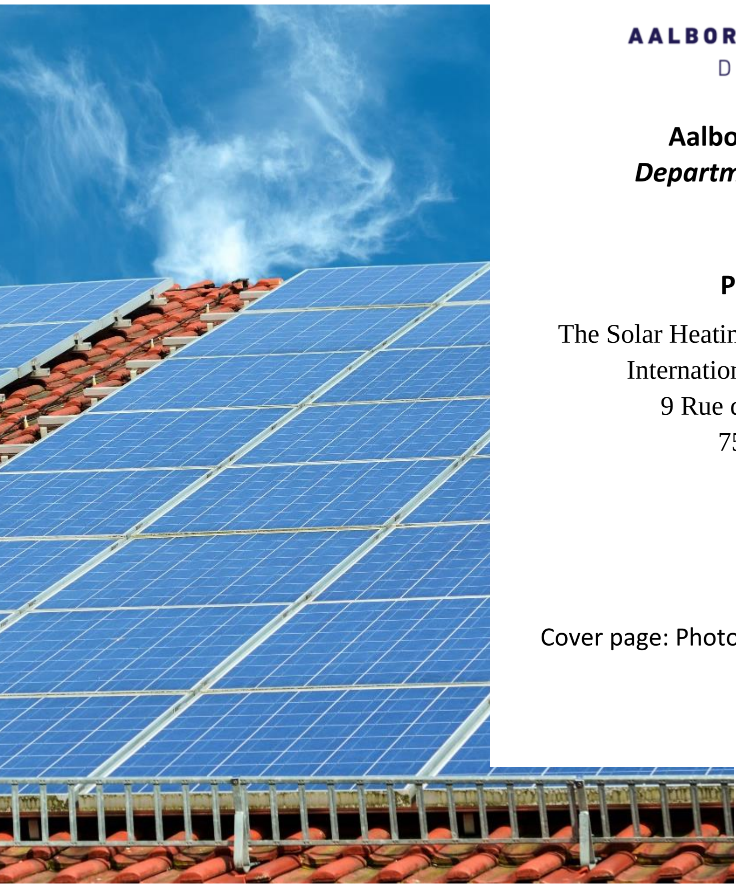

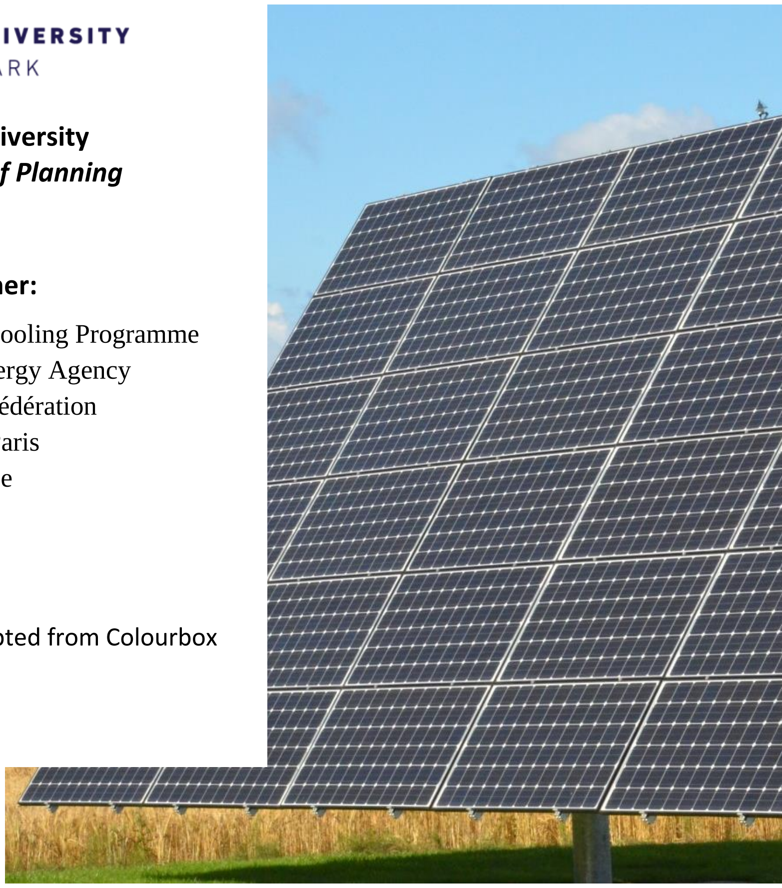

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International Energy Agency
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SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Task 52
Solar Heat and Energy Economics in Urban Environments

IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is

"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050."

The member countries of the Programme collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 53 such projects have been initiated to-date, 39 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52)
- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding – working agreement with solar thermal trade organizations
- Workshops and conferences

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Preface

This report deals with solar thermal technologies and investigates possible roles for solar thermal in future energy systems for four national energy systems; Germany, Austria, Italy and Denmark. The project period started in January 2014 and finished by October 2017.

This report is based on research performed by Aalborg University with the collaboration of Subtask A project partners Sebastian Herkel and Andreas Palzer from Fraunhofer ISE, Marcus Hummel and Richard Büchele from the Technical University of Vienna as well as Bengt Perers and Simon Furbo from the Technical University of Denmark. Additional collaboration with other subtask project partners has contributed to enhancing the methodology and reporting of the research. Contributions from Rasmus Lund from Aalborg University are also appreciated.

We wish to say thank you to the Danish Energy Agency who funded this work through the EUDP programme (Energy technology Research and Development programme).

September, 2017, Copenhagen

Brian Vad Mathiesen & Kenneth Hansen

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Glossary

IEA SHC	International Energy Agency – Solar heating and Cooling Programme
CHP	Combined Heat & Power plant
District heating areas	Areas supplied by district heating networks
Individual areas	Areas not in district heating areas
CEEP	Critical excess electricity production. Electricity production which exceeds demands and cannot be exported or stored. Also called unused electricity.
PV	Photovoltaics
BAU	Business-as-usual scenario for the national energy systems in 2050
High-RES	High-renewable scenario used for analysing the role of solar thermal
Thermal plants	Condensing power plants, CHP plants and district heating boilers
Solar thermal penetration rate	The solar thermal penetration rate is the share of buildings that are connected to a solar thermal system either directly or thorugh a district heating system
Solar thermal concepts	Solar thermal technologies that are selected for detailed analyses in this study
Solar thermal potential	The maximum solar thermal that technically can be installed in an energy system given the solar thermal penetration rate. Further details in section 7.2.

1 Executive summary

Solar thermal technologies have expanded rapidly in Europe in the last 5 years, more than doubling in production [1]. This has primarily taken place in individual buildings, but solar thermal for district heating is also growing, particularly in Denmark. However, the question remains regarding the potential for installing solar thermal in energy systems and whether solar thermal is a viable solution for Europe to achieve its energy targets, or if better alternatives exist. These questions have been investigated thoroughly in this study for four European countries; Germany, Austria, Italy and Denmark.

This study is part of Subtask A in the IEA SHC Task 52 entitled Solar thermal and Energy Economy in Urban Environments. Further reports in Subtask A include other ways of investigating solar thermal in Germany, the potential for heat savings in selected European countries as well as analysis of the cost performance of small solar thermal systems.

The primary objective of this study is to enhance the understanding of the role of solar thermal in future energy systems. The role of solar thermal is analysed with a horizon of 2050 and a high renewable energy target at the national or international level.

The analysis is based on the creation of scenarios for selected countries and reflects the combined view of electricity, heat and transport while taking into account the dynamics of changes in the energy systems, in particular on the parts of the system that directly link to solar thermal energy. Focus is the role of solar thermal in future smart energy systems with integrated electricity, heat and transport sectors.

All of this is combined in this report using an energy system model called EnergyPLAN (www.EnergyPLAN.eu), which simulates the hourly operation of the heating, cooling, electricity, industry, and transport sectors over a single year. Using EnergyPLAN, the current and future energy system for each of the four countries is simulated based on the historical year 2010 (Ref 2010), and based on a future 'Business-As-Usual' forecast by the European Commission for the year 2050 (BAU 2050). These two scenarios represent where we are today and where we are likely to end up if we continue using energy in the same way in the future as we do today. Subsequently, a number of scenarios are created for each country for the year 2050. The scenarios that are used for solar thermal analysis also includes future systems with lower heat demands due to building retrofits (Heat savings scenario) and expansions in the district heating supply (District heating scenario). Ultimately, the scenarios aim at designing a high-renewable energy system (high-RES scenario) in the heating and electricity sectors. The role of solar thermal is afterwards thoroughly analysed in each of these scenarios for the four countries to cover a variety of future energy system trajectories. In total, more than 250 hour-by-hour scenarios have been developed for this research project for the creation of the future renewable energy systems, the various types of solar thermal analyses as well as the sensitivity analyses. This makes the research robust across a variety of conditions and energy system types.

The role of solar thermal in the energy system is measured by quantifying its impact separately for each country in terms of three key metrics: energy (primary energy supply), environment (carbon dioxide emissions), and economy (total annual energy system costs). The economic costs in this study are understood as the societal energy system costs in terms of infrastructure investments, operation and maintenance, fuel costs and CO_2-costs, excluding taxes, subsidies and externalities such as health costs, climate change, etc.

The solar thermal concepts that are analysed in the study include five different types:

- Concept 1: CS-SFH. Solar-combi systems in single family houses.
- Concept 2: CS-MFH. Solar-combi systems in multi-family houses.
- Concept 3: BH-DE. Solar assisted heating of building blocks and urban quarters (roof-mounted collector field).
- Concept 4: SDH-DK Diurnal. Solar assisted district heating (ground mounted collector field) with diurnal storage.

- Concept 5: SDH-DK Seasonal. Solar assisted district heating (ground mounted collector field) with seasonal storage.

Solar concepts 1-3 are individual heat supply options while solar concepts 4-5 are district heating options.

The role of solar thermal has been analysed in three different ways:

- The marginal impact of installing 1 TWh solar thermal (individual and district heating) in each country and scenario
- The maximum solar thermal potential in each country and scenario
- The impact of installing the maximum solar thermal potential

1.1 Conclusions and recommendations

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 results show that the overall solar thermal potential across the countries and various energy system types is in the range of 3-12% of the total heat production. The socio-economic costs are higher in a high-renewable energy system with high shares of solar thermal compared to installing solar thermal in the current energy systems. Similarly, the advantages of solar thermal reduce in terms of reductions of fossil fuels and CO_2-emissions when transitioning towards a high-renewable energy system.

The main conclusions and recommendations from the solar thermal analysis are outlined below.

1. The energy system design is crucial in terms of solar thermal feasibility
2. The solar thermal penetration is crucial for the solar thermal potential
3. Based on the analyses in this report the technical solar thermal potential is in the range of 3-12% of the heat production
4. Installing solar thermal could lead to higher energy system socio-economic costs
5. Solar thermal could ease the pressure on scarce renewable resources such as biomass
6. Solar thermal will be competing with other renewable sources in a high-renewable energy system
7. Some advantages of solar thermal decrease in a high-renewable energy system
8. A full energy system perspective is required to analyse the feasibility of solar thermal
9. The findings in this study apply to a variety of energy system types
10. Certain factors might improve the solar thermal feasibility
11. Further research is required regarding the role of solar thermal in future energy systems

1.2 Marginal impact analysis

The marginal impact of installing 1 TWh solar thermal is analysed to identify the impacts of supplying a small share of the heat supply with solar thermal. The solar thermal capacity installed is selected so it is comparable across the countries, since these differ considerably in terms of overall heat demands.

Figure 1 shows that installing 1 TWh of solar thermal in the individually supplied areas (solar concepts 1-3) and in district heating areas (solar concepts 4-5) will in some cases lead to increasing socio-economic costs and in other cases to decreases in the 2050 scenarios. This shows that the overall socio-economic impacts depend on a number of factors such as fuel prices, solar thermal production costs, energy system design, etc.

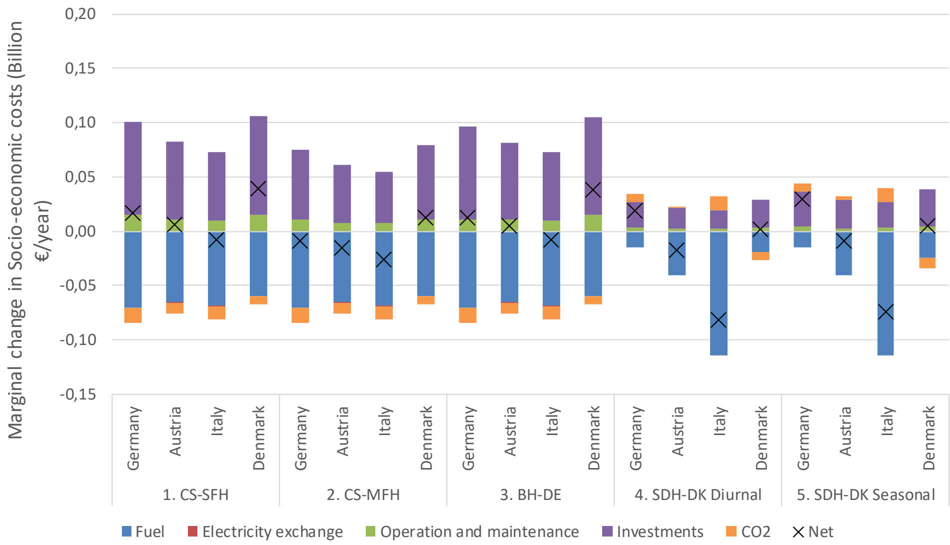

Figure 1: Marginal changes in socio-economic costs in the BAU 2050 scenarios when installing 1 TWh of solar thermal.

For the high-RES scenarios in Figure 2 the socio-economic impact is more uniform as the socio-economic costs increase in all scenarios in all countries when installing 1 TWh of solar thermal energy. This is due to the decreasing cost reductions from fuel savings, since fuel is now supplied by low cost fuels such as industrial excess heat and heat pumps using renewable electricity. This suggests that the economic feasibility of solar thermal might reduce when moving towards a high-renewable energy system.

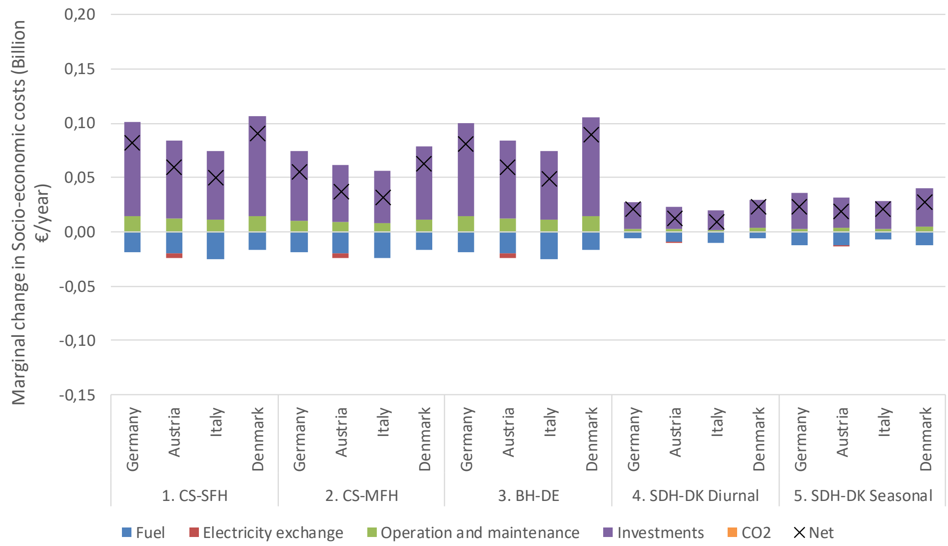

Figure 2: Marginal changes in socio-economic costs in the high-RES scenarios when installing 1 TWh of solar thermal.

The key findings from the marginal impact analysis show that the solar thermal impact depends on what is directly and indirectly replaced in the energy system meaning that integrated energy systems analysis is necessary to analyse the role of solar thermal.

The impacts on primary energy are related to three factors; the technologies that are replaced, the efficiency of the replaced technology as well as the fuel source for the replaced technology (fossil fuel, biomass consumption or fuel free, e.g. wind power, geothermal).

The key factors impacting socio-economic costs are; the fuel prices, the discount rates, the technology investment prices as well as the solar thermal production costs.

- Findings for four of the five scenarios (the scenarios where there is still significant fossil fuel consumption; 2010, 2050 BAU, heat savings and district heating):
    - Installing 1 TWh of solar thermal replaces 1 TWh of alternative heat production (individual oil, gas or biomass boilers or CHP plants and district heating boilers in district heating areas)
    - Installing 1 TWh of solar thermal replaces approximately 1 TWh of primary energy in individual areas. For district heating systems the total primary energy increases, while the fossil fuel consumption decreases.
    - Installing solar thermal in district heating areas reduces CHP electricity production and conversely increases the condensing power plant production.
    - The CO_2-emissions decrease when installing solar thermal in individual areas. In the district heating areas, some countries experience increasing CO_2-emissions while other countries experience decreasing emissions depending on the fuels replaced.
    - The socio-economic costs increase in individual areas when installing solar thermal as the additional investment costs exceed the savings in fuel expenditures. In district heating areas, the economic impacts are cost-neutral, but depend on the fuels replaced.
- Findings for the high-RES scenario where fossil fuels are only consumed in the transport sector:
    - Installing 1 TWh of solar thermal in the individual areas replaces 1 TWh of heat production from heat pumps or biomass boilers. In the district heating areas, less than 1 TWh of heat production is replaced due to mismatches between periods with solar thermal supply and district heating demand.
    - Installing additional solar thermal in individual areas results in decreasing electricity demand due to lower heat pump operation. When installing additional solar thermal in district heating areas the CHP plants produce less heat and electricity, thereby requiring the condensing power plants to produce more.
    - Less than 1 TWh of biomass is replaced in the individual areas when installing solar thermal as highly efficient production from heat pumps is replaced. In district heating areas, the biomass reductions are even lower due to the system design with fuel-free heat sources such as geothermal and industrial excess heat and efficient supply from large heat pumps.
    - There are no impacts on CO_2-emissions in the high-RES scenario as no fossil fuels are consumed.
    - The socio-economic costs increase in the high-RES scenarios in both individual and district heating areas in all countries when increasing the solar thermal production due to the lower value of the fuels replaced (biomass, wind power) and since there are no CO_2 costs.

1.3 The technical solar thermal potential analysis

The second type of analysis is the maximum technical solar thermal potential in each country for the different scenarios in both individual areas and district heating areas. The technical solar thermal potential is defined as the solar thermal production potential that the energy system might accommodate in terms of reducing mismatches between energy supply and demand. For example, this includes reducing the overproduction of solar thermal to district heating networks and reducing the overproduction in individual houses where solar thermal produces more energy than is required or can be stored. No considerations have been included regarding space requirements, manpower for installing the plants, impact on landscapes, etc. Further criteria are defined in section 7.2.

Figure 3 is an illustration of the solar thermal potential as a share of the total heat production in individual supplied areas when assuming a solar thermal penetration rate of 35%. A 35% solar thermal penetration rate means that 35% of all buildings are connected to a solar thermal plant, either directly in the building or through a district heating network. The 35% solar thermal penetration rate is an example to illustrate the solar thermal production potentials and the potentials might increase with a higher penetration rate. The figure shows that the solar thermal production share for individual areas is between 4-7% of the total individual heat production across the countries with a solar thermal penetration rate of 35%. The potential is limited to 4-7% as further solar thermal does not align with the heat demand profiles and hence overproduction is created.

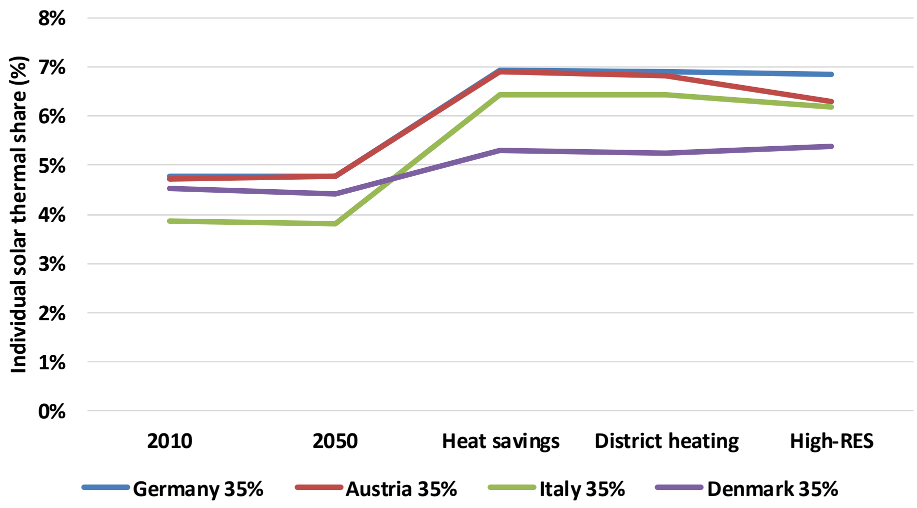

Figure 3: Solar thermal share potentials for individual heating in the four countries with a solar thermal penetration rate of 35%.

The solar thermal share in the district heating areas is 6-10% of the total district heat production with a 35% solar penetration rate as shown in Figure 4. This indicates that the solar thermal share can be higher in district heating areas than in individually supplied areas and is caused by further options to store and share the heat between consumers and the larger flexibility through technologies such as CHP plants and heat pumps.

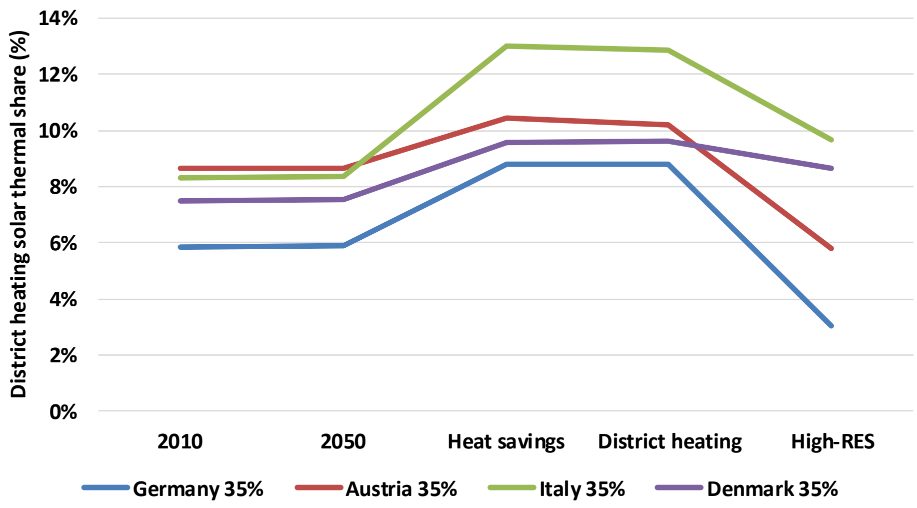

Figure 4: Solar thermal share potentials for district heating in the four countries with a solar thermal penetration rate of 35%.

When combining the individual heating and district heating solar thermal potentials, an analogous trend appears between the countries, see Figure 82. Overall, the solar thermal production share might be 5-8% when assuming a solar penetration rate of 35%. When increasing the penetration rate to 50% the combined solar thermal potential is 6-12% while a lower penetration rate of 20% will lead to a maximum potential of

3-6% of the heat production. This indicates that the number of buildings connected to the solar thermal plants is crucial for the overall solar thermal production potential.

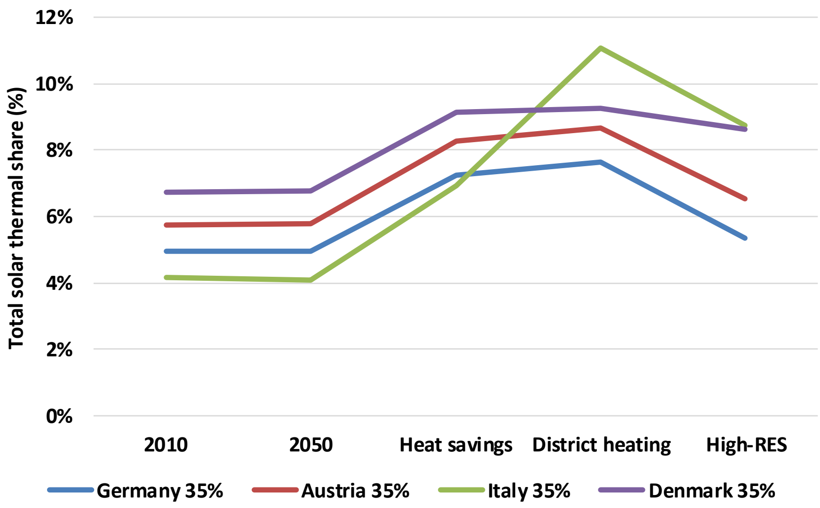

Figure 5: Total solar thermal share potentials in the four countries with a solar penetration rate of 35%.

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 key findings from the maximum solar thermal potential analysis are:

- The solar penetration rate is essential for the overall solar thermal potential in both individual and district heating areas.
- The energy system flexibility is crucial for the ability to integrate solar thermal energy and is based on two key factors:
  - The share of baseload district heating production affects the ability of the system to integrate solar thermal.
  - The share of variable renewable electricity sources and the link to the heating sector through heat pumps and CHP plants.
- The technical production potential is impacted by the total heat demand in each country. However, the heat demand differences between the countries has only a slightly impact on the overall potential for the solar thermal share of the total heating production.
- The potential solar thermal share is between 5-8% of the heat production when assuming a solar penetration of 35%. This might increase to 6-12% with a 50% penetration and decrease to 3-6% with a 20% penetration.

1.4 The impact of installing the solar thermal potential

The third type of analysis is the impact of installing the maximum solar thermal potential (50% solar thermal penetration rate) in each country in the various scenarios. The impacts are specified in terms of fossil fuel consumption, biomass consumption, CO_2-emissions and socio-economic costs.

The impacts of installing the maximum solar thermal potential on the fossil fuel consumption differ between the district heating areas and the individual heat areas as can be seen in Figure 6. In the individually supplied areas, installing the maximum solar thermal potential decreases the fossil fuel consumption by 0.5-1.5% of the total fossil fuel consumption in the energy system compared to installing no solar thermal. This does not apply to the high-RES scenario where no fossil fuels are replaced.

For the district heating areas, there is less impact on the fossil fuel consumption when installing the maximum solar thermal potential as the highest reduction in fossil fuel consumption is 0.5% in Denmark. For the other countries, installing the maximum solar thermal potential results in small fossil fuel changes. The increases in fossil fuels are caused by the solar thermal plants replacing CHP plants thereby reducing the CHP heat and electricity production. As a consequence, condensing power plants operate more resulting in an overall lower energy system efficiency. With the current fuel mix this results in more coal consumed in the power plants and a reduction in natural gas consumption in the CHP plants. This depends on the model assumptions regarding electricity supply as a different energy system design, where more renewable electricity sources and energy storage are installed simultaneously as the solar thermal would result in different impacts.

When combining the impacts for the individual and district heating areas the maximum fossil fuel reductions are between 1-2% of the total energy system's fossil fuel consumption. When moving towards the high-RES scenario less fossil fuels can be saved and in the high-RES scenario no fossil fuels are replaced.

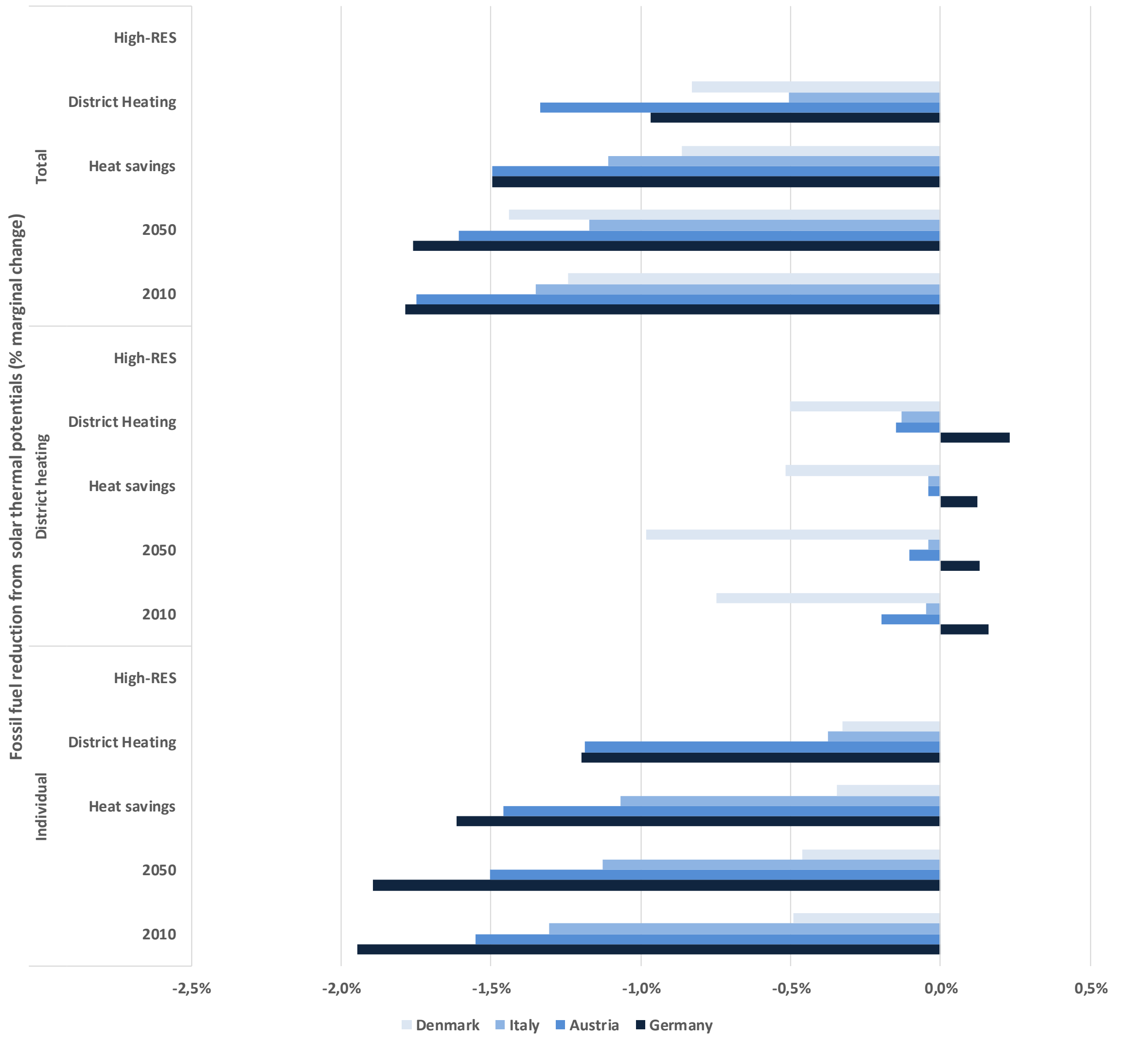

Figure 6: Fossil fuel reductions as a share of the energy system consumption for individual and district heating networks when installing the maximum solar thermal potentials.

A similar analysis has been conducted regarding the biomass consumption as illustrated in Figure 7. In all the countries, the largest biomass reductions take place in the individual heat supply where biomass boilers are replaced in the 2010, 2050 and in heat savings scenarios. In the District heating and high-RES scenarios more heat pumps are installed, which are supplied by electricity that is partly based on biomass consumption through power plant production. The reductions in biomass demands are a result of the technologies replacement, i.e. the share of biomass supply already installed in the energy system. Overall, these biomass reductions, as a share of the total biomass consumption, are largest in the 2010 scenarios and decrease when moving towards the high-RES scenario. In the 2010 system 2-4% of the biomass can be saved when installing the maximum solar thermal potential in both individual and district heating areas. In the high-RES scenario, the biomass reduction decreases to a level around 1-2% of the total biomass consumption. This suggests that solar thermal can contribute to reducing the dependence on biomass resources in the future. The combined fuel savings in terms of fossil fuels and biomass is in the region of 2% of the total consumption.

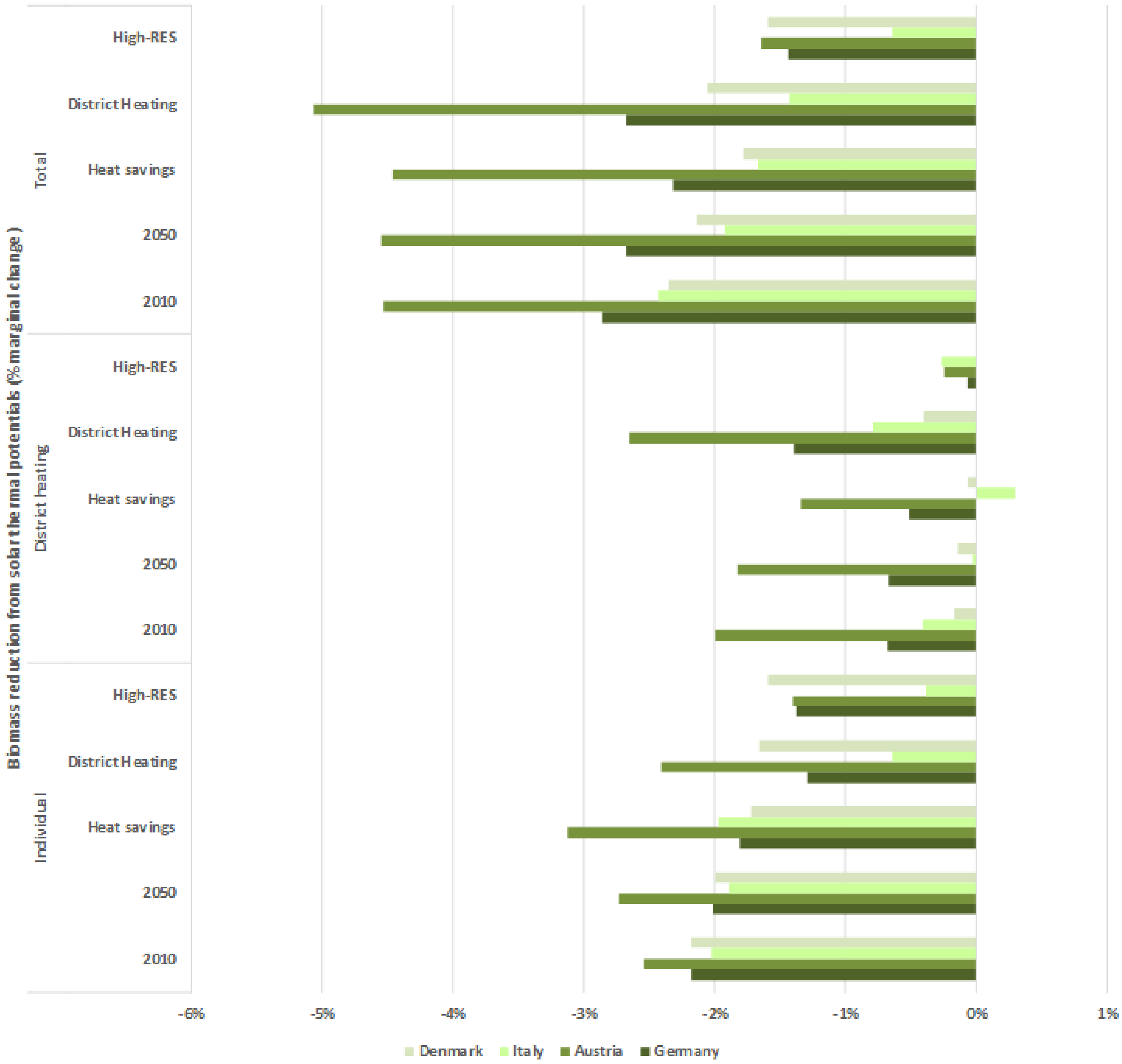

Figure 7: Biomass reductions as a share of the energy system consumption for individual and district heating networks when installing the maximum solar thermal potentials.

When analyzing the impacts on the energy systems' CO_2-emissions, all the scenarios for individual heat supply lead to CO_2-savings, as also indicated by the changes in fossil fuels in Figure 6. For the district heating areas CO_2-emissions will either decrease or increase slightly depending on the fuels that are replaced when installing the solar thermal potentials. When combining the solar thermal potentials for individual and district heating areas the emissions reductions are between 0.5-1.5% of the total energy system emissions. Only the high-RES scenarios experience no impacts on CO_2-emissions from solar thermal.

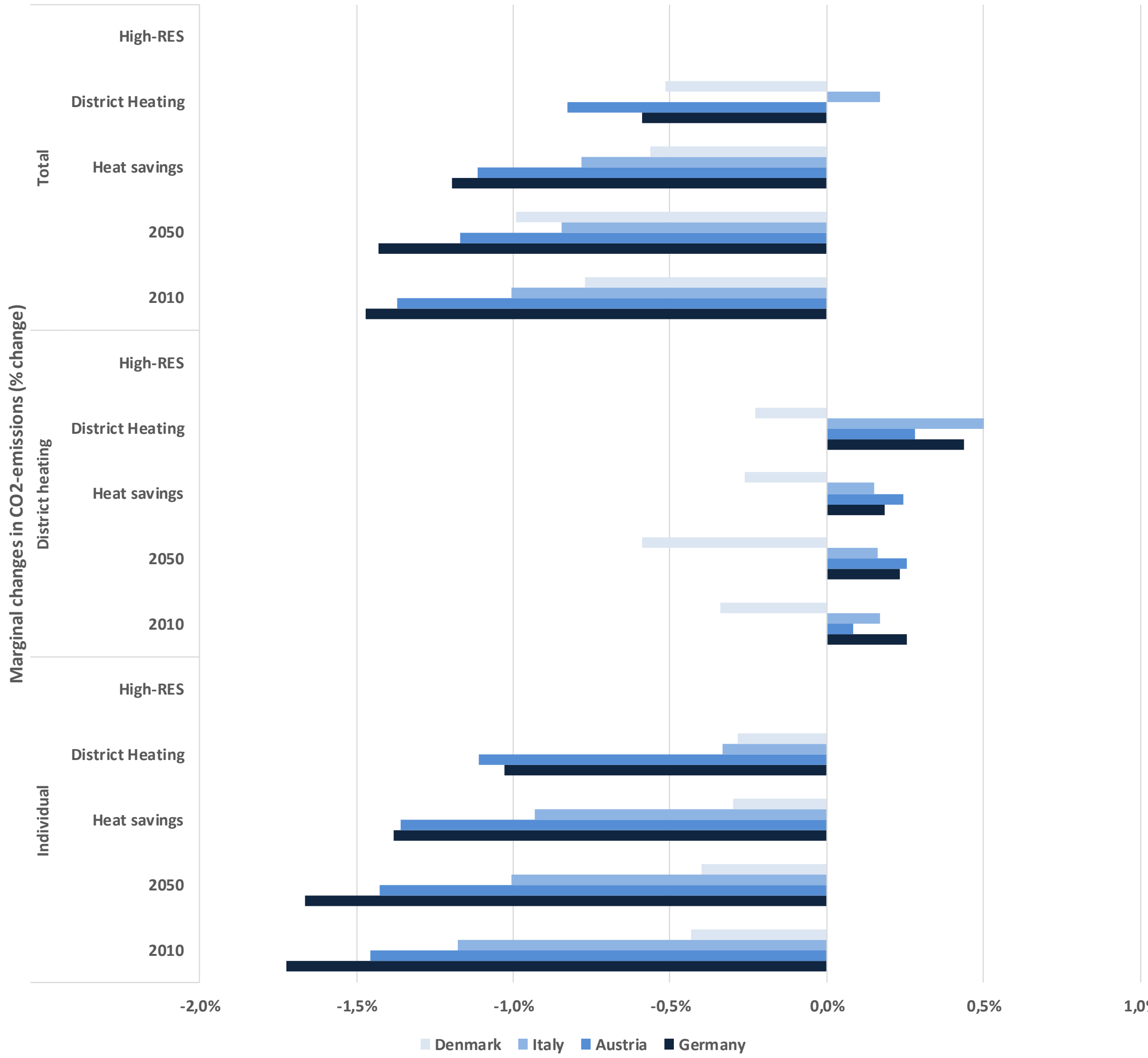

Figure 8: Marginal changes to overall energy system CO_2-emissions when installing the maximum solar thermal potentials.

Finally, the impacts of installing the solar thermal potentials have also been analysed in terms of socio-economic costs, see Figure 9. Installing the maximum solar thermal potentials in the individually supplied areas results in higher socio-economic costs in all countries and scenarios. The largest cost increases are in the 2010 scenarios as it is assumed that the fuel prices increase in 2050 along with reductions in solar thermal production costs. For the district heating areas, the impacts on the socio-economic costs can be considered as cost-neutral as some scenarios increase in costs while others decrease. When combining the economic impacts of solar thermal installations in individual and district heating systems the costs increase in almost all the scenarios. The largest impact in terms of cost increases occurs in the 2010, 2050 and high-RES scenarios while the impacts are smaller in the heat savings and District heating scenarios smaller. Overall, the cost increases are between 0-1%, suggesting that installing the maximum solar thermal potentials might increase the overall system costs. When excluding the energy system costs for vehicles, transport and industrial fuels, the significance of installing solar thermal increases. In a situation like this, the marginal change is three times as significant, i.e. if the solar thermal leads to an increase of total energy system costs of 0.5%, then the increase will be approximately 1.5% when excluding the costs for vehicles and transport and industry fuels. If the costs increase by 1%, then the increase will be approximately 3% without the costs for transport and industry. This occurs as the energy system costs are 60-70% lower when these costs are excluded and hence, the solar thermal integration has a larger influence on the socio-economic costs.

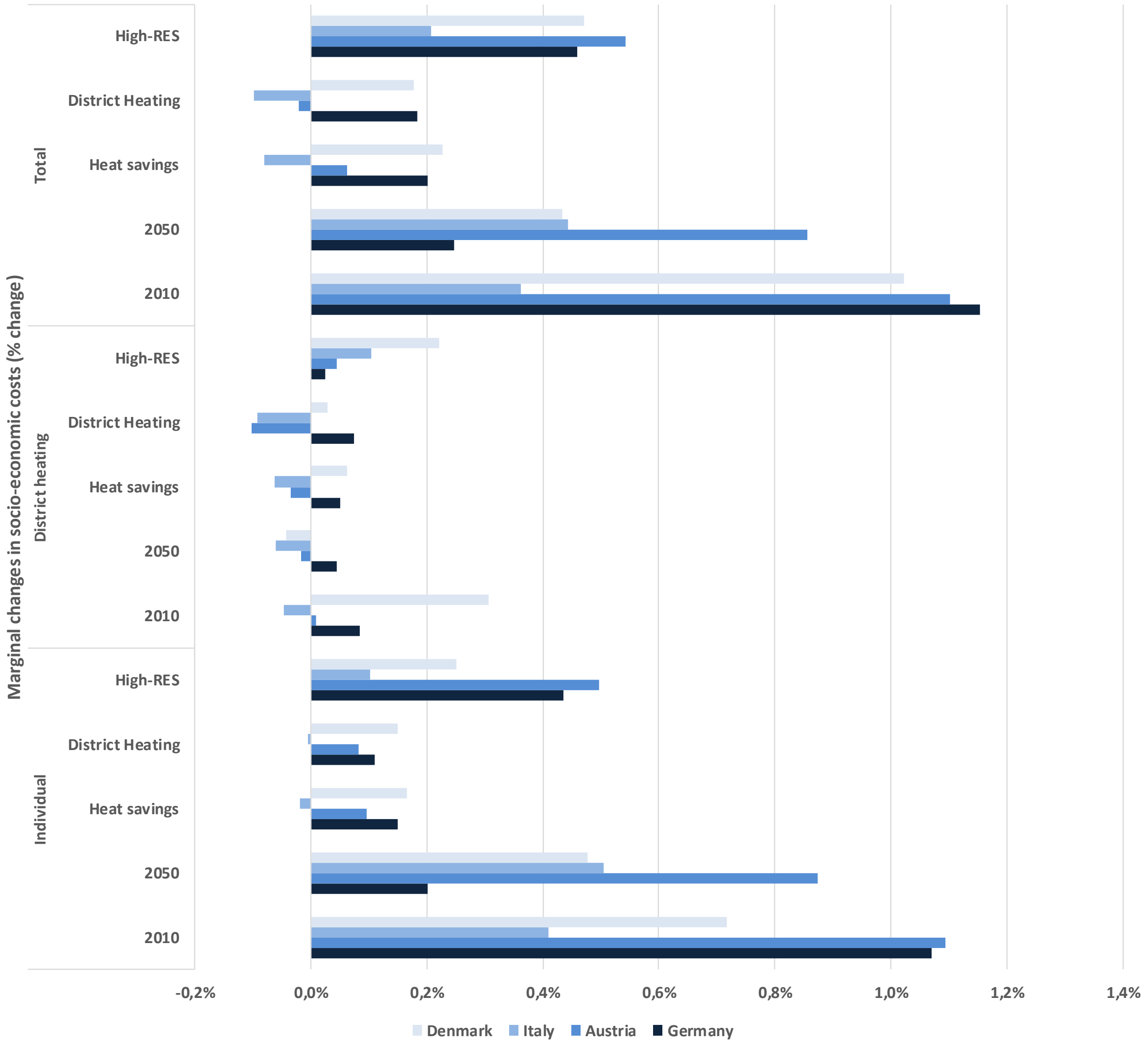

Figure 9: Marginal changes in overall socio-economic costs when implementing the maximum solar thermal potentials.

The key findings from this analysis are listed below:

- Installing the maximum solar thermal potential with a 50% solar penetration is an extreme situation. The other extreme is in the marginal analyses when 1 TWh solar thermal is installed. The overall results are expected to be somewhere in between these.
- Installing the maximum solar thermal potential in individually supplied areas reduces the fossil fuel and biomass consumption.
- If the maximum solar thermal potentials are installed in the district heating areas the impact on fossil fuels is insignificant as oil and gas is replaced by a higher coal consumption. Moreover, the biomass consumption decreases in all scenarios for district heating areas. The amount of fuels replaced is also impacted by the thermal plant efficiencies.
- Overall, the fossil fuel reductions are 1-2% of the total consumption while the biomass reductions are 2-4% of the total consumption.
- The changes in fuel consumption impact the CO_2-emissions, which decrease by 0.5-1.5% of the total emissions with the largest reductions in individually supplied areas. In the district heating areas,

some scenarios have increased emissions and others will decrease when installing the full solar thermal potential.

- No emission reductions occur in the high-RES scenario as no fossil fuels are consumed. The biomass reductions in the high-RES scenario is around 1-2% across all scenarios.
- The socio-economic costs increase when installing the maximum solar thermal potential in the individual areas. In the district heating areas, the solar thermal implementation is close to cost-neutral with increasing costs in some countries and reductions in other countries.
- Overall, the costs increase by 0-1% of the total system costs when installing the maximum solar thermal potentials in both the individual and district heating areas.
- The most important factor for cost differences between the countries is the solar thermal production costs.

Numerous sensitivity analyses have been performed for key factors regarding solar thermal technologies and their impact on the energy system. Firstly, the reduction of solar thermal investment prices and improved technological efficiency will improve its feasibility, however extreme cost reductions are required for solar thermal to prove a positive socio-economy. Secondly, different fuel prices were analysed showing that fuel prices might impact the feasibility of solar thermal, but will not impact the overall findings of the study.

2 Introduction

The IEA Solar Heating and Cooling Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. The country members of the Programme collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

This Task focuses on the analysis of the role of solar thermal in future energy supply systems in urban environments. Based on an energy economic analysis - reflecting future changes in the whole energy system - strategies and technical solutions as well as associated tools are developed.

Recent discussions questioning the role of solar thermal systems in urban areas are being raised at different levels, which have to be considered when developing new energy supply concepts for the urban environment.

In order to facilitate this, questions in three main R&D areas have to be answered and compiled in a common structure:

- Subtask A: Energy Scenarios
- Subtask B: Methodologies, Tools & Case studies for Urban Energy Concepts
- Subtask C: Technology and Demonstrators

This report contains activities within parts of Subtask A.

2.1 Purpose and content of report

The main objective of Task 52 is to better understand the role of solar thermal systems in future urban energy supply systems.

The role of solar thermal in the energy system of urban environments is identified with a horizon of 2050 and a high renewable energy goal at the national or international level, but not necessarily on a city or regional level solely. The scenarios reflect the combined view of electricity and heat as well as other key heat supply technologies, such as electrical and thermal heat pumps and CHP. Different district structures are taken into account as well as different scenarios regarding the development of the energy system. The scenarios simulate all sectors including mobility. They are based on detailed time-series in order to reflect the dynamic of the solar energy availability.

Objective of Subtask A

The objective of Subtask A is to analyse the role of solar thermal in the energy system of urban environments with a horizon of 2050. The analysis are based on the development of scenarios for selected countries taking into account modelling results with different analytical approaches. The scenarios reflect the combined view of electricity, heat and transport and take into account the dynamics of changes in the energy systems, focusing on the parts of the system that directly link to solar thermal energy. The competition between solar thermal and other key heat supply technologies like electrical and thermal heat pumps and CHP as well as PV are issues in the analysis. Different district structures are taken into account and different scenarios regarding the development of efficiency, costs and prices. The scenarios also take into account selected key differences in current configurations of national energy systems, that is, levels of renewable energy, nuclear, hydro, etc. and the potential developments in the future as for example a high share of renewable energy, fossil fuel or nuclear energy. Particularly the role of solar thermal in future smart energy systems with integrated electricity, heat and transport supplies is addressed.

The objectives are summarised as:

- Using energy system analyses with different analytical approaches in combination with spatially disaggregated data for creating scenarios focusing on the use of solar thermal in future energy systems.
- Identifying balances between heat savings and supply systems with relation to solar thermal.
- Identifying balances between building level solar thermal and solar thermal in local district heating networks.
- Identifying the role of solar thermal in integrated renewable energy systems and in particular the interrelation with combined heat and power (CHP) and heat pump production.

The main activities of Subtask A:

- A1 Identification of relevant solar thermal concepts and establishing energy system models for enabling energy system analysis of key solar thermal concepts.
- A2 Development of energy system scenarios for selected countries focusing on the analysis of the role of solar thermal with a time horizon of 2050.
- A3 Analyses of the role of solar thermal concepts in future energy systems including sensitivity analyses regarding cost developments, national and international system integration.

Based on existing work and experiences of all partners in the Task relevant concepts for the integration of solar thermal energy in urban areas are identified. There are two main outcomes: on the one hand this leads to a common understanding of how to qualify the results of the different modelling approaches regarding the use of solar thermal energy, on the other hand a common methodology for the development of scenarios within the Task is defined. The existing models are partly extended if it shows to be necessary in order to reflect the common methodology.

For selected countries energy system scenarios are developed with the target of a significant increase in renewable energy supply in 2050. Main focus of the analysis is to identify the role of solar thermal energy in the overall energy system and the barriers and drivers related to different solar thermal energy concepts. Therefore the parts of the energy system that are directly linked to solar thermal energy are investigated in detail mainly based on existing scenarios and ongoing projects.

2.2 Objectives of Subtask B and Subtask C

Subtask B aims at providing methodologies to support technical and economical calculations for successful integration of solar thermal in urban environments. Depending on the energy scenario the use of solar thermal may or may not be energetically rational or economically viable. The intention is to identify urban planning methodologies and calculation techniques capable to ensure an objective evaluation of the role of solar thermal in urban energy scenario’s reflecting future regional, national and international boundary conditions.

Objectives of Subtask B

- Development of methodologies with focus on performance indicators
- Energy planning tools and toolboxes (from urban planning to neighbourhoods)
- Case studies analysis of different regions

In Subtask C best practice examples of solar systems with direct linkage to urban, suburban but also municipal energy supply systems are investigated in more detail.

