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Beyond sector coupling: Utilizing energy grids in sector coupling to improve the European energy transition

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ABSTRACT

Sector coupling and system integration are key concepts in the energy transition from fossil fuels to fully decarbonized energy systems based on renewable energy. An intelligent use of sector coupling – such as that expressed in the concept of a smart energy system –accommodates for the identification of a more energy-efficient and affordable green transition. However, these benefits are often not fully identified in scenario modelling for the simple reason that not all energy systems analysis tools are equipped to do so. Here, we use the EnergyPLAN tool to replicate the EU Baseline and 1.5 TECH scenarios of the report "A Clean Planet for All", which we then compare to a smart energy systems scenario for Europe. Due to its focus on sector coupling, we show how such a smart energy Europe scenario can be more energy efficient and affordable than the other scenarios.

1. Introduction

With the European Union's target to be climate neutral by 2050 and be in line with The Paris Agreement of limiting global warming to well below 2 °C [1], the decarbonization of the energy system plays a major and important role [2]. Carbon emissions from the energy sector can and should be reduced to zero - and even potentially go towards negative emissions [3]. In turn, this could compensate for emissions from harder-to-abate sectors such as non-energy industry and agriculture [4]. Hence several different analyses have been made to investigate the potential transition towards a fully decarbonized energy system in the EU in 2050 [5–8]. In most of these studies, two of the main points are:

- A vast build-out of renewable energy capacity, primarily onshore and offshore wind power, and photovoltaics.
- The utilization of sector coupling, whereby renewable electricity generated from wind and solar energy is used not only in the electricity sector but also for heating, cooling, transport and industry, and – in return – using these other sectors and their infrastructures to provide for low-cost balancing of the electricity supply [9].

To illustrate these points, three current studies investigating EU27+UK are included to show the inclusion of renewable energy built outs and how the scenarios depend on sector coupling. These models represent current modelling trends in European energy system modelling, but there are many other scenarios with similar results. The objective is not to make a comprehensive list of models and scenarios.

The first study is the decarbonization of Europe as modelled in Euro-Calliope [10,11], where the current version includes sector coupling in vehicles, heating, and fuel production [7]. It suggests 5400 GW of renewable capacity, covering 96% of the total power capacity in the cost-optimal scenario.

The second study shows PyPSA-Eur-Sec [12,13] models [6], which include vehicles, fuel production and heating. The study points to a smaller build-out of renewable energy capacity, with 3800 GW of renewable electricity capacity equaling 86% of the power capacity. Here, heating is covered primarily by power-to-heat technologies, either in individual households or district heating grids, pointing to the sector coupling between electricity and heat. The PyPSA models for decarbonization of Europe also highlight the electrification of the transport sector and the potential use of smart charge and vehicle-to-grid technologies. Overall PyPSA-Eur-Sec represents more sector coupling than is the case with the Euro-Calliope models.

The PRIMES [14,15] modelling of Europe [8,16] includes all energy sectors. The 1.5 TECH scenario implements 2240 GW of variable renewable energy, covering 80% of the total power capacity. This is due to the use of gas turbines and nuclear power, which the other two models find less feasible. The PRIMES 1.5 TECH scenario also implements a

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large share of electrification in the heating and transport sectors. District heating covers very little demand; instead, individual heat pumps and hydrogen boilers cover the heat demand.

Together, the three studies represent how renewable energy and sector coupling in many cases are investigated. To a large extent the models can evaluate power-to-heat options and power-to-X options such as hydrogen and synthetic fuel production, but the synergies from waste heat from industry and power to X to supply heating is lacking. This is partially due to missing considerations in term of gas and heating infrastructures. To different degrees, the models utilize sector coupling, and model the different energy grids required, but generally, the three presented studies mainly consider sector coupling as electrification efforts. However, it is crucial to elaborate further the understanding of sector coupling, so it is seen as more than just the electrification of heating, cooling, transport, and industry.

1.1. *Beyond sector coupling*

To go beyond the understanding that sector coupling equals electrification, there is a need to look at the interactions between different energy grids to reap all benefits of the potential synergies. This means that, for instance, when producing hydrogen and e-fuels, waste heat can be utilized in district heating and cooling [17]. Studies only tend to look at the electrification of the different sectors [2,3,18–23]. To reap the benefits from sector coupling, all the different energy grids need to be included. This means the utilization of not only electricity grids but also heating [24], cooling [25], and gas grids are [26] potentially key to achieving the full benefits of sector coupling and, thus, the most efficient implementation of renewable energy. This is also emphasized by Gea--Bermúdez et al. [27]. However [27], is missing a link between e-fuel production and utilization of excess heat for district heating.

The principle of the two different concepts investigated is shown in Fig. 1, with the illustration on the left showing a simple understanding of sector coupling as electrification and the second illustration showing the concept of Smart Energy Systems [9,26,28] going beyond the simple understanding of sector coupling.