The investigation is limited to the following conditions:

- Solar thermal systems with direct connection to heat and, more general, to energy supply networks (urban, suburban and municipal level)
- Solar-assisted building blocks (micro-grids) in urban environments (urban level only)
- Renewable heating and cooling systems like Heat pumps in combination with PV

The objectives of Subtask C

- Classification of relevant (renewable-based) technologies and demonstrators in urban environments
- Screening of best practice examples
- Analysis and documentation of selected best practice examples
  - Technological and economic analysis
  - Analysis of bottleneck's and success factors, lessons learned
  - Analysis of monitoring data (subject to data availability)

Findings from Subtasks B and C have been used in this report when reasonable. For example, the definition of solar thermal concepts for the energy system analyses are based on the findings from Subtask C. Furthermore, solar thermal technical and economic performances are based on findings from Subtask C.

3 Development of the energy system models

The countries that are modelled are Germany, Austria, Denmark and Italy, which differ significantly both in terms of size and in terms of energy system design. For example, the energy demands in Germany and Italy are significantly larger than in Austria and Denmark. Furthermore, in countries such as Denmark and Germany a large share of the electricity demands might potentially be supplied from wind power due to their location around the North Sea, while Austria has a large hydropower potential. Also in terms of climatic conditions the countries differ with Italy located in the south of Europe and Denmark located in the northern part of Europe. These differences allow for drawing conclusions for various types of energy systems with regards to renewable energy systems and the integration of solar thermal technologies.

The assessment of the scenarios developed is carried out by applying a number of key parameters that describe the feasibility of a system compared to other systems. The key parameters in this study are 1) the economy measured as the total socio-economic costs of the systems, 2) the energy required to operate the systems measured as primary energy supply with a particular focus on biomass demand and availability, and 3) the environmental impacts measured in CO_2-emissions from the energy system. Finally, the flexibility of the system will be analysed when developing a high-renewable system and when analysing the integration of various solar thermal concepts. This is measured in terms of electricity exchange and imbalances in the district heating networks throughout the year. The district heating imbalance is defined as the periods where there is a mismatch between the district heating demands and production. A typical example is during the summer period where the baseload district heating production from technologies such as waste incineration, industries and geothermal exceeds the district heating demand.

Socio-economy in this study is understood as the total energy system costs in terms of infrastructure investments, operation and maintenance, fuel costs and CO_2-costs. These are calculated applying an interest rate of 3% and excluding taxes and subsidies. By assessing the socio-economic costs, it will be possible to assess what the future total system costs are and also if alterations in the cost distributions take place, i.e. if investments in technologies replace expenses for fuels. The socio-economic perspective is furthermore selected to enable analyses of the system costs directly rather than the markets around them that might not be feasible for a future high-renewable system.

The solar thermal concepts are analysed in a number of different energy system models to allow for the investigation of the role of solar thermal in various systems. Hence, a system similar to the existing system (reference system 2010), a future 2050 business-as-ususal (BAU) system, and alterations in the future BAU system towards a high-renewable system is created. These scenarios are created for national energy systems on an aggregate level, meaning that no analysis of the individual plants is included. For example, the solar thermal plants investigated are aggregated for the entire country rather than for plants in each building, city or region.

The high-renewable energy models that are designed in this study do not aim at achiving an optimal system design for a future high-renewable energy system in the target countries. This means that most likely there will still be possibilities for optimising the high-renewable energy systems in terms of for example fuel consumption and costs. Rather, the purpose of these high-renewable energy systems is to investigate the role of solar thermal under such conditions. Furthermore, no restrictions have been set on the biomass consumption in these scenarios, which is also discussed in section 7.3.

The development of the reference, BAU and the high-renewable national system models include a number of phases. These can be seen in Figure 10 and are described in further details below the figure.

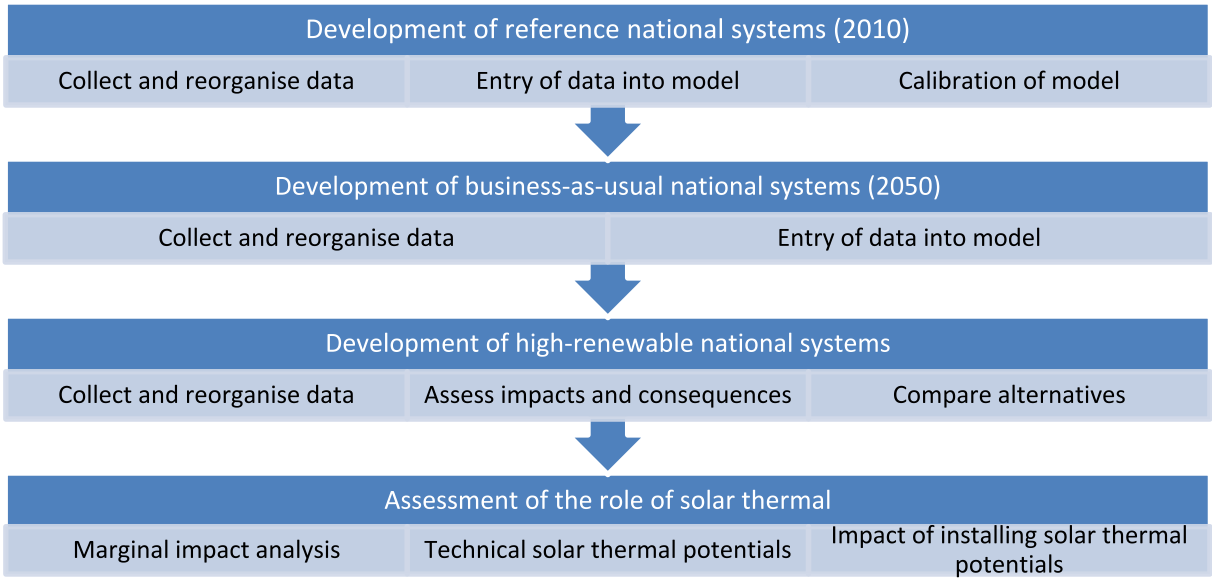

Figure 10: Overview of steps to develop high-renewable energy systems in the four countries.

The first phase involves developing reference systems for the four countries for the year 2010. These are based on statistical data that are collected from a number of national sources and reorganized so they are usable in the energy modelling tool EnergyPLAN. Next, the data is entered into the model and the outputs are assessed and calibrated against the statistical data available. The calibration entails comparing key data such as primary energy, energy demands and production as well as CO_2-emissions.

After finalizing the reference models business-as-usual models are developed based on data for projected developments in energy sector demands and production. This data is entered into the model and small modifications are carried out to ensure that the models can operate simulating near to real conditions. These small modifications might include lack of capacity, unrealistic heat imbalances and electricity exchange, etc. The reference and BAU systems are described in chapter 5.

The final phase is the development of scenarios for high-renewable energy systems. Also for this step a significant amount of data is required and must be reorganized to match the modelling tool characteristics. After creating a number of scenarios the impacts are assessed to allow for comparing the different options and creating recommendations. The concrete scenarios that are developed in this phase are described in section 6.

Finally, the role of solar thermal is assessed by integrating solar thermal into the different scenarios. The solar thermal impacts are assessed in three ways:

- The marginal impact of installing 1 TWh
- The maximum solar thermal potentials
- The impacts of installing the maximum solar thermal potentials

The findings from these analyses are presented in chapter 7.

Based on these analyses conclusions are drawn regarding the possible role of solar thermal in future energy systems when a small amount of solar thermal is installed (the marginal impact analysis) and with a very high share of solar thermal (the maximum impact analysis).

In order to carry out all the phases described an appropriate energy modelling tool has to be utilized. Some of the specifications that are required for the modelling tool include:

- The model must integrate all energy sectors (electricity, heating, cooling, transport, industry) in order to assess the impacts and dynamics across sectors
- The model must integrate hourly variations as this is key when analysing intermittent renewables such as wind power and solar thermal
- The model must be able to quantify impacts on economy, energy and environment when developing future high-renewable energy scenarios

The tool selected to meet these requirements is the EnergyPLAN tool, which is further described below.

3.1 The characteristics of the EnergyPLAN tool

The analysis of high-renewable energy systems calls for tools and models which can provide similar and parallel analyses of electricity, thermal and gas grids. The advanced energy systems analysis model, EnergyPLAN, has been developed to fulfil such a purpose on an hourly basis (www.EnergyPLAN.eu), so that optimal solutions can be identified. The model has been used for analyses in numerous papers with a large variety of topics [2]. 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. However, the model has also been applied to the European level as well as to a local level such as towns and/or municipalities. The design of EnergyPLAN emphasises the option of looking at the complete energy system as a whole. Therefore, EnergyPLAN is designed to be a tool in which, e.g., electricity smart grids can be coordinated with the utilisation of renewable energy for other purposes than electricity production.

In the tool, renewable energy is converted into energy carriers such as electricity, heat, hydrogen, synthetic gases and biofuels, as well as energy conservation and efficiency improvements, such as combined heat and power (CHP) and improved efficiencies, e.g., in the form of fuel cells. All such measures have the potential for replacing fossil fuels or improving the fuel efficiency of the system. The systems relevant in the long term are those in which such measures are combined with energy conservation and system efficiency improvements. As a consequence, the EnergyPLAN tool does not only calculate an hourly electricity balance, but also hourly balances of district heating, cooling, hydrogen and natural gas, including contributions from biogas, gasification as well as electrolysis and hydrogenation. The EnergyPLAN tool also provides a numer of options for energy storages, including storages for electricity (batteries, hydro, etc.), heating, hydrogen, various types of gases and liquid fuels. These storages are used in the tool for optimizing the hour-by-hour operation of the entire energy system based on the installed storage capacities, demands, etc. For example, the district heating storages are utilised in the model for storing heating in the periods where production exceeds demands, which typically occurs during the summer. Additionally, it is worth noticing that the seasonal storages that are analysed for solar thermal do not provide a storage opportunity for other heating production units such as CHP plants and boilers.

A complete overview of the energy flows, technologies, and regulation strategies in the EnergyPLAN tool are outlined in Figure 11.

The EnergyPLAN model includes hour-by-hour data for a number of demand profiles such as electricity, individual heating, district heating and renewable sources for one year. This allows for a high-resolution analysis of the integration of intermittent renewable energy sources such as solar thermal. The renewable sources are included in the model as an aggregate production for the country. In addition, cost data are included in terms of investments, operation and maintenance, lifetimes, fuel costs, CO_2 costs and interest rates which is crucial when analysing the socio-economic costs of an energy system. No residual value is included in terms of the lifetimes of each technology.

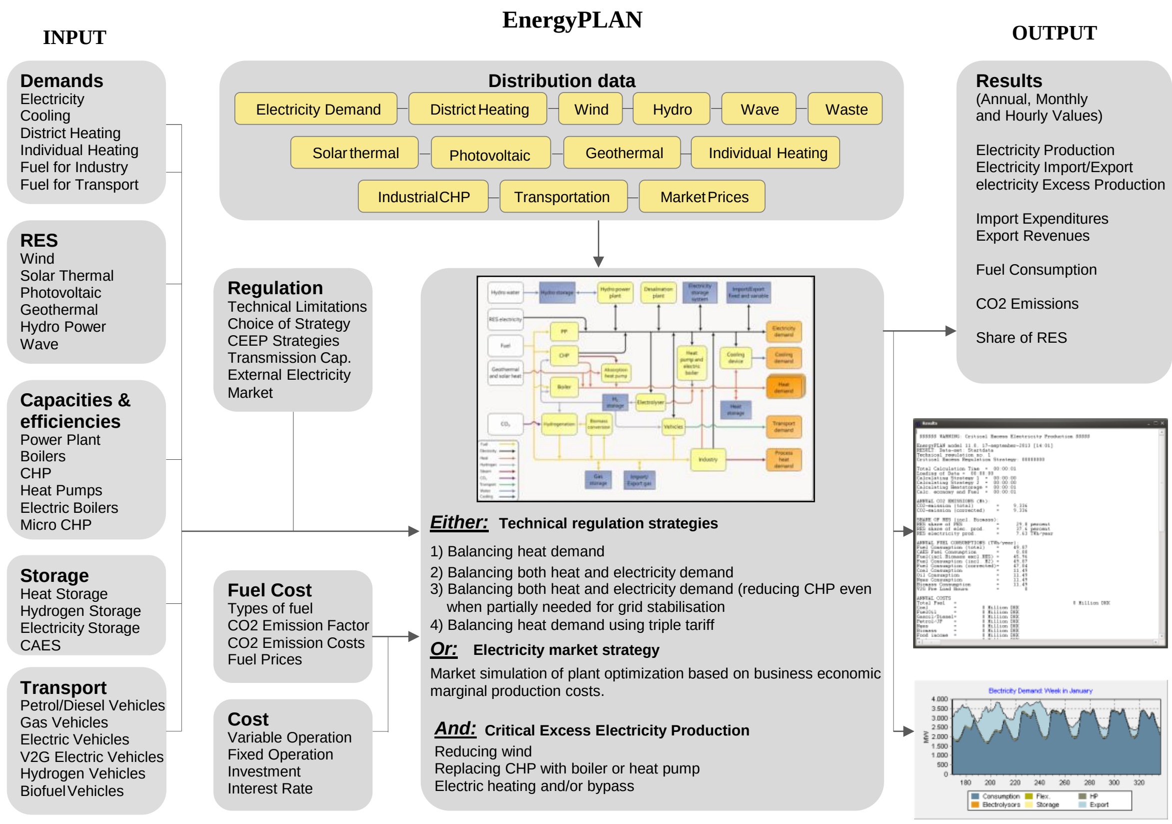

Figure 11. EnergyPLAN energy flows, technologies, and regulation strategies.

The EnergyPLAN tool optimizes the operation of the energy system for one year and does not optimize the installed capacities of the energy technologies. Instead, this is defined by the user as the input values for production units, storages, etc. and might be altered through a number of simulations.

The model can optimize the operation of the system in two ways:

- Technical simulation strategy
- Market economic simulation strategy

The technical simulation strategy optimizes the operation of the system in terms of energy efficiency with the aim of reducing the fuel consumption. The market economic simulation strategy optimizes the system in terms of costs and relies to a higher degree on electricity markets and electricity exchange between countries. In the energy system analysis using EnergyPLAN in this report technical simulation strategy number 2 has been selected as this allows for a more transparent analysis of the impacts of installing solar thermal. If a market economic simulation strategy was selected other factors such as electricity markets and exchange could potentially influence the operation of the system thereby prioritizing other technologies in cases where it is cheaper to import electricity than to produce it domestically. This could change the operation of technologies such as heat pumps and CHP plants. In addition, it is uncertain what future energy markets will look like when a higher share of intermittent renewable sources is implemented.

4 Data

This chapter contains a description of the various data inputs used in the analysis of the future energy systems and in the development of cost curves for heat savings in Germany, Austria, Italy and Denmark.

4.1 Data for national energy systems

This section describes and documents the replication of the national energy systems of Germany, Austria, Italy and Denmark in the energy systems analysis tool EnergyPLAN.

In order to develop national energy systems a significant amount of data has to be collected and organized to meet the modelling demands. This chapter describes the types of data required, the data collection and data management.

Energy systems consist of multiple types of demands, production profiles, capacities, efficiencies, etc., which makes data collection and management crucial for developing energy models of national energy systems. In this project, the most significant data types collected can be divided into two sections: data for creating models of the existing energy systems and data for future energy systems. The most significant data types include:

Existing energy systems:

- Energy demands for all energy sectors (electricity, heating, cooling, transport, industry)
- Energy generation data including capacities, efficiencies, operation hours and fuel distribution
- Energy storage capacities
- Energy generation hourly distribution profiles aggregated for each country
- Energy system costs in terms of investments, operation & maintenance, lifetimes, fuel and electricity costs, interest rate

Future energy systems:

- Energy demand development
- Electricity generation capacity development
- Potentials and costs for district heating expansion
- Potentials and costs for energy savings
- Potentials for electrification of industry, heating and transport
- Renewable energy potentials

In the analysis only the energy demands that are actually met are included, i.e. the model does not include heating or cooling demands that could potentially be supplied to improve comfort levels. This might somewhat alter the future energy demands, but is difficult to project for the future.

In order to create the 2010 reference models a variety of data is collected from a number of sources. In general, the data required can be grouped into the following categories:

- Energy demand and supply data
- Hourly distribution data
- Cost data

4.2 Energy demand and supply data

In the project it was decided to rely on the local experts in the Task group to collect and assess data for each country, i.e. local experts from Austria was responsible for collecting the necessary data for Austria and similarly for Germany and Denmark. However, no local expert from Italy was part of the Task group and hence data was gathered from previous projects for the Italian energy system.

For the German 2010 model a large share of the data was collected from the German Federal Ministry for Economic Affairs and Energy (BMWi) in the 2015 version of the "Zahlen und Fakten Energiedaten". In this publication energy demand data for various sectors, heat production, energy production and emissions were reported and covered a large share of the data requirements. Other data sources include e.g. the Power Plant List published by the Bundesnetzagentur (Federal Network Agency for Electricity, Gas, Telecommunication, Post and Railways) under the Federal Ministry of Economics and Energy, emission data from the German Federal Environment Agency as well as data already collected by Fraunhofer ISE for other projects regarding the future energy transition in Germany [3].

For the Austrian model the main source for creating the 2010 model was the national energy balance [4] providing various types of input data. Current electricity system capacities for larger sources are from [5] and for renewables from [6] while electricity grid data is from [7]. The heating and cooling in buildings is from the Invert/EE-Lab database, where the most recent version is presented in [8]. The district cooling data is from [9]. Industrial excess heat in district heating for the current system and future potentials are from [10]. Wind energy and electricity distribution data is taken from [7], while the district heating hourly data is based on measured data from 3 existing district heating systems with different sizes; the weighted average is built to derive the profile for one "typical" size in Austria. The electricity prices are downloaded from [11]. The future potentials for district heating and renewable energy in Austria are based on [12] and [13].

The Danish 2010 model was primarily created based on data from the Danish Energy Agency and is a continuation of the model that was created for the CEESA project, where the initial national 2010 model of Denmark was developed [14]. An elaborate description of data sources can therefore be found here.

For Italy no local expert was part of the project and hence data for the Italian 2010 model are from the STRATEGO project where a 2010 model was developed for analysing the heating sector. Main data sources for this model was [15] and [16]. More details about the data sources for the Italian model can be found in [17].

4.2.1 Hourly distribution data

The EnergyPLAN model is an hourly model accounting for every hour in a single year. In that regard data about demands and production patterns are required for a number of technologies and demands. The distributions are aggregated temporal profiles for each country based on either measured historical data or own calculations based on factors such as solar irradiation, degree days, etc. The distributions necessary in EnergyPLAN are listed below.

- Heat demand
    - District heating
    - Individual heating (non district heating areas)
- Electricity demand
- Cooling demand
- Renewable electricity
    - Onshore wind power
    - Offshore wind power
    - Solar PV
    - Hydro power
    - River hydro

- Solar thermal
    - Individual heating
    - District heating
- Electricity Exchange
- Transport demand
- Electricity market prices

Some of these distributions such as for electricity market prices are based on measured data from the reference year, while other distributions are based on calculations. The latter is the case for some of the renewable energy distributions. For few of the distributions it was not possible to create these based on local data as this was not available in the country. Hence, neighbouring country distributions were used if available. This applies for example for the Austrian cooling demand and solar thermal distribution where no local data was available and hence the German distributions were applied for Austria.

4.2.2 Cost data

The primary data source for the costs applied in the scenarios are from the EnergyPLAN cost database that has been built over a long timespan for numerous projects. Data in the cost database is updated on a continuous basis and further information about the database can be found in [18] and in Appendix A.

The fuel prices assumed in the analysis for 2050 are outlined below in Table 1.

Table 1: Fuel prices assumed for the analysis for 2050. Source: [18].

2015-€/GJ	Coal	Natural gas	Fuel oil	Diesel fuel/ Gas Oil	Petrol/ JP1	Straw/ Wood chips	Energy Crops
	3.4	12.2	16.1	20	20.6	6.3	8.1

These fuel prices might be rather high compared to today's fuel prices. However, fuel prices are found not to be decisive for the findings in the report, a more detailed breakdown of the fuel price impact is included in section 7.4.1. Moreover, no changes to biomass prices have been included despite of increasing biomass demands in the scenarios.

The CO_2-prices assumed in the analysis are outlined in Table 2 below.

Table 2: CO_2-costs assumed in the analysis. Source: [19].

CO_2-costs €/t	2010	2050
	28.6	46.6

4.3 Solar concepts

Five different solar concepts have been selected for analysis in this report. In total seven solar concepts are defined in the Subtask C report entitled "*C1: Classification and benchmarking of solar thermal systems in urban environments*" and afterwards five of these have been selected and interpreted for modelling purposes. This section outlines the characteristics of each of the five solar concepts along with the technical and economic details for the concepts. In addition, summary tables of the solar concepts can be found in Appendix B – solar thermal benchmark figures.

In general, the five concepts are divided into three types:

- A: Solar thermal systems in single and multi-family homes
- B: Roof-mounted solar thermal systems connected to (block) heating grids
- C: Ground-mounted solar thermal systems connected to (district) heating grids

Two systems were selected for further analysis from types A, one system from type B and two systems from types C. The systems that are selected have been defined as five different solar thermal concepts. These concepts are described in Table 3.

Table 3: Solar thermal concepts selected for analysis in the country analysis.

Concept 1: CS-SFH Solar-combi systems in single family houses. Solar thermal system providing heating for both domestic hot water and space heating in single-family houses. These systems can be found in multiple countries.  Picture source: AEE INTEC
Concept 2: CS-MFH Solar-combi systems in multi-family houses. Solar thermal system providing heating for both domestic hot water and space heating in multi-family houses. These systems can be found in multiple countries.  Picture source: AEE INTEC
Concept 3: BH-DE Solar assisted heating of building blocks and urban quarters (roof-mounted collector field). Solar thermal system, typically roof-mounted, supplying heating for a building block. Typical countries are Austria and Germany. Storage type is tank thermal energy storage.  Picture source: ZAE Bayern
Concept 4: SDH-DK Diurnal Solar assisted district heating (ground mounted collector field) with diurnal storage.

This solar thermal system can be either ground or roof mounted and is typically accompanied by diurnal tank thermal energy storage. Exsting systems can be found in Denmark, Austria and Germany.

Picture source: Sæby Varmeværk

Concept 5: SDH-DK Seasonal

Solar assisted district heating (ground mounted collector field) with seasonal storage.

This solar thermal system is based on ground mounted collectors and has seasonal storages in the form of pit thermal energy storage. Current examples can be found in Denmark.

Picture source: Vojens Fjernvarme

Some of the main characteristics for each of the concepts can be found in Table 4. The data is based on an extensive data collection process of existing solar thermal plants and the data represents average values of a large number of plants. More information is available in [20].

Table 4: Key characteristics of the five solar thermal concepts based on inputs from [20].

Solar concept characteristics	Unit	Concept 1 (CS-SFH)	Concept 2 (CS-MFH)	Concept 3 (BH-DE)	Concept 4 (SDH-DK Diurnal)	Concept 5 (SDH-DK Seasonal)
Type of solar collector		FPC	FPC	FPC	FPC	FPC
Solar fraction (annual)	% of heating demand covered	20%	15%	50%	12%	50%
Type of storage		TTES* (pressurized)	TTES* (pressurized)	TTES* (pressurized)	TTES* (non-pressurized)	PTES*
Peak capacity per unit	kW	13	70	3,500	7,000	35,000
Production per unit	MWh/year	5.9	39.5	1,500	4,100	17,500
Solar energy yield**	kWh/year/m^2 gross	330	400	300	410	365
Specific cost (ready installed, excl. VAT/subsidies)	1,000 €/m^2 gross	0.76	0.66	0.64	0.24	0.29
Fixed O&M	€/m^2 gross/year	6.1	5.5	4.0	1.7	2.0
Variable O&M	€/m^2 gross/year	1.2	1.4	1.1	1.5	1.3

* TTES = Tank Thermal Energy Storage, PTES = Pit Thermal Energy Storage

** 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.

An elaborate description of the concepts is available in the Subtask C1 report as well as in the summary tables in Appendix B – solar thermal benchmark figures.

The production data has been compared with the investment prices for different countries due to the different solar yields for the four countries. A heating unit investment cost is given in Table 5 for each concept and country for both 2010 and estimates for 2050. The heating unit costs are estimated to decrease around 25-35% for the various solar concepts going towards 2050 compared to the current costs. This is based on a previous study about small-scale systems in Austria where it was found that these technologies experienced a cost reduction of average 1.3% between 1997 and 2010 [21]. Based on inputs from project partners in Subtask C and considering that the cost reduction potentials might be slightly lower for larger systems it is estimated that cost reductions around 0.7-1.0% between 2015 and 2050 could potentially take place. This results in an overall reduction of 25-35% depending on the solar thermal technology.

Table 5: Solar heating unit costs in 2010 and 2050 for the five solar concepts.

Solar thermal heating unit costs (million €/TWh annual yield)		Germany	Austria	Italy	Denmark
2015	Concept 1 (CS-SFH)	2303	1888	1686	2421
	Concept 2 (CS-MFH)	1650	1353	1208	1735
	Concept 3 (BH-DE)	2133	1749	1562	2243
	Concept 4 (SDH-DK Diurnal)	559	458	409	588
	Concept 5 (SDH-DK Seasonal)	762	625	558	801
2050	Concept 1 (CS-SFH)	1515	1242	1109	1593
	Concept 2 (CS-MFH)	1125	923	824	1183
	Concept 3 (BH-DE)	1500	1230	1098	1577
	Concept 4 (SDH-DK Diurnal)	419	344	307	441
	Concept 5 (SDH-DK Seasonal)	578	474	423	608

5 The energy systems of Germany, Austria, Italy and Denmark

This chapter contains a description of the 2010 and 2050 models. Firstly, the methodological considerations about developing the 2050 models are described followed by a validation of the models to ensure that the EnergyPLAN tool is able to replicate the existing energy systems to a satisfactory degree. Finally, the models are described in terms of their energy systems characteristics.

5.1 Development of the 2050 models

The scenarios developed in the project have a scope towards 2050 as radical changes are required to take place if a high-renewable energy system is to be achieved. Therefore, a 2050 BAU (business-as-usual) scenario was created for each of the four countries serving as a starting point and as comparison to the alternative scenarios. These BAU scenarios indicate what a future 2050 energy system could look like if we continue using energy in a similar way as we do currently. The 2050 BAU scenarios were created on the basis of the 2010 reference models, but with adjusted energy demands, adjusted electricity generation capacities and adjusted costs according to current expectations. The European Commission projections were used for all the countries as a guideline regarding expectations for the future energy systems [15].

5.1.1 Adjusted energy demands

The adjustments implemented in the 2050 BAU scenarios include projections of the energy demands in a number of sectors including electricity, individual heating and district heating, transport, industry and cooling. The largest energy demand changes occur in the electricity sector where demands grow by up to 30% in Italy compared to the 2010 demands. For the other sectors the demands remain more or less constant compared to the 2010 demands, except for in Germany where all sectors, but the electricity sector, is expected to decline compared to 2010.

Table 6: Changes in energy demand between the 2010 models and the 2050 models.

Energy demand change (%)	Germany	Austria	Italy	Denmark
Electricity demand*	12	28	36	26
Individual heating	-15	-1	-1	-3
District heating**	-4	-4	-3	-2
Cooling	-8	-1	0	-2
Industry***	-19	-1	6	11
Transport	-22	1	1	0

* Electricity demand includes final consumption (e.g. electric heating, individual heat pumps, Centralised heat pumps, centralised electric boilers, PHES pumps, electric vehicles), own use (industries) and electricity losses
** District heating demand includes own use (industries), residential and services, industry and heat losses
*** Industrial demand includes fuel for main product, own use and non-energy use

The energy demands for both 2010 and 2050 are listed for each country in Table 7. This gives an indication of the size of the energy system as e.g. the German energy demands are between 10-20 times higher than the Danish energy demands.

Table 7: The energy demands in the 2010 models and the 2050 models for each country.

Energy demands (TWh)	Germany		Austria		Italy		Denmark	
	2010	*2050*	*2010*	*2050*	*2010*	*2050*	*2010*	*2050*
Electricity	615	677	70	92	392	512	36	46
Individual heating	725	613	62	62	370	367	23	22
District heating	131	125	22	21	26	26	32	31
Cooling	9	9	2	1	49	49	0*	0*
Industry and other	694	564	88	87	451	479	52	58
Transport	692	547	91	92	520	523	70	70

* No data was available for cooling in the Danish energy system when the models were developed.

5.1.2 Adjusted electricity generation capacities

The projections for the 2050 energy demands indicate that the largest demand changes will occur in the electricity sector. This is the reason why the electricity production capacities for the technologies in the energy system also are projected towards 2050 according to the European Commission projections [15]. The changes to electricity production capacities are outlined in Table 8 below. The condensing power plants decrease in capacity while the CHP plants increase. The largest growth rates are found for renewable sources such as wind power and PV.

Table 8: The changes assumed for electricity supply technologies between the 2010 and the 2050 models. A negative value assumes that the capacity decreases while a positive value indicates a growing capacity.

Electricity production capacity changes (%)	Germany	Austria	Italy	Denmark
Condensing power plants	-2%	-39%	-37%	-44%
Centralised CHP	42%	-20%	29%	-3%
Nuclear power plants	-100%	-	-	-
Geothermal power plants	>2000%	10%	96%	-
Wind power plants	229%	595%	434%	172%
Hydro power plants (excluding pumped hydro)	69%	14%	10%	-
Solar PV	329%	>2000%	1298%	>2000%

Some of the technologies have growth rates higher than 2000%, which is both due to the large increases expected and because the 2010 capacities in many cases are almost negligible.

The actual capacities for the 2010 reference and the BAU 2050 models are listed in Table 9 below. The 2050 capacities indicate that the thermal capacities (power plants and CHP plants) decrease in all the countries except in Germany. The increase in Germany might be caused by the decommissioning of all nuclear plants and hence other forms of capacity is required. In addition, significant increases in wind and PV capacities are expected even with the current policies and trends and will grow by more than 100% in all the countries. The capacities for industrial production and waste incineration are assumed to remain constant as no data was provided for these technologies. Furthermore, the fuel mix in the thermal plants in 2050 is assumed to be the same as in 2010 for each of the countries. The fuel mix assumed for the thermal plants will impact the fuels replaced when installing renewable technologies such as solar thermal.

Table 9: The electricity production capacities in the 2010 and the 2050 models.

Electricity production capacities (MW)	Germany		Austria		Italy		Denmark	
	2010	*2050*	*2010*	*2050*	*2010*	*2050*	*2010*	*2050*
Condensing power plants	35,545	34,888	1,670	1,010	58,261	36,674	5,022	2,795
Centralised CHP	50,055	71,311	5,761	4,618	17,443	22,587	2,500	2,421
Nuclear power plants	21,500	0	0	0	0	0	0	0
Geothermal power plants	50	510	0	0	728	1,429	-	-
Wind power plants	27,400	89,901	1,014	7,042	5,814	31,042	3,802	10,354
Hydro power plants (excluding pumped hydro)	3,200	6,501	14,921	13,823	21,521	23,688	-	-
Solar PV	17,900	79,759	95	3,566	3,484	48,694	7	767

5.1.3 Adjusted cost data

The costs are projected towards 2050 as some technologies are expected to improve resulting in lower costs. This is particularly the case for some of the renewable technologies that will reduce the investments costs, but projections have also been made for thermal plants, storage technologies, etc. The cost assumptions for 2010 and 2050 are outlined in Appendix A – cost database.

5.2 Calibration of the 2010 and 2050 models

After collecting the data required to develop the 2010 and 2050 models for the four countries a calibration process was carried out to ensure that the EnergyPLAN model was able to replicate the existing energy systems to an acceptable degree. This calibration process is depicted in the figures for Germany and Austria below. The Italian and Danish 2010 models have already been calibrated in other projects [22][23].

The first indicator is the primary energy supply which summarises all the energy sectors into a single indicator. Hence, if the data align for this indicator it is likely that the model to some degree is also aligned for all the individual sectors as well. The categories used for comparison with the 2010 reference models differ between Figure 12 and Figure 13 for Germany and Austria depending on the categories defined by the statistical agencies.

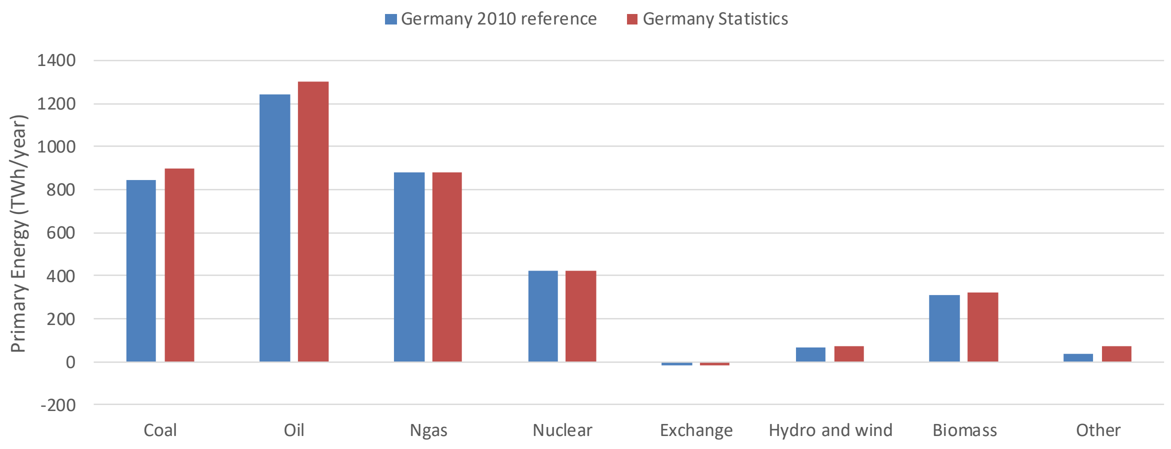

Figure 12: The Primary Energy Supply in the German 2010 reference compared to statistics from 2010

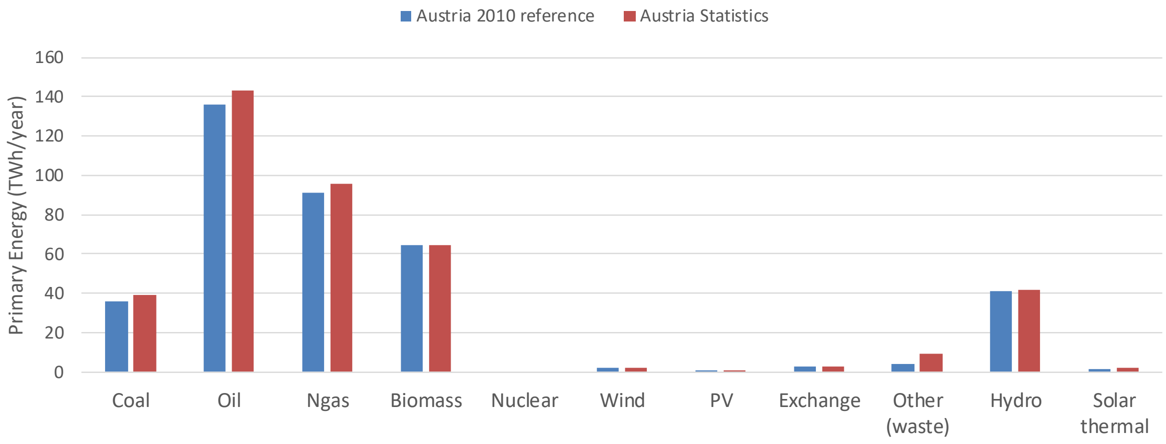

Figure 13: The Primary Energy Supply in the Austrian 2010 reference compared to statistics from 2010

A similar exercise has been carried out for electricity production in the 2010 reference models. This is crucial since the electricity production is optimised on an hourly basis by EnergyPLAN and this has to align to the annual statistical data. Hence, in these figures it is possible to compare the aggregate hourly production in EnergyPLAN with the annual data from the statistics.

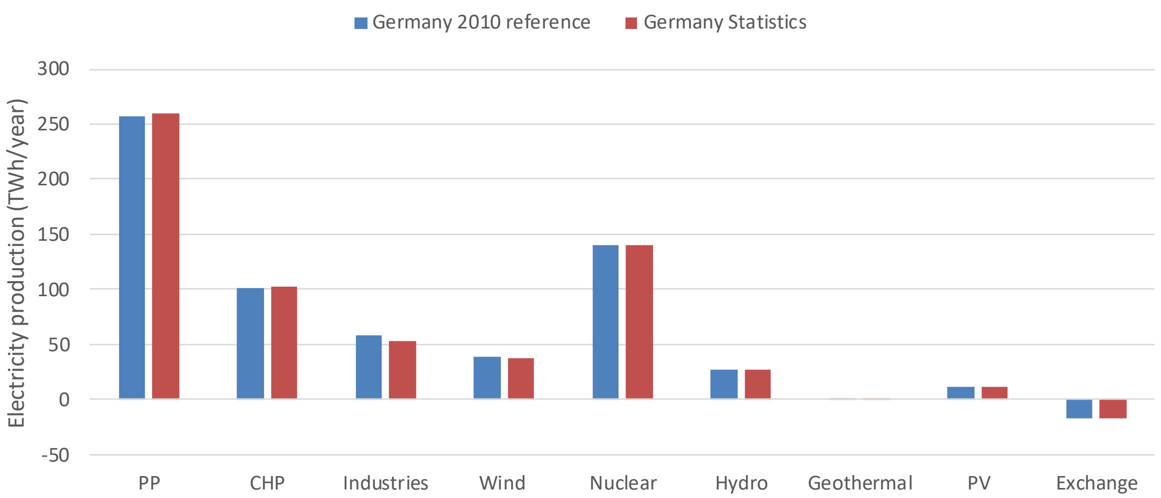

Figure 14: The electricity production in the German 2010 reference compared to statistics from 2010

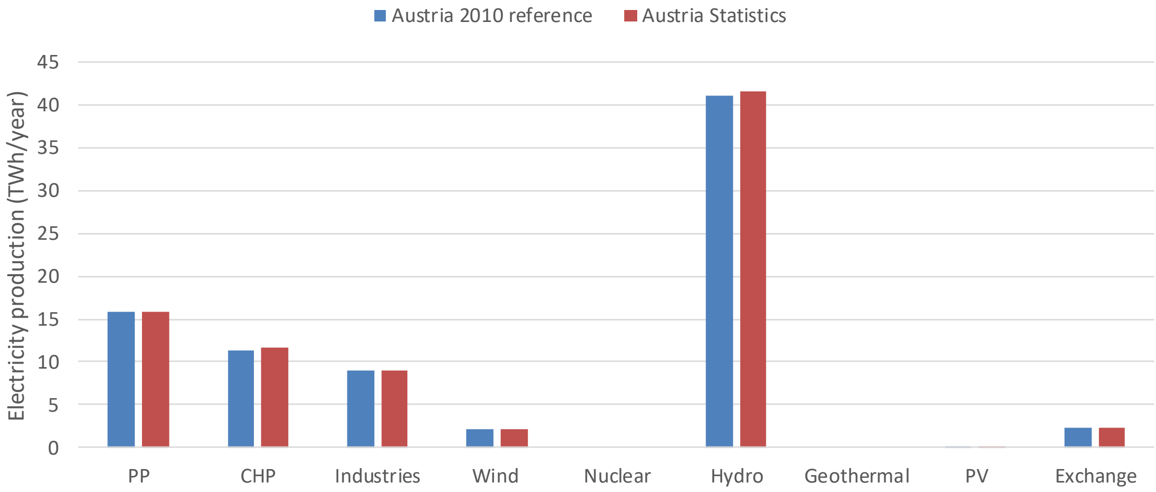

Figure 15: The electricity production in the Austrian 2010 reference compared to statistics from 2010

Also for the heating production a calibration has been performed as indicated on Figure 16 and Figure 17. EnergyPLAN optimises the production of district heating from CHP plants and district heating boilers, which is the reason for the difference for the district heating boilers between the 2010 model and the statistics. The solar thermal production for individual households differ from the statistics, but this does not impact the subsequent analysis since the marginal analysis investigates the impact of installing the first TWh of solar thermal. Hence, the solar thermal installed in 2010 is removed from the model and afterwards 1 TWh of solar thermal is installed in order to make the results comparable across the different countries.

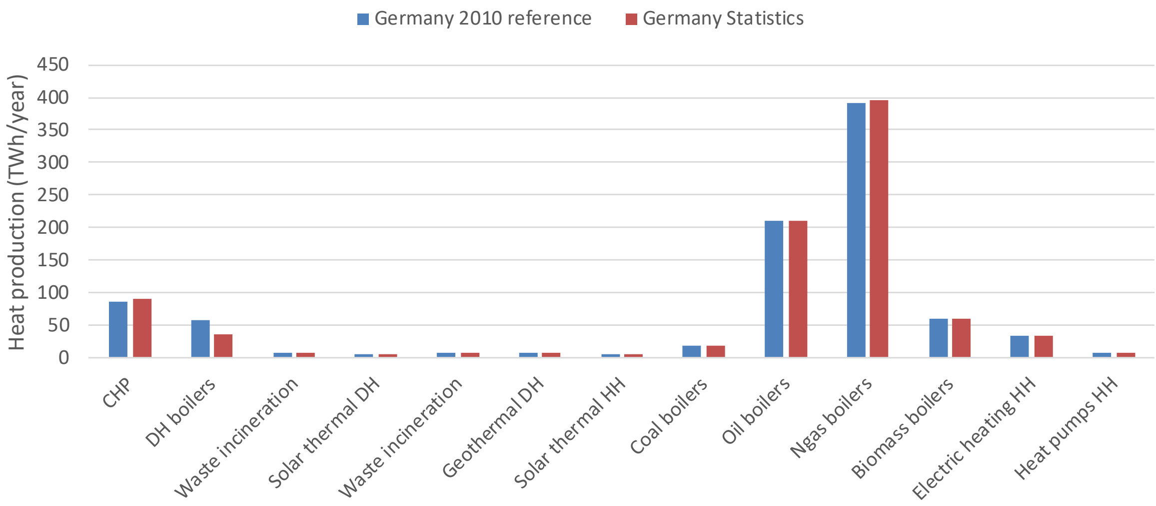

Figure 16: The heat production in the German 2010 reference compared to statistics from 2010

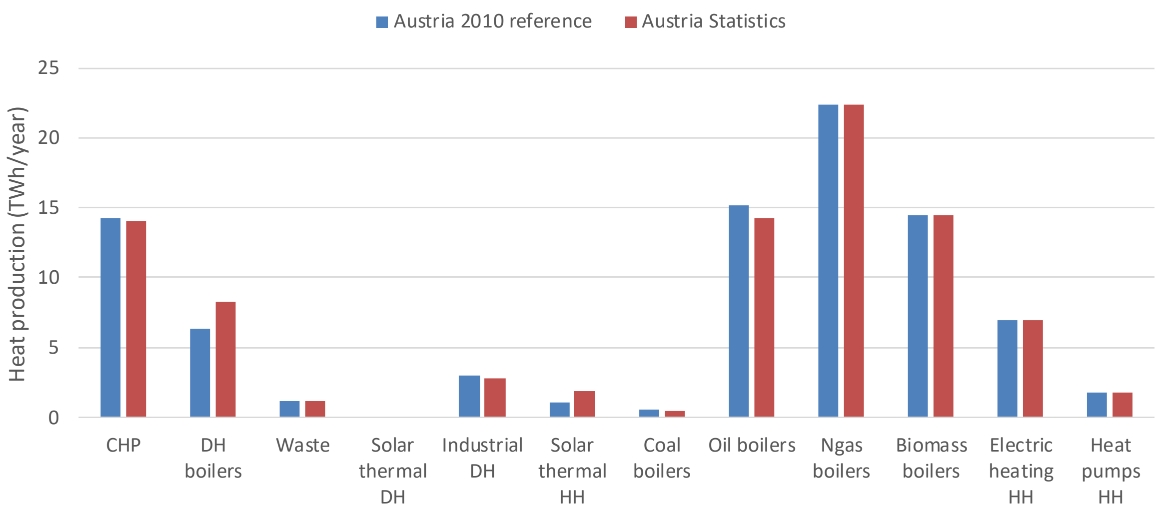

Figure 17: The heat production in the Austrian 2010 reference compared to statistics from 2010

Finally, also the Carbon Dioxide Emissions in the 2010 references have been compared to the 2010 statistics for validation. It shows minor differences which can be related to the CO_2-emissions assumed in the model from different fuels and the actual CO_2-emissions. For example, EnergyPLAN assumes a single value of CO_2 from coal consumption while in reality this value consists of various types of coal that all impact the total CO_2-emissions.

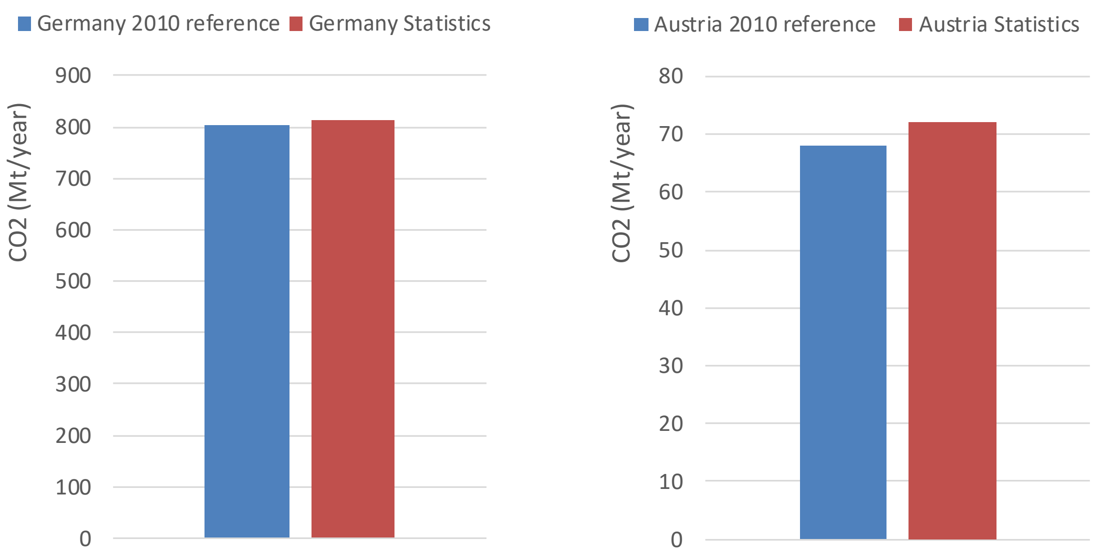

Figure 18: The Carbon Dioxide Emissions in the German and Austrian 2010 references compared to statistics from 2010

Overall, the EnergyPLAN 2010 reference models show a satisfying degree of replication of the 2010 energy systems and will accordingly be used for further modelling of the 2050 scenarios.

5.3 Energy system scenarios for 2010 and 2050

In this chapter the 2010 and 2050 models are presented for the four countries in terms of primary energy supply, electricity production, heat production, carbon dioxide emissions as well as socio-economic costs. The models are firstly presented in terms of their national fuel shares and secondly compared in terms of the demand or supply per capita.

The demographic projections assumed are based on Eurostat data. In the study no considerations of urbanization have been considered directly, but it could be argued that this is part of the analysis when expanding the district heating networks, which typically takes place in the cities.

Table 10: Population in the four countries in 2010 and projected for 2050 [24].

Population (million)	Germany	Austria	Italy	Denmark
2010	81.80	8.35	59.19	5.53
2050	81.80	9.75	67.06	6.42
Change (%)	0%*	16.7%	13.3%	15.9%

* According to the Eurostat projections the German population will decline by more than 7% towards 2050. However, this was agreed to be unrealistic between the project partners and it was therefore decided to assume a similar population in 2010 and 2050.

According to the Eurostat projections population will increase by around 15% in Austria, Italy and Denmark towards 2050 while it was decided to keep the German population at a level similar to 2010. This tendency can also be seen in the expected energy demands as presented in the next section.

5.3.1 Primary Energy Supply

Table 11: The total primary energy supply in 2010 and 2050 for the four countries.

Primary Energy supply (TWh/year)	Germany		Austria		Italy		Denmark	
	2010	*2050*	*2010*	*2050*	*2010*	*2050*	*2010*	*2050*
	3817	3130	376	374	2077	2367	250	265

The most common type of primary energy in the four countries is oil, except in Italy where natural gas covers a larger share of the national fuel demand. In all the countries more than 60% of the total fuel is fossil fuels in the forms of coal, oil and natural gas and in Italy this fossil fuel share is more than 85% of the total fuel in both 2010 and 2050. Nuclear power only exists in Germany in the 2010 reference while it is expected to be decommissioned by 2050. Austria meets more than 10% of its energy demands through hydro power production and also has a similar share of biomass. In Denmark wind power covers around 4% of the primary energy and is expected to increase to around 9% in 2050. The solar thermal shares are negligible in all countries for both individual heating and district heating.

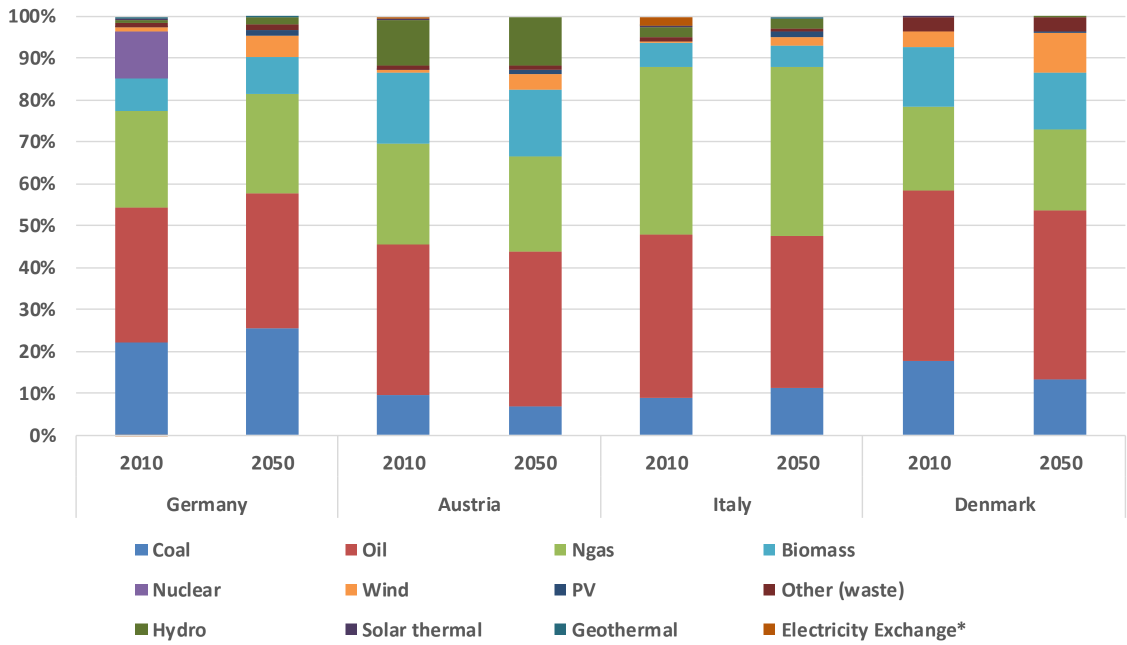

Figure 19: The proportion of primary energy supply in the energy systems in the four countries in the 2010 and 2050 models.

When considering the primary energy supply per capita the four countries show rather similar demands within a range of 35-45 MWh/capita/year. The most fuel intense countries per capita are Denmark and Germany while Italy has the lowest fuel consumption per capita in both 2010 and 2050.

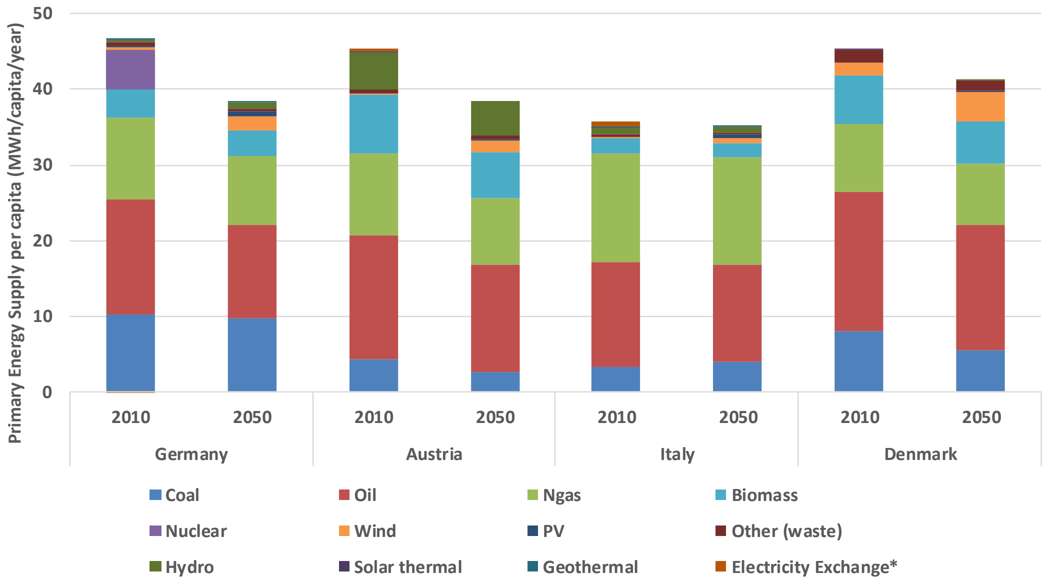

Figure 20: The primary energy supply per capita for the different countries in the 2010 and 2050 models.

5.3.2 Electricity production

Table 12: The electricity production in 2010 and 2050 for the four countries.

Electricity production (TWh/year)	Germany		Austria		Italy		Denmark	
	2010	*2050*	*2010*	*2050*	*2010*	*2050*	*2010*	*2050*
	616	679	82	92	392	510	37	49

In terms of the electricity production mix in the four countries significant differences can be found. In Germany around 65% of the electricity is produced from thermal plants and industries in 2010 and 2050. However, in 2010 around 20% of the total electricity is produced from nuclear while this is replaced by renewable electricity production from wind and solar power in 2050. The thermal production share in Austria is around 45% in 2010 and decreases to 35% in 2050. Austria has a large hydropower potential available producing around 50% of the total electricity production. Wind power also grows substantially in Austria towards 2050. Italy is heavily dependent on condensing power plants and CHP plants to produce electricity with more than 70% of the electricity produced from fossil fuels in these plants. In 2050 the wind power and PV share increases, but is still only around 15% of the total electricity production. Denmark has the highest share of wind power amounting to 25% in 2010 and approximately 50% in 2050. The thermal production from CHP plants reduce due to lower operation times because of increased wind power.

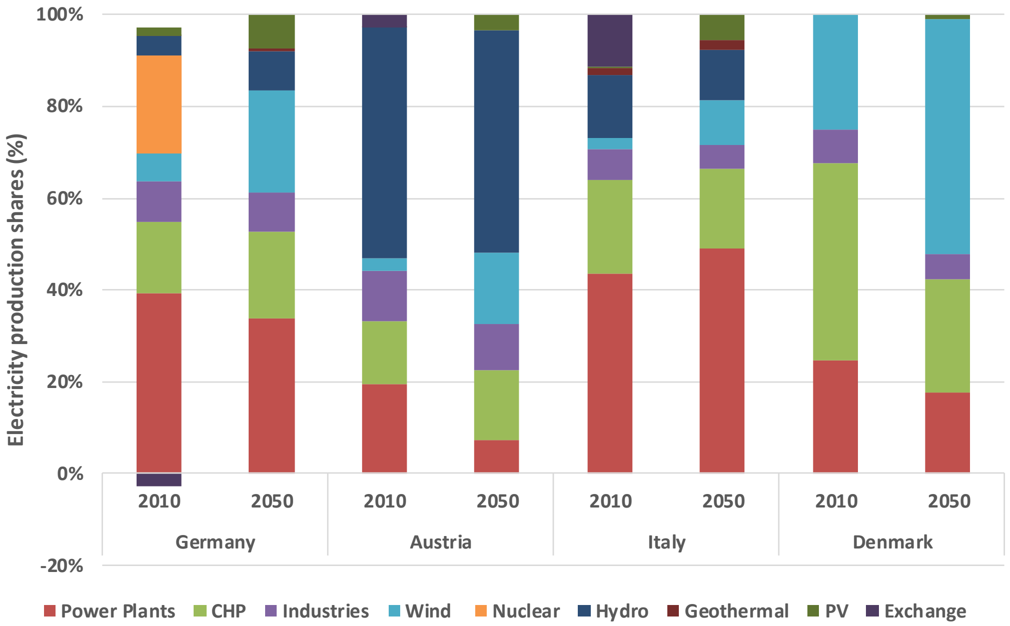

Figure 21: The proportion of electricity production from various technologies in the four countries in the 2010 and 2050 models

The electricity production per capita is 6-10 MWh/capita/year in 2010 and is expected to increase towards 2050 in all countries. Austria has the highest production per capita which indicates that the energy system to a larger degree is based on electricity than in the other countries.

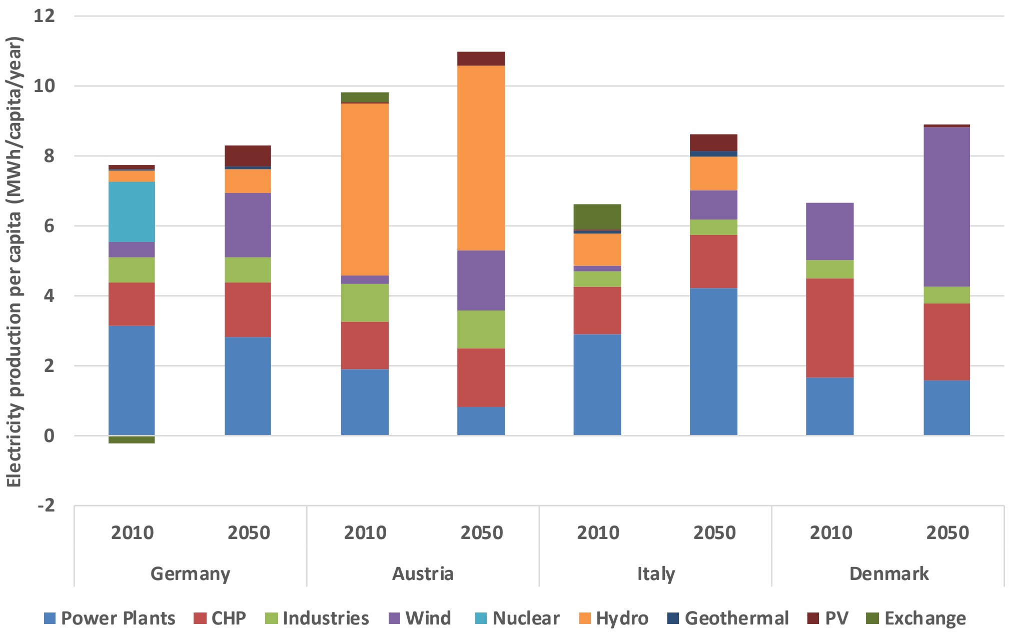

Figure 22: The electricity production per capita for the different countries in the 2010 and 2050 models

5.3.3 Heat production

Table 13: The total heat production in 2010 and 2050 for the four countries.

Heat production (TWh/year)	Germany		Austria		Italy		Denmark	
	2010	2050	2010	2050	2010	2050	2010	2050
	883	766	86	85	399	395	47	45

The largest differences between the countries regarding heat production is the share of individual heat supply and district heating. The district heating production shares are around 20% for Germany, 30% for Austria, 8% for Italy and 50% for Denmark. District heating can be produced in numerous ways and for example in Italy a large share of the district heating production is for industrial purposes. The availability of district heating systems also influence the types of technologies that are possible to integrate in the systems. This can for example be seen in the Danish energy system which has a much higher share of CHP and waste incineration plants compared to the other countries.

In Austria and Denmark 15-20% of the total heating is produced from biomass boilers in individual heating areas while Italy has a high reliance on natural gas covering more than 65% of the total heat production. Solar thermal shares are low around 1% in Germany and Austria when accounting for solar thermal for both district heating networks and individual houses. In the 2050 models no solar thermal has been included as these are used as the basis for the analysis in section 7 where the impact of installing the first TWh of solar thermal is investigated as well as extreme scenarios with a high solar thermal share.

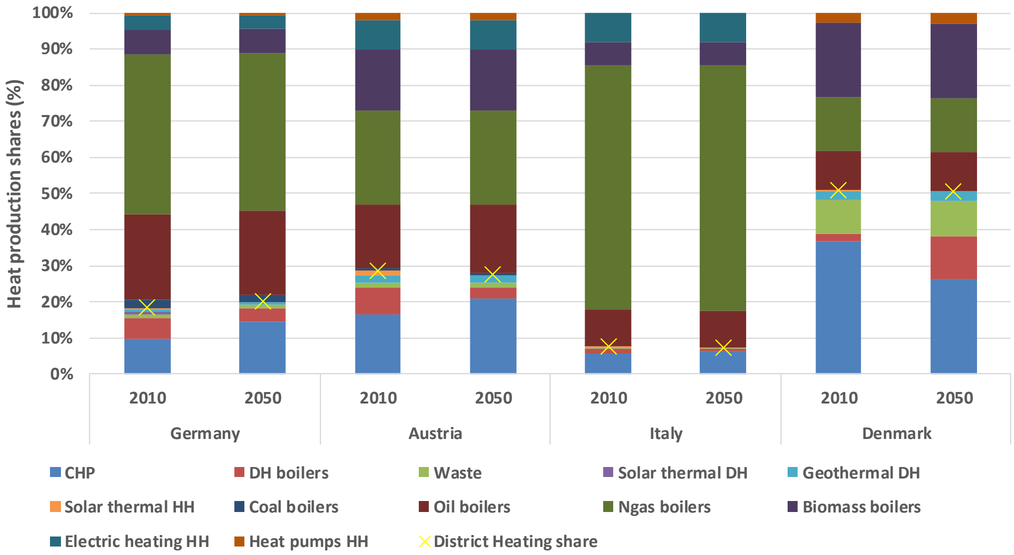

Figure 23: The proportion of heat production from various technologies in the four countries in the 2010 and 2050 models. HH = Households/individual supply.

The heating production per capita reveals that the highest demands can be found in Germany followed by Austria and Denmark. Italy has the lowest heating production per capita. Factors that influence the heating production in the countries are e.g. climate, building standards and consumer habits (for example the desired living room temperature). Also, the heat production is influenced by the heating demands and the efficiency in the system as some technologies such as heat pumps can have higher efficiencies than conventional boilers. For all countries the heat production per capita decreases between 2010 and 2050.

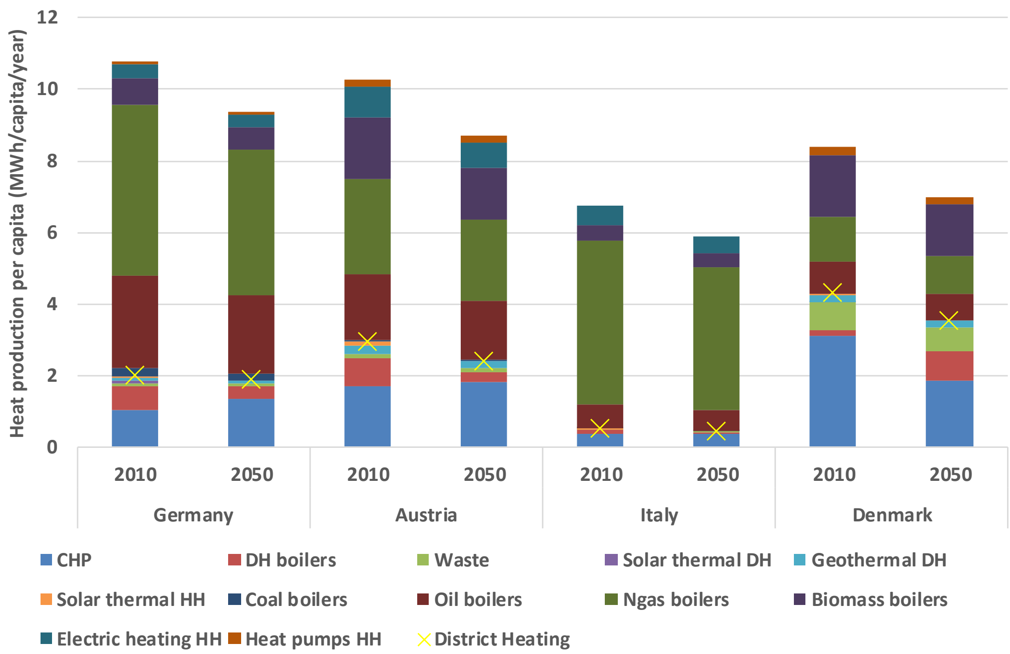

Figure 24: The heat production per capita for the different countries in the 2010 and 2050 models.

5.3.4 Carbon Dioxide Emissions

Table 14: The total carbon dioxide emissions in 2010 and 2050 for the four countries.

Carbon Dioxide Emissions (Mt/year)	Germany		Austria		Italy		Denmark	
	2010	2050	2010	2050	2010	2050	2010	2050
	803	697	68	64	461	518	54	52

The carbon dioxide emissions associated with the energy systems vary significantly in terms of total amounts, but when measured per capita the emissions are between 8-10 t/capita/year. The carbon emissions per capita is impacted by factors such as energy demands on one side and supply technologies and fuels on the other side. When these are combined the differences between the countries are rather limited. Austria is projected to experience the largest decrease in emissions per capita towards 2050 due to a higher share of renewables and a reduced heating demand.

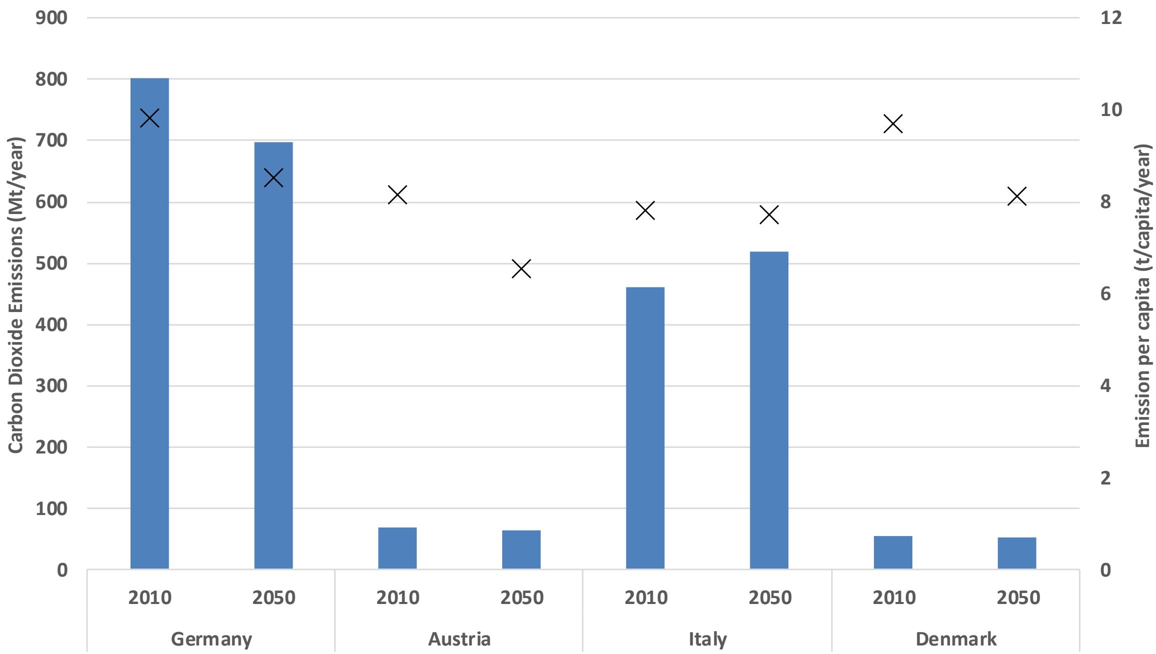

Figure 25: The total energy system carbon dioxide emissions and the emission per capita for the different countries in the 2010 and 2050 models.

5.3.5 Socio-economic costs

Table 15: The total socio-economic costs in 2010 and 2050 for the four countries.

Socio-economic costs (Billion €/year)	Germany		Austria		Italy		Denmark	
	2010	2050	2010	2050	2010	2050	2010	2050
	456	465	38	42	282	330	25	28

The socio-economic costs are divided between investments, operation and maintenance, fuels, CO_2 and electricity exchange. The proportions between the countries are rather similar with investments being around 35-40% of all costs, operation and maintenance 20-30%, fuel costs are 25-35% of the total costs while CO_2 costs are around 5-10%. These total energy systems costs include costs for vehicles.

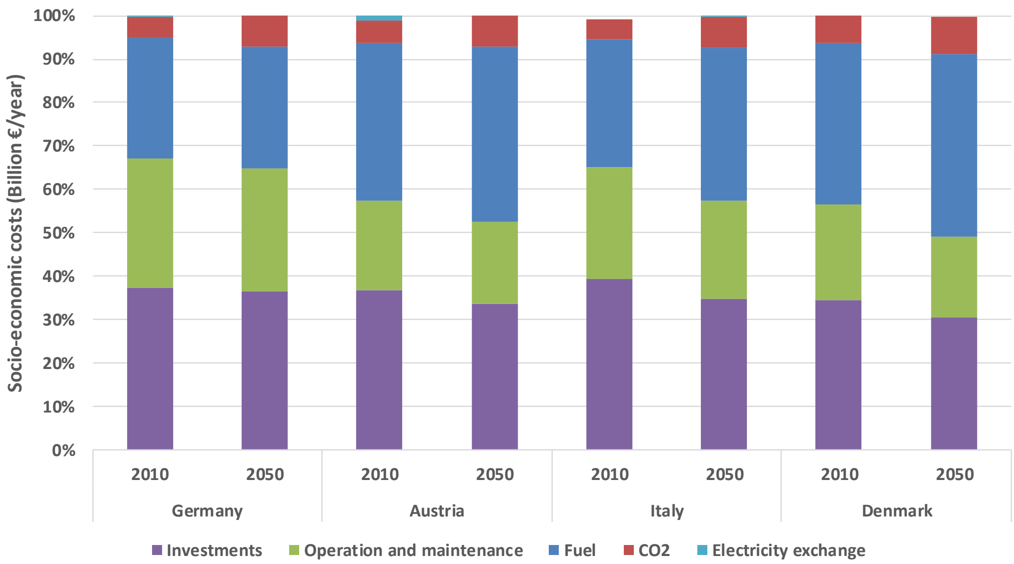

Figure 26: The proportion of socio-economic costs in the energy systems in the 2010 and 2050 models, <u>including vehicle costs</u>.

The largest cost in the energy system are the vehicle costs that are responsible for between 40-55% of the entire costs in the energy systems based on the vehicle cost assumptions presented in Appendix A – cost database. The largest cost share of vehicles are in Germany and Italy around 55% while the costs in Austria and Denmark are just above 40% of the total costs.

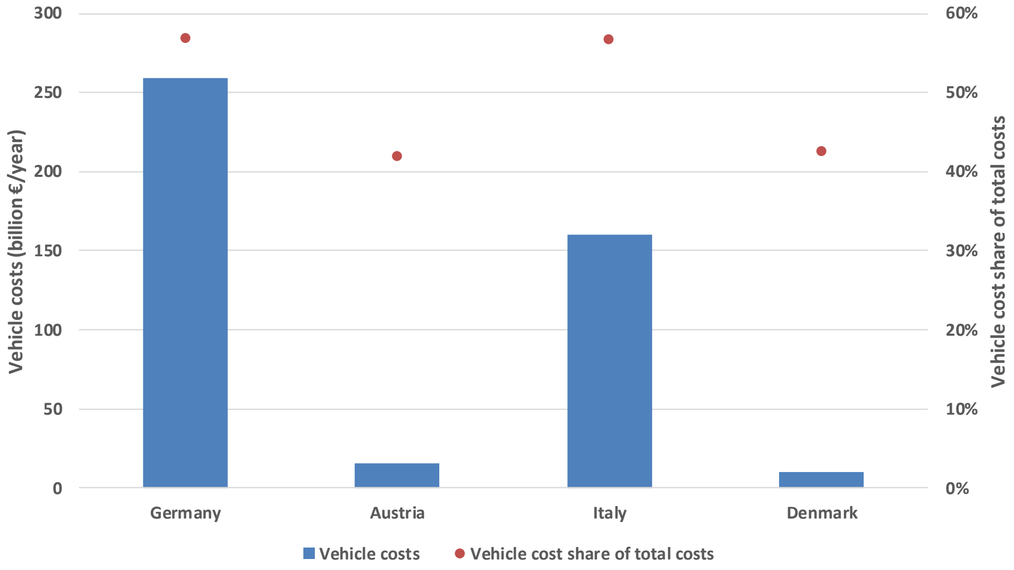

Figure 27: The total vehicle costs in the four contries along with the proportion of vehicle costs compared to the total energy system costs in the 2010 models.

When comparing the number of vehicles per capita across the countries it is clear that Italy has the highest number of vehicles per capita. This is also reflected in Figure 27 as indicated by the vehicle costs as a share of the total costs.

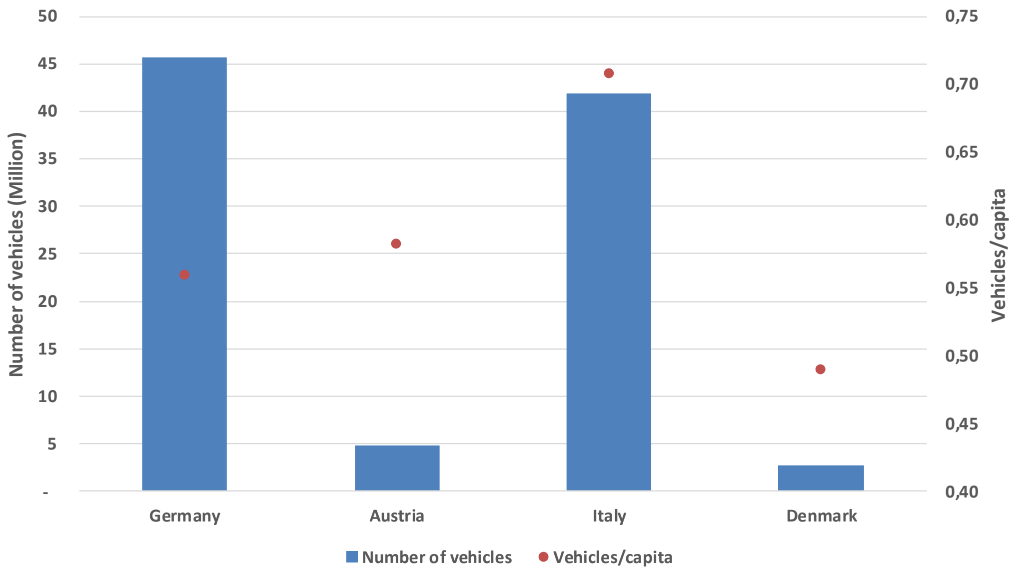

Figure 28: The number of vehicles in each country along with the number of vehicles per capita in 2010.

The socio-economic costs have also been calculated excluding the vehicle costs since they are such a high proportion of the total costs. When excluding vehicle costs the fuel cost share grows significantly and is now between 50-60% of the total costs in the various energy systems in 2010 and 2050.

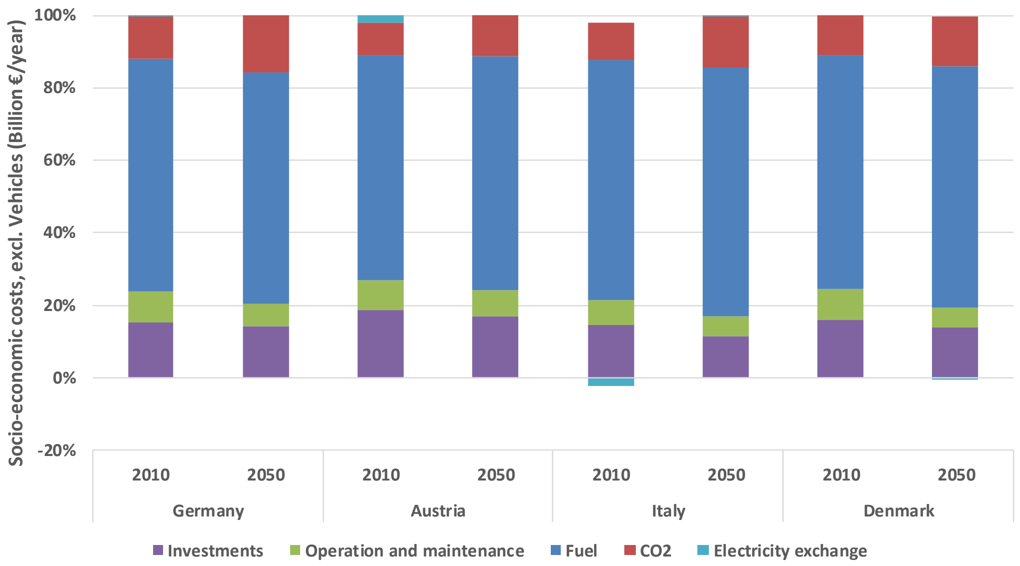

Figure 29: The proportion of socio-economic costs in the energy systems in the 2010 and 2050 models, excluding vehicle costs.

The cost proportions are rather similar, but if the costs per capita are compared some differences are visible. The highest costs per capita in both 2010 and 2050 can be found in the German system with total costs around 5,500 €/capita/year when vehicle costs are included. The three other countries have costs around 4,000-5,000 €/capita/year. The same costs would be around 2,500-3,000 €/capita/year when excluding the vehicle costs.

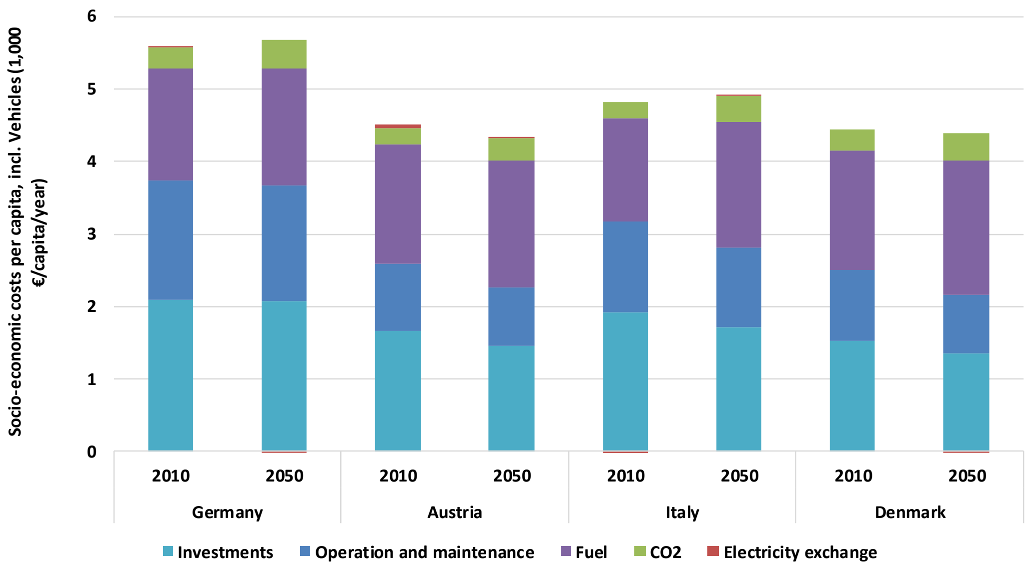

Figure 30: The socio-economic costs per capita for the four countries in 2010 and 2050, including vehicle costs.

6 Developing high renewable scenarios

This report analyses the role of various types of solar thermal systems in future energy systems under different conditions for four countries. These varying conditions are created through developing a number of energy system scenarios in which solar thermal potentially could play a role. Concretely, the scenarios in which solar thermal is analysed is based on five energy system models for each country; a 2010 model, a 2050 model continuing the trends of today, a 2050 scenario with focus on heat savings, a 2050 scenario with focus on heat savings and district heating and finally a high-renewable scenario where only the transport sector consumes fossil fuels. These scenarios have been created for all four countries to investigate whether the system design and energy resources available also influences the potential role of solar thermal in the future. The key purpose of these scenarios are therefore to create various conditions in which solar thermal is analysed rather than to create optimal pathways to a high-renewable scenario for the future. Also, the steps do not necessarily reflect how the implementation of a high-renewable energy system might be created, as no time aspect is included in the steps. The scenarios reflect a future snapshot of what a high-renewable system might look like around 2050.

The high-renewable energy systems are developed through a number of steps, starting from the 2050 BAU models of each country. These steps build on top of each other so that the second step also implements the measures from the first step and so on. This means that the last steps build on top of a number of previous steps and measures to form the final high-renewable scenarios.

The scenarios developed are:

1. 2010 model: A system reflecting the current energy systems
    - ➔ Solar thermal analyses in the 2010 model
2. 2050 model: A BAU system continuing the current trends
    - ➔ Solar thermal analyses in the 2050 model
3. Heat Savings: Savings in individual heating and district heating areas
    - ➔ Solar thermal analyses after heat savings
4. District heating: Investigations of expanding the district heating network
    - ➔ Solar thermal analyses after changes in heat supply
5. Individual heating: Comparison of various individual heat supply options
6. Renewable heating: Integration of renewable heating sources other than solar thermal
7. Transport: Electrification of cars
8. Industry: Changes in industrial sector through electrification and conversion to biomass
9. Renewable electricity: Integration of renewable electricity
10. High-renewable: Changes in remaining sectors to biomass
    - ➔ Solar thermal analyses in high-renewable systems

The measures in each step as well as the results of implementing these measures are described in the next sections.

6.1.1 Step 1: Heat savings

The first step initiates from the 2050 BAU model and contains a reduction of space heating demands through savings in buildings supplied by both individual heating and district heating. The feasible saving levels are determined according to the economic system impact of the savings, i.e. a certain share of heat savings is selected if the energy system costs are lower than for the alternative saving levels. The heat savings are analysed in levels of 10% and is based on the heat saving costs presented in Figure 31 and Figure 32. The source for these heat saving costs and potentials is the Subtask A report about heat savings cost curves.

The additional investments due to heat savings increases along with the growing saving shares as the cheapest saving options are selected first. It is assumed that the savings are distributed evenly to all types of supply technologies, i.e. 10% heat savings will reduce the heat demand 10% for all buildings with natural gas boilers, oil boilers and district heating supply.

Only existing buildings are included in the saving levels as the share of new buildings towards 2050 are assumed to be insignificant compared to the share of the existing building stock still existing in 2050. Furthermore, the new buildings have significantly higher costs for renovations compared to renovations in the exsting buildings that are not being demolished, see Figure 31.

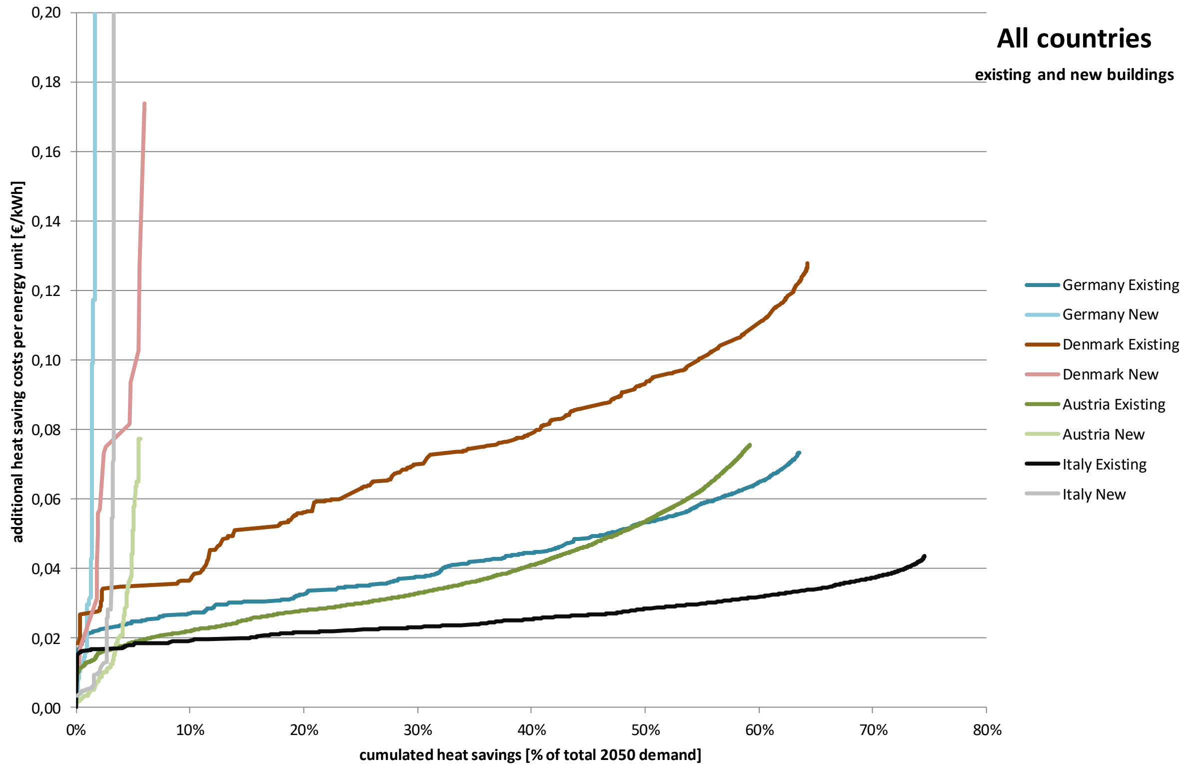

Figure 31: Heat saving costs for existing and new buildings in each country measured in additional investments per energy saved.

The heat savings are analysed by changing following inputs for the modelling in each country:

- Heat demands are reduced evenly for all heat supply technologies.
- Additional investments required to carry out the heat savings.
- The number of heating units remain constant despite a lower heat demand (lower heat demand per building).
- Investment prices in heating units decrease by the same ratio as the saving level implemented, i.e. 10% heat savings results in 10% lower investment prices for boilers, district heating substations, etc.
- District heating production capacity is reduced when carrying out heat savings.
- Space heating demands are reduced while the domestic hot water demand remains constant.
- The distribution of the hourly heating demands are changed resulting in a lower peak demand during winter.

Changes in heating and cooling demands due to climate change and changes to the number of heating and cooling degree days have not been considered in the analysis.

The total costs for building renovations increase as the share of heat savings increase, see Figure 32. This means that there is a certain point where it is more economical to produce heating rather than to continue to save heating, see also [25]. Heat savings affect multiple areas of the energy system and it can be difficult to measure impacts on other sectors such as the electricity sector. Hence, the heat savings are analysed in a full energy system perspective applying the energy system analysis tool EnergyPLAN previously described. This allows for quantifying the impacts for the entire energy system.

The accumulated heat savings costs are presented in Figure 32 for the four countries. These curves form the basis for calculating the additional investments required to achieve a certain heat saving level.

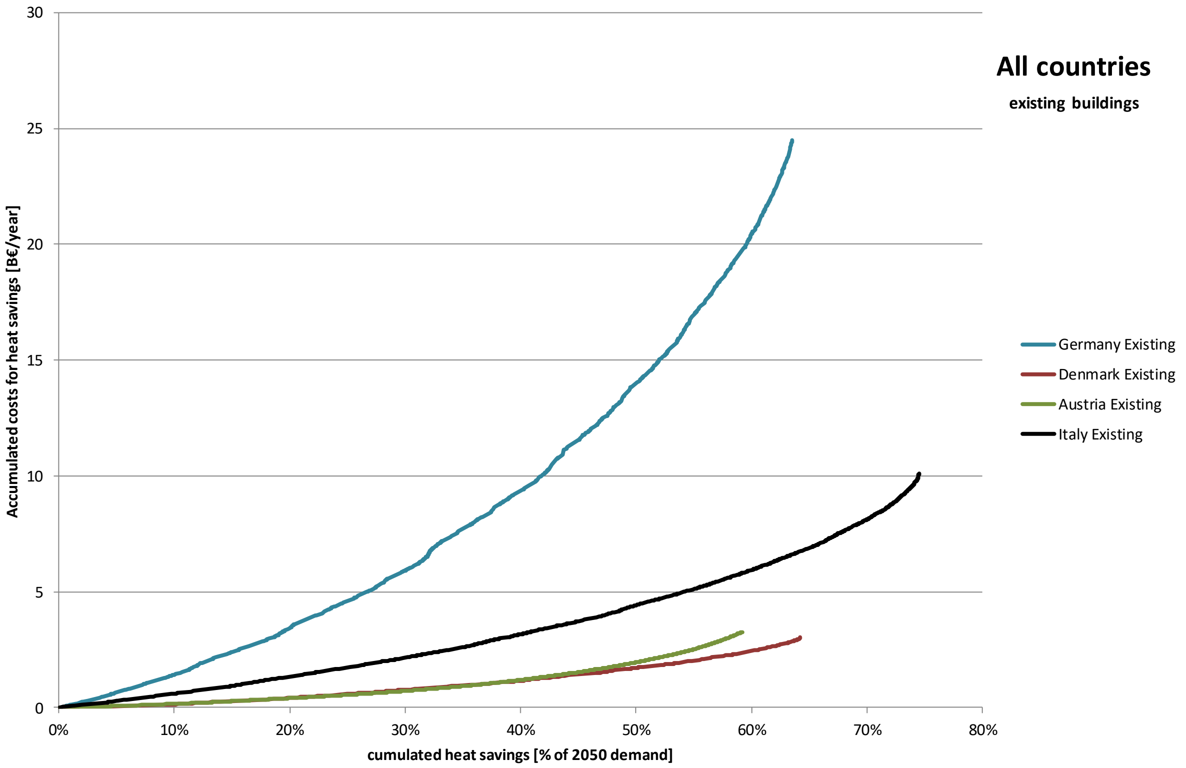

Figure 32: The accumulated heat saving costs as a share of the 2050 heat demand for the four countries

In Figure 36-Figure 36 the results of various heat saving level simulations for the four countries are outlined. It was chosen to use 50% heat savings for Germany, 40% heat savings for Austria and 40% heat savings for Denmark as these were found to be the options with the lowest socio-economic costs for the energy system. For Italy however, the costs continued declining as more heat savings were installed. Therefore, it was chosen for Italy to use a 50% saving level as a higher level might be too difficult to achieve from an implementation perspective. In order to achieve higher saving levels the renovation rates would need to increase significantly compared to existing and possible renovation rates.

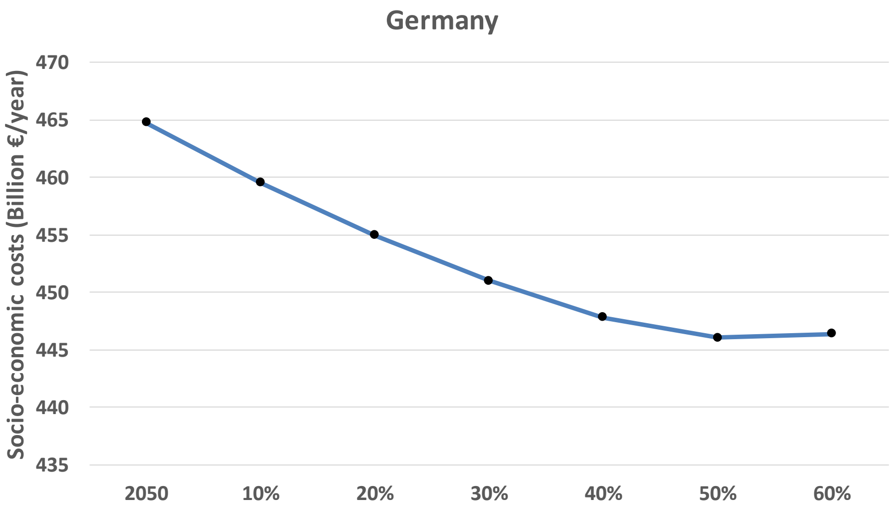

Figure 33: Socio-economic costs for various saving levels for Germany. The heat saving level with the lowest energy system costs have been selected for further analyses.

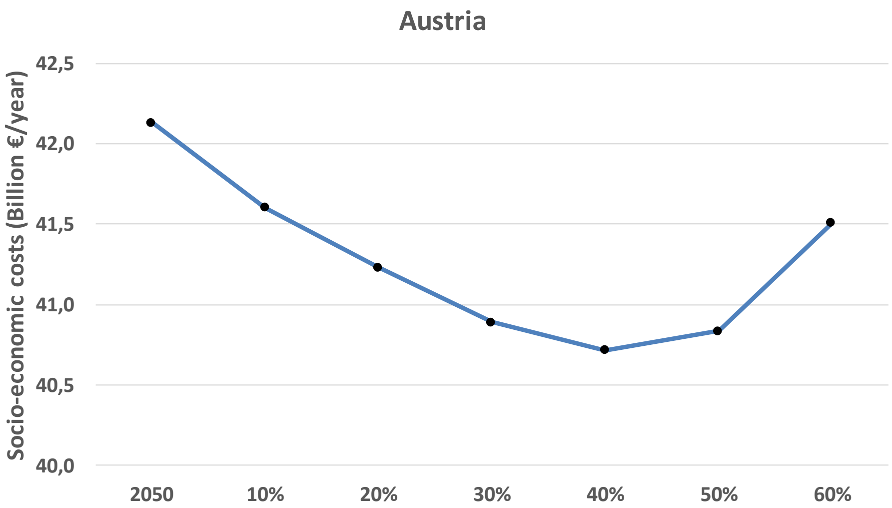

Figure 34: Socio-economic costs for various saving levels for Austria. The heat saving level with the lowest energy system costs have been selected for further analyses.

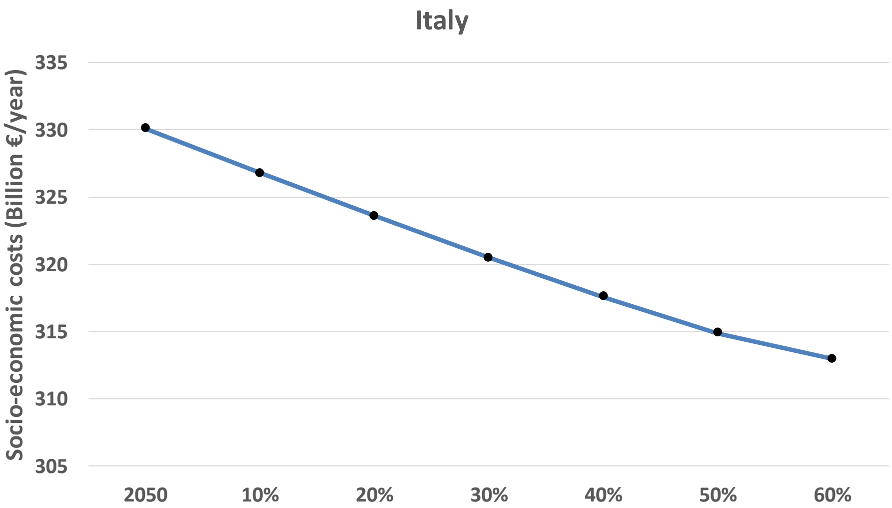

Figure 35: Socio-economic costs for various saving levels for Italy. The heat saving level with the lowest energy system costs have been selected for further analyses.

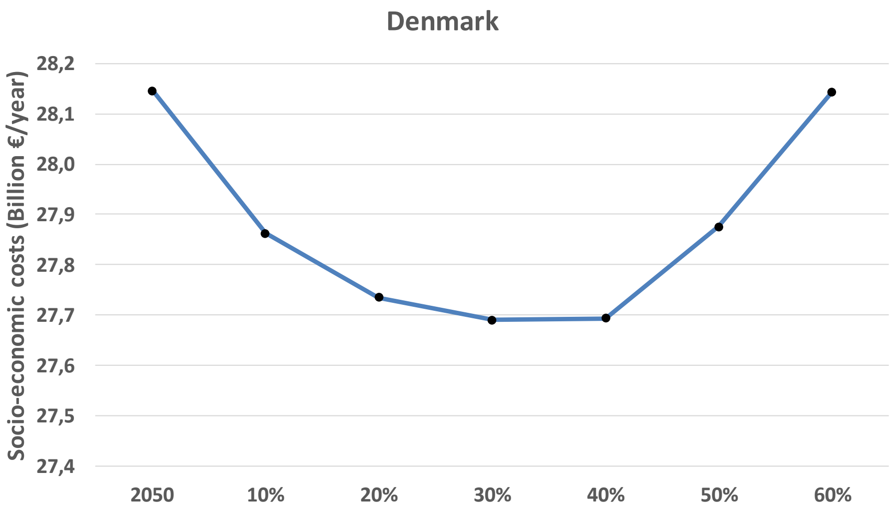

Figure 36: Socio-economic costs for various saving levels for Denmark. The heat saving level with the lowest energy system costs have been selected for further analyses.

In Table 16 the heat production before and after the heat savings are listed. Furthermore, the additional investments required for the heat savings can be found for each country.

Table 16: Heat production before and after heat savings as well as the additional investments for implementing the heat savings.

Country	2050 heat production	Heat saving level with lowest costs	2050 heat production after savings	Investments in heat savings
	TWh/year	%	TWh/year	Billion €/year
Germany	766	50%	383	13.8
Austria	85	40%	50.9	1.2
Italy	396	50%	198	4.4
Denmark	45	40%	27	1.2

Carrying out heat savings also impact the overall primary energy demand with a reduction between 8-13% depending on the country, the heat saving levels carried out and the proportion of the heat sector in the country. Also, the electricity production in the system decrease due to a lower electricity demand for heating with the largest electricity reduction in Austria and the smallest in Denmark. For CO_2-emissions the heat savings leads to a reduction of 5-12% of the total energy system emissions.

In Step 1 the solar thermal concepts are subsequently analysed to investigate whether heat savings impact the potential role of solar thermal in the future. This analysis is outlined in section 7.

6.1.2 Step 2: District heating expansion

After reducing the heat demand in step 1 it is analysed how much of the remaining heat demand district heating might supply. The feasibility of district heating expansions are compared based on both technical and economic feasibility.

Similarly, to the heat saving levels the district heating levels are analysed in steps of 10% to find the most cost-effective level. The district heating expansions are analysed before the integration of further renewable sources in the district heating networks (step 4) and could potentially impact the district heating levels. This has previously been analysed in [22] where this proved to only slightly change the district heating levels.

District heating levels are analysed by changing following inputs for the modelling in each country:

- Additional investments for piping (transmission, distribution, branch pipes).
- Additional costs for installing substations in each building converted to district heating.
- Reductions in costs for individual boiler investments in buildings converted to district heating.
- Changes in heat supply technologies affecting system efficiencies and losses.
- Adjusted district heating boiler capacity (120% of peak demand) and CHP capacity (75% of peak demand). The latter is either a conversion of existing condensing power plants to CHP plants or the construction of new CHP plants. CHP plants are assumed to have a similar fuel mix as in the 2050 reference scenario.
- The thermal efficiencies of CHP plants are improved for Italian CHP plants (from 12% to 40%).

Investments in piping for district heating increases per heat delivered because of the lower heat density. This means that the costs per heat delivered is lower in city centres than in rural areas. This is reflected from Figure 37 and Figure 38 where it is clear that the piping costs increase as the heat density reduces [22]. The district heating network cost curves are based on geographical analysis of each country on a 1 km2 resolution. Firstly, the location of the heat demands are estimated, followed by calculations of the required lengths for each district heating network in areas with a sufficiently high heat density. Based on this the network costs are estimated for urban areas and depending on the district heating share of the total heat demand [22].

The heat savings carried out in the first step might potentially affect the costs of increasing the district heating networks as the heat demand reduces in every building. This is not taken into account in the district heating network costs applied in the analysis, where it is assumed that the network costs are based on the 2050 reference heat demands. A methodology for including the impact of heat savings is currently under development in [26].

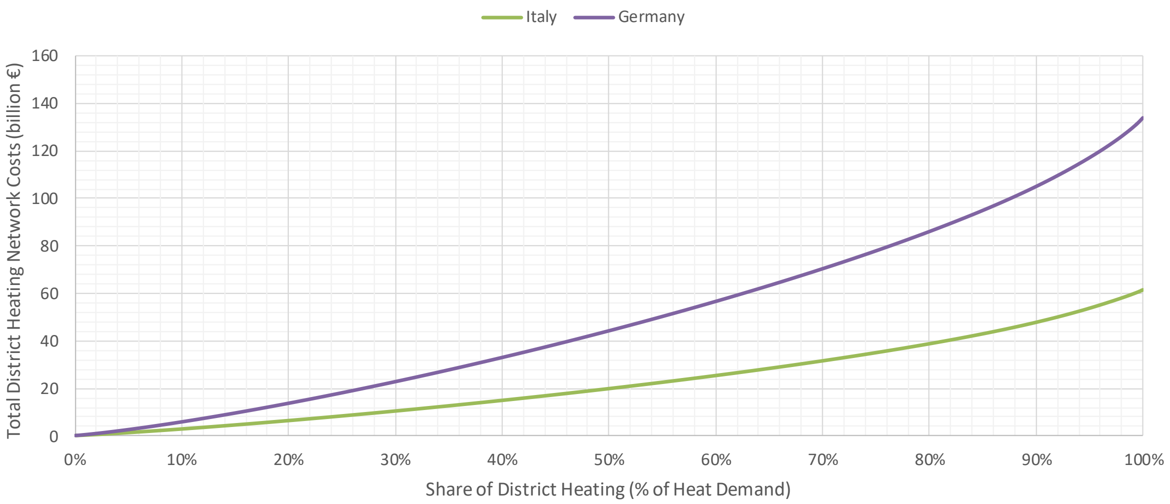

Figure 37: The district heating network costs according to the share of district heating in Italy and Germany.

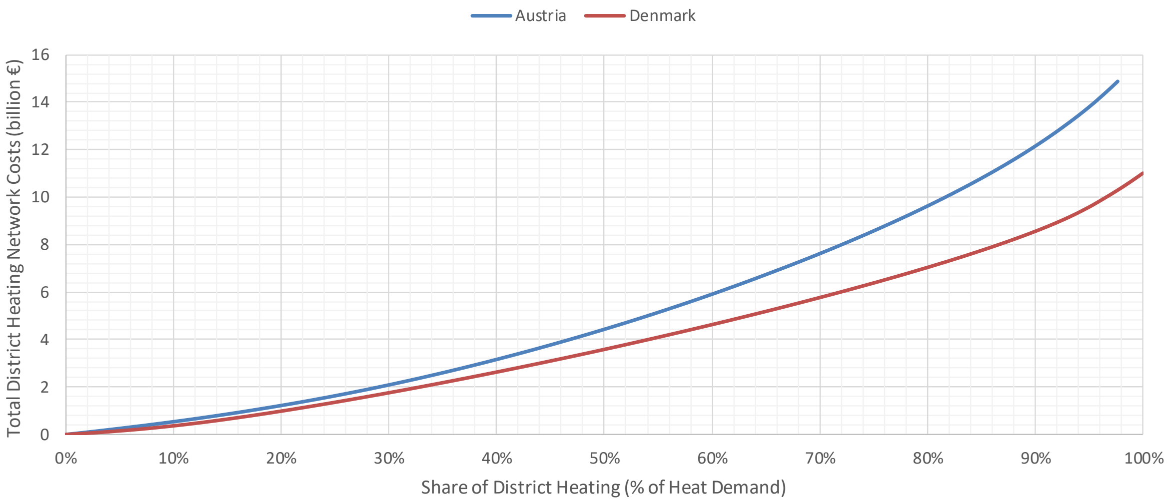

Figure 38: The district heating network costs according to the share of district heating in Austria and Denmark.