This paper, therefore, presents such a Smart Energy System solution for the European energy system, utilizing sector coupling beyond direct electrification of the specific sector, but by linking energy grids through electrification, waste energy utilization and storing excess energy in relatively cheap thermal, gas and fuel storages, instead of more costly electricity storages [29]. The objective is to investigate the potential of including the entire scope of sector coupling strategies in energy modelling, to ensure that the most cost-efficient solutions are found comparing to models where electrification is the main sector coupling measure. The novelty of the paper is therefore to keep expanding on the concept of sector-coupling, with a clear focus on looking not only at electrification, but the coupling found in the entire energy system. Furthermore, this paper concretely compares a smart energy system to a sector coupled system, only focusing on electrification which also provides novel insights. Finally, compared [27] this paper focuses on the use of hourly modelling to enable coherent modelling of renewable energy and storage content across the different sectors.

2. Methods

To highlight the benefits of the Smart Energy System approach, and the need to include this in energy modelling to achieve the most cost-efficient scenarios, the methodology requires a tool that can handle the various aspects of sector coupling beyond the different electrification aspects. For this EnergyPLAN is chosen. Secondly, to compare the benefits, the system based on a smart energy approach is compared to a

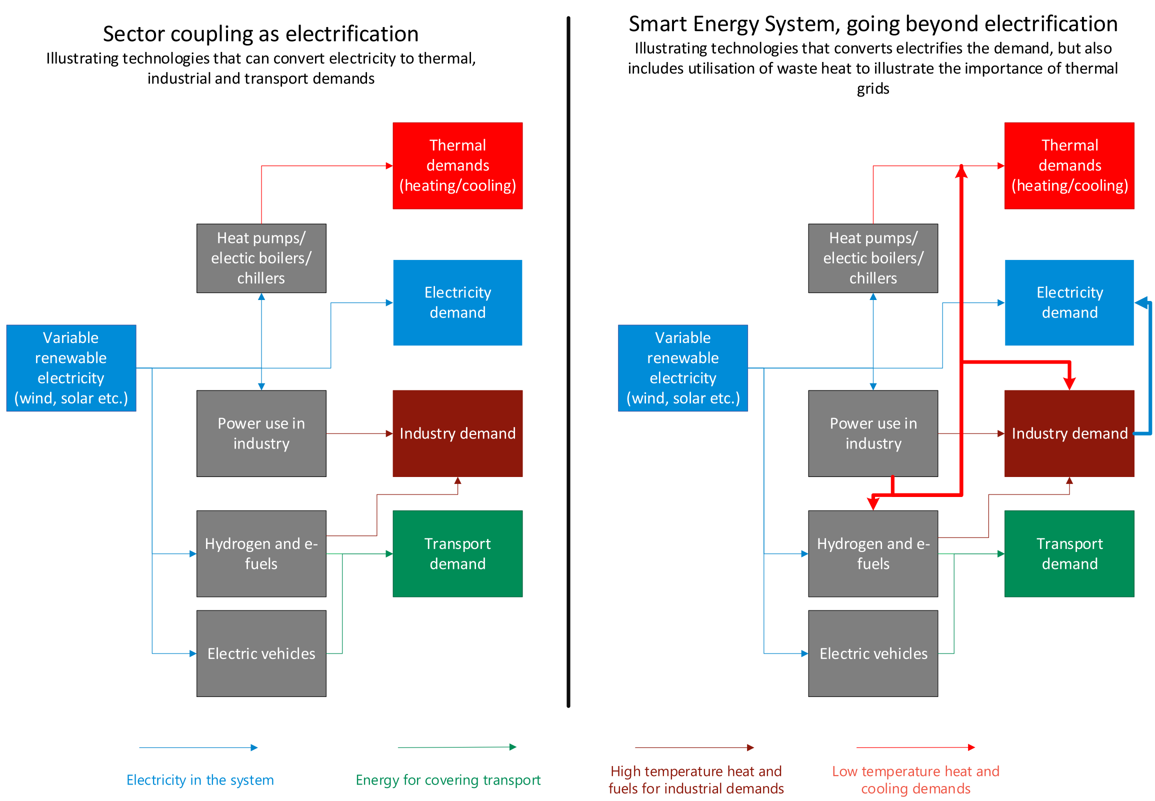

Fig. 1. The left-hand illustration shows sector coupling relying on electrification, and the right-hand illustration shows the Smart Energy System that goes beyond electrification and utilizes, in this case, district heating grids for waste heat utilization as an example of utilizing all energy grids. The colors associate with either electricity (blue), transport (green), industry (maroon) and space heating/cooling (red). The new flows in the figure are illustrated with bold lines. The different grids can furthermore be associated with electricity, thermal, gas and fuel storages not depicted in the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

system with less sector coupling. Here the PRIMES "A Clean Planet for All" 2050 baseline and 1.5 TECH scenarios are used for comparison. Finally, the smart energy scenario has been developed. Section 3.1 describes the recreation of the PRIMES scenarios into EnergyPLAN, section 3.2 highlights the creation of smart energy systems, within the context of Europe, and section 3.3 explains the EnergyPLAN modelling.