District heating impacts many areas of the energy system such as the share of CHP and the integration of excess heating and therefore it is necessary to apply a full energy system analysis perspective. The figures below shows the total socio-economic costs when integrating various levels of district heating in the energy systems. In Germany the energy system costs are lowest when the heat supply is 40% district heating, in Austria a similar share is feasible while higher shares have been identified for Italy and Denmark. The district heating level with lowest costs in Italy is 70% while the share in Denmark is at 60%. These district heating levels are analysed after heat savings have been carried out in step 1. Without any heat savings slightly higher district heating shares would lead to the lowest costs.

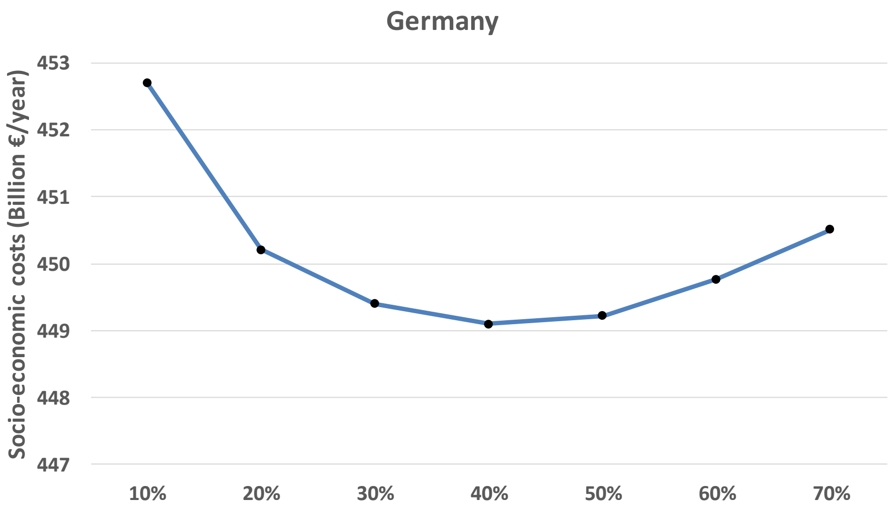

Figure 39: Socio-economic costs for various district heating levels for Germany. The district heating level with the lowest energy system costs have been selected for further analyses.

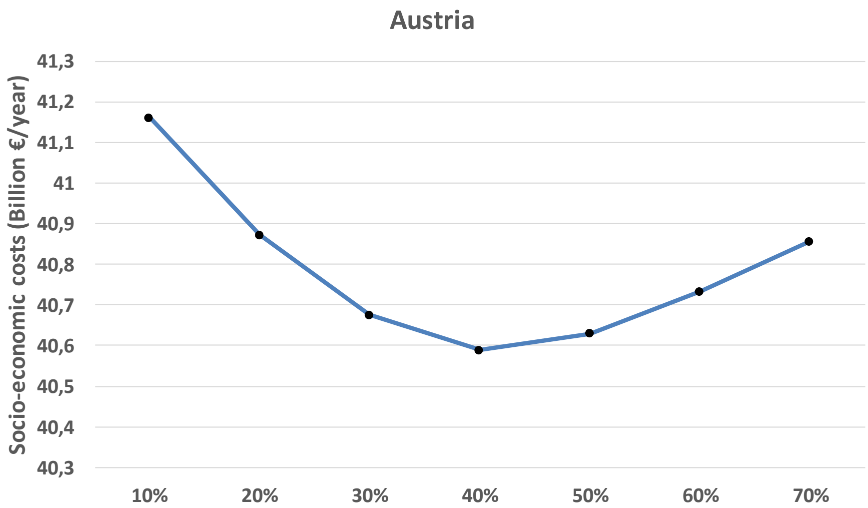

Figure 40: Socio-economic costs for various district heating levels for Austria. The district heating level with the lowest energy system costs have been selected for further analyses.

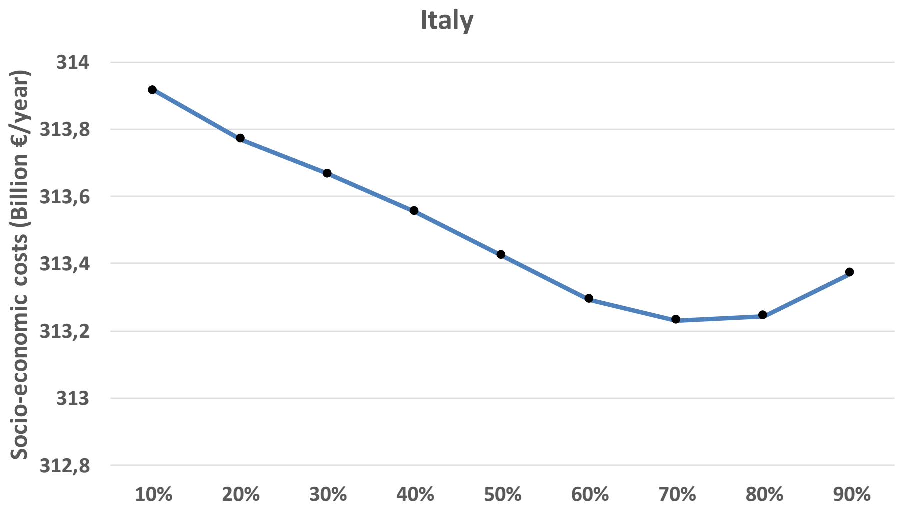

Figure 41: Socio-economic costs for various district heating levels for Italy. The district heating level with the lowest energy system costs have been selected for further analyses.

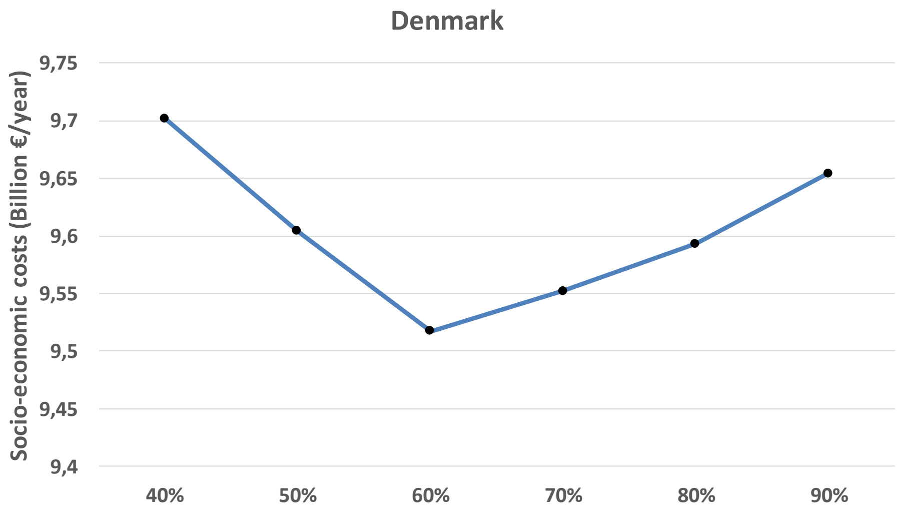

Figure 42: Socio-economic costs for various district heating levels for Denmark. The district heating level with the lowest energy system costs have been selected for further analyses.

The feasible district heating levels all result in higher district heating shares compared to the current levels and what is expected for 2050. Especially in Italy the district heating potential seems significant, which is in line with [22]. Also in Germany, the district heating level might double compared to the current level while smaller increases in Austria and Denmark seems feasible.

The feasible district heating levels depend on a number of factors with the most significant types described below. The heat density in the country is one of the determining factors for district heating feasibility and this is the explanation for the significant district heating expansions suggested for e.g. Italy. In Italy the population lives rather close to eachother (in cities), which means that a small amount of district heating networks might reach a large proportion of the heat demand. Currently, 43% of the population lives in the 10 largest cities in Italy indicating that these areas could be feasible for district heating. This number is for example only 38% in Denmark, 30% in Austria and 13% in Germany. Current trends indicate that the urbanisation rate will only increase in the future, which is not accounted for in the analysis. These conditions might also impact the feasibility for district cooling, but since this is only a minor part of the energy demand it has negligible impact on the overall energy system.

Furthermore, the Italian energy system has a large potential for utilizing excess heat from condensing power plants that might be converted to CHP plants in order to utilize this excess heat. This is less costly than building new CHP plants for district heating supply and will provide a relatively low cost solution for supplying the new district heating areas. The high district heating potential in Italy can also be explained by the energy system design as the Italian energy system currently only has a small share of baseload production of electricity and heating from technologies such as industrial production, geothermal, waste incineration and nuclear power. This means there is more space for CHP plants to produce in cogeneration mode and thereby produce heating for district heating purposes.

Table 17: District heating shares in the 2050 scenarios and after district heating expansions.

Country	District heating share 2050	District heating share with lowest cost	District heating network costs
	%	%	Billion €
Germany	19.9%	40%	24.17
Austria	27.5%	40%	1.41
Italy	7.2%	70%	29.54
Denmark	51.5%	60%	0.15

This step could potentially also impact the role of solar thermal in the future and is therefore selected as one of the five scenarios in which the solar thermal analyses are conducted.

6.1.3 Step 3: Individual heating

After determining how much of the heat demand should be saved and what district heating levels are feasaible the remaining heat supply is supplied by individual heating technologies. Here, three alternatives are investigated having in mind that the aim is a high-renewable system: Biomass boilers, electric heating and heat pumps.

The changes that are implemented when analysing the individual heating options are:

- Heat demands supplied by different technologies.
- Changes in heating unit investments when converting to a different heat supply technology.
- Adjustments in electricity production capacities due to increased electricity demands for heating purposes.

The scenarios are rather extreme scenarios as the majority of the heat demand is supplied by a single technology. This might not seem realistic, but enables a better comparison across the three technologies. It is deemed unrealistic to supply all individual heating from either electric heating or heat pumps and therefore biomass boilers are included in these sceenarios. Hence, in the scenario comparisons for electric heating and heat pumps 80% of the individual heat demand is supplied by these technologies while the remainder for the largest part is from biomass boilers, see Table 18.

Table 18: Division between supply technologies in the three individual heating scenarios. The numbers indicate the share of the total individual heating supply.

Technology	Biomass option	Electric heating option	Heat pumps option
Biomass boilers	95%	17.5%	17.5%
Electric heating	2.5%	80%	2.5%
Heat pumps	2.5%	2.5%	80%

To assess the feasibility of the three options, firstly, the economic impact on the energy systems are compared, see the figures below.

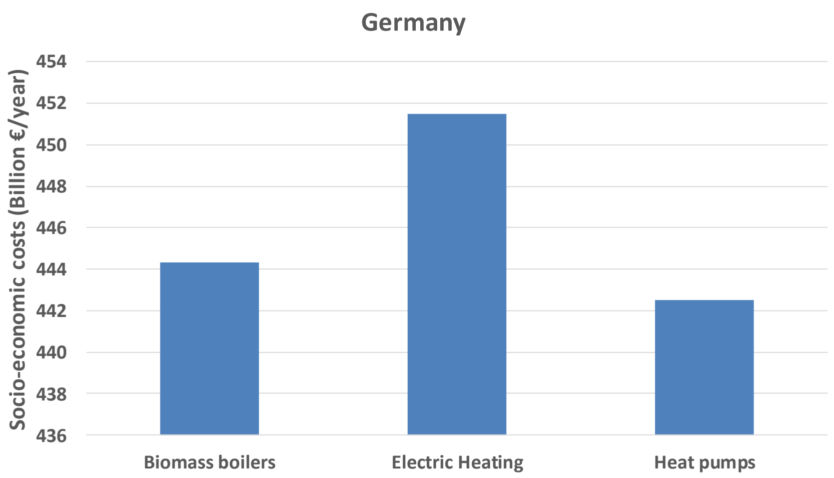

Figure 43: Socio-economic costs for different individual supply technologies for Germany. The costs represent the total socio-economic costs in the energy systems when the majority of the individual heat supply is supplied by these technologies.

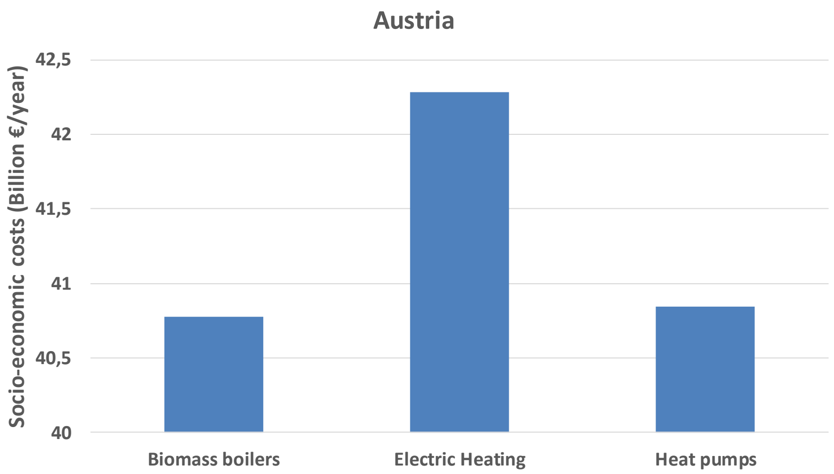

Figure 44: Socio-economic costs for different individual supply technologies for Austria. The costs represent the total socio-economic costs in the energy systems when the majority of the individual heat supply is supplied by these technologies.

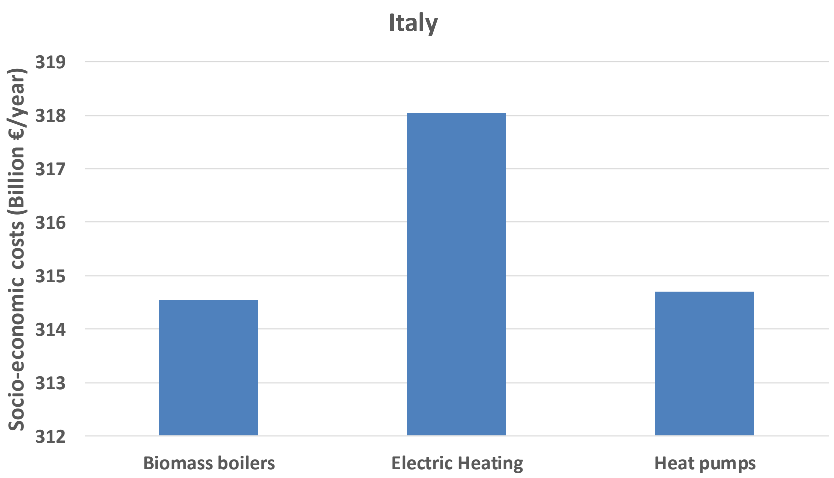

Figure 45: Socio-economic costs for different individual supply technologies for Italy. The costs represent the total socio-economic costs in the energy systems when the majority of the individual heat supply is supplied by these technologies.

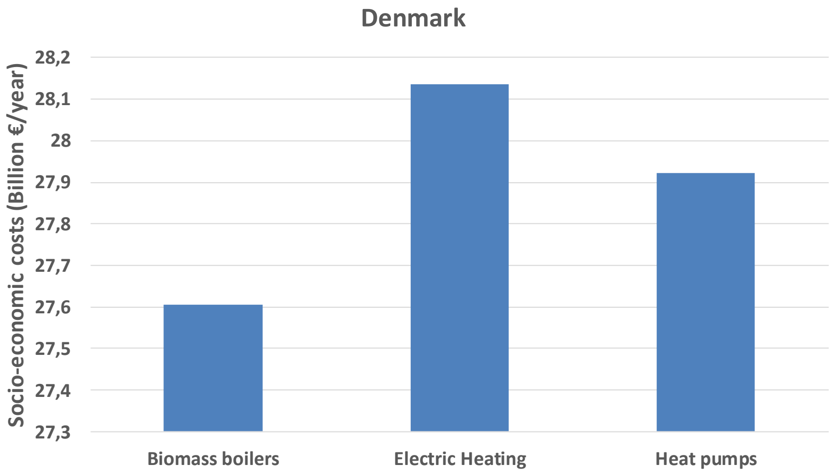

Figure 46: Socio-economic costs for different individual supply technologies for Denmark. The costs represent the total socio-economic costs in the energy systems when the majority of the individual heat supply is supplied by these technologies.

In all four countries electric heating is the most costly option and is therefore disregarded as a feasible solution. In the Austrian, Italian and Danish systems biomass boilers is the least costly option while heat pumps are preferable from an economic perspective in the German system. The primary reason for the differences depends on the type of heating supply that is replaced.

The three options have a significant impact on the efficiency and fuel consumption in the systems. These impacts are illustrated in Figure 47 and Figure 48.

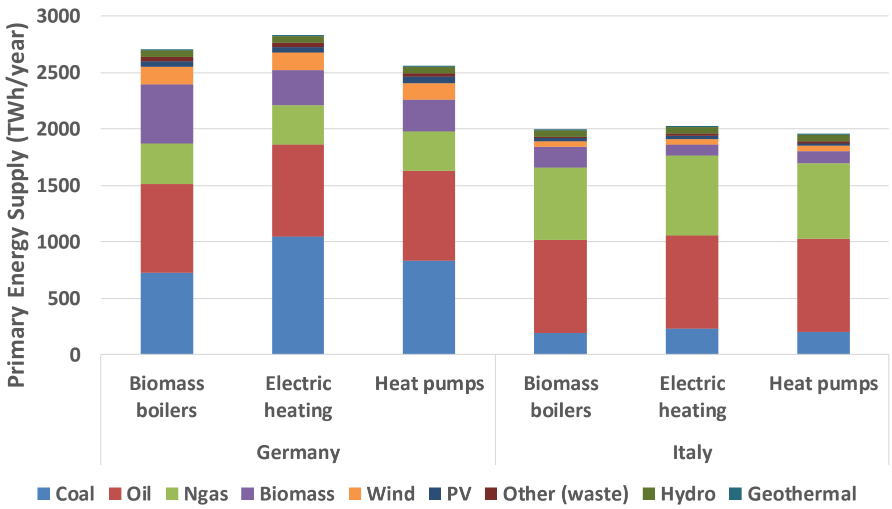

Figure 47: The primary energy supply for Germany and Italy when the individual heating is supplied by either biomass boilers, electric heating or heat pumps.

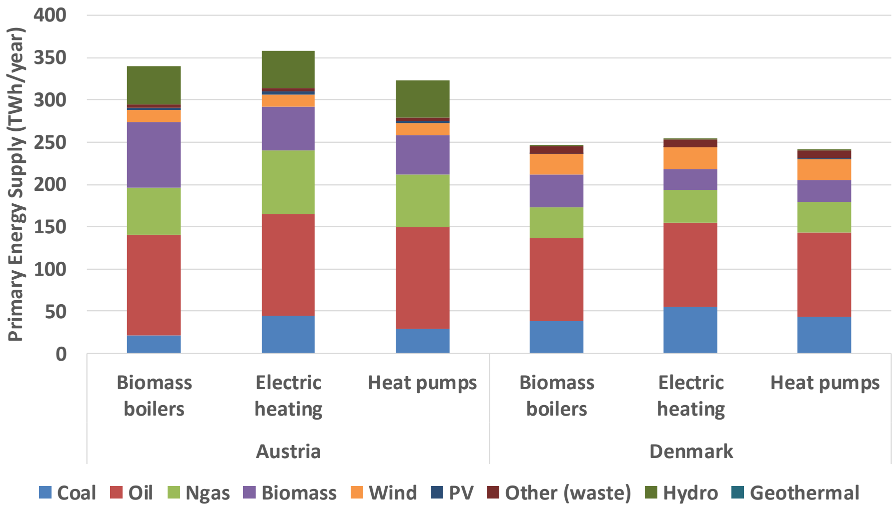

Figure 48: The primary energy supply for Austria and Denmark when the individual heating is supplied by either biomass boilers, electric heating or heat pumps.

In all four countries heat pumps lead to a more efficient energy system consuming less primary energy and more importantly, also reduces the biomass consumption. In later steps this becomes a key factor. Biomass boilers increase the total primary energy consumption by 1-2% while heat pumps reduce the total primary energy by 1-3%.

Biomass boilers increase the total biomass demand by between 30-130% which is significant taking into consideration that this measure only relates to the individual heating sector and to a minor degree the electricity sector. Heat pumps on the other hand increases biomass consumption up to 20% in Germany while it decreases by 10% in Denmark. This is because the electricity production to a higher degree is based on biomass consumption in Germany and that there are relatively few buildings relying on biomass boilers. In Denmark the situation is opposite where only a small share of the power plants consume biomass (with the reference 2050 created in this study) while there is a larger share of biomass boilers that can be replaced by heat pumps to reduce the overall biomass demand. In this step no alternative electricity sources such as wind power and PV is installed at the same time and the additional electricity demand is therefore supplied by power plant production.

For the next steps it is decided to install 80% heat pumps in the systems as well as a share of biomass boilers and electric heating units due to the efficiency improvements described and the reduced reliance on biomass for heating.

6.1.4 Step 4: Renewable heating in district heating

After the first three steps the heating demands have been reduced, district heating has been expanded and the majority of the individual heating supply is converted to heat pumps. Step 4 also deals with the heating sector aiming at integrating a higher share of renewable sources in the district heating networks. Expanding the district heating network enables the utilisation of excess heat and renewable sources that would otherwise not have been possible to integrate. These sources are for example industrial excess heat, heating from waste incineration and geothermal. A large share of these resources would be wasted or unused without the existence of district heating networks. By introducing these renewable sources the demand for other sources such as fossil fuels and biomass will decrease.

The changes in this step include:

- Integration of alternative heating sources in the district heating supply.
- Reductions in fuels consumed by other district heating production technologies.

The excess and renewable heating potentials have previously been assessed in the STRATEGO project [27] and is listed for each of the four countries in Table 19.

Table 19: The excess and renewable heating resources for district heating purposes in each country [27].

Heat source potential (TWh/year)	Waste incineration	Industrial excess heat	Geothermal	Excess heat from conversion to CHP
Germany	44.8	157.3	1.8 (a)	549.9
Austria	5.7	23.2	3.2 (b)	17.4
Italy	11.9	94.7	20.8 (c)	244.1
Denmark	6.8	3.5	-	28.7

(a): [3], (b): [28], (c): [27]

No solar thermal technologies are installed in this step as the solar thermal feasibility is analysed separately in section 7. In addition, the development of the district heating networks also allows for installing large-scale heat pumps in the district heating supply mix. These can utilise excess electricity production in hours of overproduction by converting excess electricity into heating that can be fed into the district heating networks. Large-scale heat pumps for the district heating networks are also installed in this step.

The integration of these heating resources have been carried out taking into account the following limitations:

- The baseload production share of the district heat supply should not exceed 35% [29].
- The supply should not exceed the potentials for each resource.
- The technologies with the lowest heating production costs have to some degree been prioritised, see data for production prices in Appendix A – cost database.
- Security of supply in the energy system must be maintained (industries can close down or move).

Table 20 shows the heat supply mix before and after the integration of further excess and renewable heating sources in the district heating supply mix.

Table 20: District heating supply mix divided by technologies before and after the integration of further excess and renewable technologies

Technology shares of district heating supply (%)	Before integration of excess and renewable sources				After integration of excess and renewable sources			
	Germany	Austria	Italy	Denmark	Germany	Austria	Italy	Denmark
CHP	79	78	93	50	59	53	61	45
DH boilers	13	8	6	13	2	1	1	6
Waste incineration	4	5	1	31	13	14	10	31
Industrial excess heat	4	8	0	4	14	18	13	4
Geothermal	0	1	0	1	4	7	7	7
Heat pumps	0	0	0	1	8	6	8	7
DH imbalance*	0	0	0	0	4	3	0	0
Baseload share	8	14	1	36	31	39	30	41
Total DH demand (TWh/year)	180	22	154	22	180	22	154	22

* The District heating imbalance represents the share of district heating production that cannot be used in the energy system due to a mismatch between heat supply and demand, primarily taking place in the summer period.

The share of CHP and district heating boiler production decreases in all countries as other heating sources are introduced. These sources (waste incineration, industries and geothermal) operate as baseload production and therefore also impacts the district heating imbalance of the systems. This results in some hours of the year where heat production exceeds the demands and this heat therefore has to be wasted (in a sea, lake, air, etc.). These imbalances are however within an acceptable level for all the countries after integrating further baseload production technologies. The baseload share in Denmark is higher than in the other countries due to the high production of district heating from waste incineration, which has been kept at a similar level to the current level.

The integration of these renewable and excess heating sources lead to a lower CHP production which then has to compensated through an increased condensing power plant production. The impact on the primary energy and CO_2 is therefore negligible and actutally increases slightly in Austria and Italy. This is only valid as no alternative renewable electricity production is introduced such as wind power or PV, which takes place in Step 7. In terms of the overall socio-economic costs there is a slight reduction in all countries as some of these energy sources have lower costs than the production technologies they replace.

The introduction of other heating sources could possibly impact the feasible district heating levels as the heat supply might be less costly. The impact of integrating the renewable and excess heat sources on the overall feasible district heating levels was analysed in [22], where it was found that the change in heat supply mix has an insignificant impact on the district heating level.

6.1.5 Step 5: Transport

The transport sector has limited impact on the feasibility of solar thermal and accordingly only few measures have been implemented in the transport sector. This step therefore converts personal vehicles and vans from internal combustion engines to electricity driven battery technologies. Current technology projections indicate that battery technologies will not be realistic to install in heavy-duty transport, aviation and shipping and therefore no changes have been conducted for these modes of transport. They are still consuming fossil fuels similar to the situation expected in the 2050 scenario. Also other technologies for heavy-duty transport such as eRoads are under development, but goes beyond the scope of this study [30].

The changes in this step include:

- Conversion of 75% of petrol and diesel cars to battery electric vehicles
- Conversion of 50% of vans to electric drive vehicles
- Changes in vehicle investment costs and operation and maintenance based on the conversions to alternative technologies
- Additional investments equal to one charging station for every electric vehicle (1,000 €/vehicle)
- Increased power plant capacities due to the increase in electricity demands for transport

The fuels before and after the conversion to electric vehicles are given in Table 21.

Table 21: Transport fuel mix in the four countries before and after the conversions to a higher share of electricity

Transport fuels (TWh/year)	Before conversion				After conversion			
	Germany	Austria	Italy	Denmark	Germany	Austria	Italy	Denmark
Jet fuel	78	8	48	10	78	8	48	10
Diesel	258*	63	274	41	155	38	165	25
Petrol	171	20	160	20	43	5	40	5
Natural gas	0	0	8	0	0	0	8	0
LPG	6	0	16	0	6	0	16	0
Biofuel	34	0	17	0	34	0	17	0
Electricity	9	3	11	0	84	21	88	8

* No fuels for shipping is included for Germany as this data was not available.

The reduction in oil consumption in the transport sector is replaced by a higher demand for coal, natural gas and biomass consumed in the power plants to produce the additional demand for electricity. Due to this the

CO_2 emissions decrease around 3% in all the countries at the same time as the socio-economic costs also decrease.

6.1.6 Step 6: Industry

In Step 6 the industrial sector is converted towards a higher share of renewable sources. The industrial sector is complex to convert to renewable sources as many types of energy demands exist in this sector such as space heating, process heating in various temperatures, cooling and electricity. Industrial demands in this study represents production of goods in industries, but also other types of energy demands such as lubricants, non-energy purposes, flaring of oil, etc.

The changes in this step are:

- Increase in production efficiencies for production of goods due to improved technologies. This has previously been assessed to have a potential that may reduce the overall industrial fuel demand by 20% [31–33].
- Next, it is estimated that 15% of the total fuel demand can be electrified to reduce the depence on solid fuels. This electricification also leads to additional efficiency gains of 20% since electrical driven engines are more efficient [31,34].
- After gaining a higher production efficiency and electrifying a share of the solid fuels the last measure ensures a high-renewable industrial sector. This is ensured through a conversion from the remaining fossil fuel consumption to biomass.

These measures ensures that also the industrial sector is fuelled by a high share of renewable energy. No additional costs have been included for these measures beyond the changes in fuel costs. Other options such as renewable gasses, production of hydrogen and introduction of electrofuels [35] have not been studied in further details as the focus is on solar thermal.

The industrial fuel demand before and after the measures are listed in Table 22.

Table 22: The industrial fuel mix in the four countries before and after the measures are implemented.

Industry fuels (TWh/year)	Before measures				After measures			
	Germany	Austria	Italy	Denmark	Germany	Austria	Italy	Denmark
Coal	94	15	25	3	0	0	0	0
Oil	210	24	252	27	0	0	0	0
Natural gas	229	34	194	24	0	0	0	0
Biomass	32	14	9	3	452	69	364	45
Additional electricity	-	-	-	-	34	5	35	4
Total	564	87	480	58	485	74	398	49

The measures carried out in the industrial sector leads to a reduction in fossil fuels, but a significant increase in biomass consumption. The biomass demands in the industrial sectors after carrying out the measures described are more or less similar to the total domestic biomass potentials in each of the four countries according to the potentials in [36]. This demonstrates that there will be a substantial pressure on future biomass resources and that further actions must be implemented in the industrial sectors. This is however out of the scope of this study where the focus is on solar thermal analysis rather than to create the optimal high-renewable energy system.

The measures in the industrial sector results in overall socio-economic cost reductions of 4-7% compared to before the measures. These reductions originate from the introduction of fuels with lower costs and from the efficiency gains assumed.

6.1.7 Step 7: Renewable electricity supply

In previous steps the electricity demand has increased in the heating, transport and industrial sectors. In Step 7 the electricity production is converted to a higher share of renewable sources especially by integrating more variable sources such as onshore and offshore wind power and photovoltaics. No optimal mix of these resources have been analysed in this study.

The changes in Step 7 include:

- Installation of more variable electricity production (wind and PV).
- Enhanced capacity factors for wind power and PV to what is expected in 2050 [29]

A single data source is used for estimating the renewable potentials across the four countries in order to ensure comparability and therefore data from the JRC (EU Commissions Joint Research Centre) has been used for all countries. It was found that the hydropower potentials in the countries to a large degree already is utilised and is therefore kept constant in the scenarios. The renewable production potentials are presented in Figure 49.

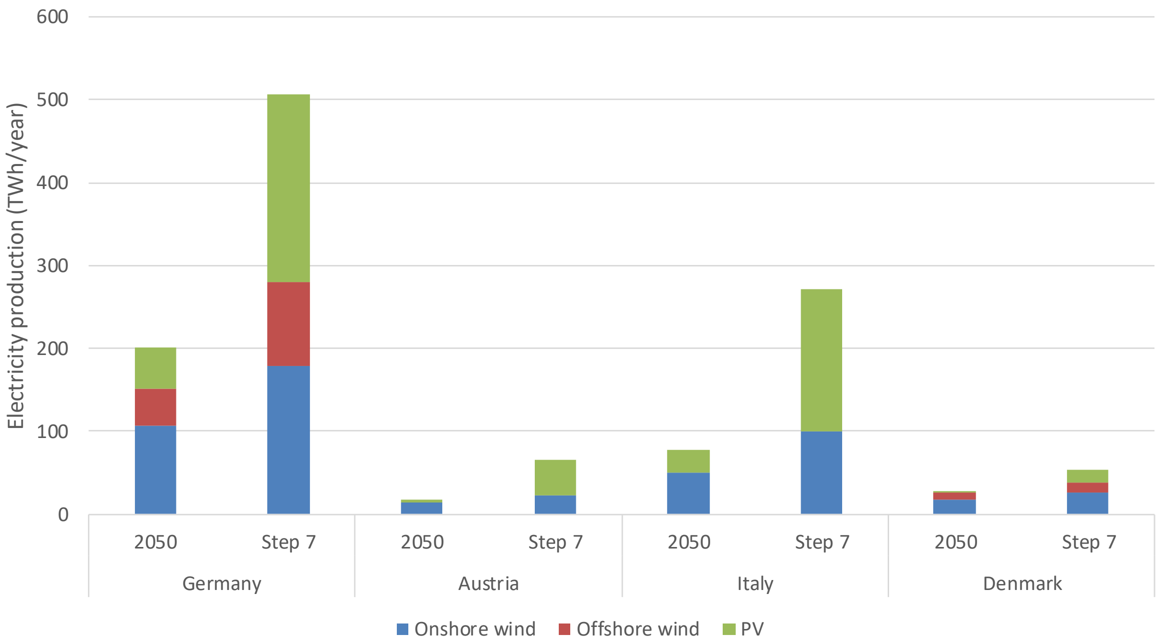

Figure 49: Renewable electricity production before and after installing additional wind power and PV. No offshore wind potentials were identified for Austria and Italy.

The electricity production from variable renewable sources increases by between 100-270% for the four countries. The largest potentials in Austria and Italy are PV while wind power has a higher potential in Germany and Denmark. The variable production replaces electricity production from condensing power plants and CHP plants, see Figure 50.

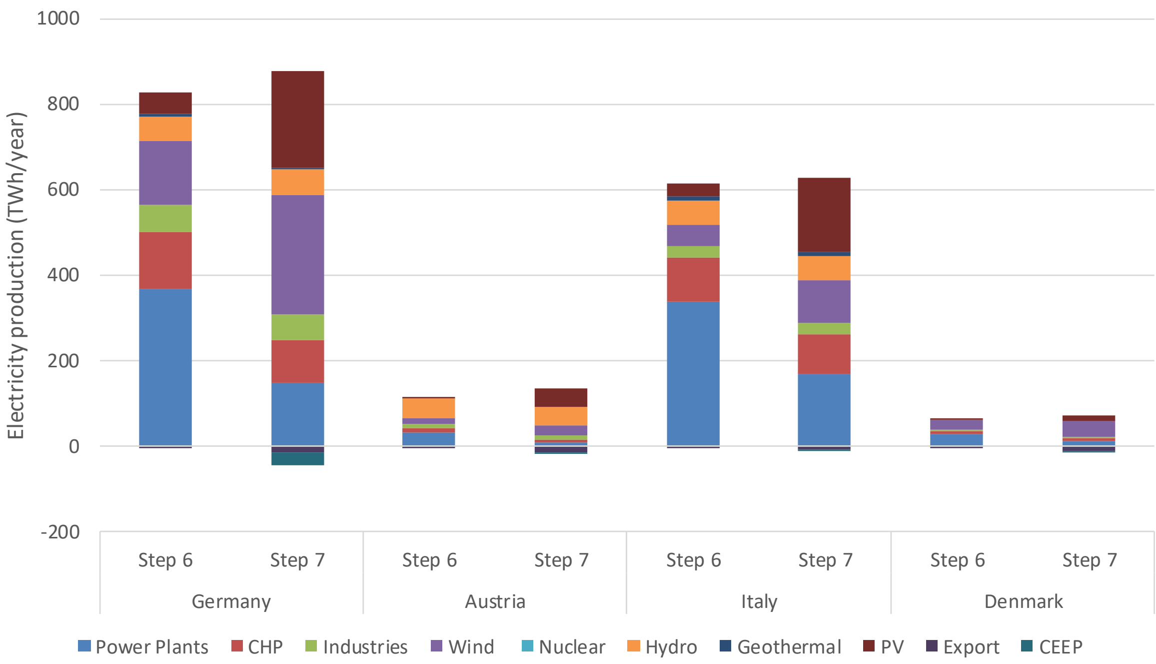

Figure 50: Electricity production technology mix before and after installing additional wind power and PV. CEEP = Critical excess electricity production (unused electricity).

By installing more variable electricity sources the export and unused electricity production (CEEP) increases due to more hours where the electricity production exceeds the electricity demands. In Step 7 the export of electricity is between 2-15% of the electricity production with the highest share in Denmark and the lowest in the German system. On top of this between 0.5-3% of the total electricity produced is wasted as the electricity production exceeds both the electricity demands in a given hour and what is possible to export or store. In these periods the production from variable sources might shut down. This overproduction occurs even though the production is aggregated for a country taking into consideration the differences in weather patterns, etc.

The integration of further renewables highly impact the CO_2-emissions as these decline by 30-40% compared to the previous step. In addition, the overall socio-economic costs also decrease. After this step the primary energy consists of 50-70% renewable sources (including biomass).

6.1.8 Step 8: Biomass conversion – High-RES

In the final Step 8 the remaining fossil fuels consumed in the system are in the transport sector and from thermal plants (condensing power plants, CHP plants and district heating boilers). To ensure a high-renewable system the thermal plants are converted to biomass consumption, which significantly increases the biomass consumption, but ensures a renewable share of the primary energy of 80-85%. The biomass potentials included in Figure 51 are based on data from the Joint Research Centre under the European Commission comparing data across all EU countries [36].

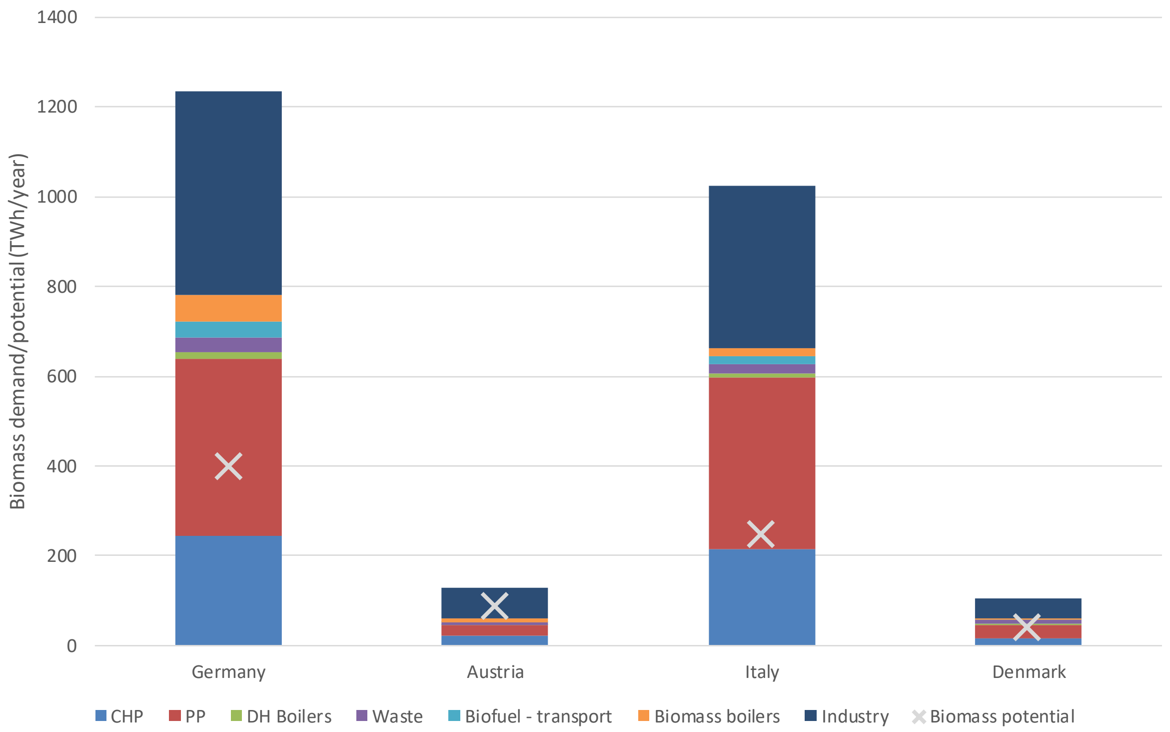

Figure 51: Biomass consumption for the four countries divided by technologies in the high-RES scenario

Figure 51 shows the total biomass consumption in all sectors divided by technologies. For all countries the biomass demand exceeds the biomass potentials with the lowest domestic coverage in Italy where the demand is around 400% higher than the potential. In Austria the demand is around 150% of the domestic potential. This signifies the fact that biomass resources will be a scarce resource in the future.

Biomass becomes the primary fuel in the energy system going from 8% of the total primary energy in 2010 in Germany to 58%, while the numbers for Austria change from 17% to 44%. For Italy the biomass share in 2010 is 6% while it in the high-RES scenario is 62% and for Denmark the share increases from 14% to 48%.

Some measures that could contribute to reducing the biomass demand might be savings in conventional electricity consumption, transport demands (modal shifts, etc.), integration of more renewable electricity and heating, and additional measures related to the industrial sector.

6.1.9 Overall results for the steps

The steps are presented in the figures below for heat production, electricity production, primary energy supply, CO_2-emissions and socio-economic costs. All the figures are presented per capita as this allows for a better comparison across countries.

6.1.9.1 Heat production

The heat produced is highest for all countries in the 2010 scenarios and is expected to decrease per capita towards 2050. Heat savings have a large impact on the overall heat production. After expanding the district heating shares almost half of the heat produced is from CHP plants or district heating boilers. In the individual heating step heat pumps are integrated and supplies a large share of the heating in the high-renewable scenarios. The heat produced per capita in the high-renewable scenarios are between 3-5 MWh/capita/year with the lowest production per capita in Italy.

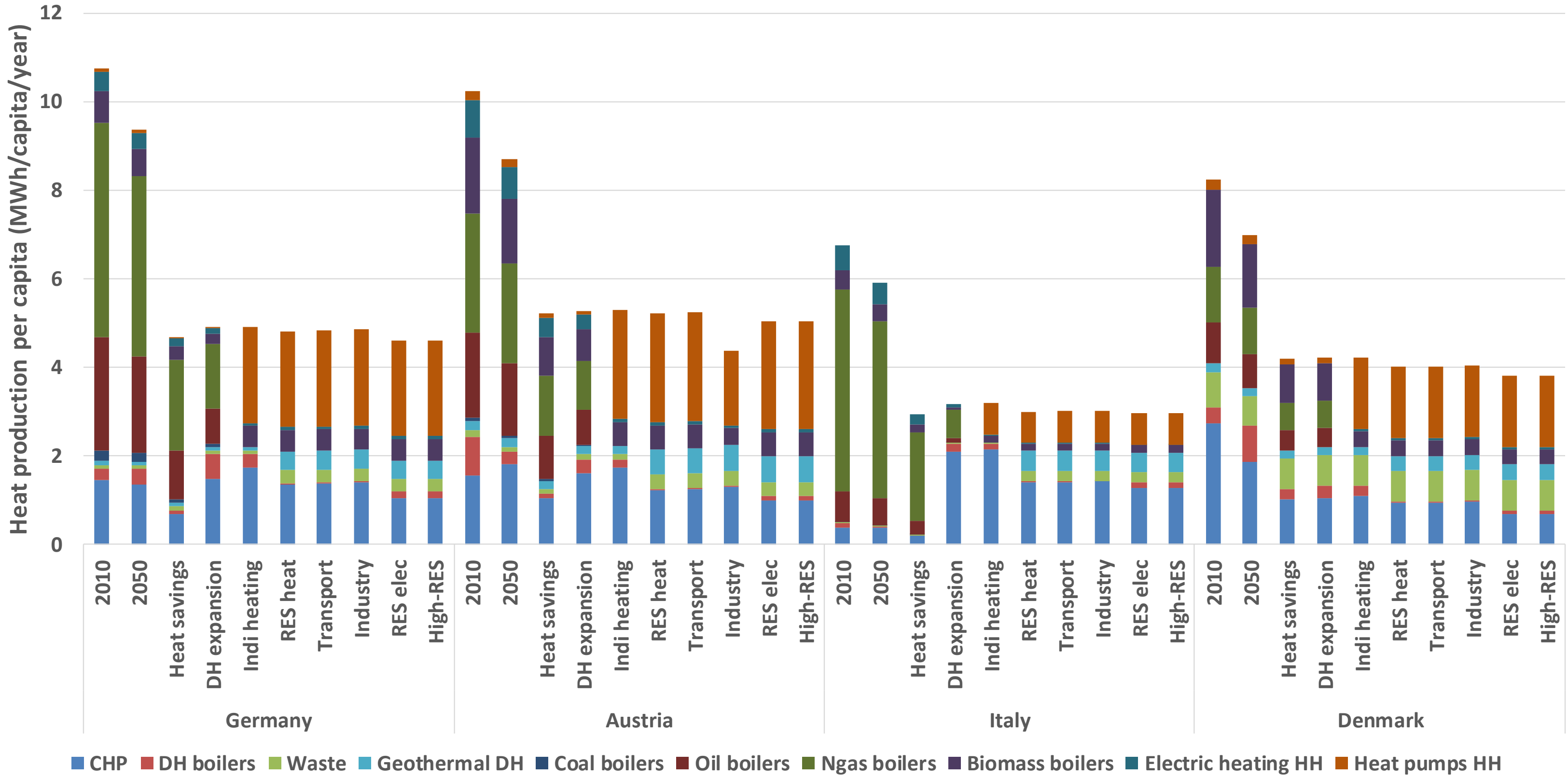

Figure 52: Heat production per capita for each scenario step in the four countries.

6.1.9.2 Electricity production

The electricity production increases for all countries as some sectors such as industry, transport and individual heating increase in electricity consumption. For all countries the share of renewable sources increases while the thermal production (CHP and condensing power plants) remains constant or decreases. In Germany the main technologies for electricity production in the high-renewable scenario are PV and wind power while the nuclear production is phased out. For Austria the main sources are hydropower and PV while in Italy the highest share of the production is from thermal plants. Denmark has the highest share of wind power installed and has no access to hydropower resources. The electricity produced per capita in the high-renewable scenarios are between 10-16 MWh/year.

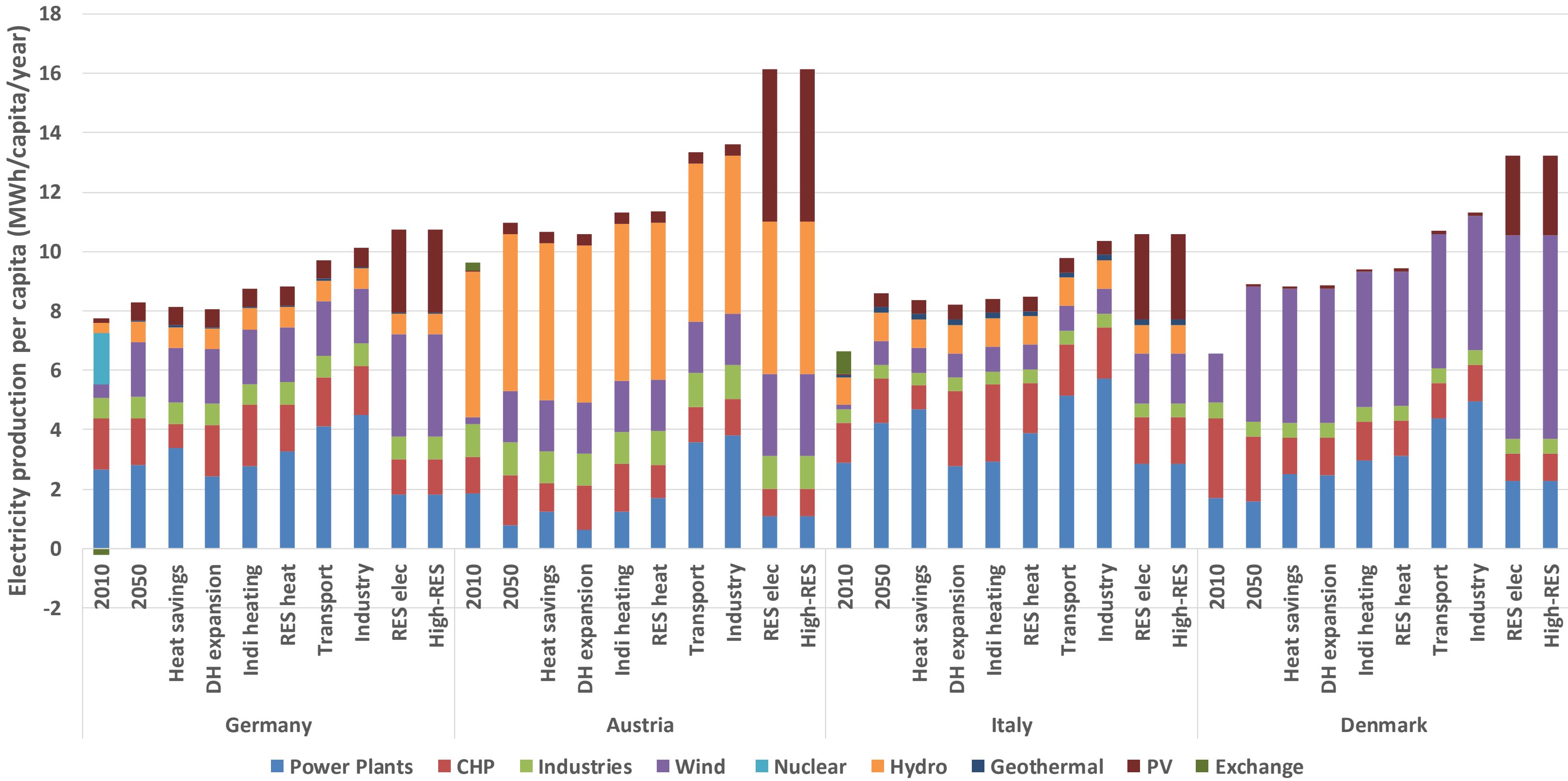

Figure 53: The electricity production per capita for each scenario step in the four countries.

6.1.9.3 Primary energy

The primary energy decreases in all countries when moving towards the high-renewable scenarios as a consequence of the measures implemented. Some of the measures with the highest ability to reduce the fuel demand are heat savings and the integration of more renewable electricity sources because this reduces the conversion losses in the system. The fuel mix changes from a high dependence on fossil fuels in 2010 and 2050 to a higher share of biomass and variable renewables. The highest fuel demands per capita are in Denmark followed by Austria, Germany and Italy.

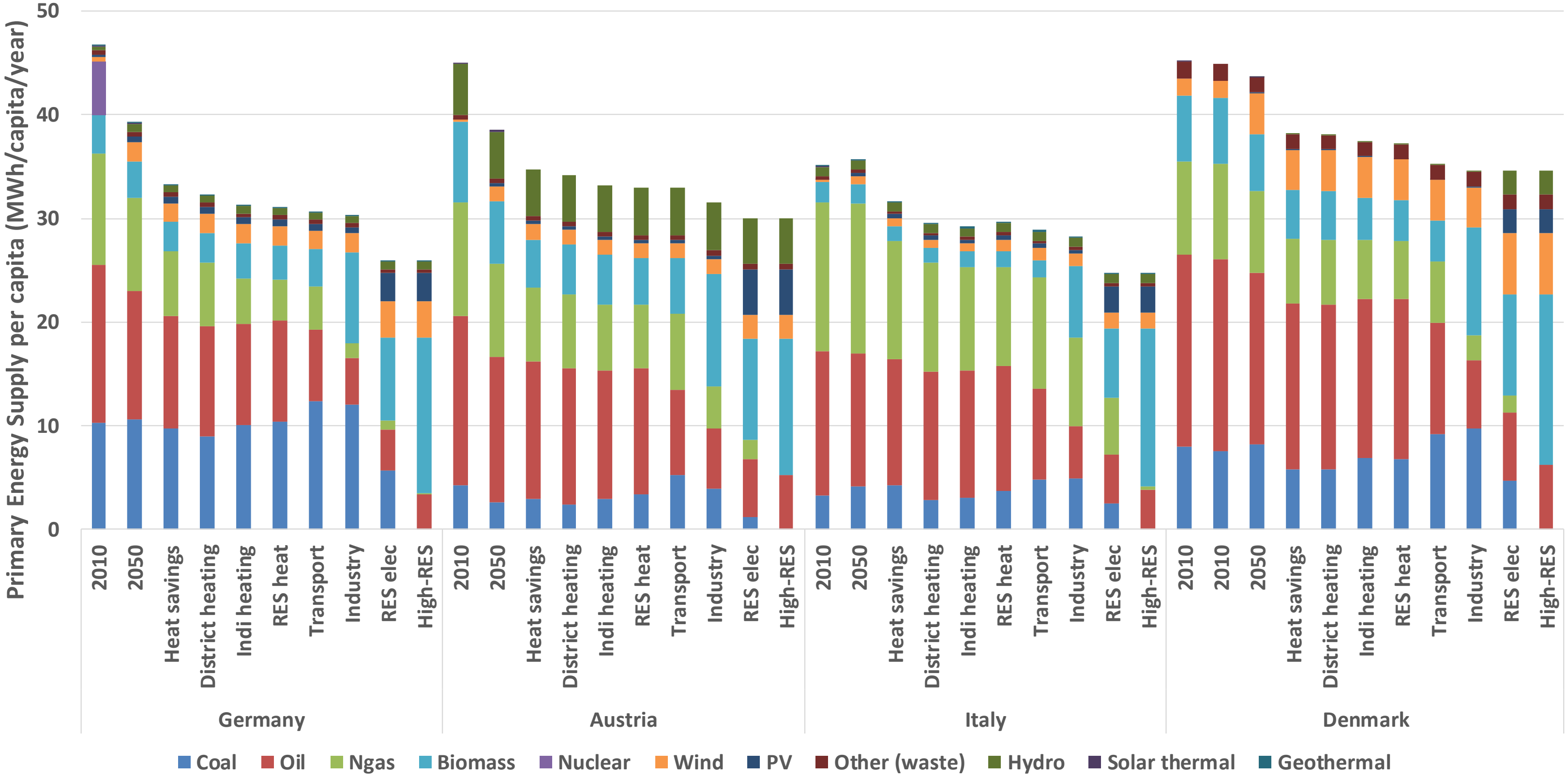

Figure 54: The primary energy sources per capita for each scenario step in the four countries.

6.1.9.4 CO_2-emissions

The scenarios are created to achieve a high share of renewable sources and consequently the CO_2-emissions drop by 80-90% in the high-RES scenario compared to the 2010 scenarios. The emissions in the high-RES scenarios are between 1-2 t/capita/year compared to the current average EU-emission of around 8-9 t/capcita/year. The CO_2 emitted in the high-renewable scenarios is from the transport sector.

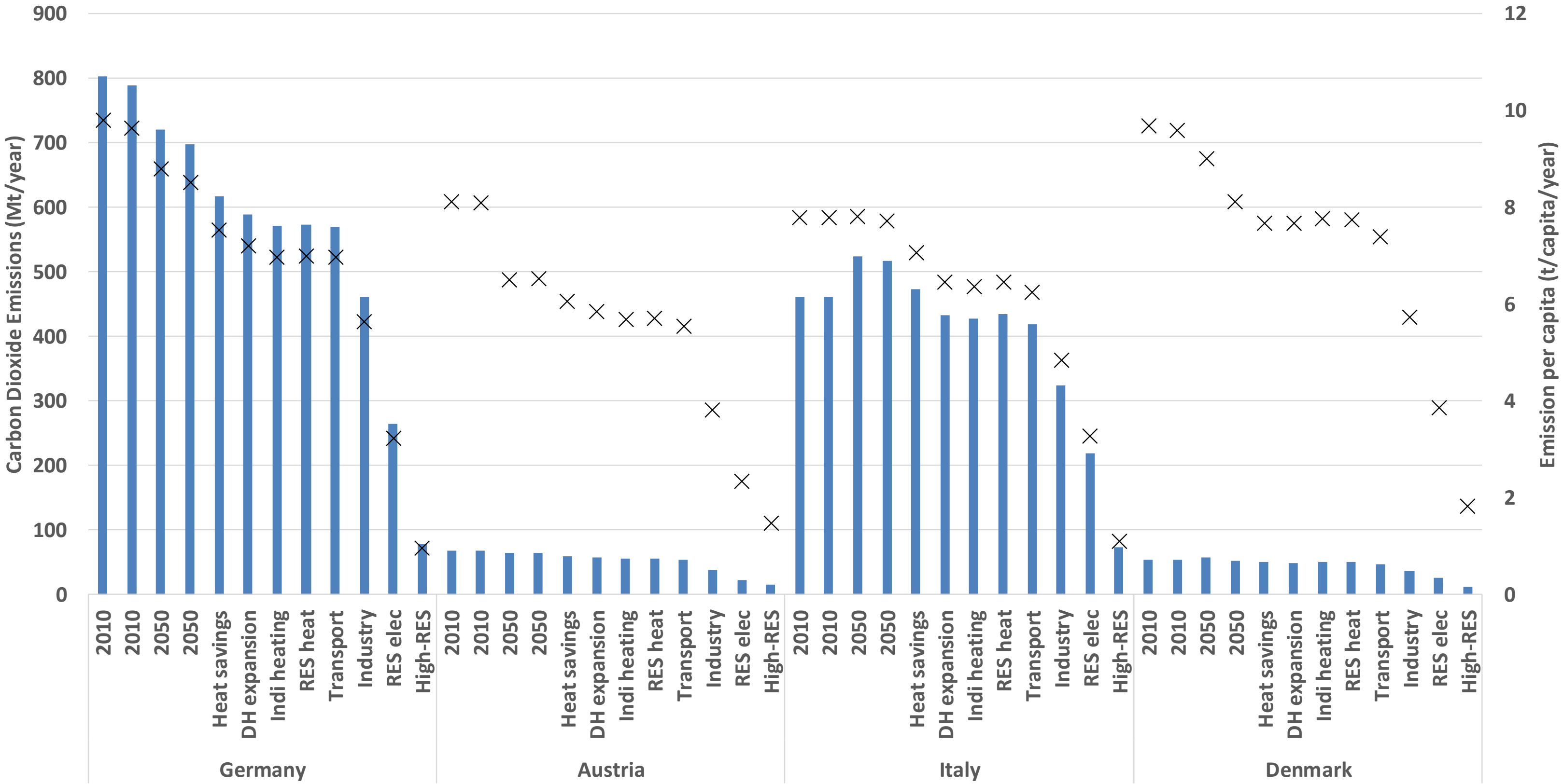

Figure 55: The CO_2-emissions per capita for each scenario step in the four countries. The blue bars represent the total emissions in the countries while the X's indicate the emissions per capita.

6.1.9.5 Socio-economic costs – including vehicles

In terms of socio-economic costs Figure 56 shows that the costs are on a level more or less similar to the 2050 level when moving towards a high-RES energy system. In some cases there are even small reductions, but these are affected by fuel prices, discount rates, etc. The annual costs per capita are between 3,500-5,000 €/year including investments in vehicles in the high-RES scenarios. When excluding vehicle costs the costs are 1,500-2,000 €/capita/year. The trend in the steps indicates that the fuel costs decrease and are replaced by a higher share of investments and operation and maintenance costs. This is the case as e.g. coal and gas power plants are replaced by investments in PV and wind power and that heat savings require significant investments while reducing the fuel costs.

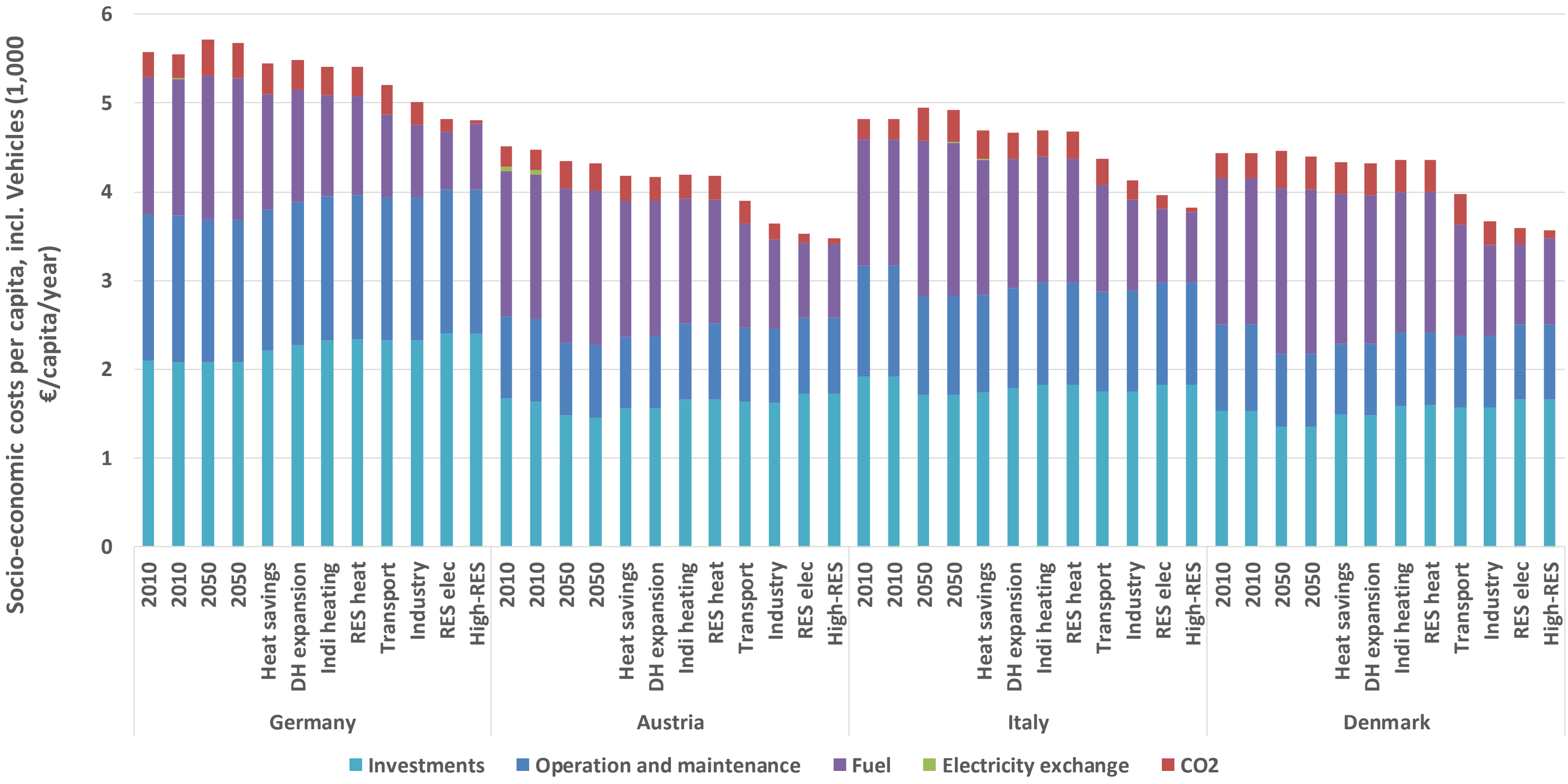

Figure 56: The socio-economic costs per capita for each scenario step in the four countries.

7 Solar thermal analysis

The scenarios described in the previous section are used for the solar thermal analyses presented in the following sections. First, a description of the analysis design is outlined followed by the results of 1) the marginal impact analysis, 2) the analysis of solar thermal system potential and 3) the impact of installing the solar thermal potentials. Finally, this chapter concludes with some sensitivity analysis and a discussion of the connection between solar thermal and temperature requirements.

The solar concepts defined in section 4.3 are analysed in the EnergyPLAN models for five different scenarios. This is to analyse whether the energy system characteristics impact the feasibility of solar thermal and also whether solar thermal might play a larger role in certain countries than in others. Figure 57 illustrates the analysis of the solar thermal concepts, i.e. these are analysed in the 2010 system, the 2050 system and in three of the steps; after heat savings, after district heating is expanded and finally in the high-renewable systems. This allows for a comprehensive assessment of the role of solar thermal under different conditions and in different countries.

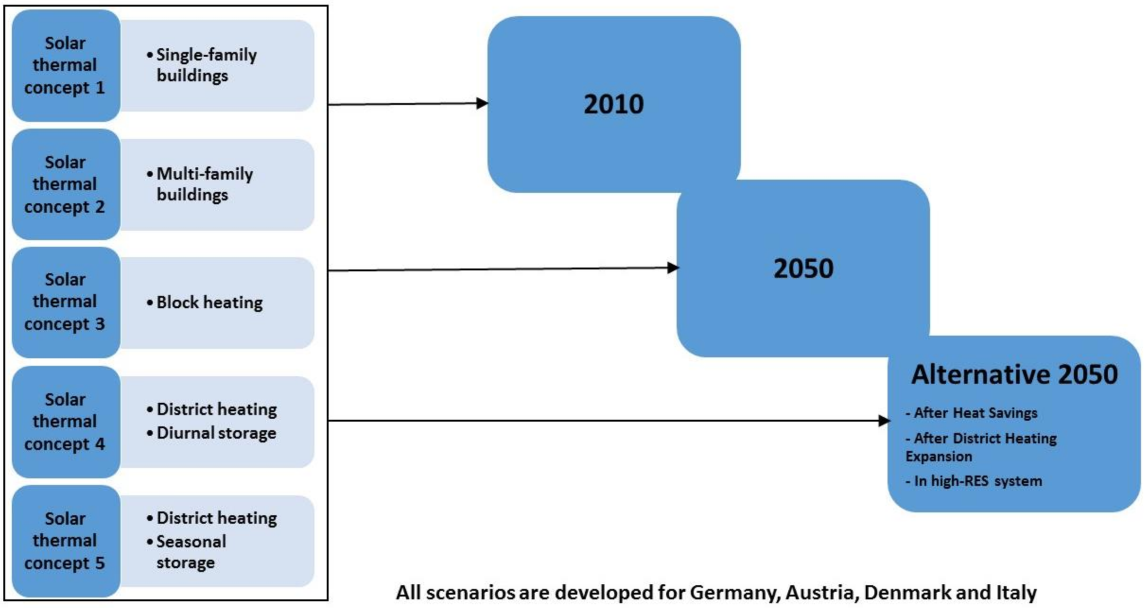

Figure 57: Illustration of the scenarios in which the solar thermal concepts are analysed.

7.1 Marginal impacts of solar thermal

The first type of analysis for identifying the role of solar thermal is a marginal impact analysis. This involves analysing the impact of installing 1 TWh of each solar thermal concept in each country under different conditions. No solar thermal production is installed in the scenarios before this analysis in order to simplify the impact of solar thermal on a given energy system. The impacts are analysed in an energy system perspective meaning that indirect impacts between sectors, investments, etc. are also included. A high number of scenarios have been created as part of this analysis and therefore it is not possible to include all the results. Hence, exemplary findings are presented to highlight the main impacts of the solar thermal integration. In most cases the findings are similar for the 2010, the 2050 and the heat savings scenarios and therefore only one of these are presented.

This analysis investigates the marginal impact of installing the first TWh of solar thermal into the system. However, this impact might not necessarily be the same impact as installing 1 TWh of solar thermal in a system that already has a higher share of solar thermal installed. Other factors such as system dynamics and the flexibility of the systems will be more relevant when a system already has solar thermal. An example might be regarding the imbalances in a district heating network as solar thermal only produces heating in periods with sun. If solar thermal is already installed there is less flexibility left for installing additional solar thermal which could lead to overproduction of heating exceeding the demands or the volume that is possible to store. The marginal impact analysis of installing the first TWh of solar thermal will however provide valuable insights into the impacts of installing solar thermal in an energy system. The subsequent analyses in section 7.2 investigate the maximum solar thermal potentials that might be installed in a country. Combined with the marginal analysis in this section a large range of solar thermal capacities are therefore analysed. The future solar thermal shares will most likely be somewhere in between these two extreme scenarios.

The marginal impacts of solar thermal are presented for heat production, electricity production, primary energy, CO_2-emissions and socio-economic costs.

7.1.1 Heat production

Installing solar thermal has an impact on the heat supply as other technologies will need to produce less. In the individual areas heat supply from three types of boilers is replaced depending on the fuel consumed in that boiler. In Germany and Italy the majority of the boilers replaced are fuelled from natural gas while in Austria and Denmark more boilers also consume biomass. Overall, 1 TWh of solar thermal replaces 1 TWh of heat produced from other sources.

In the district heating areas in the 2010 scenarios the district heating supply is mostly from district heating boilers and CHP plants. Hence, the solar thermal replaces these types of technologies.

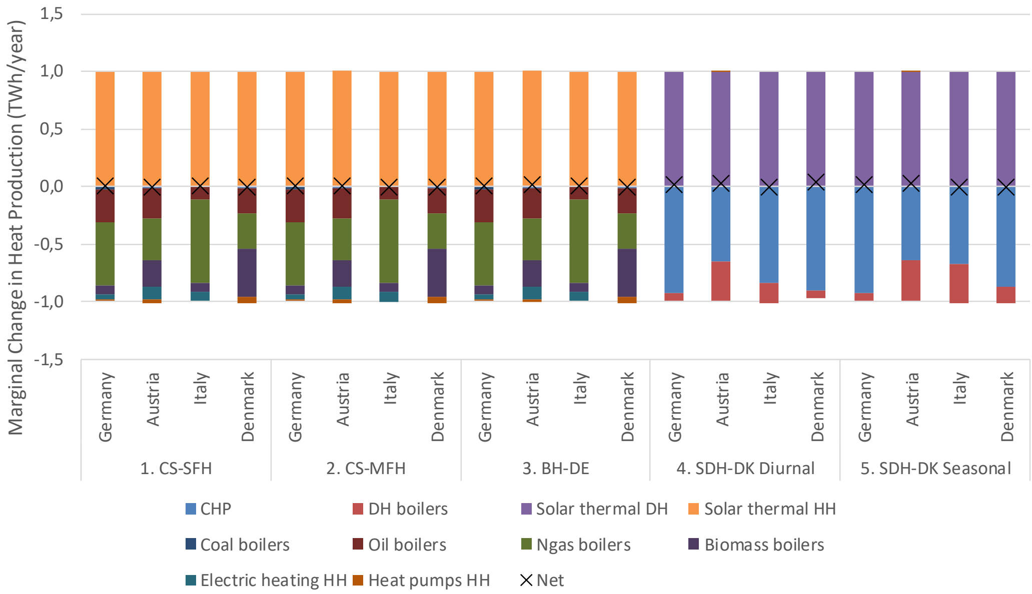

Figure 58: Marginal changes in heating supply in the 2010 scenarios when installing 1 TWh of solar thermal.

The marginal impacts of installing solar thermal in the 2050, heat savings and district heating scenarios are rather similar to the impacts in the 2010 scenarios and are therefore not illustrated.

In the high-RES scenarios installing solar thermal results in a different impact as the heat supply mix is different. In the individual areas the majority of the heat supply is from heat pumps and to a lesser degree from biomass boilers and electric heating. In the district heating areas the solar thermal replaces a smaller share of other heating technologies. Even though 1 TWh of solar thermal is installed only between 0.2-0.9 TWh of other heat supply is replaced due to the impact that solar thermal has on the district heating balance.

The solar thermal production reduces the production from CHP plants and district heating boilers in the energy systems.

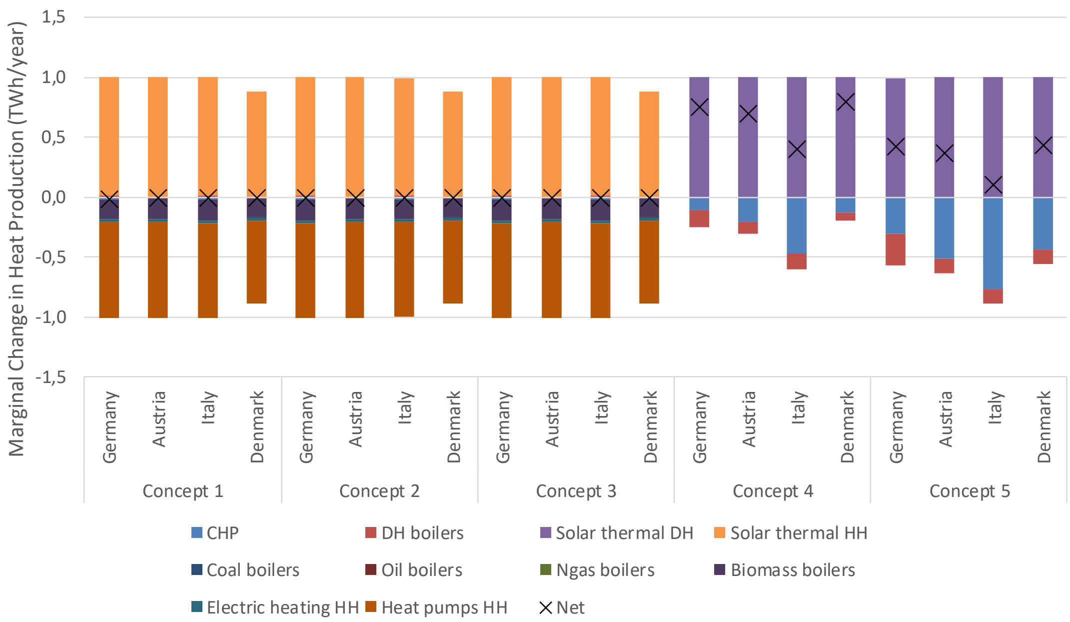

Figure 59: Marginal changes in heating supply in the high-RES scenarios when installing 1 TWh of solar thermal.

7.1.2 Electricity production

The solar thermal installations also impact the electricity production mix. In the 2010 scenarios it is only the district heating solar thermal technologies that affect the electricity production as the majority of the individual supply replaced is produced from oil, gas or biomass boilers. In the district heating networks however, the CHP production decreases as it is replaced by solar thermal production and therefore the condensing power plants need to operate more. This is the case in a system similar to the current system and could potentially change in a system where more variable renewable electricity production is implemented.

The high impact on the electricity production in the Italian energy system is due to the low thermal efficiency for CHP plants assumed in the model. This means that when 1 TWh of heat production from CHP plants is replaced by solar thermal a higher electricity production also has to be produced by alternative sources.

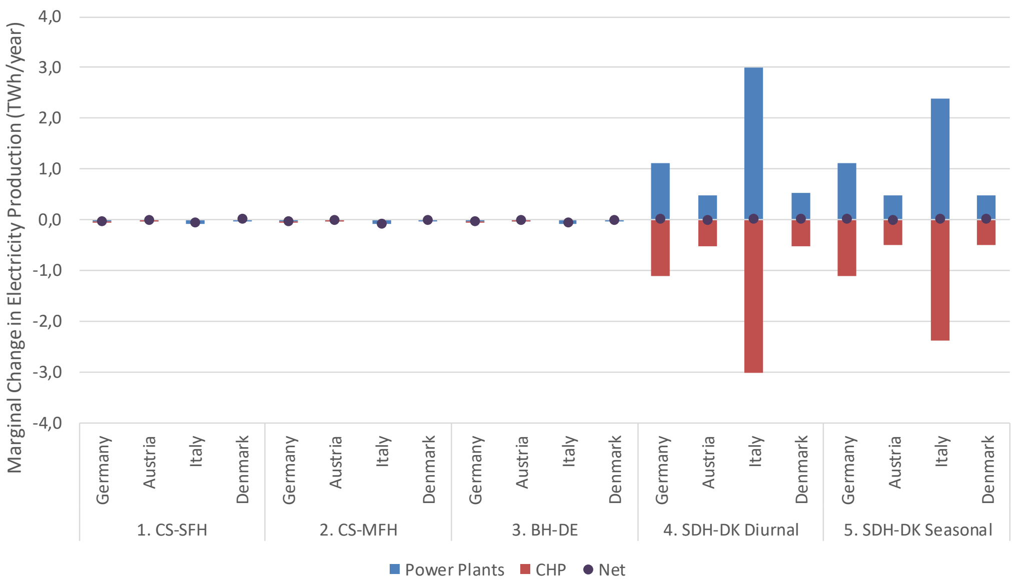

Figure 60: Marginal changes in electricity supply in the 2010 scenarios when installing 1 TWh of solar thermal.

Rregarding electricity production the 2050, heat savings and district heating scenarios are rather similar to the impacts on the 2010 scenarios.

When investigating the electricity production in the high-RES scenarios also the individual solar thermal impacts the electricity production due to the higher share of heat pumps. However, for the individual areas the solar thermal integration simply reduces the electricity demand while in the district heating areas the production mix is affected to a higher degree. Here, CHP plant production is replaced by more production at condensing power plants.

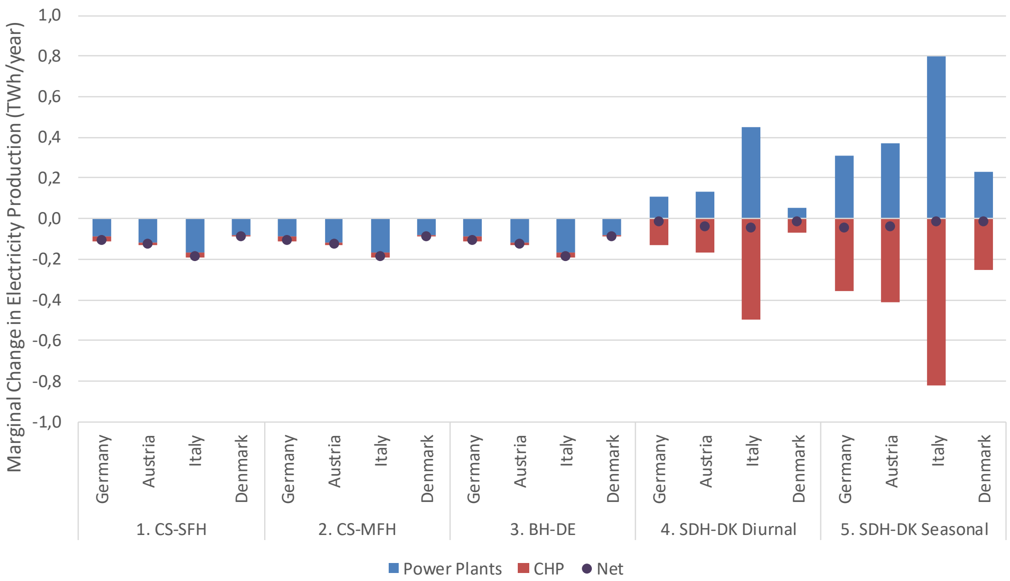

Figure 61: Marginal changes in electricity supply in the high-RES scenarios when installing 1 TWh of solar thermal.

7.1.3 Primary energy

The primary energy demand is impacted based on a number of factors including; which technologies are replaced, their efficiencies and how these technologies are fuelled. This differs between the countries and consequently differences appear regarding the fuels that are replaced when installing solar thermal, see Figure 62. In general, when installing 1 TWh of individual solar thermal (concept 1-3) around 1 TWh of fuels are replaced, primarily oil and gas, but also biomass in Austria and Denmark. This is a direct consequence of a reduction in boiler production.

For concepts 4 and 5 where solar thermal is installed in district heating networks more dynamics occur in the energy system impacting the electricity sector. By installing solar thermal in the district heating networks less production is needed from CHP plants which in turn must be replaced by electricity production from condensing power plant. This means a lower energy system efficiency leading to an overall higher primary energy demand. When comparing only the fossil fuel demands solar thermal does however lead to a reduction.

An example is in Italy where installing 1 TWh of solar thermal reduces the CHP production by around 1 TWh of heat production and since the thermal efficiency of CHP plants in Italy is rather low in the 2010 scenario these plants also produce 3 TWh of electricity less. The low thermal efficiency is based on the data input sources and is improved for the 2050 scenarios where the thermal efficiency in Italy is similar to the other countries. This reduced CHP production then has to be produced by condensing power plants consuming coal and natural gas. The CHP plants on the other side consume oil and gas and this is why the coal demand increases while the oil and gas demand decreases in Figure 62. In the 2050 BAU scenario where the thermal efficiency of CHP plants in the Italian system is improved the impacts in Italy become more similar to the impacts of installing solar thermal in the district heating networks in Germany and Austria.

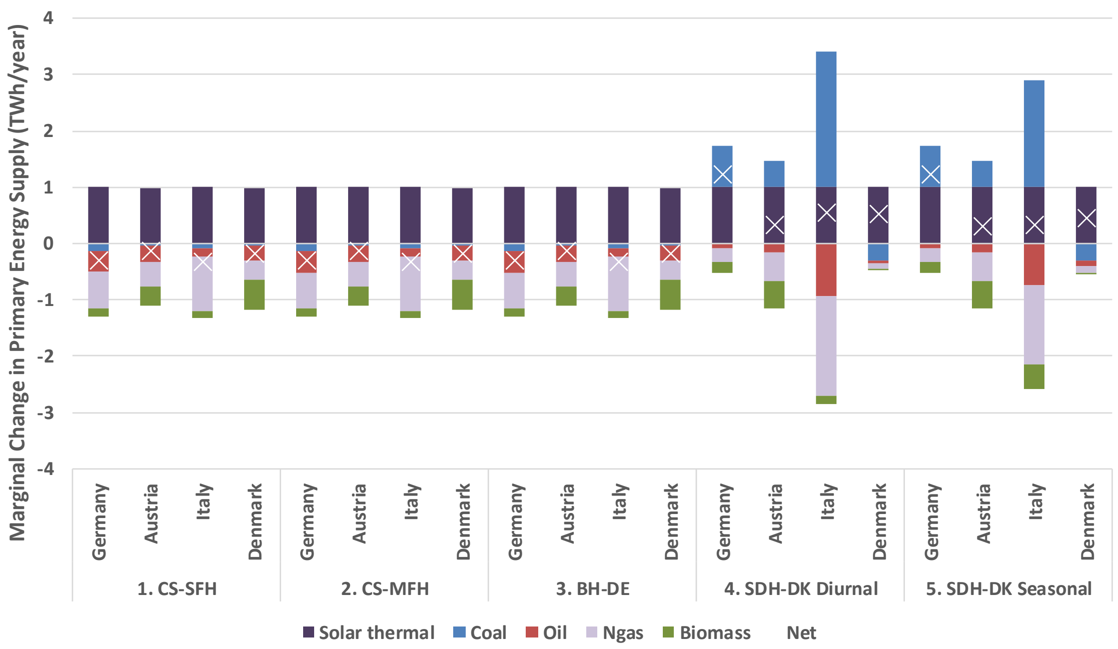

Figure 62: Marginal changes in primary energy supply in the 2010 scenarios when installing 1 TWh of solar thermal.

A similar impact as in the 2010 scenarios is valid for the 2050, heat saving and district heating scenarios.

After converting the energy system into a high-renewable system with heating and electricity sectors supplied only by renewable sources the solar thermal integration has a different impact compared to the other scenarios. Here, only biomass is replaced as no fossil fuels are consumed. Installing 1 TWh of solar thermal in individual areas will replace between 0.5-0.7 TWh of biomass in the high-RES scenario.

In the high-RES system less than 0.5 TWh of biomass is replaced when installing solar thermal in the district heating areas. This is because in this system many sources to supply the heating is installed beyond CHP plants and district heating boilers. For example, some of the district heating production technologies replaced are large scale heat pumps consuming wind power. When installing solar thermal there is less need for heat production from the large heat pumps and consequently, the excess production of wind power increases slightly making the system less flexible. This also occurs for the individual technologies where the individual heat pump demand reduces thereby increasing the excess wind production throughout the year.

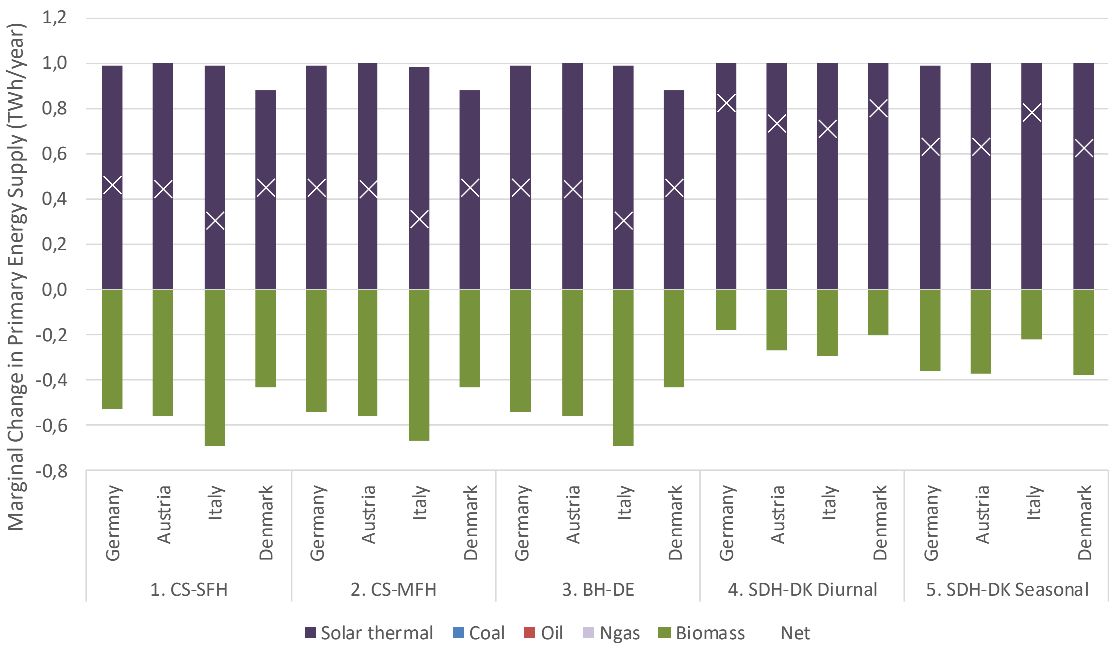

Figure 63: Marginal changes in heating supply in the district heating scenarios when installing 1 TWh of solar thermal.

7.1.4 CO2-emissions

The changes in primary energy subsequently impacts the CO_2-emissions in the system. In the analysis it is assumed that the combustion of biomass does not impact the energy system CO_2-emissions, even though this is debated in recent years. If this assumption is altered the overall results will also change.

In the 2010 system all individual solar thermal technologies lead to a reduction in CO_2-emissions as natural gas and oil boilers are replaced. In the district heating areas the situation is more diverse as Germany and Italy experience an increase in emissions while Austria is unaffected and the Danish energy system emissions decreases with the installation of solar thermal. The reason for the reductions in the Danish system is that the CHP production replaced by solar thermal to a higher degree is supplied by coal than in the other countries where the majority of the CHP plants are fuelled from natural gas.

The increase in emissions for Germany and Italy is due to the decreasing CHP production and the increasing production from condensing power plants leading to a higher coal demand. With a situation much similar to today the solar thermal integration in the district heating networks might therefore lead to an increase in CO_2-emissions, but this depends on the fuels are replaced.

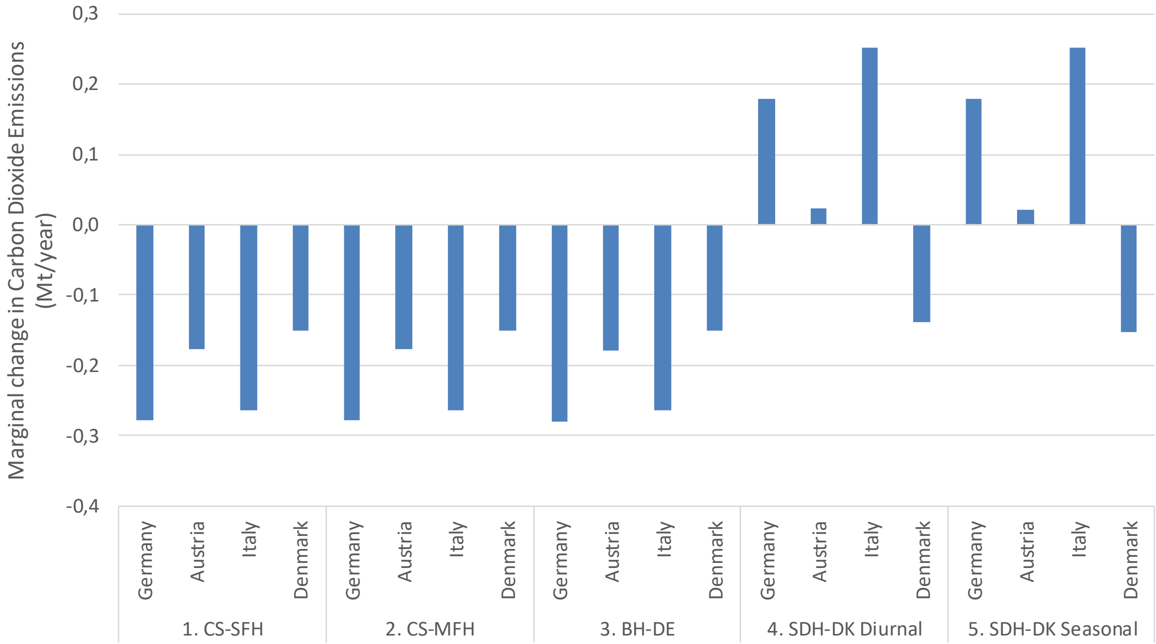

Figure 64: Marginal changes in CO_2-emissions in the 2010 scenarios when installing 1 TWh of solar thermal.

Similar trends as in the 2010 scenarios occur for the 2050, heat savings and district heating scenarios.

In the high-RES scenarios no emission changes take place when installing solar thermal as the fuel mix in the heating and electricity sectors is already CO_2-neutral. Hence, solar thermal will only replace other renewable sources.

7.1.5 Socio-economic costs

The marginal socio-economic cost changes illustrated in Figure 65 is a consequence of a number of factors including; the fuel prices, discount rates, the technology investment prices as well as the solar production costs in the various countries. These can all be contested and a more thorough sensitivity analysis can be found in section ?. Accordingly, the cost analysis should be seen as best indications when taking into consideration the uncertainties mentioned.

In the 2010 scenarios the additional costs for installing solar thermal exceed the savings in fuels and CO_2 costs for the individual solar thermal technologies in all countries. When installing solar thermal in the district heating networks the investment costs are lower and lead to cost reductions in Italy and Austria. This can be contributed to the lower solar thermal production costs in the district heating technologies compared to the individual technologies. The largest cost reductions occur in Italy where the largest share of gas is replaced which has a higher cost than coal and biomass. Another factor benefitting the Italian system are the lower solar thermal production costs.

For the Danish system the analysis shows that the socio-economic costs will increase when installing solar thermal in the district heating networks. This is counterintuitive when considering the current trends in Denmark where large solar thermal plants are being installed. This can be contributed to the fact that there are different incentives when considering socio-economic costs and private-economic costs. The large solar thermal plants in Denmark might demonstrate a feasible business case from a private-economic perspective where other factors such as subsidies, regulations and fuel taxations also impact the economy. In Denmark, solar thermal plants can for example contribute to energy efficiency improvements for the district heating companies, which have to improve their energy efficiency performance every year according to existing legislation.

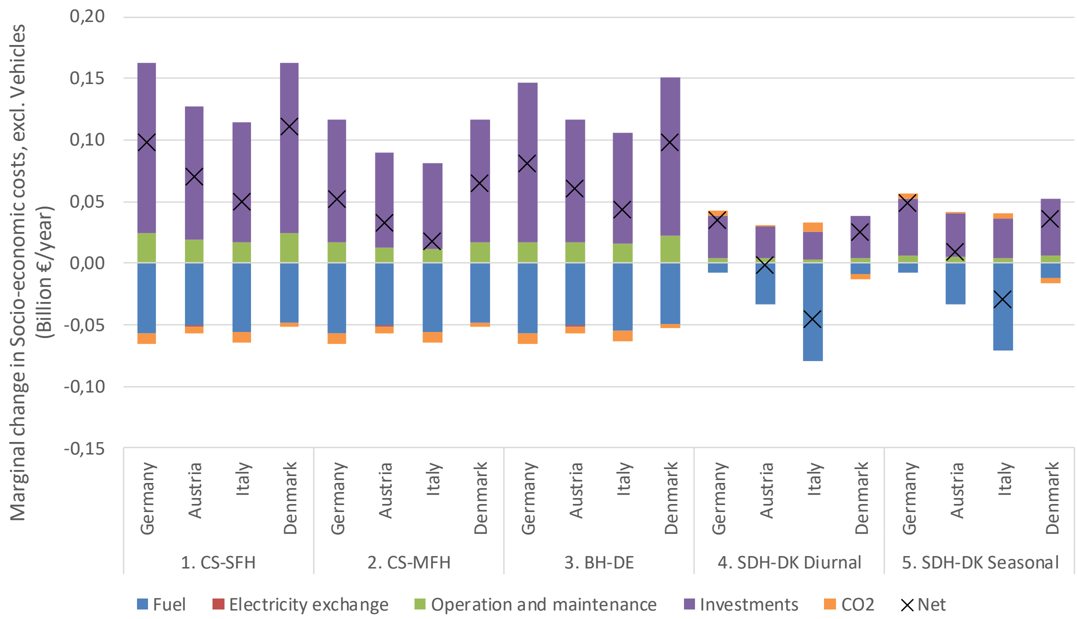

Figure 65: Marginal changes in socio-economic costs in the 2010 scenarios when installing 1 TWh of solar thermal.

In the 2050 scenarios changes are assumed for three main factors influencing the overall socio-economy of solar thermal. Firstly, the fuel prices are expected to be higher than currently leading to larger cost savings, secondly the CO_2 costs are also slightly higher and thirdly, the solar thermal investment prices are lower than in 2010. All of these factors lead to an improved economic impact of installing solar thermal in both individual and district heating areas compared to the 2010 scenarios.

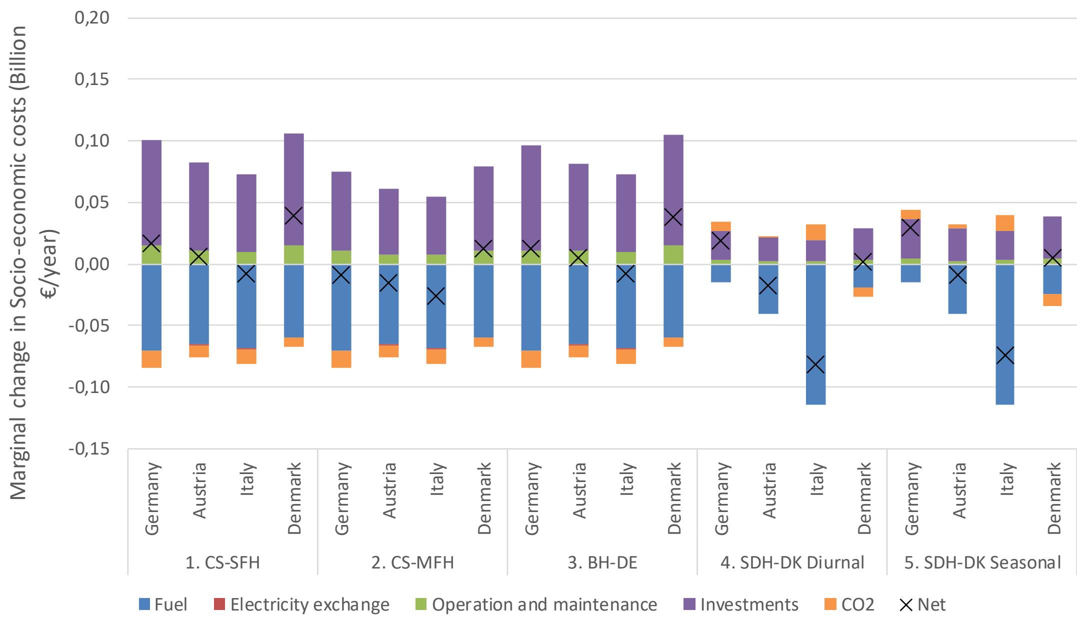

Figure 66: Marginal changes in socio-economic costs in the 2050 scenarios when installing 1 TWh of solar thermal.

Installing solar thermal in the high-RES scenarios increases the socio-economic costs for all solar concepts in all countries. The reason is that there no longer are any economic savings from CO_2 costs when installing solar thermal as the heat supply is already CO_2-neutral. Furthermore, the fuel replaced is now based on cheaper fuels such as heat from heat pumps supplied by PV or wind power. Hence, the investments remain the same, but the savings decrease leading to overall higher costs when installing solar thermal.

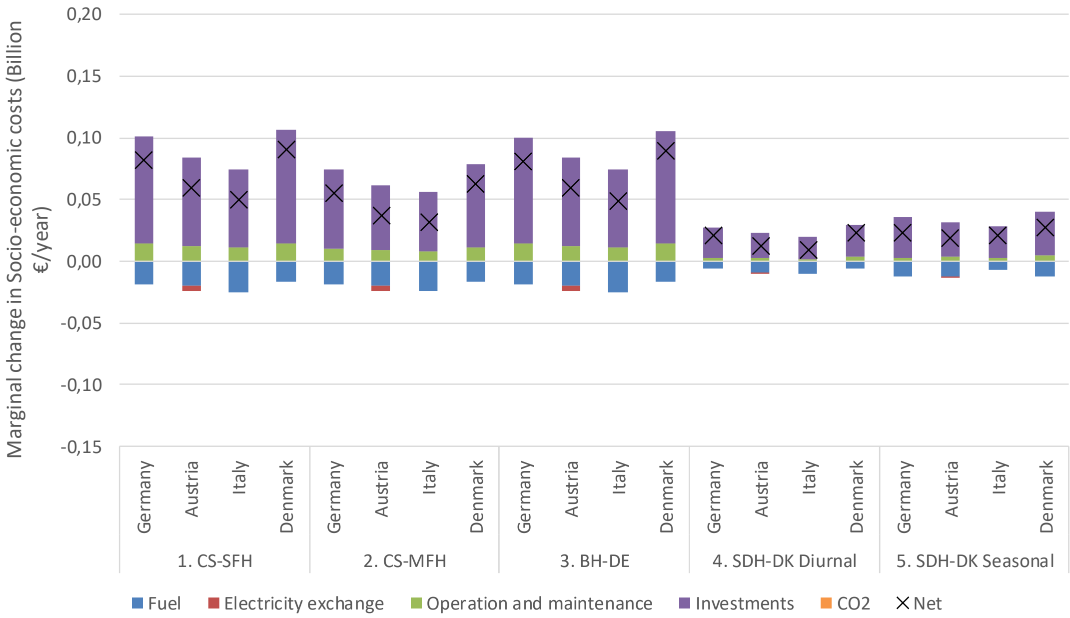

Figure 67: Marginal changes in socio-economic costs in the high-RES scenarios when installing 1 TWh of solar thermal.

The key findings from the marginal impact analysis show that the solar thermal impact depends on what is directly and indirectly replaced in the energy system meaning that integrated energy systems analysis is necessary to analyse the role of solar thermal.

The impacts on primary energy are related to three factors; the technologies that are replaced, the efficiency of the replaced technology as well as the fuel source for the replaced technology (fossil fuel, biomass consumption or fuel free, e.g. wind power, geothermal).

The key factors impacting socio-economic costs are; the fuel prices, the discount rates, the technology investment prices as well as the solar thermal production costs.

- Findings for four of the five scenarios (the scenarios where there is still significant fossil fuel consumption; 2010, 2050 BAU, heat savings and district heating):
  - Installing 1 TWh of solar thermal replaces 1 TWh of alternative heat production (individual oil, gas or biomass boilers or CHP plants and district heating boilers in district heating areas)
  - Installing 1 TWh of solar thermal replaces approximately 1 TWh of primary energy in individual areas. For district heating systems the total primary energy increases, while the fossil fuel consumption decreases.
  - Installing solar thermal in district heating areas reduces CHP electricity production and conversely increases the condensing power plant production.
  - The CO_2-emissions decrease when installing solar thermal in individual areas. In the district heating areas, some countries experience increasing CO_2-emissions while other countries experience decreasing emissions depending on the fuels replaced.
  - The socio-economic costs increase in individual areas when installing solar thermal as the additional investment costs exceed the savings in fuel expenditures. In district heating areas, the economic impacts are cost-neutral, but depend on the fuels replaced.
- Findings for the high-RES scenario where fossil fuels are only consumed in the transport sector:
  - Installing 1 TWh of solar thermal in the individual areas replaces 1 TWh of heat production from heat pumps or biomass boilers. In the district heating areas, less than 1 TWh of heat

production is replaced due to mismatches between periods with solar thermal supply and district heating demand.

- Installing additional solar thermal in individual areas results in decreasing electricity demand due to lower heat pump operation. When installing additional solar thermal in district heating areas the CHP plants produce less heat and electricity, thereby requiring the condensing power plants to produce more.
- Less than 1 TWh of biomass is replaced in the individual areas when installing solar thermal as highly efficient production from heat pumps is replaced. In district heating areas, the biomass reductions are even lower due to the system design with fuel-free heat sources such as geothermal and industrial excess heat and efficient supply from large heat pumps.
- There are no impacts on CO_2-emissions in the high-RES scenario as no fossil fuels are consumed.

  The socio-economic costs increase in the high-RES scenarios in both individual and district heating areas in all countries when increasing the solar thermal production due to the lower value of the fuels replaced (biomass, wind power) and since there are no CO_2 costs.

7.2 Technical system potential of solar thermal

This section presents the analysis of the solar potentials that might be installed in each country. Similarly to previous analysis the solar thermal potentials are analysed for five different scenarios (2010, 2050, heat savings, district heating and high-RES) as well as for the four countries. The maximum solar thermal potential is presented for each of the countries followed by a description of the measures that impact the solar thermal potentials.

7.2.1 Defining the technical system potential

The technical solar thermal potential is defined as the solar thermal potential that the energy system might accommodate in terms of reducing mismatches between energy supply and demand. Hence, no considerations have been included regarding space requirements, manpower for installing the plants, impact on landscapes, etc.

Some key assumptions are defined below as these determine the solar thermal potentials for each system.

Firstly, it is found that the solar thermal "penetration" has a significant impact on the solar thermal share that can be installed in a system. The solar penetration refers to the share of buildings that are connected to a solar thermal system, i.e. a solar penetration share of 20% means that 20% of all heat consumers are connected to a solar thermal plant, either directly in the building or connected via a district heating system. In the analysis two values are defined as border values for the solar penetration; 20% and 50%. Therefore, in the analysis it is assumed that the maximum share of consumers that are connected to a solar thermal system can be 50%. If this value is higher than 50% then the solar thermal potential will also increase.

The solar thermal penetration is crucial because when more consumers are connected to a solar thermal plant the peak production during summer periods can be distributed to a higher number of consumers. If a low share of consumers are connected to the plant the 5% overproduction might equal a lower solar thermal production as the peak production in more hours exceeds the demands.

Secondly, solar thermal is a variable energy source and as more capacity is installed in the system more of the production might be "wasted" due to the system flexibility. Hence, it is necessary to define a threshold for overproduction of solar thermal. This has been defined using two factors; 1) the overproduction of solar thermal can be maximum 5%, i.e. maximum 5% of the solar produced at the plant can be wasted in the system and 2) the district heating imbalance must not exceed 5% meaning that the annual district heating production that is wasted due to a mismatch between demand and production is below or around this threshold.

The significance of selecting the maximum solar thermal overproduction as 5% is indicated in Figure 68 showing the maximum solar thermal potential as a share of the heat production at different overproduction levels. The example shows the case of Germany 2010 for both individual solar thermal and district heating solar thermal. The figure shows on the x-axis the level of overproduction that is acceptable before the maximum solar thermal potential is identified while the y-axis indicates the solar thermal share in the energy system. The impact of this threshold is investigated for four different scenarios, i.e. solar thermal for individual and district heating purposes as well as with a low and high solar thermal penetration rate.

The figure shows that the overproduction level has an impact on the solar production that can be installed in the system, but that the impact is less significant than other factors. When increasing the overproduction level from 5% to 10%, then 10% more solar thermal production might be installed in the system. This corresponds to an increase in the solar thermal share of up to additionally 1% of the heat production.

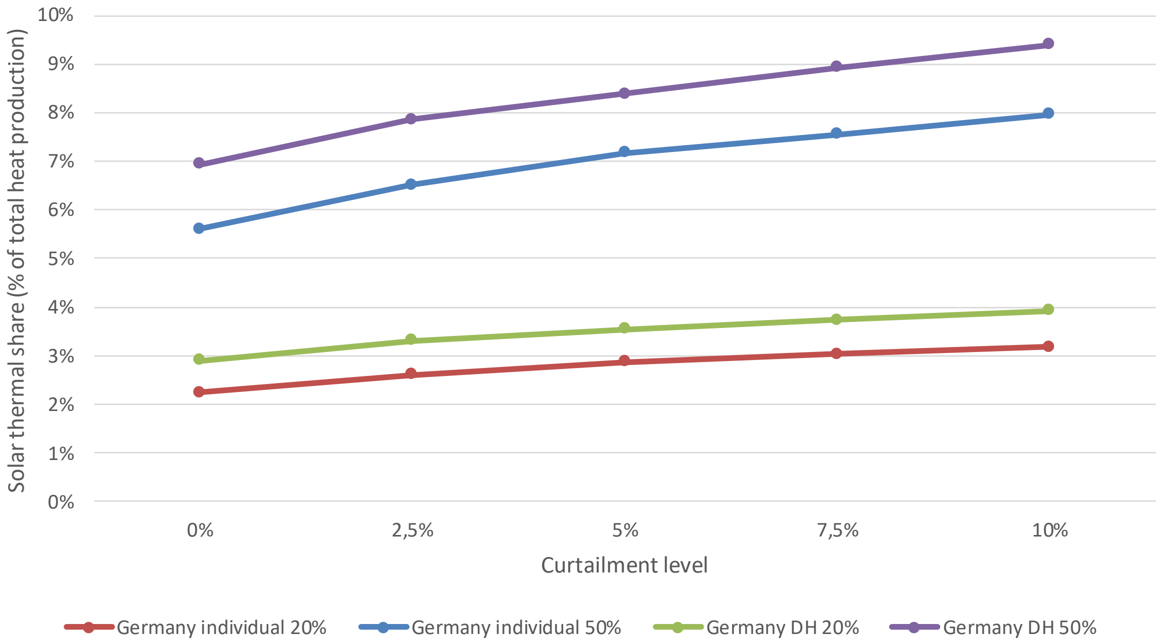

Figure 68: Solar thermal share of heat production at different overproduction levels. The figure shows that the difference in terms of solar thermal share is around one percentage point when increasing the overproduction level from 5% to 10% with a high solar penetration rate and around half a percentage point when the solar penetration rate is lower.

For all analysis of the solar thermal potentials solar concept 1 (Combined system – Multi Family houses) and solar concept 4 (Solar District heating – diurnal storage) are analysed, see section 4.3 for further details on the solar concepts. This means that no analysis of solar concepts 2, 3 and 5 are carried out as the number of models would increase significantly. It is assumed that these two solar concepts will be the most common types of future solar installations for individual and district heating areas.

7.2.2 Solar thermal potentials for Germany, Austria, Italy and Denmark

The maximum solar thermal potentials are investigated for two different solar penetration levels, respectively 20% and 50%. This creates an interval for the solar thermal potentials and changes according to the assumed solar penetration levels. The solar penetration levels impact the potential analysis, but are deemed as sensible for what might be expected for future developments.

7.2.2.1 Germany

In Germany the solar thermal potentials are highest in the 2010 model with a total solar thermal production around 30-60 TWh/year decreasing to around 15-25 TWh/year in the high-RES scenario. The decrease in solar thermal potential is primarily in individual heating areas where heat savings lead to an overall lower heat demand. When the heat demand decreases there is accordingly less potential for installing solar thermal. Furthermore, converting to a higher share of district heating supply reduces the solar thermal potentials in individual buildings and increases the solar thermal potentials in district heating networks. In the high-RES scenario the district heating solar thermal decreases as the solar thermal is being pushed out of the district heating supply by alternative heating sources such as industrial excess heat, geothermal heating and waste incineration. These alternative renewable heating sources are to a large degree baseload production technologies reducing the energy system flexibility leading to less demand that can be supplied by solar thermal. In addition, more variable renewable electricity sources are implemented leading to a lower overall system flexibility making CHP plants more important for the balancing of the electricity system. This also impacts the district heating system where less flexibility is allowed for the integration of solar thermal plants.

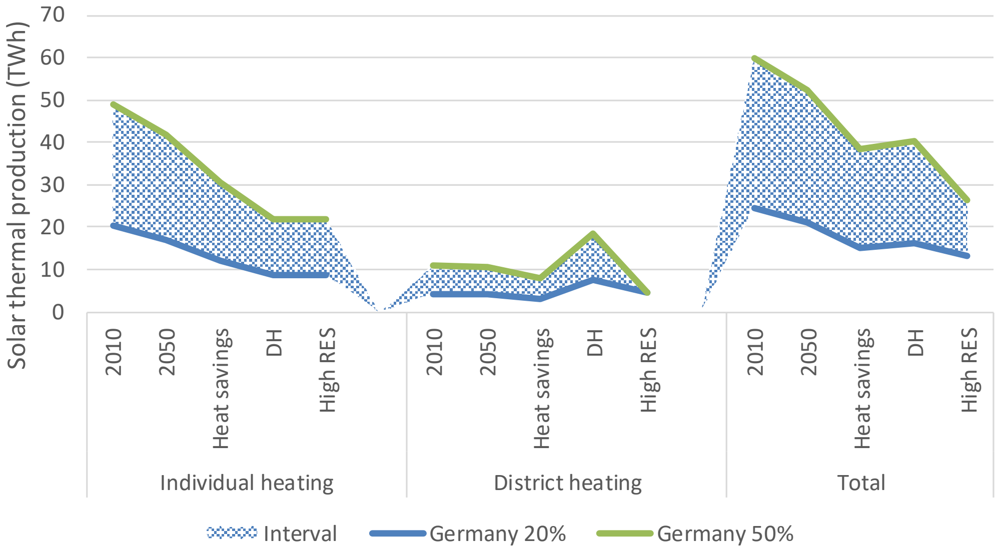

Figure 69: German solar thermal potentials for individual heating and district heating under different conditions.

Even though the solar thermal production decreases the solar thermal potential as a share of the heating production is similar around 3-7% between the 2010 and the high-RES scenarios. The solar thermal share increases for both individual and district heating areas when carrying out heat savings, but decreases again in the high-RES scenario due to lower flexibility and the integration of other renewable supply technologies. The total solar thermal share is in the range of 3-5% of the heating production with the low solar penetration rate and 7-11% with the high penetration rate.

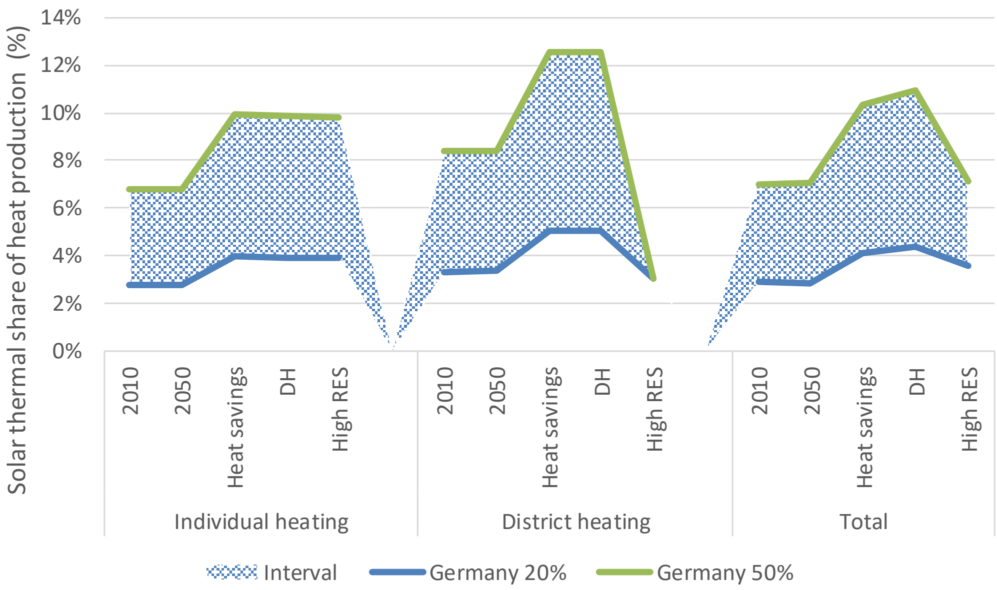

Figure 70: German solar thermal potential share of the heat production for individual heating and district heating under different conditions.

7.2.2.2 Austria

In the Austrian energy system the solar thermal potentials for individual and district heating systems are rather similar between 1-4 TWh/year. The total solar thermal production for the various scenarios are 2-7 TWh with a declining trend going from the 2010 system towards the high-RES system. Also in Austria solar thermal will start competing with other renewable technologies in the high-RES scenario.

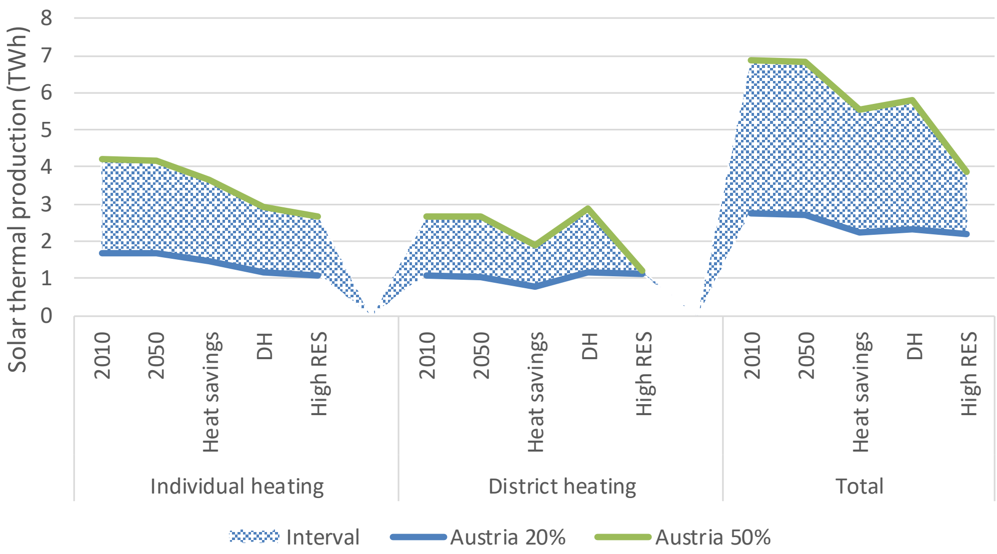

Figure 71: Austrian solar thermal potentials for individual heating and district heating under different conditions.

The solar thermal share in the district heating systems in Austria is higher than for individual systems in all the scenarios, except for in the high-RES scenario. The total solar thermal share for the low penetration level is between 3-5% while the high penetration rate leads to a maximum solar thermal share of 8-12%.

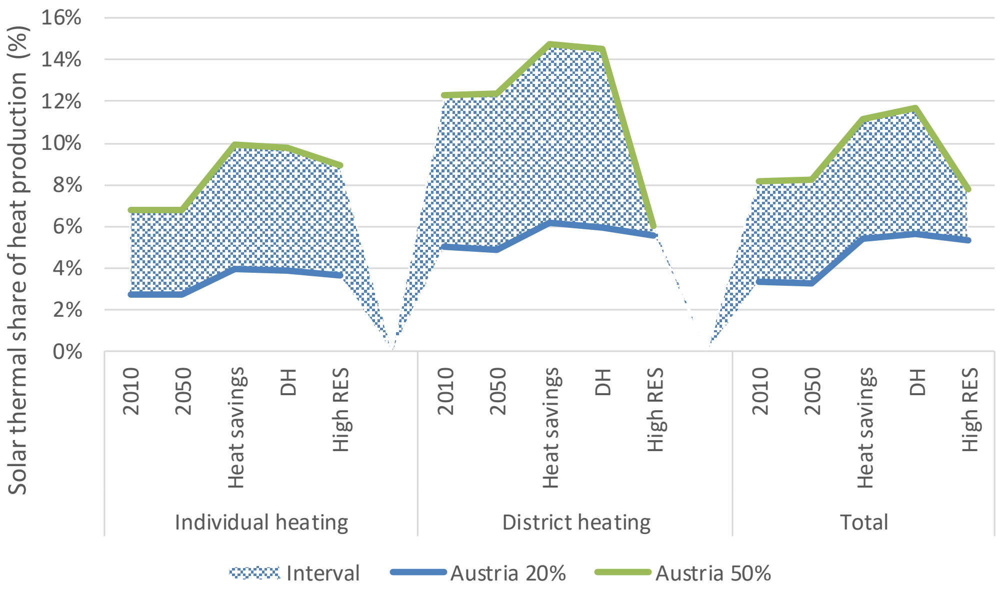

Figure 72: Austrian solar thermal potential share of the heat production for individual heating and district heating under different conditions.

7.2.2.3 Italy

The Italian system of 2010 has a limited amount of district heating implemented and consequently a high share of individual heating. This is also reflected in the solar thermal potentials where the majority of the solar thermal potentials in the 2010, 2050 and heat saving scenarios are in individual heating areas. After conversion to a higher share of district heating this changes as the majority of the solar thermal potential moves to the district heating areas. Overall, the combined solar thermal production potential is rather constant throughout the scenarios despite the change between potentials in individual and district heating. The production potentials are in the range of 10-25 TWh/year depending on the solar penetration.

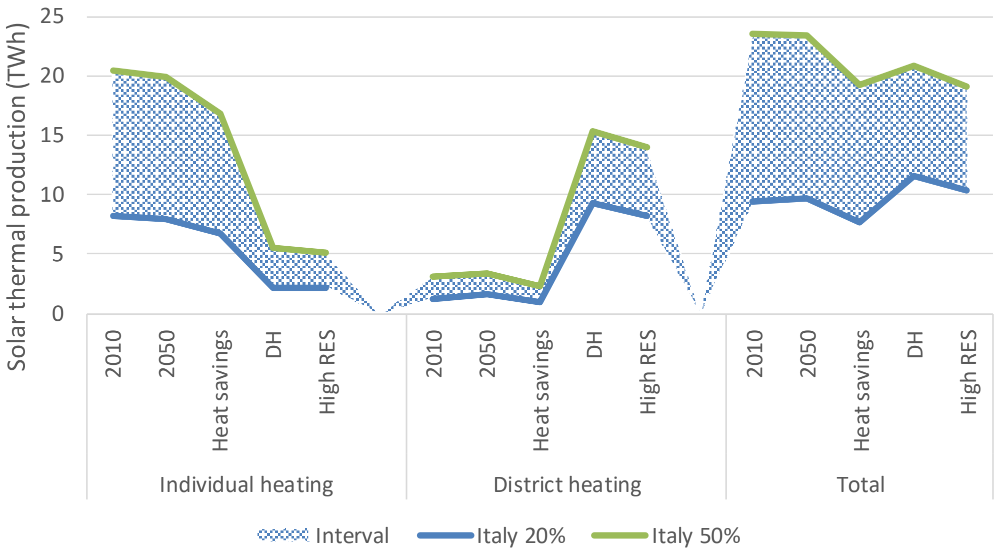

Figure 73: Italian solar thermal potentials for individual heating and district heating under different conditions.

When analysing the solar thermal potentials as a share of the overall heat production the Italian potential increases when moving from the 2010 scenario to the high-RES scenario. This is mainly due to the increased solar thermal share after carrying out heat savings. The solar thermal shares are higher in the district heating areas than in the individual heating areas for all scenarios. The overall solar thermal share in Italy is in the range of 2-6% for the low penetration rate and 6-10% with the higher penetration, slightly lower than in the German and Austrian systems.

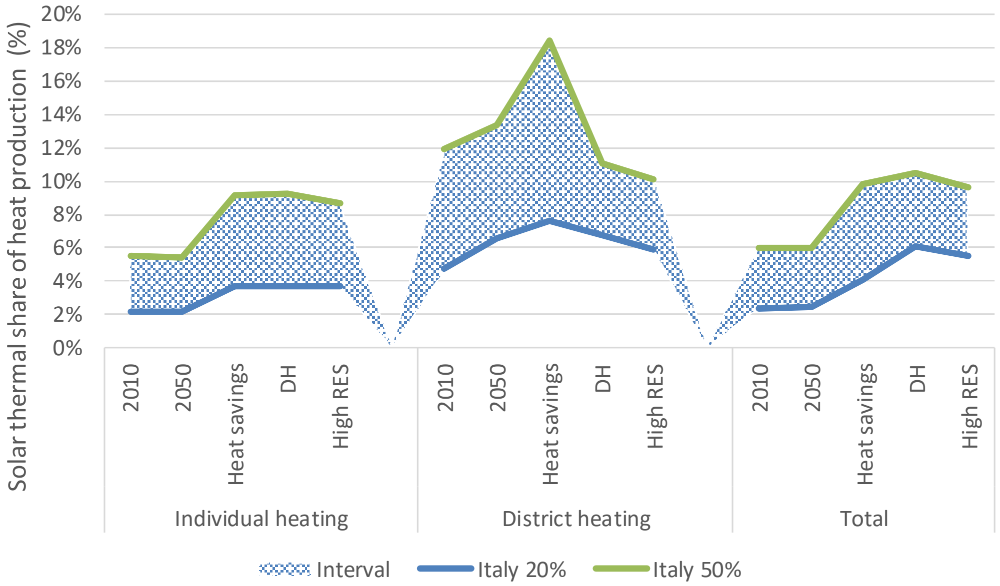

Figure 74: Italian solar thermal potential share of the heat production for individual heating and district heating under different conditions.

7.2.2.4 Denmark

The Danish solar thermal potential is higher for district heating networks than for individual heating areas due to the high share of district heating installed already in the 2010 scenario. Consequently, the largest decline in solar thermal potential can also be found in the district heating areas when heat savings are implemented. Similarly to the other countries the total solar thermal production potential decreases when moving towards the high-RES scenario. The combined production potential is between 1-5 TWh/year.

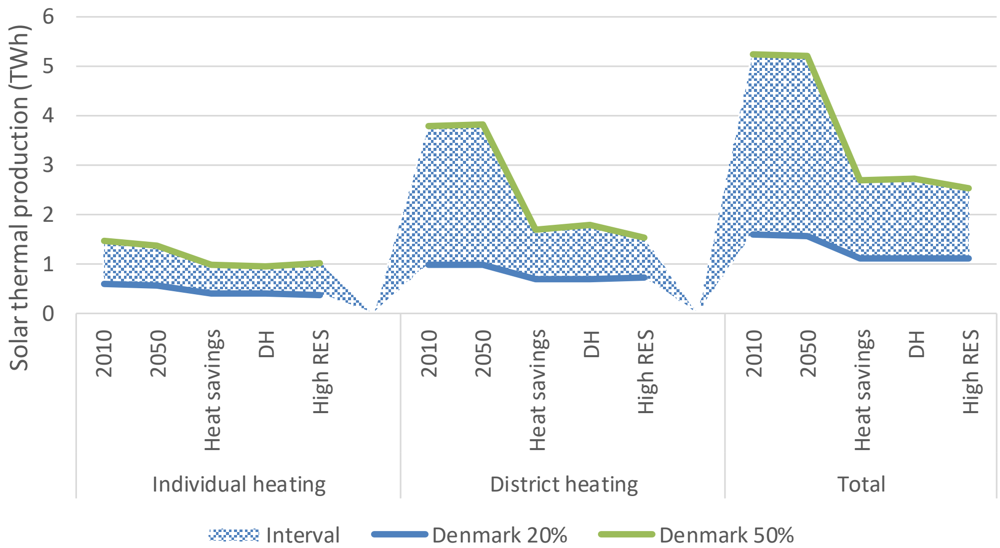

Figure 75: Danish solar thermal potentials for individual heating and district heating under different conditions.

The potential solar thermal share remains rather constant for the individual heating solutions in all the scenarios while the share in the district heating networks increase, especially after heat savings are implemented in the energy system. Heat savings reduce the overall solar thermal production that can be installed, but increases the solar thermal share in the system. Overall, the solar share is around 3-4% assuming a low penetration level and between 8-10% with the high penetration rate.

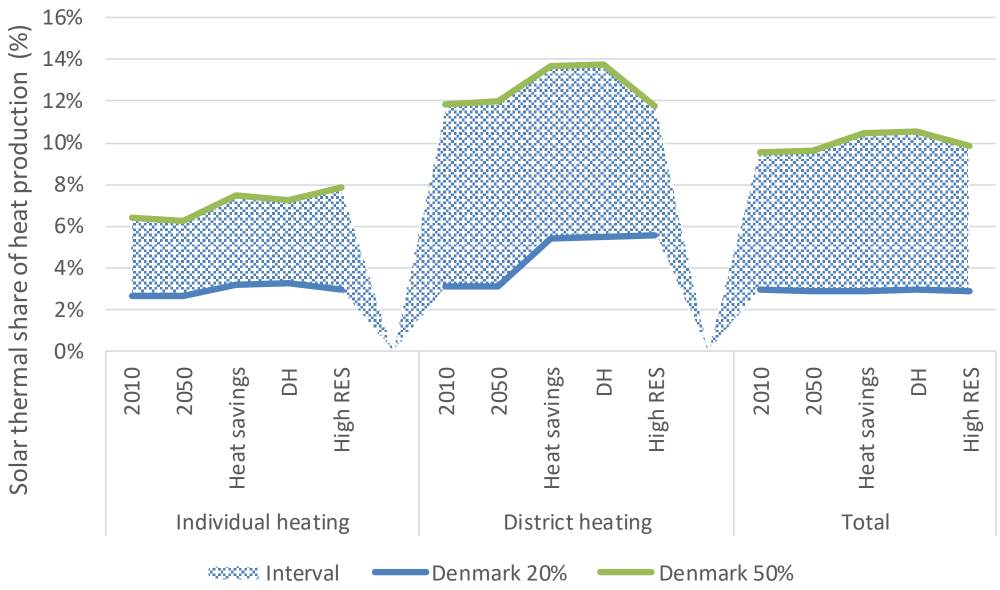

Figure 76: Danish solar thermal potential share of the heat production for individual heating and district heating under different conditions.

7.2.2.5 Comparison between countries

In this section a solar thermal penetration rate of 35% is assumed as an average of the two levels previously presented. If this rate is changed then the solar thermal potentials also change.

When comparing the countries rather similar trends can be identified indicating a decreasing production when going from today's system towards a system with a lower heat demand and a higher share of renewable sources installed. The exception is for Italy, see Figure 78, where the solar thermal production is rather similar for all the scenarios.

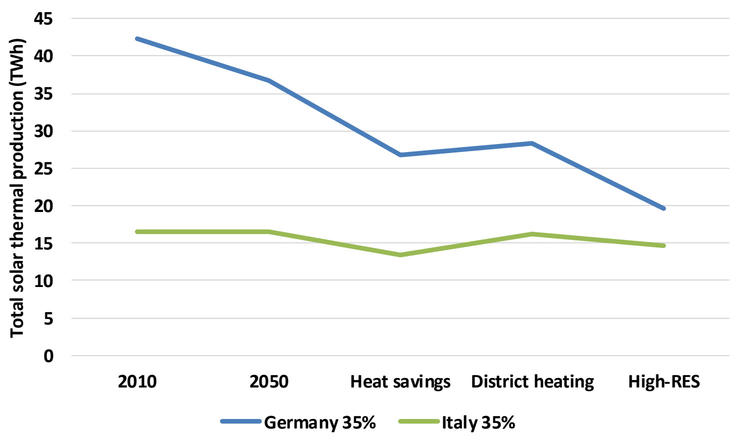

Figure 77: Solar thermal production potentials for Germany and Italy with a solar penetration rate of 35%.

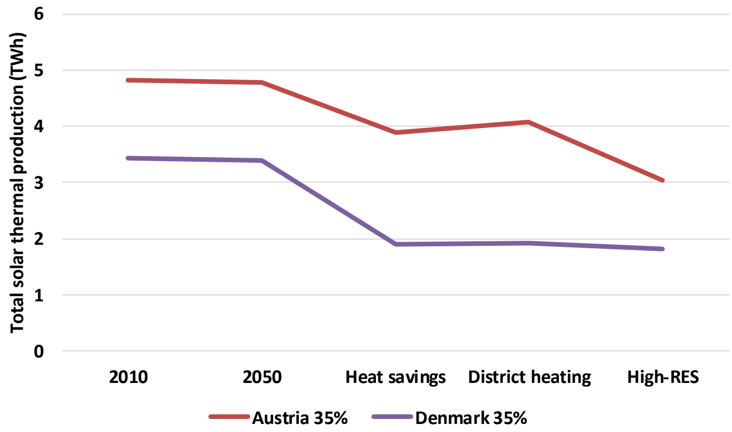

Figure 78: Solar thermal production potentials for Austria and Denmark with a solar penetration rate of 35%.

When comparing the solar thermal potential shares for individual heating rather similar potentials can be identified for the four countries. Here, the potential shares increase from around 4-5% to 6-7% of the total individual heat supply after heat savings are implemented. The individual solar thermal potential across all countries and scenarios is in the range of 4-7% when assuming a solar thermal penetration rate of 35%. This potential is limited to 4-7% as further solar thermal does not align with the heat demand profiles and hence overproduction is created.

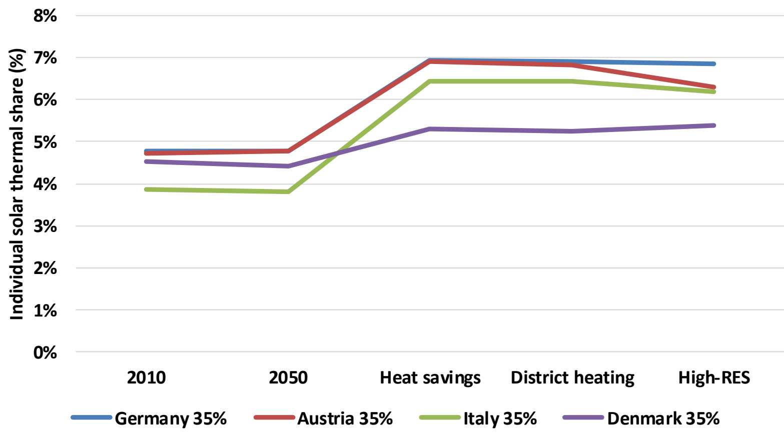

Figure 79: Individual solar thermal potentials as a share of the the total individual heat production with a solar penetration rate of 35%.

For district heating networks there are more differences between the countries regarding the solar thermal potential shares, particularly after expanding the district heating network. After heat savings have been implemented Italy has the highest potential share around 12%. In the high-RES scenarios the decreases in solar thermal potential shares are largest for Austria and Germany compared to Denmark and Italy. This difference is due to the flexibility of the energy systems where the district heating imbalances are more heavily impacted in Austria and Germany. This can be seen in Figure 81 where the district heating imbalance is impacted more when going from the district heating scenario to the high-RES scenario with no solar installed in Austria and Germany than in Italy and Denmark.

Overall, across all countries and scenarios the district heating solar thermal potential share is between 6-10% of the heating production.

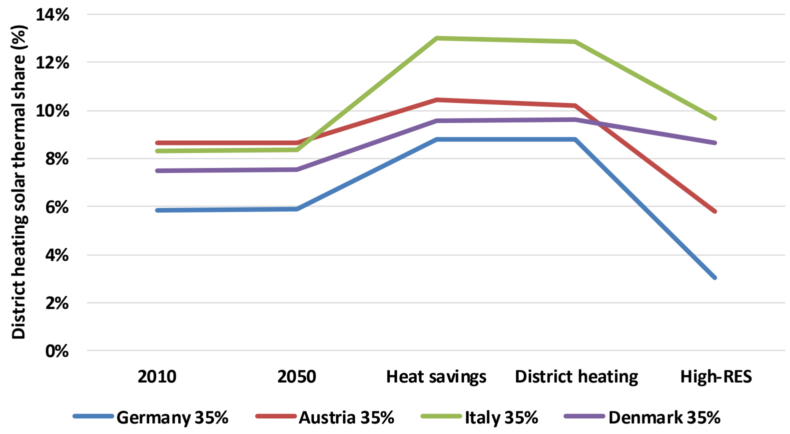

Figure 80: District heating solar thermal potentials as a share of the the total district heat production with a solar penetration rate of 35%.

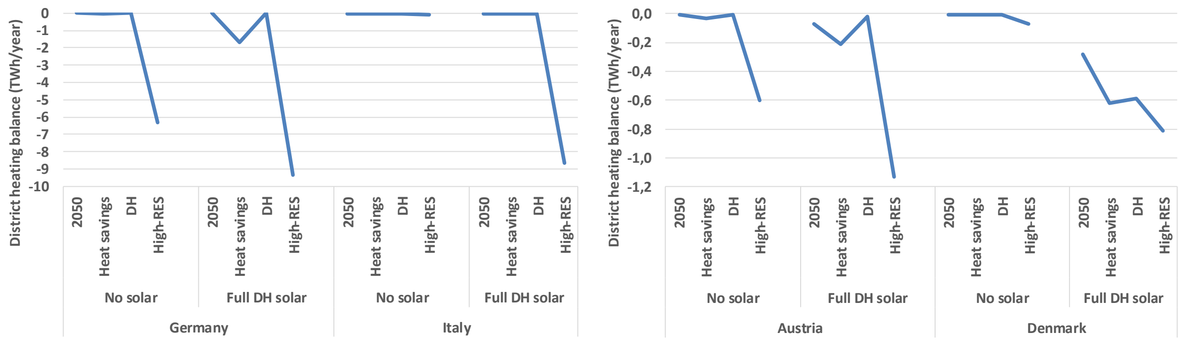

Figure 81: District heating balances for the four countries with no solar and full solar district heating potential installed. A negative value indicates an overproduction of district heating in the system.

When combining individual heating and district heating, see Figure 82, there are small differences in terms of potential solar thermal share between the countries. Overall, the solar thermal share is between 5-8% when assuming a solar penetration rate of 35%. When increasing the penetration rate to 50% the combined solar thermal potential is between 6-12% while a lower penetration rate of 20% will lead to a maximum potential of 3-6% of the heat production.

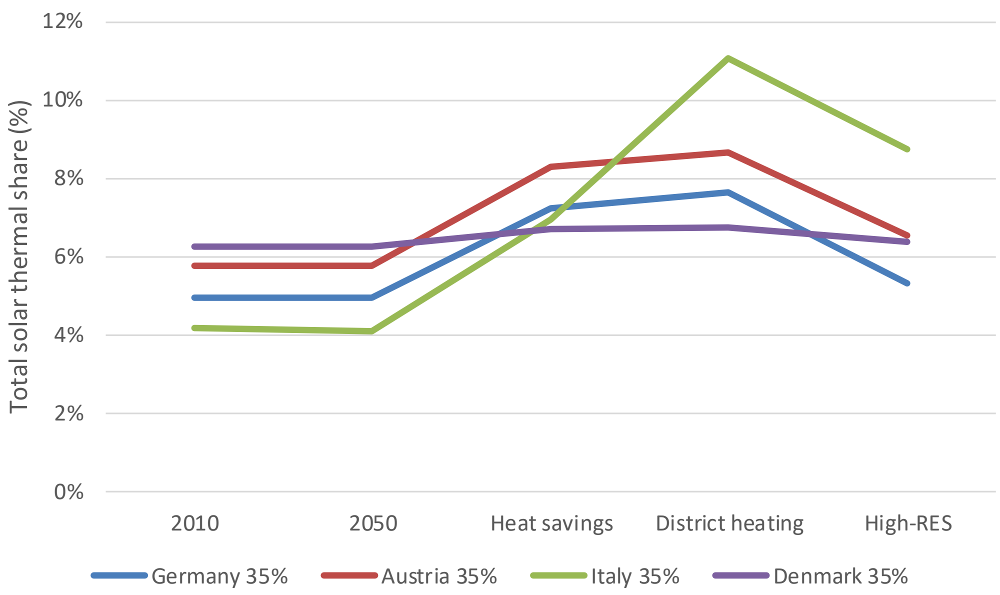

Figure 82: Total solar thermal share potentials in the four countries with a solar penetration rate of 35%.

The key findings from the maximum solar thermal potential analysis (50% solar thermal penetration rate):

- The solar penetration rate is essential for the overall solar thermal potential in both individual and district heating areas.
- The energy system flexibility is crucial for the ability to integrate solar thermal energy and is based on two key factors:
  - The share of baseload district heating production affects the ability of the system to integrate solar thermal.
  - The share of variable renewable electricity sources and the link to the heating sector through heat pumps and CHP plants.
- The technical production potential is impacted by the total heat demand in each country. However, the heat demand differences between the countries only slightly impact the overall potential for the solar thermal share of the total heating production.
- The potential solar thermal share is between 5-8% of the heat production when assuming a solar penetration of 35%. This might increase to 6-12% with a 50% penetration and decrease to 3-6% with a 20% penetration.

7.2.2.6 Solar thermal potential as collector area

The solar thermal potentials estimated can be converted to solar collector area. This is depicted in Figure 83-Figure 86 showing the potentials from the previous section with a solar thermal penetration rate of 35%.

The solar collector areas are based on the solar yields assumed for each country. The solar yields are specified in Table 23 and is based on the average solar yields in the capital of each country.

Table 23: Solar yields in each country for solar concepts 1 and 4 [37].

Solar yields (kWh/m^2)	Germany	Austria	Italy	Denmark
Concept 1 (CS-MFH)	330	402	451	314
Concept 4 (SDH-DK-Diurnal)	410	500	560	390

The potential solar collector area in Germany is between 40-160 million m^2, in Austria the potential is between 5-20 million m^2, for Italy the potential is 30-70 million m^2 and finally in Denmark the potential is in the range of 4-12 million m^2. The potentials are higher in the 2010 and 2050 scenarios where no heat savings have been carried out and if high solar thermal penetration rates are assumed.

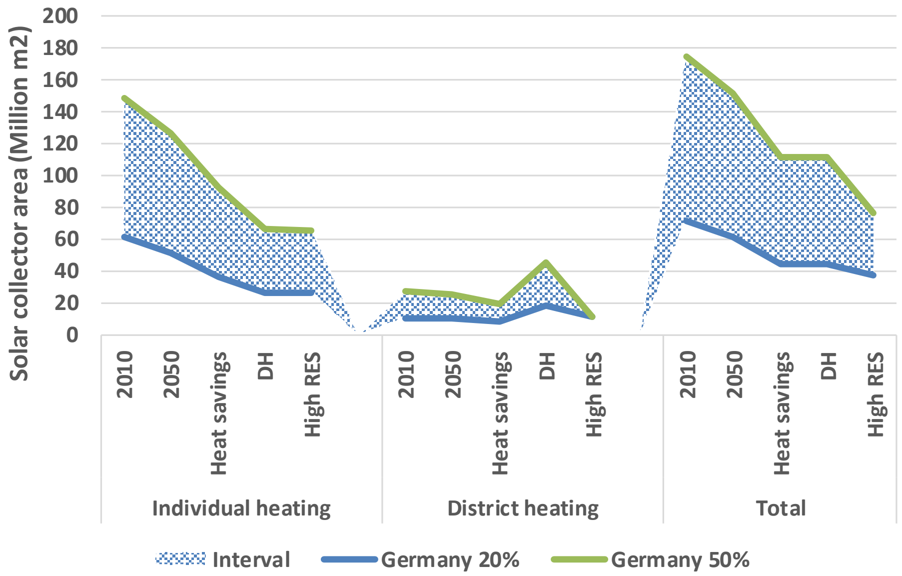

Figure 83: German solar thermal potentials illustrated as solar collector areas in the various scenarios.

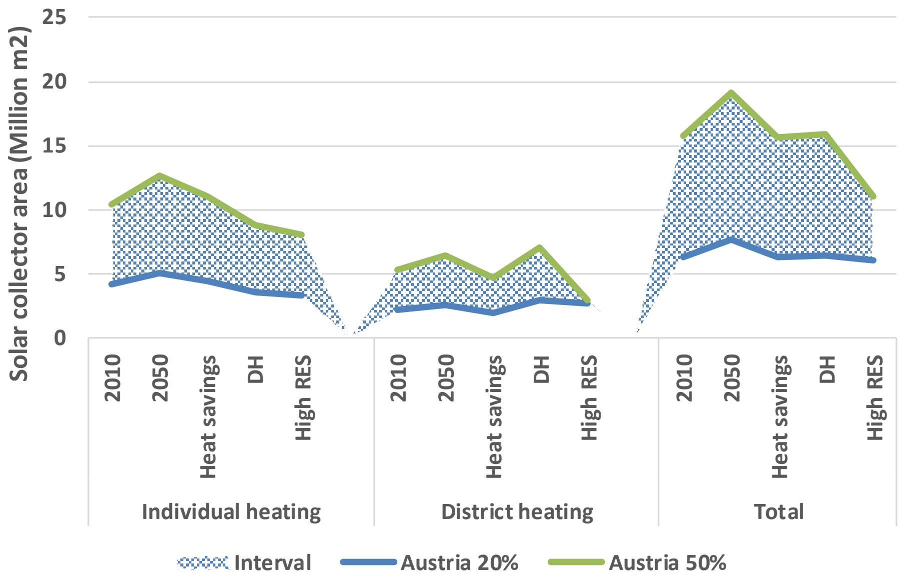

Figure 84: Austrian solar thermal potentials illustrated as solar collector areas in the various scenarios.

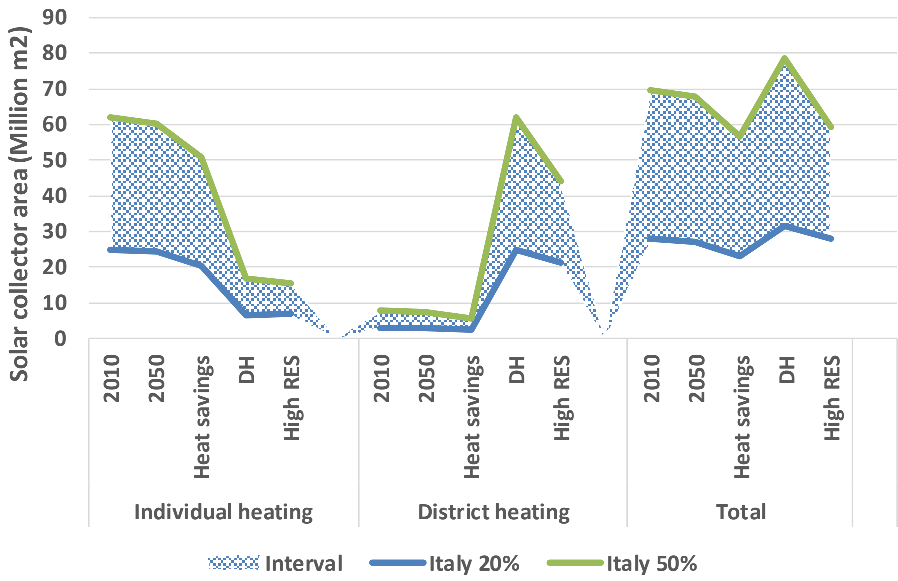

Figure 85: Italian solar thermal potentials illustrated as solar collector areas in the various scenarios.

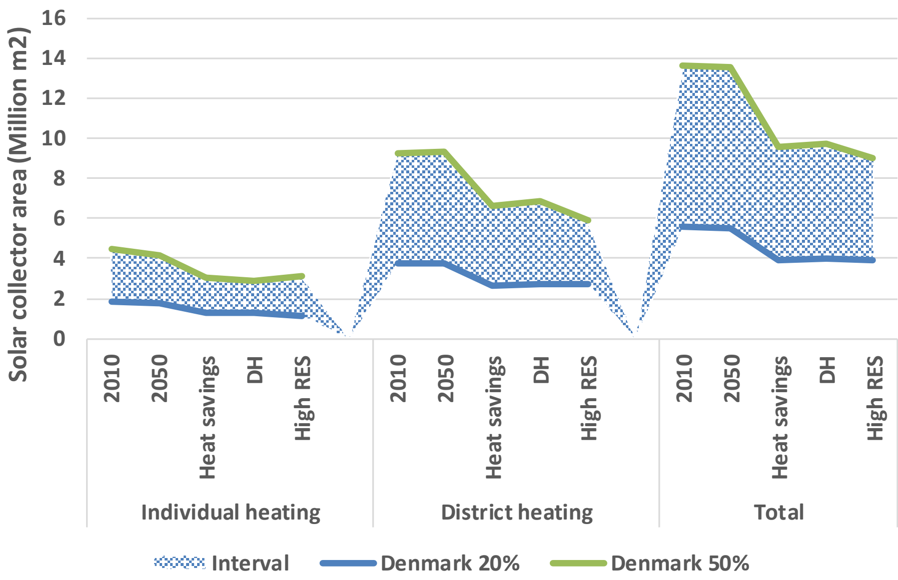

Figure 86: Danish solar thermal potentials illustrated as solar collector areas in the various scenarios.

The solar thermal potential can also be measured as the potential per capita. This is illustrated in Figure 87 with a solar thermal penetration rate of respectively 20% and 50%. The figure shows that Itlay has a lower potential per capita than the other countries and that the solar thermal potential decreases in all countries when moving towards the high-RES scenario, in line with previous results.

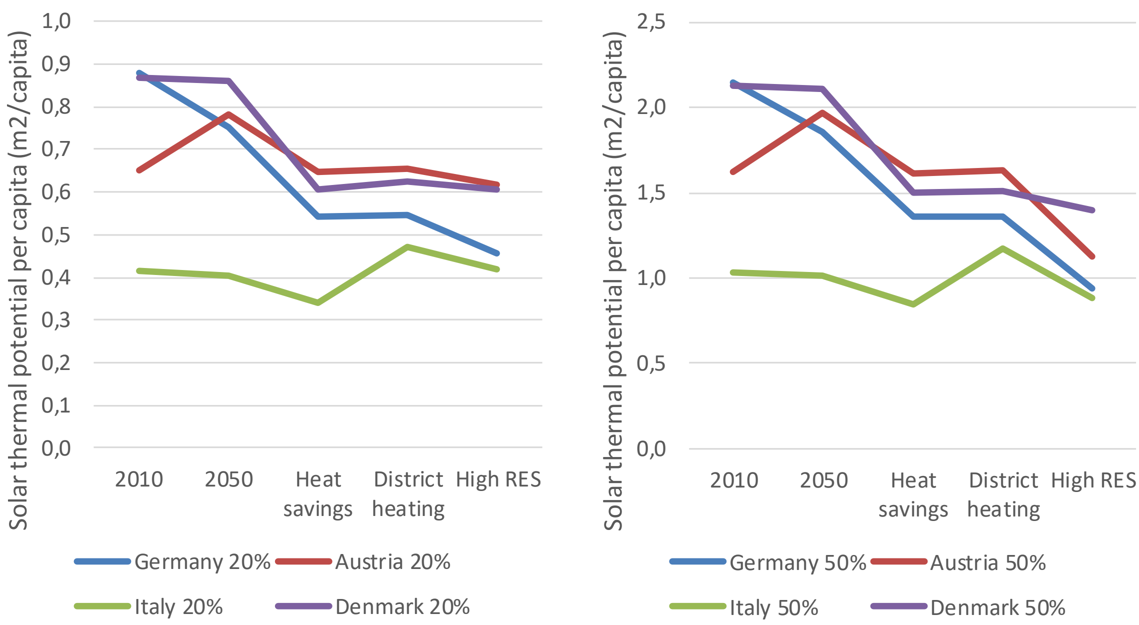

Figure 87: The solar thermal potential per capita in the four countries with 20% and 50% solar thermal penetrations.

7.2.2.7 Solar thermal potential for industrial processes

In this study solar thermal for industrial purposes has not been analysed in details. Instead, this section presents the findings of the IEA SHC Task 49 study regarding Solar heat integration in industrial processes [38]. Task 49 deliverable C5 is about “potential studies on solar process heat worldwide” containing a literature review of the solar thermal potentials in industrial process heat.

In the study it is estimated, based on a number of case studies for Spain and Portugal, that the largest potentials for integration of solar thermal in industries is within the food and beverages sector [39]. The technical potential is 3-4% with the limiting factor in these countries being the available roof area. Other industrial sectors could be chemicals, paper, tobacco, as well as leather and textiles. In the Netherlands a similar study was carried out where the solar thermal potential of the industrial heat demand is assessed to be 3.4% [40]. In this study the barriers for solar thermal integration are described as the use of excess heat, roof area and competing technologies such as heat pumps and CHP. A third study estimates that the industrial solar thermal potential in Sweden is 1.5-2% [41] while the potential for Austria is estimated to be around 4% of the industrial heat demand [42].

In Germany the theoretical potential for industrial solar thermal is estimated to be 134 TWh/year while the technical potential is around 16 TWh/year [43].

Furthermore, it was found that the global solar thermal potential for industries is around 1,500 TWh/year corresponding to 2% of the total final energy demand for industries. Also here food and beverage industries are found to be most suitable for solar thermal integration. UNIDO finds that the global potential could be slightly higher around 2,200 TWh/year when including concentrating collectors for chemical processes [44].

Overall, [39] finds that the technical potential for industrial solar thermal integration in a number of European countries is in the order of 3-4% of the industrial heat demand, see Figure 88.

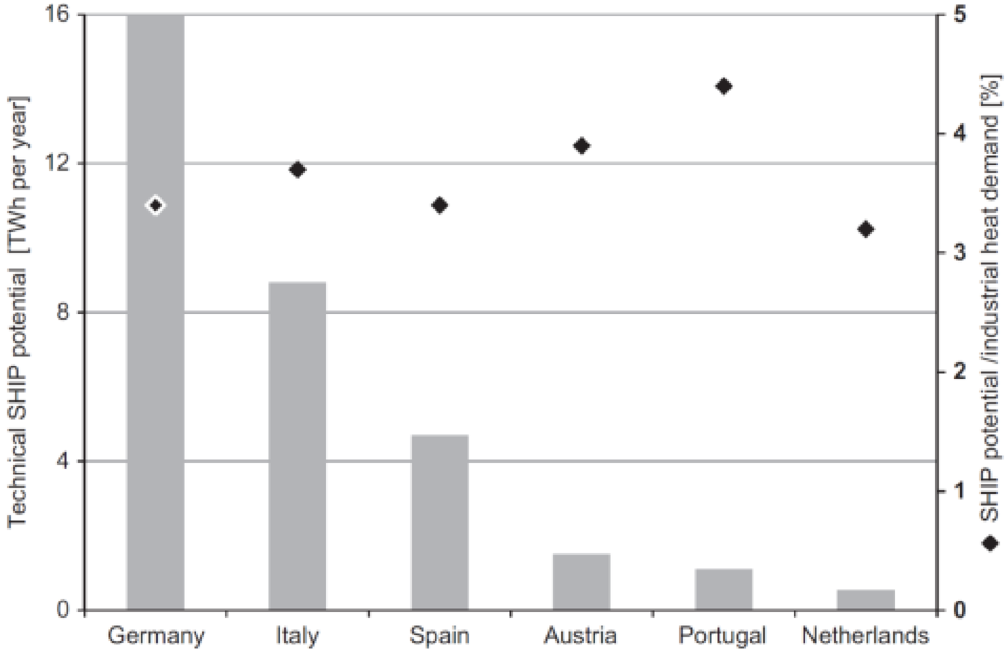

Figure 88: The solar thermal potential for industrial processes in a number of European countries. From [39].

When assuming that the solar thermal potential for industries is 3.5% of the heat demand the solar thermal potential increases by around 10 TWh in Germany, 1.5 TWh in Austria, 11 TWh in Italy and 1 TWh in Denmark.

7.3 Impacts of installing solar thermal potentials

The impacts of installing the identified solar thermal potentials are analysed in this section emphasizing the impacts on fuel consumption, CO_2-emissions and energy system costs.

7.3.1 Solar thermal impact on fossil fuel and biomass consumption

A significant benefit from installing solar thermal can be to replace other types of fuels such as fossil fuels and biomass, which might benefit the system in terms of CO_2-reductions and reducing the pressure on biomass resources. This is a key issue as presented in section 6.1.9. The impacts presented below include installing the full solar thermal potentials with a 50% solar penetration rate and is affected by the fuel mix assumed for the individual and district heat supply. For example, the share of biomass and fossil fuels for electricity and heat production in CHP plants influence the biomass savings from installing solar thermal.

Installing the maximum solar thermal potential with a 50% penetration rate in the individual heating areas in all cases decreases the fossil fuel demand in the energy system, see Figure 89. The largest reductions are in the 2010 scenarios due to the largest fossil fuel share in the heat supply. The German and Italian energy systems have a larger decrease than the other countries due to a larger share of fossil fuel boilers, primarily natural gas and oil boilers. When moving towards a high-RES system other renewable technologies will supply parts of the heat demand leading to decreasing fossil fuel reductions when installing solar thermal.

The impacts of installing solar thermal for district heating are different than the impacts in the individual heat supply. For district heating areas the impacts on fossil fuel demands are less when installing the maximum solar thermal potential as the highest reduction in fossil fuel demand is approximately 0.5%. The decreasing fossil fuel demand is caused by the solar thermal plants replacing CHP plant production. As CHP plants decrease their production condensing power plants will conversely produce more resulting in an overall lower energy system efficiency. In the analysis it is assumed that the condensing power plants primarily consume coal while the CHP plants are fuelled primarily by natural gas. Overall, this leads to minor fossil fuel reductions in three out of the four countries. However, in the German system the fossil fuel demand increases when installing the maximum solar thermal potential because it is assumed that the condensing power plants in Germany have a slightly lower efficiency (37%) than in the three other countries (~40%). When improving this power plant efficiency to 40% Germany would have a similar minor decrease in fossil fuel demand as the other countries. This demonstrates that the thermal plant efficiencies also have some impact on the fuels replaced when installing solar thermal. The impacts on the fossil fuel demand are however rather insignificant regardless of the assumptions for condensing power plant efficiencies and the fuel mix.

When combining the impacts in the individual and district heating areas the maximum fossil fuel reductions are 1-2% of the total fossil fuel demand. When moving towards the high-RES scenario less fossil fuels are saved and in the high-RES scenario no fossil fuels are replaced.

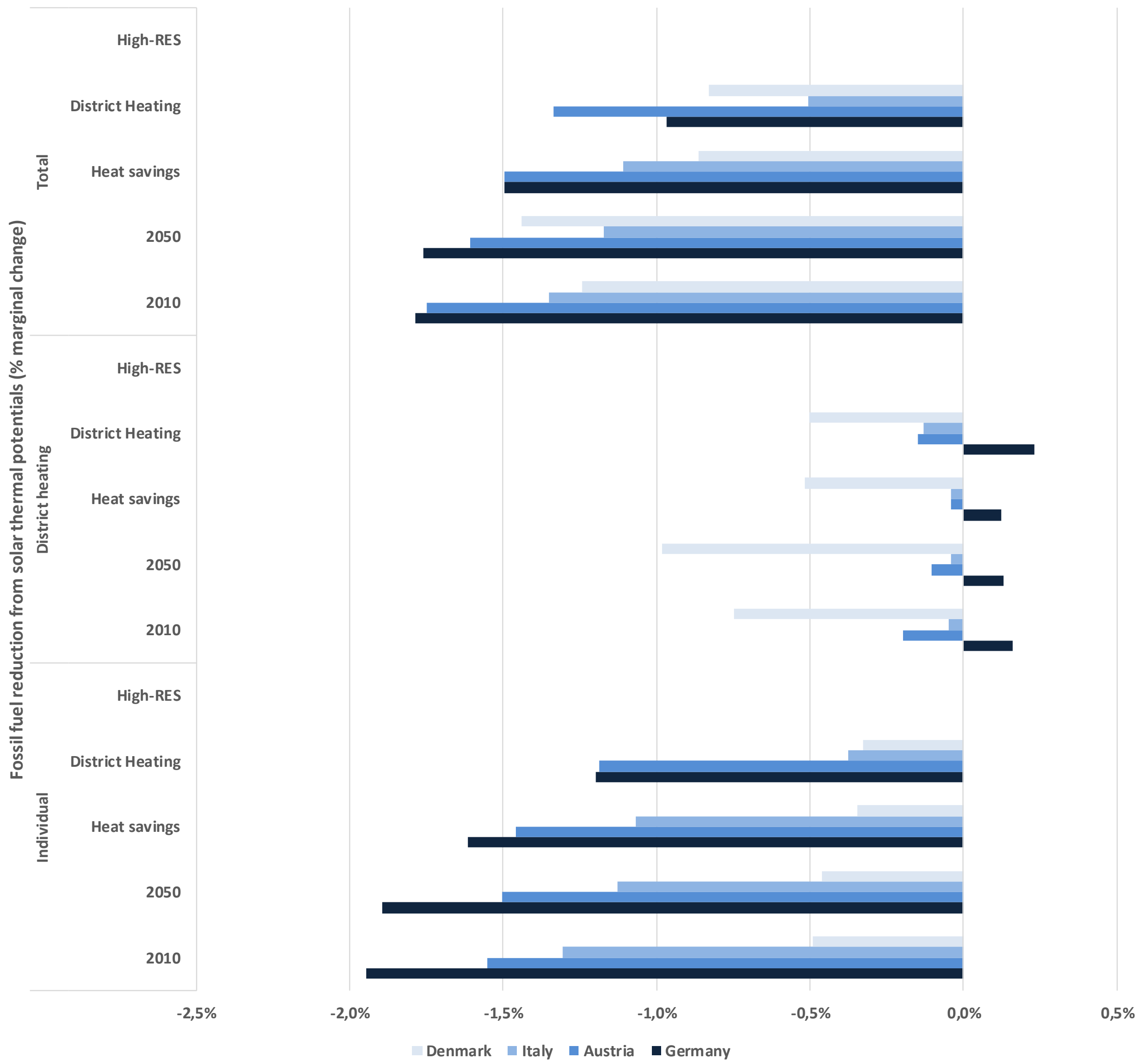

Figure 89: Fossil fuel reductions in individual and district heating networks when installing the full solar thermal potentials.

The effect of installing the maximum solar thermal potential in regards to the biomass demand are illustrated in Figure 90. In general, the largest biomass reductions for all countries are in the individual heat supply where some biomass boilers are replaced in the 2010, 2050 and heat savings scenarios. In the District heating and high-RES scenarios more heat pumps are installed supplied by electricity which are, to some degree, based on power plants consuming biomass. The biomass reductions are a result of the technologies replaced, i.e. the share of biomass supply installed in the energy system.

The district heating biomass reductions are lesser as more renewable heating sources are installed (excess industrial heating, geothermal, etc.) and consequently a lower share of the heat supply is based on biomass. The largest reductions are in the Austrian system where a larger share of the CHP and district heating boiler production is based on biomass than in the other countries.

Overall, the biomass reductions as a share of the total biomass consumption is largest in the 2010 scenarios and decrease when moving towards the high-RES scenario. In the 2010 system 2-4% of the biomass can be saved when installing the maximum solar thermal potential. In the high-RES scenario the biomass reduction decreases to a level around 1-2% of the total consumption.

When combining these fuels the overall fossil fuel and biomass reduction is in the range of 1-3% depending on the scenario and if the savings are compared to the heating and electricity sectors only or the entire energy system fuel consumption.

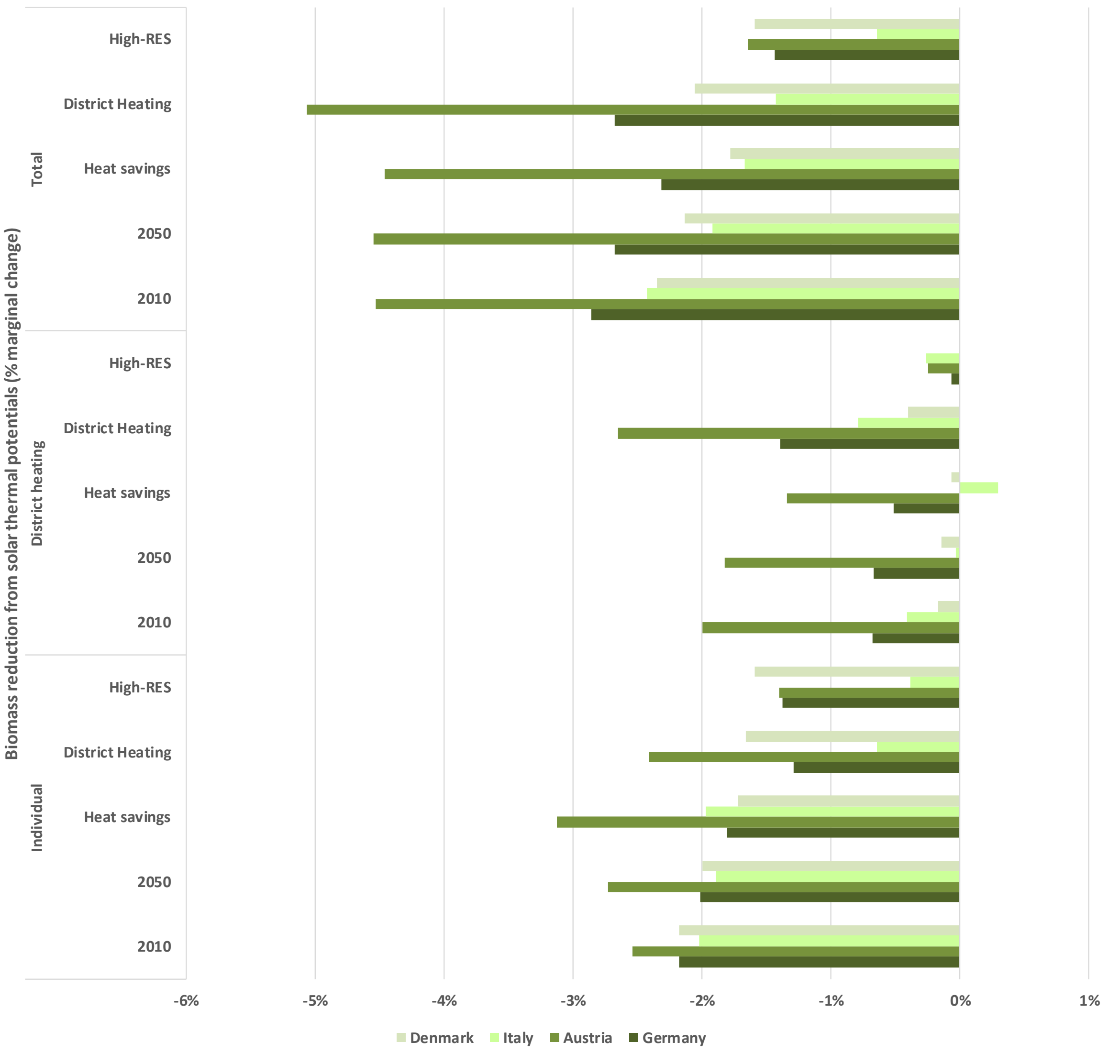

Figure 90: Biomass reductions in individual and district heating networks when installing the full solar thermal potentials.

7.3.2 Solar thermal impact on CO_2-emissions

Solar thermal impacts the CO_2-emissions in the system as it displaces other fuels. In this section the changes in CO_2-emissions are presented for individual solar thermal, district heating solar thermal as well as the two of them combined. The impacts on CO_2-emissions are based on the assumption that combustion of biomass has no impact on the energy system CO_2-emissions and furthermore that the production of the technologies are not included in the analysis.

Installing the maximum individual solar thermal potential leads to a reduction in CO_2-emissions for all scenarios except in the high-RES scenario. In this scenario solar thermal replaces other renewable sources thereby having no impact on the emissions. The emission reductions for the individual solar thermal is highest in Germany and Austria and lowest in Denmark depending on the share of fossil fuel boilers and biomass boilers. The reductions in CO_2-emissions from installing the individual solar thermal potential is 0.5-1.5% of the total system emissions.

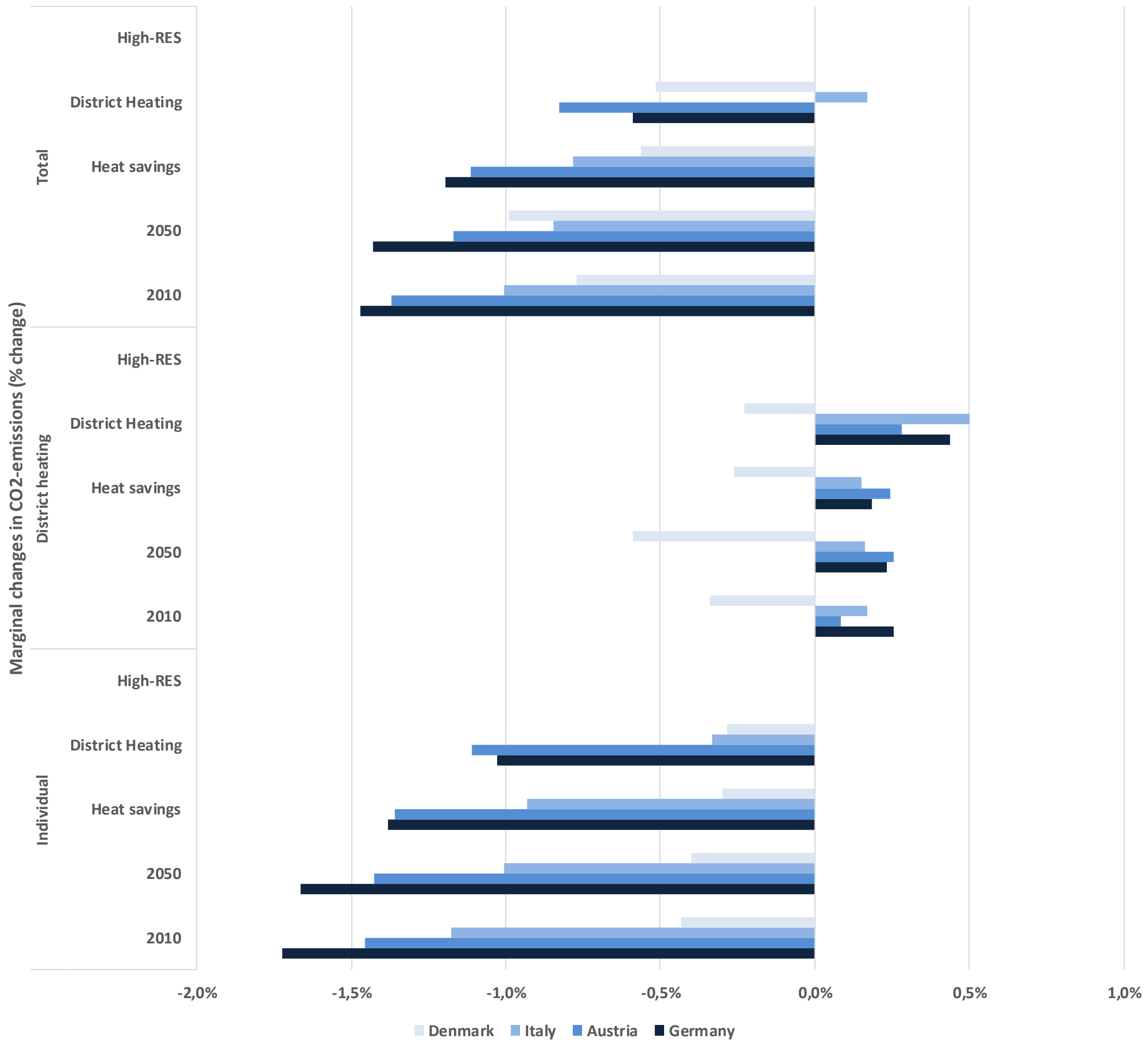

Figure 91: Marginal changes to overall energy system CO_2-emissions based on the solar thermal technology installed for the various scenarios in the four countries.

When installing solar thermal in the district heating networks the CO_2-emissions are impacted differently than in the individual heating areas. For three out of the four countries the CO_2-emissions increase when installing solar thermal, see also section 7.1.3. Only in Denmark the emissions decrease caused by the high share of coal consumption in CHP plants in Denmark while a higher share of natural gas is consumed in CHP plants in the other countries. Coal has a higher emission factor than natural gas and this makes a difference regarding reductions or growing emissions. This is highly impacted by the energy system design and the type of production units that will operate more when reducing the electricity production from CHP plants.

In the scenarios in this study these units are fuelled by fossil fuels, but if the energy system allows for implementing further variable renewable electricity sources, then a different impact on CO_2-emissions might occur. The CO_2-emissions calculated in Figure 91 also change according to the energy system CO_2-emissions assumed from biomass (in this study no emissions are assumed). No impacts occur on the emissions in the high-RES scenarios when installing solar thermal. The CO_2-emission impacts from solar thermal in the district heating networks are however rather insignificant with a maximum change of 0.5% compared to the total energy system CO_2-emissions.

When combining the impacts of the individual and district heating solar thermal potentials the majority of the scenarios lead to CO_2-savings. The emission savings are 0.5-1.5% of the total energy system emissions. The exception is in the high-RES scenarios where there are no impacts from installing the maximum solar thermal potential.

The figures presented in this section are compared to the total energy system emissions, including transport and industry. As solar thermal has no impact on these sectors the impact of solar thermal on only the electricity and heating sectors are relatively higher.

7.3.3 Economic impact of solar potential

Installing the maximum solar thermal potential also impacts the socio-economy of the energy systems. For individual solar thermal the system costs increase as the solar thermal production has higher costs than the heat supply replaced. The Italian system result in better economic impacts from installing solar thermal compared to the other countries, caused by the lower solar thermal production costs, which is a consequence of the solar irradiation. The largest cost increases occur in the 2010 scenarios as the investment prices for solar thermal are higher than in 2050 and also the fuel prices are lower leading to less cost savings for fuels. Overall, the cost increases are 0-1% for the entire energy system when integrating the maximum solar thermal potential in the individual areas.

For solar thermal in district heating networks the impacts differ more between the countries. Here, solar thermal in some instances lead to cost reductions, primarily in the Austrian and Italian systems, while in Denmark and Germany the solar thermal implementation result in slightly higher costs. This is caused several factors; firstly, the solar thermal production costs are lower in Italy and Austria, and secondly, cheaper fuels such as biomass is replaced in Denmark. In the high-RES scenario all countries experience cost increases when installing solar thermal as lower cost heating sources are replaced (e.g. heat pumps consuming wind and PV, biomass, industrial excess heating, etc.). Overall, the impacts of installing the maximum solar thermal potentials in the district heating areas are in some scenarios a decrease of 0.1% and in other scenarios an increase of 0.2%. The socio-economic impacts of installing solar thermal district heating are therefore close to cost-neutral.

When combining the economic impacts of solar thermal in individual and district heating systems the overall costs increase for almost all scenarios in all the countries. The largest impact in terms of cost increases occurs in the 2010, 2050 and high-RES scenarios while in the Heat savings and District heating scenarios smaller impacts ensue. Overall, the cost increases are in the range of 0-1%.

The costs presented here include all energy systems costs (also transport vehicles) and if the transport sector and the industry is excluded so only the heating and electricity sectors are considered the relative increase in costs would be higher.

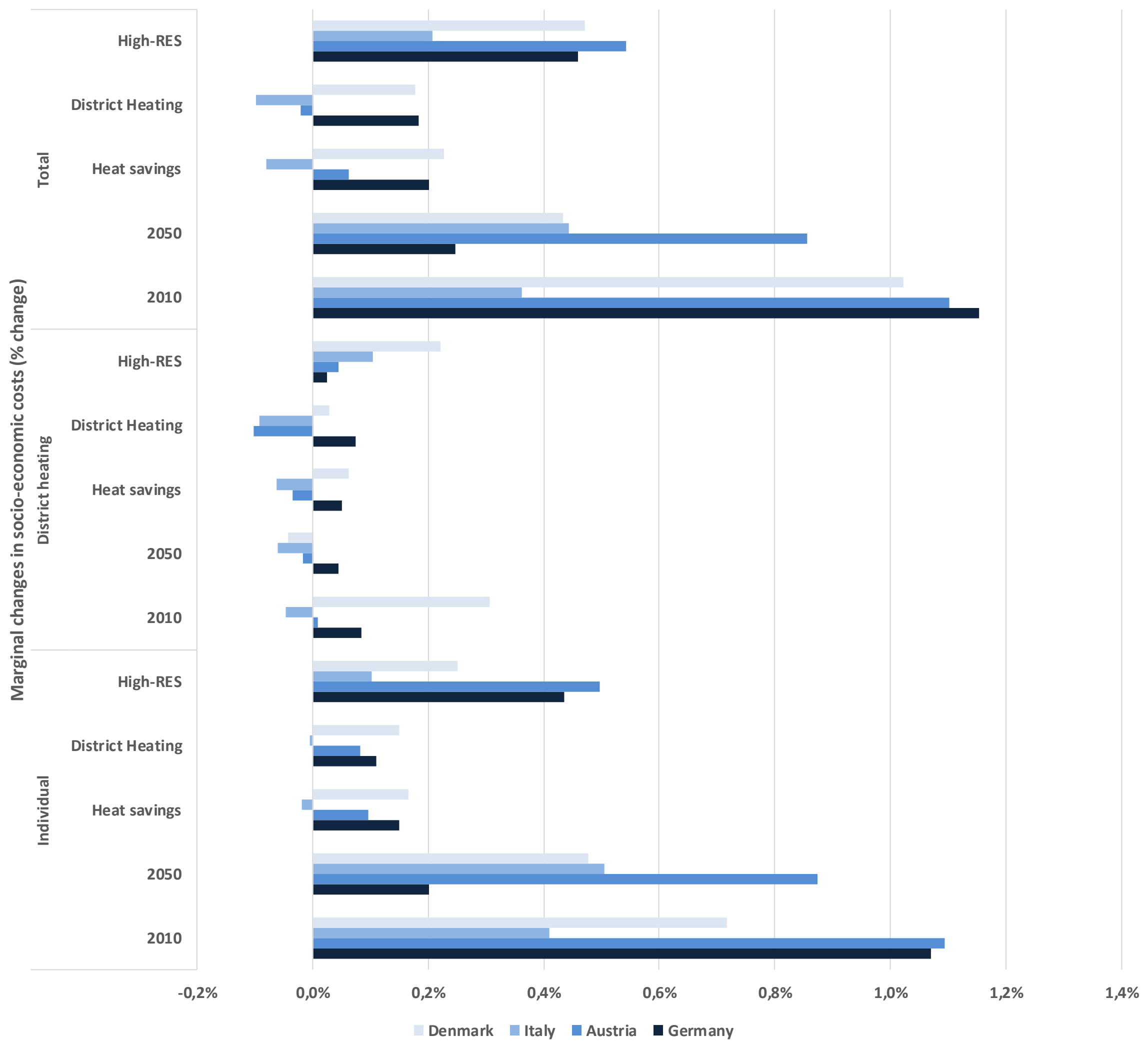

Figure 92: Marginal changes in overall socio-economic costs when implementing the maximum solar thermal potential in the individual and district heating areas for the various scenarios in the four countries.

A summary list of the key findings is specified below.

- Installing the maximum solar thermal potential with a 50% solar penetration is an extreme situation. The other extreme is in the marginal analyses when 1 TWh solar thermal is installed. The overall results are expected to be somewhere in between these.
- Installing the maximum solar thermal potential in individually supplied areas reduces the fossil fuel and biomass consumption.
- If the maximum solar thermal potentials are installed in the district heating areas the impact on fossil fuels is insignificant as oil and gas is replaced by a higher coal consumption. Moreover, the biomass consumption decreases in all scenarios for district heating areas. The amount of fuels replaced is also impacted by the thermal plant efficiencies.
- Overall, the fossil fuel reductions are 1-2% of the total consumption while the biomass reductions are 2-4% of the total consumption.
- The changes in fuel consumption impact the CO_2-emissions, which decrease by 0.5-1.5% of the total emissions with the largest reductions in individually supplied areas. In the district heating areas, some scenarios have increased emissions and others will decrease when installing the full solar thermal potential.

- No emission reductions occur in the high-RES scenario as no fossil fuels are consumed. The biomass reductions in the high-RES scenario is around 1-2% across all scenarios.
- The socio-economic costs increase when installing the maximum solar thermal potential in the individual areas. In the district heating areas, the solar thermal implementation is close to cost-neutral with increasing costs in some countries and reductions in other countries.
- Overall, the costs increase by 0-1% of the total system costs when installing the maximum solar thermal potentials in both the individual and district heating areas.
- The most important factor for cost differences between the countries is the solar thermal production costs.

7.4 Sensitivity analysis

In the energy system analysis a number of key assumptions have been made which potentially impact the findings. Therefore, some of these key assumptions and their significance on the findings are investigated in this section. These assumptions include fuel prices and the investment prices for solar thermal technologies.

7.4.1 Fuel prices

The fuel prices assumed in the analysis are rather high and could therefore impact the results. The impact of altering the fuel prices is investigated and described below. As previously described the EnergyPLAN simulation strategy is the Technical simulation meaning that the system is simulated regarding energy system efficiency and fuel reductions. Hence, changing the fuel prices solely impacts the socio-economic costs of the system and not the fuel consumption.

The three fuel price alternatives investigated can be found in Table 24.

Table 24: Fuel prices by fuel type, excluding costs for transport to the place of consumption for each cost scenario. The high fuel price is used for the analysis in this report.

2015-€/GJ	Coal	Natural gas	Fuel oil	Diesel fuel/ Gas Oil	Petrol/ JP1	Straw/ Wood chips	Energy Crops
Low	2.7	5.9	8.8	11.7	12.7	4.7	5.6
Medium	3.1	9.1	11.9	15	16.1	4.7	6.2
High	3.4	12.2	16.1	20	20.6	6.3	8.1

The impact of fuel prices have been investigated for some of the steps in the design of the high-renewable energy system and regarding the impact of installing solar thermal systems. The fuel price impacts have been analysed for all four countries and the German energy system is used as an example for the figures below.

The fuel price impact on the level of heat savings with the lowest energy system costs is visible in Table 25 indicating that the heat saving level with the lowest overall socio-economic costs only changes marginally when altering the fuel prices. With the high and medium fuel prices 50% heat savings is the cheapest option while lower fuel prices lead to almost identical costs for 40% and 50% heat savings. Similar trends are clear for the other countries where heat savings becomes less attractive from an economic perspective with lower fuel prices, but will only have a limited impact on the heat saving levels. Similar trends can be identified regarding the feasible district heating levels and the technology for supplying the majority of the individual heat supply.

Table 25: Overview of impacts of changed fuel price levels on the level of heat savings, district heating and individual heating supply. Some levels are almost identical in terms of socio-economic costs and hence both are included in the table.

Step	Fuel price level	Germany	Austria	Italy	Denmark
Step 1: Heat savings	High fuel prices	50%	40%	60%	30/40%
	Medium fuel prices	50%	40%	60%	20/30%
	Low fuel prices	40/50%	30/40%	60%	20%

Step	Fuel price level	Germany	Austria	Italy	Denmark
Step 2: District heating	High fuel prices	40%	40%	70%	60%
	Medium fuel prices	40%	40%	70%	60%
	Low fuel prices	30/40%	40%	70%	60%
Step 3: Individual heating	High fuel prices	Heat pumps	Biomass	Biomass	Biomass
	Medium fuel prices	Heat pumps	Biomass	Biomass	Biomass
	Low fuel prices	Heat pumps/Biomass	Biomass	Biomass	Biomass

The impact on the marginal solar thermal installations in terms of socio-economic costs have also been investigated. Figure 93-Figure 95 show that lower fuel prices lead to decreasing fuel savings when installing solar thermal and hence overall higher costs. The cost changes are however limited compared to the total system costs.

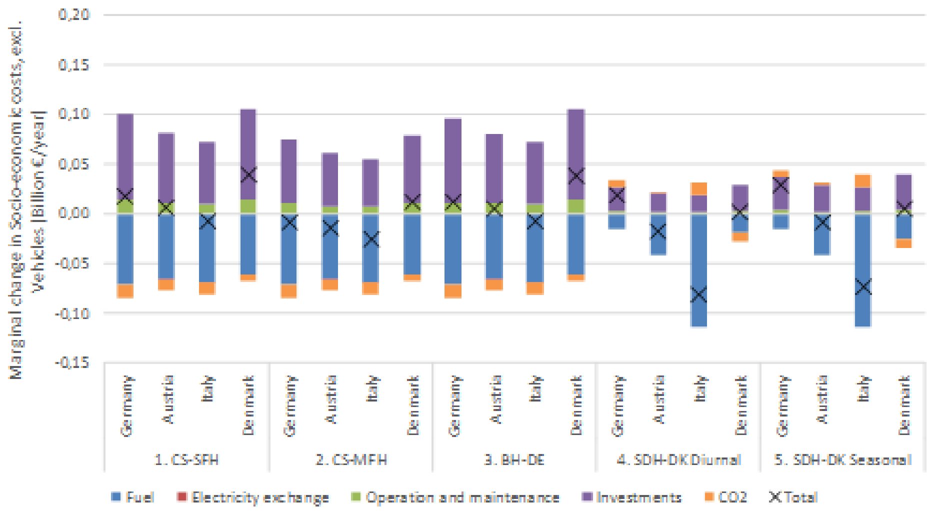

Figure 93: Marginal changes in socio-economic costs with high fuel prices in the 2050 scenarios.

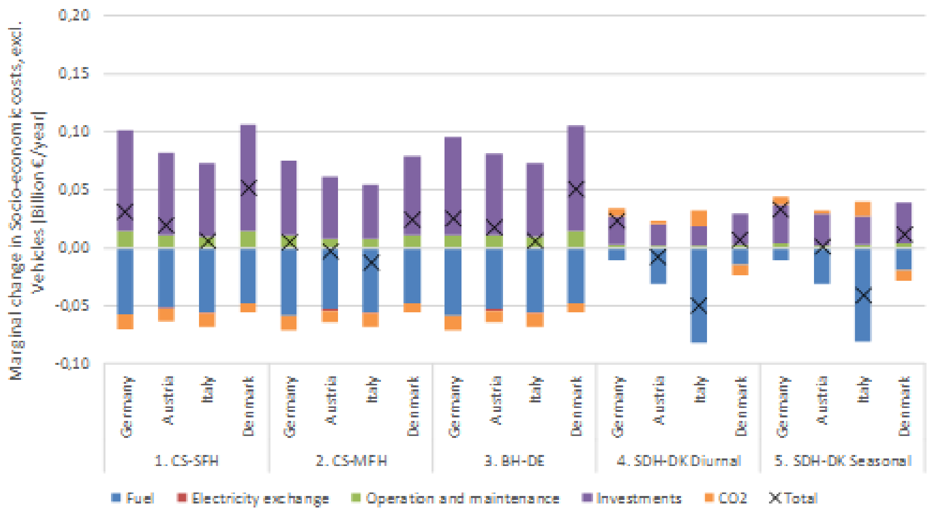

Figure 94: Marginal changes in socio-economic costs with medium fuel prices in the 2050 scenarios.

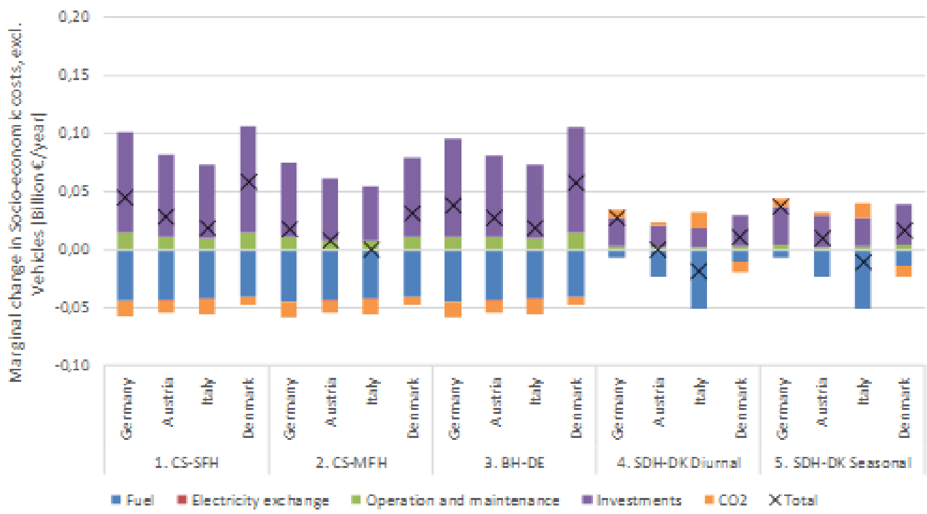

Figure 95: Marginal changes in socio-economic costs with low fuel prices in the 2050 scenarios.

Installing the maximum solar thermal potential with the high solar penetration rate impacts the overall socio-economy to a minor degree. Figure 96 and Figure 97 illustrate the marginal changes in socio-economic costs of installing the full solar thermal potential with high and low fuel prices. The costs increase as the value of fuel savings decrease from installing solar thermal and with the low prices none of the scenarios will experience cost decreases. Assuming low fuel prices rather than high prices lead to an increase in marginal cost change of around 0.2% point when comparing to the total energy system costs.

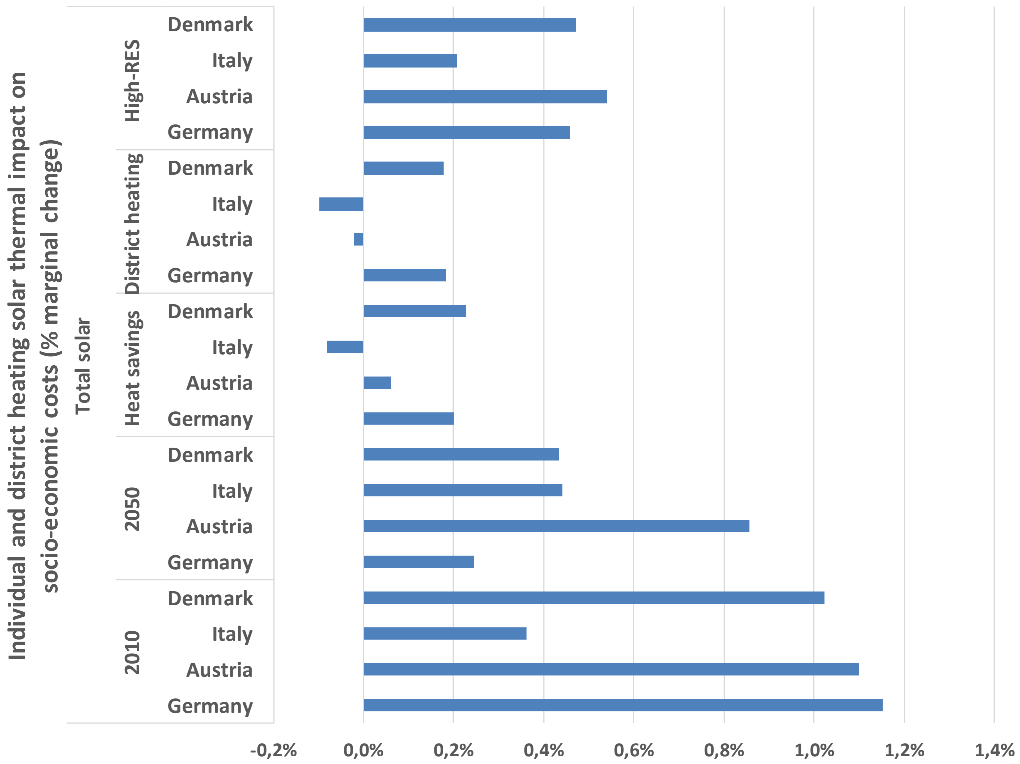

Figure 96: The marginal changes in socio-economic costs as a percentage of the total energy system costs with high fuel prices.

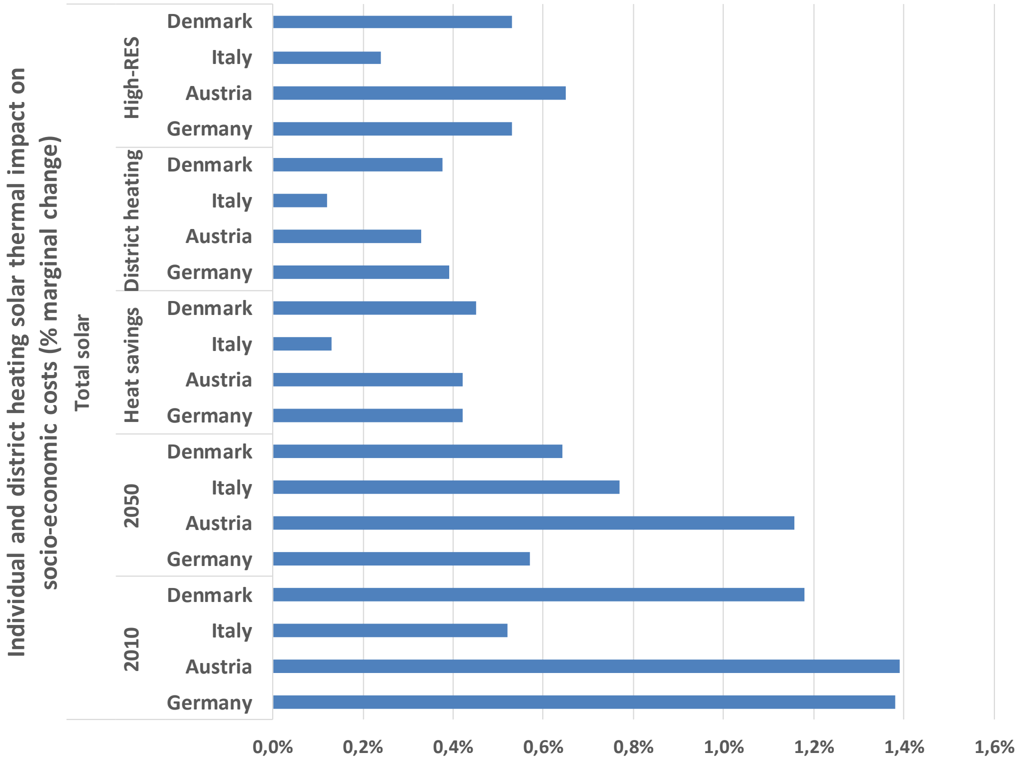

Figure 97: The marginal changes in socio-economic costs as a percentage of the total energy system costs with low fuel prices.

Based on the investigations of the significance of fuel prices it can be concluded that the fuel price only has limited impact on the overall findings in terms of designing a high-renewable energy system and the feasibility of solar thermal systems. With lower fuel prices energy efficiency measures such as heat savings, district heating and heat pumps become less attractive while renewable sources replace cheaper fuels leading to overall lower cost savings. This is also the case when installing solar thermal systems. However, the changes are insignificant in terms of their impact on the overall findings.

7.4.2 Solar thermal investment prices

This study focuses on solar thermal technologies and their role in the future energy system. Therefore, analyses of the significance of the solar thermal investment prices are included when installing the full solar thermal potentials identified previously. The solar thermal prices are assumed to decrease by 25-35% between 2015 and 2050 and additional technology improvements are investigated. The impact of investment price reductions of additional 25% and 50% price reductions compared to the 2050 prices are included in the analysis of the overall socio-economic costs of the energy system.

The impact of lower investment costs for solar thermal are illustrated in Figure 98 where the original prices are represented along with the reduced investment costs. With the original solar thermal investments for individual heating almost none of the scenarios proved overall cost reductions, but when the investment prices are 25% lower some of the scenarios prove cost reductions, especially after heat savings. A similar trend is clear when reducing the investment costs by 50% as the overall costs then decline for the scenarios with heat savings and district heating. However, none of the high-RES scenarios prove overall system cost reductions when installing individual solar thermal, even when the solar thermal investments are 50% lower.

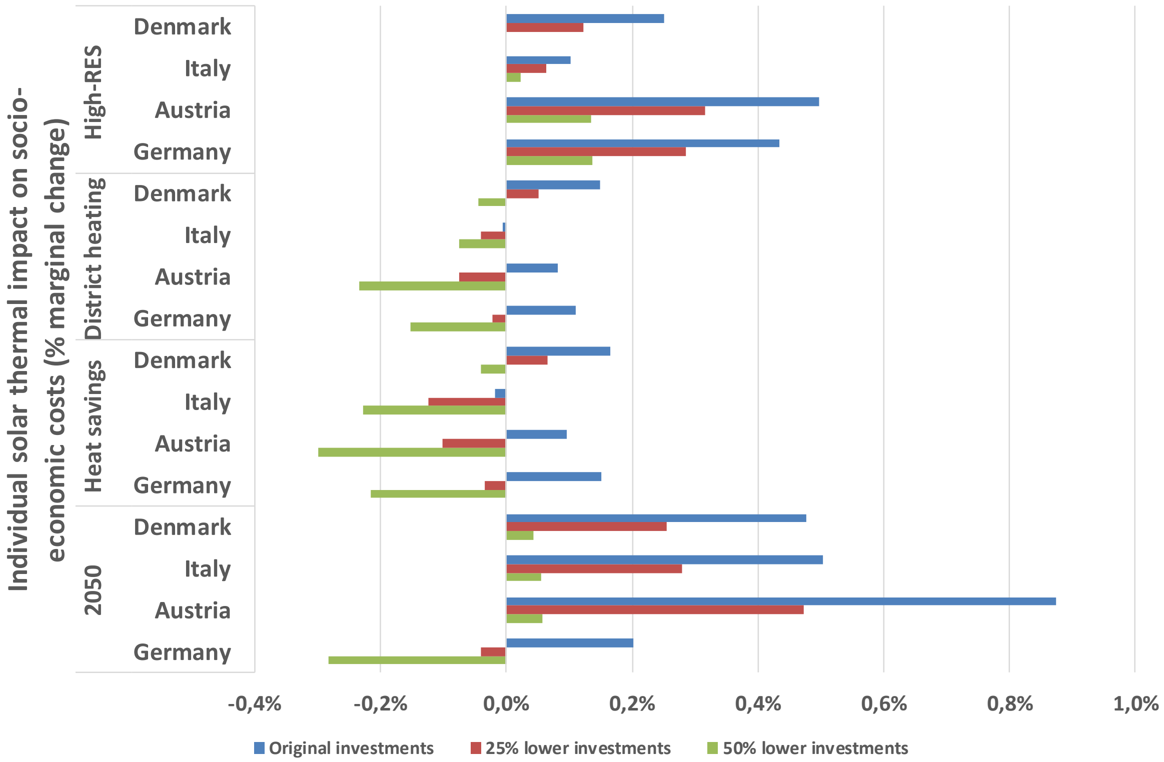

Figure 98: Marginal socio-economic cost changes for individual solar thermal potentials. The maximum potentials are installed in all the countries for three different solar thermal investment price levels; original as assumed in previous analyses with 2050 solar thermal prices, and with additional 25% and 50% lower investment prices.

The socio-economic costs are less impacted when changing the investment prices for solar thermal technologies for district heating areas. This is due to the already lower investments per energy delivered compared to the individual solar thermal technologies. When reducing the investment prices the overall cost changes do not change the overall conclusions regarding the solar thermal for district heating. However, in the high-RES scenarios all countries experience overall cost increases.

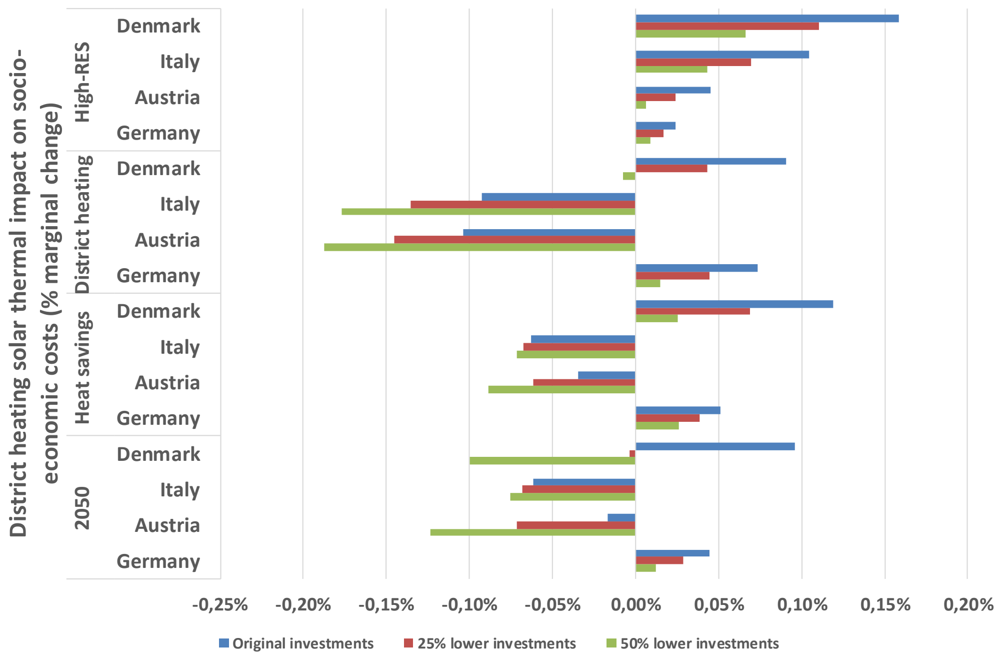

Figure 99: Marginal socio-economic cost changes for district heating solar thermal potentials. The maximum potentials are installed in all the countries for three different solar thermal investment price levels; original as assumed in previous analyses, with 2050 solar thermal prices, and with additional 25% and 50% lower investment prices.

When installing the maximum solar thermal potentials in both the individual and district heating supplied areas the reduction in solar thermal investment prices will have an impact on whether the overall costs will increase or decrease. The largest impacts occur in the individual technologies, see Figure 100.

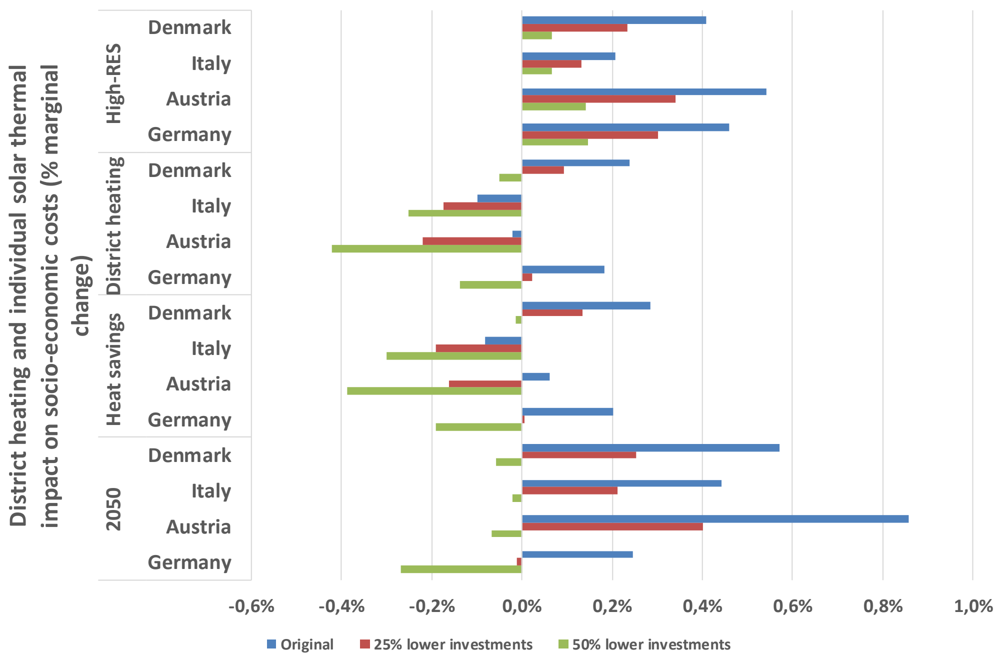

Figure 100: Marginal socio-economic cost changes for individual and district heating solar thermal potentials. The maximum potentials are installed in all the countries for three different solar thermal investment price levels; original as assumed in previous analyses with 2050 solar thermal prices, and with additional 25% and 50% lower investment prices.

The results show that with a 25% reduction in solar thermal investment prices compared to the already lower 2050 prices some of the scenarios will have decreasing costs and with a 50% reduction almost all of the scenarios will lead to lower costs. However, this is not the case for the high-RES scenarios that regardless of the investment price have higher socio-economic costs when installing the solar thermal potentials.

Furthermore, it seems unrealistic that the solar thermal investment prices will decline in a rate as investigated here. The solar thermal prices compared to the 2015 prices are in some cases 65% lower.

7.5 Efficiency improvements of reduced temperature levels in district heating networks

This section presents and discusses the potential improvement in efficiency of solar thermal connected to district heating, in case of reduced temperatures in the network. In addition, it is calculated how reduced temperatures would influence the performance of the solar thermal district heating production in the four case countries, Denmark, Germany, Austria and Italy.

7.5.1 Reducing temperature requirements in district heating networks

The temperature level in district heating networks is important to ensure the consumers a sufficient and safe supply to cover space heating and hot water demand. On the other hand the temperature in the network also defines the heat losses and requirements for heat production units, and therefore lower temperatures can also be desirable to reduce network losses and improve production efficiencies [45].

Simply speaking, district heating networks consist of supply pipes and return pipes, where the supply pipe delivers the hot water to the consumer where it is cooled and returned in the return pipe. The supply temperature can be controlled by the district heating producers whereas the return temperature depends on a number of factors related to the individual consumers, heating installations in the buildings and the pipe network. This means that a reduced supply temperature not necessarily means a reduced return temperature.

The supply temperature can be reduced to a certain extent without considering the return temperature. As the temperature difference between supply and return gets smaller, more water need to flow through the system to cover the same heating demand. This will increase the pressure in the pipes and the electricity consumption for pumping, and at a certain point it is no longer feasible to reduce the supply temperature without also considering the return [46]. If the supply temperature is reduced below about 55°C it is also necessary to consider prevention of legionella in the domestic hot water supply. This can be done by e.g. local instantaneous heat exchangers or electric temperature boosting using micro heat pumps or direct electric heating. [47,48]

It is technically possible to ensure low return temperatures from new buildings, with heating systems designed for low temperatures, especially low energy buildings with floor heating. Studies have shown that in many buildings it is also possible to reduce the return temperature from buildings without replacing the entire heating system, but only a few critical radiators or thermostatic valves and making a good adjustment of the heating system in the building [49].

7.5.2 Efficiency of solar thermal production in district heating

The thermal output of a solar panel is defined partly by the technical specifications of the individual panel type, but also by the temperature conditions at a given point in time. The efficiency is depending on the ambient temperature of the panel and the temperature of the working fluid in the panel. In a solar thermal plant connected to district heating and in individual buildings, the efficiency will therefore be depending on the supply and return temperatures of the given heating system. [50]

In Figure 101 the relation between the panel efficiency and the temperature conditions is described for district heating scale solar panel types. The efficiency of the panel is described as a function of the temperature difference between the medium working fluid temperature of the panel and the ambient air temperature. It can be seen that for larger temperature differences between panel and air the efficiency decreases. This is due to larger heat losses from the panel with a larger temperature difference. This also means that if the supply and return temperatures of the panel can be reduced, the general efficiency of the panel will increase. Examples will be given in the following section.

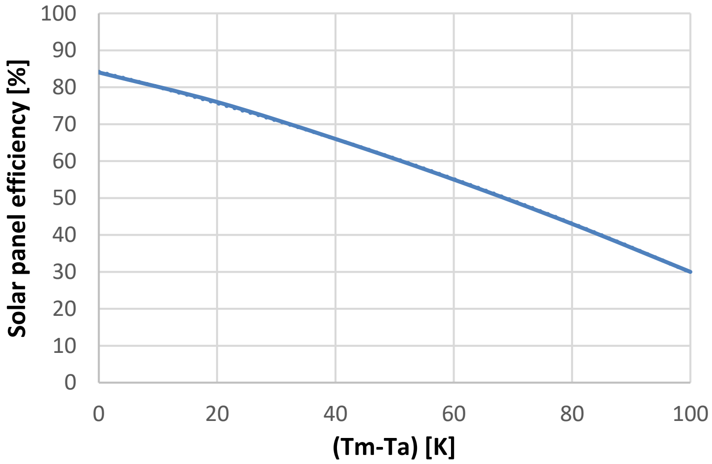

Figure 101: Efficiency of a solar panel as a function of the temperature difference between the medium panel temperature (Tm) and the ambient air temperature (Ta). Replication of figure from [51]**.**

7.5.3 Estimation of efficiency improvements for modelled case countries

To demonstrate the potential efficiency improvement of solar thermal production in district heating with reduced temperature levels, it has been calculated for the four case countries; Denmark, Germany, Austria and Italy, how the efficiencies would improve with lower supply and return temperatures.

The calculations have been performed using hourly data for one year of ambient air temperatures for the four countries and for the supply and return temperatures of a typical district heating plant in Denmark. A temperature set of 80°C in supply and 40°C in return (80/40) as annual averages are used as reference for calculating the benefit of reduced temperatures. Four different alternative temperature sets are analysed; High (100/50), Medium (70/35), Low (55/25) and Ultra-Low (45/25). The same solar collector type is used for all temperature levels, even though the Low and Ultra-Low temperature levels systems might benefit from selecting a different collector type optimised for low temperature operation.

In Table 26 the results of the calculations are presented. The ambient temperature is the only parameter that differentiates the results between the countries in this analysis, so therefore annual averages of the applied temperature series are included in the table.

Table 26: Average annual efficiency improvement of solar thermal production with reduced temperatures in a district heating network compared to the reference case.

		Denmark	Germany	Austria	Italy
Average ambient temperature	[°C]	8.6	10.3	10.8	14.2
High (100/50)	[%]	-13.0	-13.0	-12.8	-12.5
Medium (70/35)	[%]	6.1	6.1	6.0	5.9
Low (55/25)	[%]	15.7	15.7	15.5	15.1
Ultra-Low (45/25)	[%]	19.3	19.3	19.1	18.5

It can be seen that the efficiency of solar thermal production can be improved significantly by lowering the temperatures of the district heating. The benefit is slightly decreasing going from Denmark towards Italy, but in this connection it should be kept in mind that the efficiency in Italy and areas with warmer climate, the efficiency of the solar thermal production, will already be higher than those for colder areas because of the lower temperature difference between ambient air and solar panel, as discussed earlier.

In Table 27 the consequences for a solar thermal plant with an annual production of 10 GWh assuming the reference temperature set (80/40) when changing the temperatures in the district heating network.

Table 27: Production capacity and annual production for reduced temperature sets in the case countries for a solar thermal plant with a peak production of 10MW$_p$ at the reference temperature set.

		Denmark	Germany	Austria	Italy
High (100/50)	[GWh]	8.7	8.7	8.7	8.8
Reference (80/40)	[GWh]	10.0	10.0	10.0	10.0
Medium (70/35)	[GWh]	10.6	10.6	10.6	10.6
Low (55/25)	[GWh]	11.6	11.6	11.5	11.5
Ultra-low (45/25)	[GWh]	11.9	11.9	11.9	11.9

The potential improvement in efficiency can also be seen as a potential for reducing the size of a planned solar thermal plant and thereby reducing the investment costs. For example, if a solar thermal plant is being planned and reduced temperatures in the district heating network are also considered, the planned capacity of the solar thermal plant may be reduced, when taking in account the potential increased production. Furthermore, the capacities of possible thermal storages in connection to the solar thermal plant can be utilised better with lower temperatures, and the planned capacity of a connected thermal storage may therefore also be reduced.

7.5.4 Energy system consequences and 4th generation district heating

Reduced temperatures in district heating systems will have a range of different benefits to the energy system outside the district heating system itself. Reduced heat losses from the pipe networks and improved efficiencies of production units are the main benefits, resulting in lower primary energy consumption. This changes the dynamics in the energy system from hour to hour and from season to season. For example; if solar thermal plants are producing more, then a CHP plant may be producing less, because the heat demand will be covered from the solar thermal. The electricity that the CHP plant would have produced will have to be produced in an alternative way, e.g. a solar PV plant or a condensing power plant.

Low temperature district heating is today starting to be implemented in different places and the changes this causes should be taken into account when planning for future district heating production capacity and distribution systems, since these are long term investments. The feasibility of solar thermal may also change; in some district heating systems it can get more feasible because of the improved efficiency. In other systems it may be less feasible. For example, in a system with utilisation of industrial waste heat, that also may increase its efficiency which in combination with reduced heat losses will limit the remaining heat demand to cover with solar thermal.

4th generation district heating is a concept that focuses on low temperature heating in the networks, integration of energy sectors and introduction of new and renewable heat sources [52]. This is a future vision of how district heating should develop to fit into a renewable energy system in the future. This is a more cost effective and more resource efficient way of supplying heat in future energy systems than conventional district heating and alternatives to district heating. As mentioned, it is important to have the long term goal in mind when planning the district heating system, to be able to utilise the synergies of integrating solar thermal in appropriate places and avoiding sub-optimisation in the system.

8 Conclusions and recommendations

The objective of this study has been to analyse the role of solar thermal in the energy system with a horizon of 2050. This has been carried out by analysing the entire energy system at once including all energy sectors on an hour-by-hour temporal resolution.
For various energy system types across different countries the role of solar thermal in individual buildings and in district heating networks has been analysed. Furthermore, the role of solar thermal has been analysed within different energy system types, including: 1) systems analogous to the current energy systems and 2) future energy systems with lower heat demands, higher shares of district heating and with a significantly higher renewable energy share.

Three types of analysis were performed assessing the impact on the energy systems in terms of heat supply, electricity production, primary energy, CO_2-emissions and socio-economic costs (the total energy system costs including investments, operation and maintenance, fuel costs, CO_2-costs and electricity exchange). The first analysis investigated the marginal impact of installing 1 TWh of solar thermal, the second analysis the maximum solar thermal potential that might be installed in the countries and the third analysis looked into the impact of installing the maximum solar thermal potential.

The technical solar thermal potentials for each country 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 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 results show that the overall solar thermal potential across the countries and various energy system types is in the range of 3-12% of the total heat production. The socio-economic costs are higher in a high-renewable energy system compared to installing solar thermal in the current energy systems. Similarly, the advantages of solar thermal reduce in terms of reductions of fossil fuels and CO_2-emissions when transitioning towards a high-renewable energy system.

The main conclusions and recommendations from the solar thermal analysis are outlined below.

8.1 The energy system design is crucial in terms of solar thermal feasibility

Solar thermal replaces other types of heat supply in the energy system when installed (e.g. CHP, heat pumps, boilers) and it is vital to identify these technologies. The replaced technologies determine the impacts on the energy system in terms of primary energy, CO_2-emissions and socio-economic costs. The analysis proved that in certain cases the CO_2-emissions might even increase when installing solar thermal because this could lead to decreased electricity production from CHP plants (which typically consume oil and natural gas) which is replaced by condensing coal power plants. Hence, solar thermal has to be seen as part of a general transition towards renewable energy sources. The technologies that are directly and indirectly replaced by solar thermal therefore have to be considered for the specific energy system before solar thermal is installed.

8.2 The solar thermal penetration is crucial for the solar thermal potential

The solar penetration rate refers to the share of buildings that are supplied by solar thermal plants (either directly on a roof or via district heating networks). The solar thermal potential that could be installed showed a significant difference depending on the solar penetration rate. The solar thermal penetration proved essential since a high solar thermal penetration allows for the solar thermal production to be distributed to more users and thereby reducing the overproduction in peak production periods.

8.3 Based on the analyses in this report the technical solar thermal potential is in the range of 3-12% of the heat production

The technical solar thermal potential was assessed using the solar penetration rate, mismatch between district heating production and demand and the solar thermal overproduction. It was found that the solar thermal potential can cover a larger share of the district heating demands than in the individual areas. Moreover, it was concluded that 1) the largest solar thermal potentials exist in the countries with the highest heat demands and 2) the solar thermal shares that can be installed across the countries is rather similar. Furthermore, heat savings in buildings reduces the amount of solar thermal that can be installed, but increases the proportion of solar thermal possible in the energy system. With a solar penetration rate of 20% the solar thermal potential might be 3-6% of the total heat production, while a solar penetration rate of 35% means a potential of 5-8%. When assuming a higher solar penetration rate of 50% the solar potential might increase to 6-12% of the total heat production in the energy system.

8.4 Installing solar thermal could lead to higher energy system socio-economic costs

The findings in the report proved that by installing solar thermal this could increase the total socio-economic cost of the energy system irrespective of the country and the scenario. However, there is a significant difference between installing solar thermal in the individual and the district heating areas where the latter proves better total socio-economic costs. In the individual areas, the total energy system socio-economic costs increase 0-1% when installing the maximum solar thermal potential. In the district heating areas, in some countries the cost increases and in others they decrease. Factors that influence this include for example the solar thermal production costs and the price of the replaced fuels. When the maximum solar thermal potentials are installed for both individual and district heating areas it was found that this will lead to increased socio-economic costs for 17 of the 20 analysed scenarios. With higher fuel prices than current prices this conclusion also applies. If the investment prices for solar thermal decrease by 25% and 50% further below the 2050 prices, the socio-economy is improved. This does however not occur in the high-renewable scenario where the full extent of solar thermal potential is installed and it remains more expensive than installing no solar thermal.

8.5 Solar thermal could ease the pressure on scarce renewable resources such as biomass

It is crucial to ease the pressure on scarce resources such as biomass (used for heating and electricity) as well as renewable electricity (used for heat pumps) as these resources will be in high demand in all energy sectors in the future. When solar thermal is installed, the consumption of biomass decreases for both individual and district heating areas in systems that are analogous to the energy system of today as well as in energy systems with high-renewable energy. In this study, it was concluded that when installing the maximum solar thermal potential, the biomass demand could be reduced by 0-2%. More solar thermal could be installed if the aim is to further reduce the biomass consumption. Similar savings can be obtained for fossil fuel reductions from installing solar thermal.

8.6 Solar thermal will be competing with other renewable sources in a high-renewable energy system

Other types of renewable energy sources might provide similar energy system services as solar thermal does and these might start competing with solar thermal. These sources can include geothermal heating, waste-to-energy, industrial excess heating and heat pumps supplied by renewable energy. These technologies might compete in terms of cost of supplying heat, impacts on the flexibility of the system (baseload and fluctuating production) as well as for space for installing solar thermal versus photovoltaic systems. These technologies are likely to be available near larger cities so therefore in order for solar thermal to be most useful, it could be installed in areas where these heating sources are unavailable for district heating.

8.7 Some advantages of solar thermal decrease in a high-renewable energy system

When progressing towards a high-renewable energy system new types of energy sources will start supplying parts of the energy demands. In a high-renewable energy system no fossil fuels will be consumed and therefore solar thermal will compete with and replace other types of renewable energy sources. This means that when installing solar thermal there is no reduction of fossil fuels and no further reduction of CO_2-emissions (assuming biomass has no CO_2-emissions). In addition, a high-renewable energy system is less flexible due to 1) fluctuating renewable electricity sources that impact the operation of CHP and heat pumps and 2) more renewable baseload technologies are integrated into the system such as geothermal, waste-to-energy and industrial excess heat making the district heating production less flexible and thereby reducing the potential for solar thermal.

8.8 A full energy system perspective is required to analyse the feasibility of solar thermal

By analysing the entire energy system at once it is possible to capture the dynamics occurring across energy sectors such as the operation of CHP plants and how this impacts the electricity sector. Furthermore, it allows an understanding of the feasibility of different energy storages and 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.

8.9 The findings in this study apply to a variety of energy system types

The analysis in this study provides a set of clear results based on a coherent method about the extent in which solar thermal could be installed in four different countries with different conditions. These countries differ in terms of climates, energy demands and energy system design (some are based mainly on individual natural gas supply, others on hydro power, wind power and district heating). In addition, multiple scenarios have been analysed for 1) other possible developments in the future energy systems and for 2) the influence of different fuel and solar thermal prices.

The variety of energy system types analysed allowed for making general conclusions regarding the role of solar thermal in future energy systems. This might indicate that the findings can be applied to a variety of energy systems, including countries that are not directly part of this study.

8.10 Factors that might improve solar thermal feasibility

The study has identified a number of factors that could increase the feasibility of solar thermal in the future.

- In high-renewable energy systems of the future it is unlikely that there are sufficient renewable energy resources, especially regarding biomass. Solar thermal can play a role in **reducing the consumption of biomass** in the heating sector since biomass should not be prioritised for heating purposes. Rather it should be reserved for other sectors such as transport and industry where few alternatives exist. This might increase the solar thermal potentials identified in the study.
- The **reduction of investment prices and improved technological efficiency** of solar thermal will improve its feasibility, however very significant cost reductions are required to make solar thermal investments socio-economic feasible in the simulations.
- The relation between baseload heat production and **the flexibility in the system** is decisive for how much solar thermal can be installed in the system. If less baseload resources are installed the potential of solar thermal might increase.
- In the future, the **temperature of the district heat supply** might potentially be lowered and this could impact the efficiency and costs of the solar thermal production. It will improve the feasibility of solar thermal, but it requires lower temperatures in the district heating networks and buildings with lower heat demands (which will most likely mainly take place in new buildings).
- In this report, the potential for solar thermal was investigated for the heating sector but **solar thermal could supply other sectors**. For example, solar thermal might be utilised for cooling purposes and for industrial purposes within a certain temperature range.
- By integrating **seasonal heat storage** into the energy system this can possibly increase the solar thermal potential in district heating areas. However, due to space constraints and land prices this technology is primarily used in smaller district heating networks outside the larger cities. In Denmark around ~35% of the district heating demand is supplied by decentralised technologies outside the larger cities. Examples can here be found of seasonal storages in connection with solar thermal plants allowing for higher solar fractions and a more flexible district heating production. However, compared with installing solar thermal for district heating with diurnal storages, in the present analysis this solution was found to be more costly, but could possibly also provide other benefits in the forms of fuel savings and improved system flexibility.

8.11 Further research

It is recommended that further research is carried out to continue developing the knowledge about the role of solar thermal in the future energy system. Some positive externalities related to solar thermal exist that were not been considered in this study, which might improve the feasibility of solar thermal.

- For example, solar thermal could contribute to **enhancing the security of supply** by increasing local energy production and thereby reducing the dependency on fuel import. In addition, solar thermal can reduce greenhouse gas emissions and particle emissions by replacing heat supply from wood stoves and individual boilers and thereby contribute to improving health conditions.
- This study has been based on a national energy system perspective analysing the entire energy system of a country. However, **local variations** might apply meaning that solar thermal could be feasible in local energy systems and in these areas, have higher potentials than the aggregated national solar thermal potentials.
- **Other technologies can be installed in connection with solar thermal** which could create more flexible and efficient systems. These could include solar thermal combined with PV systems or solar thermal plants combined with heat pumps. These combinations were not included in this study and should be studied further.
- Another factor that might impact the feasibility of solar thermal is the **available space** on roof tops and in open fields. Some of these areas might be prioritised for the installation of PV, and therefore a deeper analysis into the implication of this conflict is necessary.

- This study applied a socio-economic perspective in order to identify the overall feasibility of solar thermal installations for society. However, this might not align with **private-economic incentives** and this could be studied further. The difference between private- and socio-economic feasibility is caused by the political framework and has significant influence on the spread of solar thermal technologies. For example, solar thermal might be installed due to beneficial subsidy schemes, regulations or taxes on fuels, however these factors will change when looking towards 2050.
- The findings in this study apply for solar thermal technologies and should be accompanied by additional analyses on the role of other renewable energy sources in order to develop a feasible **transition pathway to a high-renewable energy system** in the future.

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10 Appendix A – cost database

Preface

The EnergyPLAN cost database is created and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. It is constructed based on data from a wide variety of sources, with many of the inputs adjusted to fit with the required fields in the EnergyPLAN model. Below is a list of all the different sources currently used to construct the cost database. The result is a collection of investment, operation & maintenance, and lifetimes for all technologies for the years 2020, 2030, and 2050. Where data could not be obtained for 2030 or 2050, a 2020 cost is often assumed.

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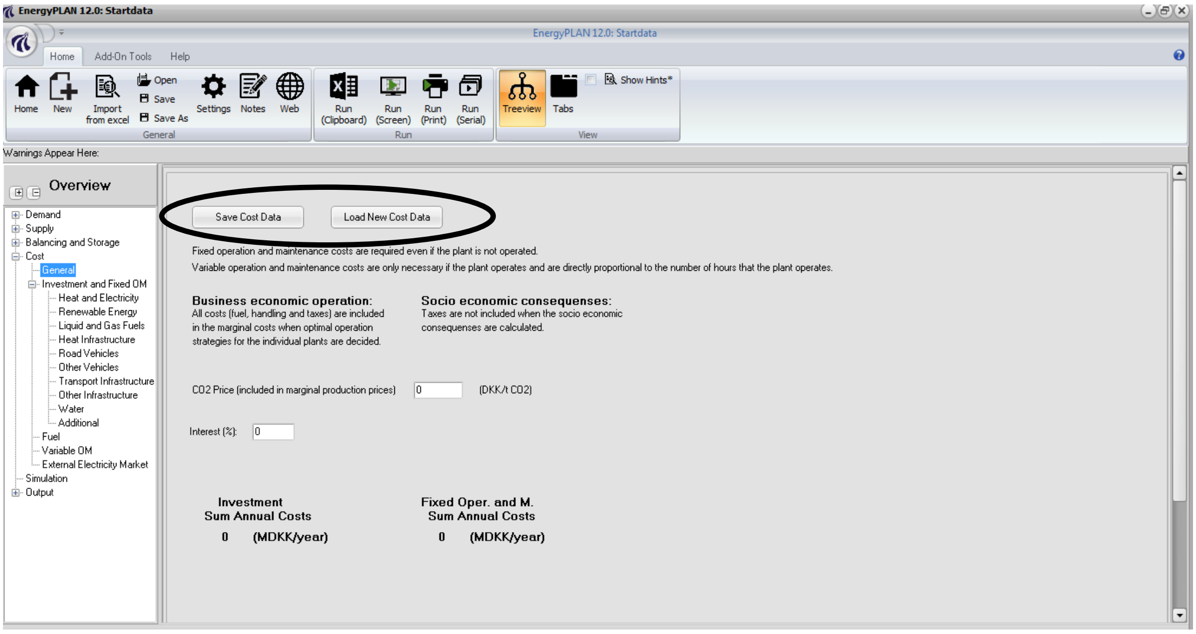
Introduction

The EnergyPLAN tool contains five tabsheets under the main 'Cost' tabsheet, which are:

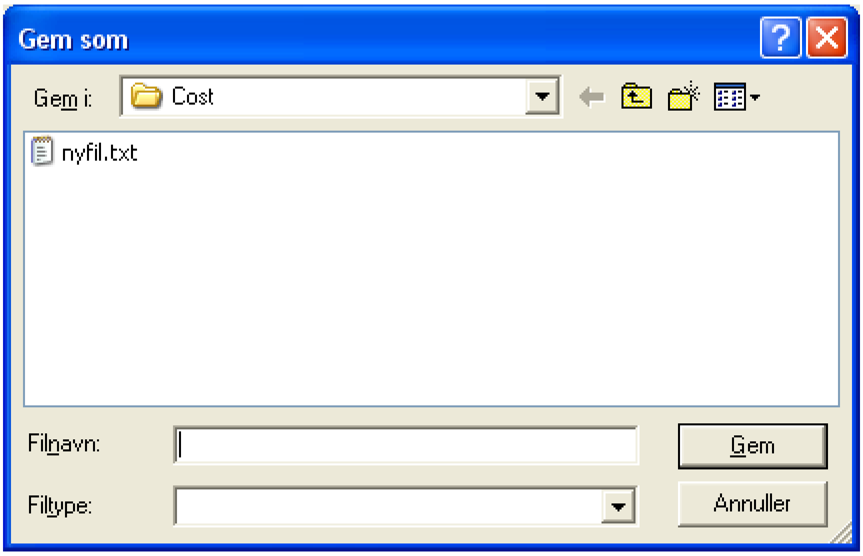
- General
- Investment and Fixed OM
- Fuel
- Variable OM
- External electricity market

The Investment and Fixed OM tabsheet further contains ten sub-tabsheets that relates to different technology groups such as Heat and Electricity, Renewable Energy, Heat infrastructure, Road vehicles, Additional, etc.

Within each of these, the user can enter over 200 inputs depending on the range of technologies being considered in an analysis. When completing an energy systems analysis, it is often necessary to change the cost data in EnergyPLAN for a variety of reasons: for example, to analyse the same system for a different year or to analyse the sensitivity of the system to different costs. To accommodate this, EnergyPLAN enables the user to change the cost data within a model, without changing any of the data under the other tabsheets. To do so, one has to go to the Cost-> General tabsheet and activate one of the two buttons "Save Cost Data" or "Load New Cost Data".



When activating one of these buttons, the user will be brought to the 'Cost' folder where one can either save a new cost data file or load an existing one. It is important to note that when you are saving a file, you should always specify a filename with .txt at the end of the name, as otherwise it may not save correctly.



Even with this function, collecting cost data is still a very time-consuming task and hence, the EnergyPLAN Cost Database has been developed. This database includes cost data for almost all of the technologies included in EnergyPLAN based primarily on publications released by the Danish Energy Agency. This document gives a brief overview of this data.

EnergyPLAN Cost Database

To date, the EnergyPLAN Cost Database consists of the following files:

- 2020EnergyPLANCosts.txt
- 2030EnergyPLANCosts.txt
- 2050EnergyPLANCosts.txt

The file name represents the year which the costs are for. These are recommended based on the literature reviewed by the EnergyPLAN team and it is the users responsibility to verify or adjust them accordingly. To date, the principal source for the cost data has been the Danish Energy Agency (DEA) [1], although a variety of other sources have been used where the data necessary is not available. Below is an overview of the data used to create the EnergyPLAN Cost Database, although it should be noted that this data is updated regularly, so there may be slight differences in the files provided.

Fuel Costs

The fuel prices assumed in the EnergyPLAN Cost Database are outlined in Table 28. Since the DEA only project fuel prices to 2030, the fuel prices in 2040 and 2050 were forecasted by assuming the same trends as experiences in the period between 2020 and 2030. These forecasts can change dramatically from one year to the next. For example, between January and August of 2012, the average oil price was $106/bbl, which is much closer to the oil price forecasted for 2020 than for the 2011 oil price.

Table 28: Fuel prices for 2011, 2020, 2030, 2040, and 2050 in the EnergyPLAN Cost Database [2, 3].

(2009-€/GJ) Year	Oil (US$/bbl)	Natural Gas	Coal	Fuel Oil	Diesel	Petrol	Jet Fuel	Straw	Wood Chips	Wood Pellets	Energy Crops	Nuclear
2011	82.0	5.9	2.7	8.8	11.7	11.9	12.7	3.5	4.5	9.6	4.7	1.5
2020	107.4	9.1	3.1	11.9	15.0	15.2	16.1	3.9	5.1	10.2	4.7	1.5
2030	118.9	10.2	3.2	13.3	16.6	16.7	17.6	4.3	6.0	10.9	5.2	1.5
	Projected assuming the same trends as in 2020-2030											
2040	130.5	11.2	3.3	14.7	18.1	18.2	19.1	4.7	6.8	11.5	5.7	1.5
2050	142.0	12.2	3.4	16.1	19.6	19.7	20.6	5.1	7.6	12.2	6.3	1.5

Fuel handling costs were obtained from the Danish Energy Agency [3]. They represent the additional costs of handling and storing fuels for different types of consumers as well as expected profit margins.

Table 29: Fuel handling costs for 2020 in the EnergyPLAN Cost Database [3].

2009 - €/GJ	Centralised Power Plants	Decentralised Power Plants & Industry	Consumer
Fuel			
Natural Gas	0.412	2.050	3.146
Coal	-	-	-
Fuel Oil	0.262	-	-
Diesel/Petrol	0.262	1.905	2.084
Jet Fuel	-	-	0.482
Straw	1.754	1.216	2.713
Wood Chips	1.493	1.493	
Wood Pellets	-	0.543	3.256
Energy Crops	1.493	1.493	

The cost of emitting carbon dioxide is displayed in Table 30 and the CO_2 emission factors used for each fuel are outlined in Table 31.

Carbon Dioxide Costs and Emissions

Table 30: Carbon dioxide prices for 2011, 2020, 2030, 2040, and 2050 in the EnergyPLAN Cost Database [3].

2009-€/Ton	CO2 Price
2011	15.2
2020	28.6
2030	34.6
Projected assuming the same trends as in 2020-2030	
2040	40.6
2050	46.6

Table 31: Carbon dioxide emission factors for different fuels in the EnergyPLAN Cost Database [4].

Fuel	Coal/Peat	Oil	Natural Gas	Waste	LPG
Emission Factor (kg/GJ)	98.5	72.9	56.9	32.5	59.64

Variable Operation and Maintenance Costs

In the Operation tabsheet, the user inputs the variable operation and maintenance costs for a range of technologies. Variable O&M costs account for the additional costs incurred at a plant when the plant has to run such as more replacement parts and more labour. Those available in the EnergyPLAN Cost Database are outlined in Table 32.

Table 32: Variable operation and maintenance costs assumed for 2020 in the EnergyPLAN Cost Database.

Sector	Unit	Variable O&M Cost (€/MWh)
District Heating and CHP Systems	Boiler*	0.15
	CHP*	2.7
	Heat Pump	0.27
	Electric Heating	0.5
Power Plants	Hydro Power	1.19
	Condensing*	2.654
	Geothermal	15
	GTL M1	1.8
	GTL M2	1.008
Storage	Electrolyser	0
	Pump	1.19
	Turbine	1.19
	V2G Discharge	
	Hydro Power Pump	1.19
Individual	Boiler	Accounted for under individual heating costs in the Additional tabsheet
	CHP	
	Heat Pump	
	Electric Heating	

***These costs need to be calculated based on the mix of technologies in the energy system, which can vary substantially from one system to the next.**

Investment Costs

Table 33 outlines the investment costs in the EnergyPLAN Cost Database for the different technologies considered in EnergyPLAN. Note that different technology costs are expressed in different units, so when defining the capacity of a technology, it is important to use the same unit in for the technical input as in the cost input.

Table 33: Investment costs for 2020, 2030, and 2050 in the EnergyPLAN Cost Database.

	Unit: M€/Unit	Unit	2020	2030	2050
Heat & Electricity	Small CHP	MWe	1.2	1.2	1.2
	Large CHP	MWe	0.8	0.8	0.8
	Heat Storage CHP	GWh	3.0	3.0	3.0
	Waste CHP	TWh/year	215.6	215.6	215.6
	Absorption Heat Pump	MWth	0.4	0.4	0.4
	Heat Pump Group 2	MWe	3.4	3.4	2.9
	Heat Pump Group 3	MWe	3.4	3.3	2.9
	DHP Boiler Group 1	MWth	0.100	0.100	0.100
	Boilers Group 2 & 3	MWth	0.075	0.100	0.100
	Electric Boiler	MWth	0.100	0.075	0.075
	Large Power Plants	MWe	0.99	0.98	0.9
	Nuclear	MWe	3.6	3.6	3.0
	Interconnection	MWe	1.2	1.2	1.2
	Pump	MWe	0.6	0.6	0.6
	Turbine	MWe	0.6	0.6	0.6
	Pump Storage	GWh	7.5	7.5	7.5
	Industrial CHP Electricity	TWh/year	68.3	68.3	68.3
	Industrial CHP Heat	TWh/year	68.3	68.3	68.3
Renewable Energy	Wind Onshore	MWe	1.3	1.3	1.2
	Wind Offshore	MWe	2.4	2.3	2.1
	Photovoltaic	MWe	1.3	1.1	0.9
	Wave Power	MWe	6.4	3.4	1.6
	Tidal	MWe	6.5	5.3	5.3
	CSP Solar Power	MWe	6.0	6.0	6.0
	River Hydro	MWe	3.3	3.3	3.3
	Hydro Power	MWe	3.3	3.3	3.3
	Hydro Storage	GWh	7.5	7.5	7.5
	Hydro Pump	MWe	0.6	0.6	0.6
	Geothermal Electricity	MWe	4.6	4.0	4.0
	Geothermal Heat	TWh/year	0.0	0.0	0.0
	Solar Thermal	TWh/year	386.0	307.0	307.0
	Heat Storage Solar	GWh	3.0	3.0	3.0
	Industrial Excess Heat	TWh/year	40.0	40.0	40.0
Liquid and Gas Fuels	Biogas Plant	TWh/year	240	240	240
	Gasification Plant	MW Syngas	0.4	0.3	0.3
	Biogas Upgrade	MW Gas Out	0.3	0.3	0.3
	Gasification Gas Upgrade	MW Gas Out	0.3	0.3	0.3
	2nd Generation Biodiesel Plant	MW-Bio	3.4	2.5	1.9

	Biopetrol Plant	MW-Bio	0.8	0.6	0.4
	Biojetpetrol Plant	MW-Bio	0.8	0.6	0.4
	CO2 Hydrogenation Electrolyser	MW-Fuel	0.9	0.6	0.4
	Synthetic Methane Electrolyser	MW-Fuel	0.0	0.0	0.0
	Chemical Synthesis MeOH	MW-Fuel	0.6	0.6	0.6
	Alkaline Electrolyser	MWe	2.5	0.9	0.9
	SOEC Electrolyser	MWe	0.6	0.4	0.3
	Hydrogen Storage	GWh	20.0	20.0	20.0
	Gas Storage	GWh	0.1	0.1	0.1
	Oil Storage	GWh	0.0	0.0	0.0
	Methanol Storage	GWh	0.1	0.1	0.1
Heat Infrastructure	Individual Boilers	1000 Units	6.1	0.0	0.0
	Individual CHP	1000 Units	12.0	0.0	0.0
	Individual Heat Pump	1000 Units	14.0	0.0	14.0
	Individual Electric Heat	1000 Units	8.0	0.0	0.0
	Individual Solar Thermal	TWh/year	1700.0	1533.3	1233.3
Road Vehicles	Bicycles	1000 Vehicles	0.0	0.0	0.0
	Motorbikes	1000 Vehicles	6.0	6.0	6.0
	Electric Cars	1000 Vehicles	18.1	18.1	18.1
	Conventional Cars	1000 Vehicles	20.6	20.6	20.6
	Methanol/DME Busses	1000 Vehicles	177.2	177.2	177.2
	Diesel Busses	1000 Vehicles	177.2	177.2	177.2
	Methanol/DME Trucks	1000 Vehicles	99.2	99.2	99.2
	Diesel Trucks	1000 Vehicles	99.2	99.2	99.2
Water	Desalination	1000 m3 Fresh Water/hour	0.1	0.1	0.1
	Water Storage	Mm3	0.0	0.0	0.0

***Power plant costs need to be calculated based on the mix of technologies in the energy system, which can vary substantially from one system to the next.**

Fixed Operation and Maintenance Costs

	Unit: % of Investment	Unit	2020	2030	2050
Heat & Electricity	Small CHP	MWe	3.75	3.75	3.75
	Large CHP	MWe	3.66	3.66	3.80
	Heat Storage CHP	GWh	0.70	0.70	0.70
	Waste CHP	TWh/year	7.37	7.37	7.37
	Absorption Heat Pump	MWth	4.68	4.68	4.68
	Heat Pump Group 2	MWe	2.00	2.00	2.00
	Heat Pump Group 3	MWe	2.00	2.00	2.00
	DHP Boiler Group 1	MWth	3.70	3.70	3.70
	Boilers Group 2 & 3	MWth	1.47	3.70	3.70

	Electric Boiler	MWth	3.70	1.47	1.47
	Large Power Plants	MWe	3.12	3.16	3.26
	Nuclear	MWe	2.53	2.49	1.96
	Interconnection	MWe	1.00	1.00	1.00
	Pump	MWe	1.50	1.50	1.50
	Turbine	MWe	1.50	1.50	1.50
	Pump Storage	GWh	1.50	1.50	1.50
	Industrial CHP Electricity	TWh/year	7.32	7.32	7.32
	Industrial CHP Heat	TWh/year	7.32	7.32	7.32
Renewable Energy	Wind Onshore	MWe	3.05	2.97	3.20
	Wind Offshore	MWe	2.97	3.06	3.21
	Photovoltaic	MWe	2.09	1.38	1.15
	Wave Power	MWe	0.59	1.04	1.97
	Tidal	MWe	3.00	3.66	3.66
	CSP Solar Power	MWe	8.21	8.21	8.21
	River Hydro	MWe	2.00	2.00	2.00
	Hydro Power	MWe	2.00	2.00	2.00
	Hydro Storage	GWh	1.50	1.50	1.50
	Hydro Pump	MWe	1.50	1.50	1.50
	Geothermal Electricity	MWe	3.50	3.50	3.50
	Geothermal Heat	TWh/year	0.00	0.00	0.00
	Solar Thermal	TWh/year	0.13	0.15	0.15
	Heat Storage Solar	GWh	0.70	0.70	0.70
	Industrial Excess Heat	TWh/year	1.00	1.00	1.00
Liquid and Gas Fuels	Biogas Plant	TWh/year	6.96	6.96	6.96
	Gasification Plant	MW Syngas	5.30	7.00	7.00
	Biogas Upgrade	MW Gas Out	15.79	17.65	18.75
	Gasification Gas Upgrade	MW Gas Out	15.79	17.65	18.75
	2nd Generation Biodiesel Plant	MW-Bio	3.01	3.01	3.01
	Biopetrol Plant	MW-Bio	7.68	7.68	7.68
	Biojetpetrol Plant	MW-Bio	7.68	7.68	7.68
	CO2 Hydrogenation Electrolyser	MW-Fuel	2.46	3.00	3.00
	Synthetic Methane Electrolyser	MW-Fuel	0.00	0.00	0.00
	Chemical Synthesis MeOH	MW-Fuel	3.48	3.48	3.48
	Alkaline Electrolyser	MWe	4.00	4.00	4.00
	SOEC Electrolyser	MWe	2.46	3.00	3.00
	Hydrogen Storage	GWh	0.50	0.50	0.50
	Gas Storage	GWh	1.00	1.00	1.00
	Oil Storage	GWh	0.63	0.63	0.63
	Methanol Storage	GWh	0.63	0.63	0.63

Heat Infrastructure	Individual Boilers	1000 Units	1.79	0.00	0.00
	Individual CHP	1000 Units	0.00	0.00	0.00
	Individual Heat Pump	1000 Units	0.98	0.00	0.98
	Individual Electric Heat	1000 Units	1.00	0.00	0.00
	Individual Solar Thermal	TWh/year	1.22	1.35	1.68
Road Vehicles	Bicycles	1000 Vehicles	0.00	0.00	0.00
	Motorbikes	1000 Vehicles	5.00	5.00	5.00
	Electric Cars	1000 Vehicles	6.99	4.34	4.34
	Conventional Cars	1000 Vehicles	4.09	4.09	4.09
	Methanol/DME Busses	1000 Vehicles	9.14	9.14	9.14
	Diesel Busses	1000 Vehicles	9.14	9.14	9.14
	Methanol/DME Trucks	1000 Vehicles	21.10	21.10	21.10
	Diesel Trucks	1000 Vehicles	21.10	21.10	21.10

Lifetimes

	Unit: Years	Unit	2020	2030	2050
Heat & Electricity	Small CHP	MWe	25	25	25
	Large CHP	MWe	25	25	25
	Heat Storage CHP	GWh	20	20	20
	Waste CHP	TWh/year	20	20	20
	Absorption Heat Pump	MWth	20	20	20
	Heat Pump Group 2	MWe	25	25	25
	Heat Pump Group 3	MWe	25	25	25
	DHP Boiler Group 1	MWth	35	35	35
	Boilers Group 2 & 3	MWth	20	35	35
	Electric Boiler	MWth	35	20	20
	Large Power Plants	MWe	27	27	27
	Nuclear	MWe	30	30	30
	Interconnection	MWe	40	40	40
	Pump	MWe	50	50	50
	Turbine	MWe	50	50	50
	Pump Storage	GWh	50	50	50
	Industrial CHP Electricity	TWh/year	25	25	25
	Industrial CHP Heat	TWh/year	25	25	25
Renewable Energy	Wind Onshore	MWe	20	25	30
	Wind Offshore	MWe	20	25	30
	Photovoltaic	MWe	30	30	40
	Wave Power	MWe	20	25	30
	Tidal	MWe	20	20	20
	CSP Solar Power	MWe	25	25	25

	River Hydro	MWe	50	50	50
	Hydro Power	MWe	50	50	50
	Hydro Storage	GWh	50	50	50
	Hydro Pump	MWe	50	50	50
	Geothermal Electricity	MWe	20	20	20
	Geothermal Heat	TWh/year	0	0	0
	Solar Thermal	TWh/year	30	30	30
	Heat Storage Solar	GWh	20	20	20
	Industrial Excess Heat	TWh/year	30	30	30
Liquid and Gas Fuels	Biogas Plant	TWh/year	20	20	20
	Gasification Plant	MW Syngas	25	25	25
	Biogas Upgrade	MW Gas Out	15	15	15
	Gasification Gas Upgrade	MW Gas Out	15	15	15
	2nd Generation Biodiesel Plant	MW-Bio	20	20	20
	Biopetrol Plant	MW-Bio	20	20	20
	Biojetpetrol Plant	MW-Bio	20	20	20
	CO2 Hydrogenation Electrolyser	MW-Fuel	20	15	15
	Synthetic Methane Electrolyser	MW-Fuel	0	0	0
	Chemical Synthesis MeOH	MW-Fuel	20	20	20
	Alkaline Electrolyser	MWe	28	28	28
	SOEC Electrolyser	MWe	20	15	15
	Hydrogen Storage	GWh	30	30	30
	Gas Storage	GWh	50	50	50
	Oil Storage	GWh	50	50	50
	Methanol Storage	GWh	50	50	50
Heat Infrastructure	Individual Boilers	1000 Units	21	0	0
	Individual CHP	1000 Units	10	0	0
	Individual Heat Pump	1000 Units	20	0	20
	Individual Electric Heat	1000 Units	30	0	0
	Individual Solar Thermal	TWh/year	25	30	30
Road Vehicles	Bicycles	1000 Vehicles	0	0	0
	Motorbikes	1000 Vehicles	15	0	15
	Electric Cars	1000 Vehicles	16	16	16
	Conventional Cars	1000 Vehicles	16	16	16
	Methanol/DME Busses	1000 Vehicles	6	6	6
	Diesel Busses	1000 Vehicles	6	6	6
	Methanol/DME Trucks	1000 Vehicles	6	6	6
	Diesel Trucks	1000 Vehicles	6	6	6

Additional Tabsheet

The additional tabsheet under the Investment and Fixed OM tabsheet can be used to account for costs which are not included in the list of technologies provided in the other tabsheets. Typically these costs are calculated outside of the EnergyPLAN tool and subsequently inputted as a total. In the past, this section has been used to include the costs of the following technologies:

- Energy efficiency measures
- Electric grid costs
- Individual heating costs
- Interconnection costs
- Costs for expansion of district heating and cooling

Some of these costs vary dramatically from one energy system to the next and hence they are not included in the cost files which can be loaded into EnergyPLAN. However, below are some costs which may provide a useful starting point if additional costs need to be estimated.

Heating

Individual heating can be considered automatically by EnergyPLAN or added as an additional cost. To use the automatic function, you must specify an average heat demand per building in the Individual heating tabsheet. Using this, in combination with the total heat demand, EnergyPLAN estimates the total number of buildings in the energy system. This is illustrated in the Cost->Investment and Fixed OM ->Heat infrastructures window. The price presented in Table 33 above represents the average cost of a boiler in a single house, which is used to automatically estimate the cost of the heating infrastructure. This is a fast method, but it can overlook variations in the type of boilers in the system. For example, some boilers will be large common boilers in the basement of a building rather than an individual boiler in each house.

To capture these details, we recommend that you build a profile of the heating infrastructure outside of the EnergyPLAN tool and insert the costs as an additional cost. Below in Table 34 are a list of cost assumptions you can use if you do this.

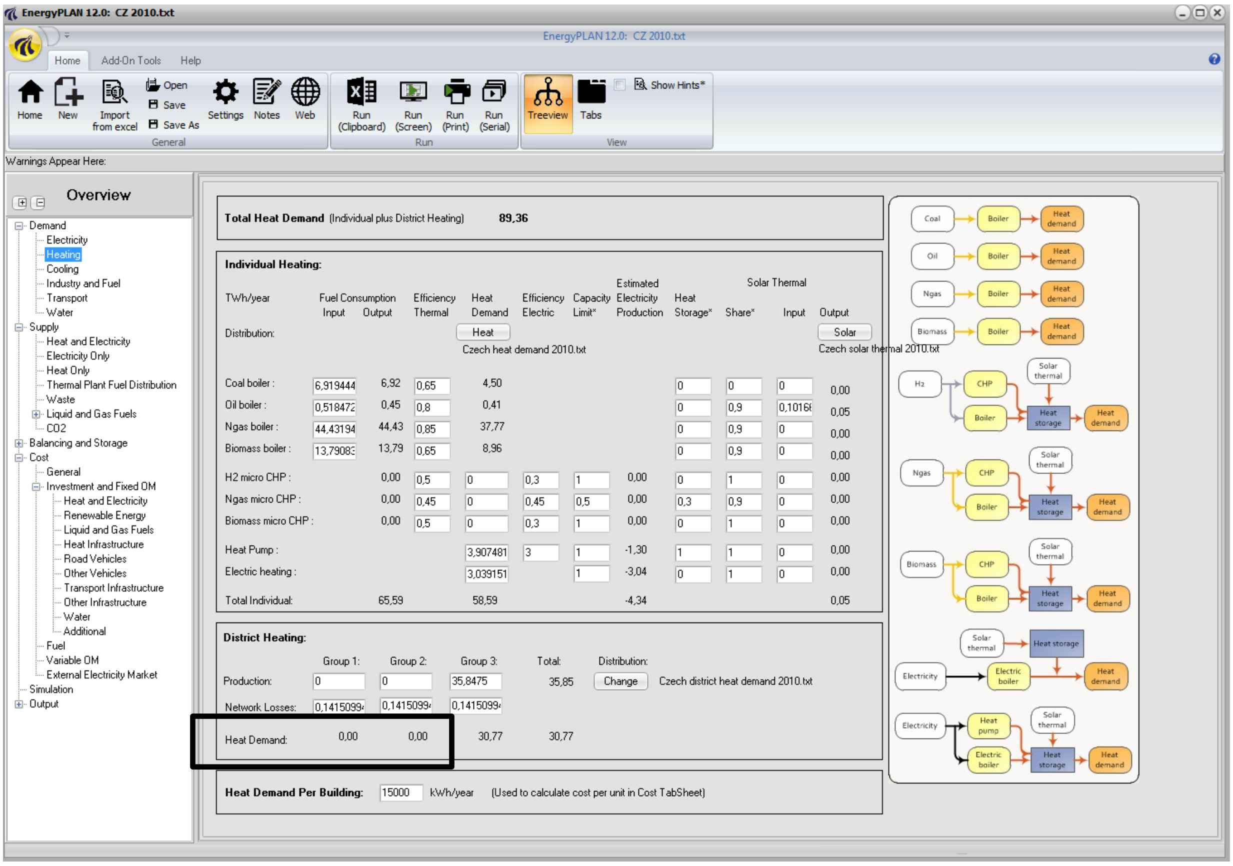


Table 34: Individual heating unit costs for 2020 in the EnergyPLAN Cost Database [17].

Parameter	Oil boiler	Natural gas boiler	Biomass boiler	Heat pump air-to-water	Heat pump brine-to-water	Electric heating	District heating substation
Capacity of one unit (kW_{th})	15-30	3-20	5-20	10	10	5	10
Annual average efficiency (%)	100	100-104	87	330	350	100	98
Technical lifetime (years)	20	22	20	20	20	30	20
Specific investment (1000€/unit)	6.6	5	6.75	12	16	4	2.5
Fixed O&M (€/unit/year)	270	46	25	135	135	50	150
Variable O&M (€/MWh)	0.0	7.2	0.0	0.0	0.0	0.0	0.0

Table 35: District heating network costs for 2020 in the EnergyPLAN Cost Database [17].

Technology	Low-temperature DH network
Heat density an consumer (TJ/km^2 land area)	45-50
Net loss (%)	13-16
Average Technical lifetime (years)	40
Average Investment costs (1000 €/TJ)	145
Average Fixed O&M (€/TJ/year)	1100
Branch Piping (1000€/substation)	3

11 Appendix B – solar thermal benchmark figures

The benchmarks presented in this chapter were derived from a set of best practice examples in operation from countries participating in IEA-SHC Task 52 (AT, DE, and DK) [20]. In sum, 46 systems covering seven all categories have been analyzed. For each system investigated at least the following characteristics and key figures were determined:

Energy / technical data:

- Solar thermal system category
- Kind of solar thermal collector
    - FPC – flat plate collector
    - ETC – evacuated tube collector
- Kind of solar energy storage
    - domestic hot water tank (DHW-tank)
    - pressurized tank thermal energy storage (pressurized TTES)
    - non-pressurized tank thermal energy storage (non-pressurized TTES)
    - BTES – borehole thermal energy storage (only seasonal storages)
    - PTES – pit thermal energy storage (only seasonal storages)
    - ATES – aquifer thermal energy storage (only seasonal storages)
- Size per unit in gross collector area [m^2_{gross}]
- Thermal peak capacity per unit [kW_{th}]
- Energy storage volume per unit [$ltr._{H2Oe}$]
- Annual *useful* solar energy supply per unit (***E_{Solar}***) [kWh/a]
- *Specific* energy storage volume per unit [$ltr._{H2Oe}/m^2_{gross}$]
- Typical *s*olar energy yield ***SE*** [kWh/(m^2_{gross}·a)]
- Typical solar fraction ***sf*** [%]
- Typical technical solar thermal system life time [yrs.]

Financial data:

- *Specific* cost per unit **ready installed** (excl. VAT, excl. subsidies) [1,000€/m^2_{gross}]
- *Specific* cost per unit for **material only** (excl. VAT, excl. subsidies) [1,000€/m^2_{gross}]
    - Cost (material) solar loop (collectors, steel structures, piping, control)
    - Cost (material) storage (tank, insulation)
- Specific cost per unit for **labor only** (excl. VAT, excl. subsidies) [1,000€/m^2_{gross}]
    - Labor required per unit (design, tendering, mounting, commissioning) [hrs.]
    - Labor cost [€/hrs.] (excl. VAT)
- Fixed O&M cost per unit [€/a]
- Variable O&M per unit [€/a]

Levelized cost of solar thermal heat:

Based on the energy and financial data levelized cost of solar thermal heat (*$LCOH_{ST}$*) were calculated

- *$LCOH_{ST}$* per unit **ready installed** (excl. VAT, excl. subsidies) [€-ct/kWh]

Summary of characteristic techno-economic benchmark figures

In the following tables characteristic technical and financial benchmark figures are summarized for

- A) solar thermal systems in single and multi-family homes (Table 36)
- B) roof-mounted solar thermal systems connected to (block) heating grids (Table 37) and
- C) ground-mounted solar thermal systems connected to (district) heating grids (Table 38)

Table 36: Benchmarks for solar thermal systems in single and multi-family homes

Solar thermal system category	**DHW-SFH** Solar domestic hot water systems in single family homes	**CS-SFH** Solar-combi systems in single family homes	**CS-MFH** Solar-combi systems in multi-family homes
All systems of this category are **roof mounted** All systems of this category are equipped **with short-term (diurnal) storages**			
Energy/technical data			
Kind of solar thermal collector used *optional*	**FPC** *ETC*	**FPC** *ETC*	**FPC** *ETC*
Kind of solar energy storage used	**DHW-tank**	**TTES (pressurized)**	**TTES (pressurized)**
Typical size per unit [m^2_{gross}] *- range (from - to)*	**7** *5 – 10*	**18** *12 – 24*	**100** *30 – 300*
Typical thermal peak capacity per unit [kW] *- range (from - to)*	**5** *4 – 7*	**13** *8 – 17*	**70** *21 – 210*
Typical storage volume per unit [ltr.]	**400**	**1,500**	**9,000**
Typical annual production per unit [kWh/a]	**2,625**	**5,940**	**39,500**
***Specific* storage volume per unit** [ltr./m^2_{gross}] *- range (from - to)*	**65** *50 - 80*	**85** *60 - 110*	**95** *70 - 120*
Typical solar energy yield *SE* [kWh/m^2_{gross}/a] *- range (from - to)*	**380** *330 - 430*	**330** *310 - 350*	**400** *350 - 450*
Typical solar fraction sf [-] *- range (from - to)*	**68%** *60 – 75%* (domestic hot water only)	**20%** *15 – 40%* (DHW + space heating)	**15%** *10 – 25%* (DHW + space heating)
Technical life time [years]	25	25	25
Financial data			
Specific cost ready installed [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.93** (+/- 13%) *(0.81 – 1.05)*	**0.76** (+/- 13%) *(0.67 – 0.86)*	**0.66** (+/- 21%) *(0.52 – 0.80)*
Specific cost (material only) [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.70** (+/- 6%) *(0.66 – 0.74)*	**0.61** (+/- 8%) *(0.57 – 0.66)*	**0.55** (+/- 20%) *(0.44 – 0.66)*
Labor required [hrs.] Labor cost [€/hr.] (excl. VAT)	18 (+/- 6hrs) 90 (reference: AT)	30 (+/- 10hrs) 90 (reference: AT)	120 (+/- 30hrs) 90 (reference: AT)
Investment per unit ready installed [1,000€/unit] (excl. VAT, excl. subsidies)	**6.5** (+/-13%) *(5.7 – 7.3)*	**13.8** (+/-13%) *(12.0 – 15.5)*	**65.8** (+/-21%) *(52.1 – 79.5)*
Fixed O&M per unit [€/m^2_{gross}/a]*	7.0	6.1	5.5
Variable O&M per unit [€/m^2_{gross}/a]**	1.4	1.2	1.4
Levelized cost of heat *LCOH* [€-ct/kWh] *- range (from - to)*	**16.2** (+/- 12%) *(14.3 – 18.1)*	**15.5** (+/- 12%) *(13.7 – 17.4)*	**11.2** (+/- 20%) *(8.9 – 13.4)*

* 1% of net investment cost (excl. labor)
** Electricity for solar pump and control (around 1.5 kWh electrical / 100 kWh heat produced). Electricity: 24€-ct/MWh

Table 37: Benchmarks for <u>roof-mounted</u> solar thermal systems connected to (block) heating grids

Solar thermal system category	**SBH: Solar block heating** Solar assisted heating of building blocks and urban quarters (roof-mounted collector field)	
All systems of this category are **roof-mounted** and may be equipped with either - short-term (diurnal) storages **(A)** or - long-term (seasonal) storages **(B)**		
Energy/technical data	**A) with diurnal storage**	**B) with seasonal storage**
Kind of solar thermal collector used *optional*	**FPC** *ETC*	**FPC** *(ETC)*
Kind of solar energy storage used *optional*	**pressurized TTES** *non-pressurized TTES*	**BTES** *non-pressurized TTES, PTES, ATES*
Typical size per unit [m^2_{gross}] *- range (from - to)*	**1,000** *500 – 5,000*	**5,000** *1,000 – 10,000*
Typical thermal peak capacity per unit [kW] *- range (from - to)*	**700** *350 – 3,500*	**3,500** *700 – 7,000*
Typical storage volume per unit [$m^3{}_{H2Oe}$]	**100**	**12,000**
Typical annual production per unit [MWh/a]	**390**	**1,500**
***Specific* storage volume per unit** [ltr./m^2_{gross}] *- range (from - to)*	**100** *75 – 125*	**2,400** *1,400 – 3,400*
Typical solar energy yield *SE* [kWh/m^2_{gross}/a] *- range (from - to)*	**390** *350 - 450*	**300** *260 - 340*
Typical solar fraction sf [-] *- range (from - to)*	**20%** *10 – 25%*	**50%** *40 – 75% (up to 90%)*
Technical life time [years]	25	25
Financial data	**A) with diurnal storage**	**B) with seasonal storage**
<u>Specific</u> cost <u>ready installed</u> [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.54** (+/- 22%) *(0.42 – 0.66)*	**0.64** (+/- 25%) *(0.48 – 0,80)*
<u>Specific</u> cost (<u>material only</u>) [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.47** (+/- 22%) *(0.37 – 0.57)*	**0.54** (+/- 25%) *(0.40 – 0.67)*
<u>Specific</u> cost (<u>labor only</u>) [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.07** *(0.05 – 0.09)*	**0.10** *(0.08 – 0.13)*
Investment per unit ready installed [1,000€/unit] (excl. VAT, excl. subsidies)	**540** (+/-22%) *(421 – 659)*	**3,200** (+/-24%) *(2,400 – 4,000)*
Fixed O&M per unit [€/m^2_{gross}/a]*	3.5	4.0
Variable O&M per unit [€/m^2_{gross}/a]**	1.4	1.1
Levelized cost of heat *LCOH* [€-ct/kWh] *- range (from - to)*	**9.2** (+/- 21%) *7.3 – 11.2*	**14.0** (+/- 24%) *10.6 – 17.4*

* 0.75% of net investment cost (excl. labor)
** Electricity for solar pump and control (around 1.5 kWh electrical / 100 kWh heat produced). Electricity: 24€-ct/MWh

Table 38: Benchmarks for ground-mounted solar thermal systems connected to (district) heating grids

Solar thermal system category	**SDH: Solar district heating** Solar assisted district heating (ground mounted collector field)	
All systems of this category are **ground-mounted** and may be equipped with either - short-term (diurnal) storages **(A)** or - long-term (seasonal) storages **(B)**		
Energy/technical data	**A) with diurnal storage**	**B) with seasonal storage**
Kind of solar thermal collector used *optional*	**FPC** *-*	**FPC** *-*
Kind of solar energy storage used *optional*	Non-pressurized TTES *pressurized TTES*	PTES *BTES, (ATES)*
Typical size per unit [m^2_{gross}] *- range (from - to)*	**10,000** *5,000 – 20,000 (up to 150,000)*	**50,000** *20,000 – 70,000*
Typical thermal peak capacity per unit [kW] *- range (from - to)*	**7,000** *3,500 – 14,000*	**35,000** *14,000 – 140,000*
Typical storage volume per unit [$m^3._{H2Oe}$]	**1,200**	**125,000**
Typical annual production per unit [MWh/a]	**4,100**	**17,500**
***Specific* storage volume per unit** [ltr./m^2_{gross}] *- range (from - to)*	**120** *90 – 150*	**2,500** *1,500 – 3,500*
Typical solar energy yield *SE* [kWh/m^2_{gross}/a] *- range (from - to)*	**410** *380 – 460*	**365** *340 – 390*
Typical solar fraction sf [-] *- range (from - to)*	**12%** *5 – 20%*	**50%** *40 – 60%*
Technical life time [years]	25	25
Financial data	**A) with diurnal storage**	**B) with seasonal storage**
Specific cost ready installed [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.24** (+/- 12%) *(0.21 – 0.27)*	**0.29** (+/- 15%) *(0.25 – 0,33)*
Specific cost (material only) [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.22** (+/- 12%) *(0.19 – 0.25)*	**0.27** (+/- 15%) *(0.23 – 0.31)*
Specific cost (labor only) [1,000€/m^2_{gross}] (excl. VAT, excl. subsidies)	**0.02** *(0.02 – 0.02)*	**0.02** *(0.01 – 0.02)*
Investment per unit ready installed [1,000€/unit] (excl. VAT, excl. subsidies)	**2,400** (+/-12%) *(2,100 – 2,700)*	**14,500** (+/-15%) *(12,325 – 16,675)*
Fixed O&M per unit [€/m^2_{gross}/a]*	1.7	2.0
Variable O&M per unit [€/m^2_{gross}/a]*	1.5	1.3
Levelized cost of heat *LCOH* [€-ct/kWh] *- range (from - to)*	**4.1** (+/- 11%) *3.7 – 4.6*	**5.5** (+/- 14%) *4.7 – 6.3*

* 0.75% of net investment cost (excl. labor)
** Electricity for solar pump and control (around 1.5 kWh electrical / 100 kWh heat produced). Electricity: 24€-ct/MWh