2.1. Recreating PRIMES scenarios in EnergyPLAN

The "A Clean Planet for All" scenarios are initially developed in the PRIMES model which can design long-term scenarios and in the case of a decarbonized Europe suggests a large number of scenarios for Europe depending on different political targets. However, the PRIMES model does not go into detail with the energy system and the hourly operation of the energy system and instead models the energy system in larger time slices, hence the need for recreating the scenarios in an energy system analysis model that can investigate the hourly operation of the systems. Here, the PRIMES scenarios are converted so they can be modelled in EnergyPLAN which allows for the hourly simulation of the energy system. At the same time, EnergyPLAN is used for the analysis of all three scenarios to be able to compare results.

Based on the "A Clean Planet for All" main report [16] and background figures [30], it is possible to identify energy demands, energy capacities, efficiencies etc., and the resulting primary energy consumptions. To validate the EnergyPLAN replication, the primary energy consumption is compared between the two models, which can be seen in Fig. 2. The full documentation for the replication can be found here [31].

After the replication, it is necessary to make a few adjustments to the Baseline and 1.5 TECH scenarios to ensure similar assumptions across the models, including Smart Energy Europe.

The changes can be described as follows:

1) Same technology costs across the three models. The specific costs are included in the supplementary files.
2) Adjustments to power plant capacities to ensure the European model does not import electricity from energy systems outside Europe.
3) Similar efficiencies for the same technologies across the systems, especially for electrolysers and e-fuel production.

The idea behind the adjustments above is to ensure that the differences between the systems in terms of costs, primary energy consumption and CO_2 emissions are due to the energy system configuration and not due to different assumptions for the same technologies. Therefore, by streamlining efficiencies and costs, the comparison becomes direct, however, this does change how the baseline and the 1.5 TECH performs,

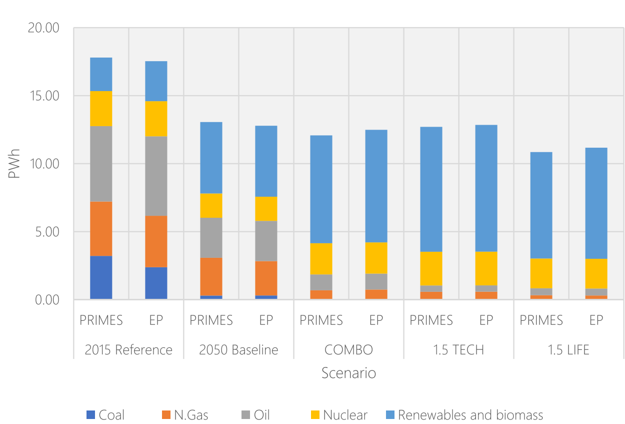

Fig. 2. Comparison between PRIMES documented primary energy outputs and EnergyPLAN (EP) modelled outputs from the "A Clean Planet for All" replication [31].

compared to the actual replication of the PRIMES scenarios. This comparison can be seen in the supplementary material.

2.2. Designing Smart Energy Europe

The second part of the methodology is the design of the smart energy system for Europe. It is based on the same technology catalogue established for the PRIMES replication scenario, allowing for a comparison between the systems.

To design the Smart Energy Europe system, an analytical approach is followed, inspired by [32]. The steps are as follows, with an offset in the 2050 Baseline scenario. Within these steps, the renewable energy capacity is constantly balanced to cover the design principles.

1) Energy efficiency first. Based on the energy efficiency first principle, the potential for energy savings is investigated and included. Specifically, the end-use demands for the heating, industry and transport sectors are investigated. The Smart Energy Europe uses knowledge from the Heat Roadmap Europe [33,34] and sEEnergies projects [35,36], to determine levels of energy consumption in industry, transport and heating.
2) Updating heating systems. Based on Heat Roadmap Europe, and in line with the energy efficiency principle, district heating is implemented in areas identified as feasible for district heating. Within the district heating system, it is necessary to utilize the potential for thermal storage, waste heat and large-scale heat pumps, to make the supply system as efficient and well-integrated with renewables as possible. Outside areas feasible for district heating, efficient use of electricity is key, which means most of the individual heating demands are covered by individual heat pumps; this ensures biomass can be used later in the transition since only a limited biomass resource is available (see bullet 5).
3) Electrification of the transport sector. The third step is the use of batteries and direct electrification of the transport sector. This has high potentials in terms of the system's energy efficiency, and the more it is possible to electrify, the easier the final steps of carbon neutrality become. Based on research from the sEEnergies project, all personal vehicles are expected to be electrified as well as most of the light-duty vehicles, with heavy transport only being somewhat electrified. Shipping and aviation are expected to have a high demand for fuels still.
4) E-Fuels in transport. To supply the demand for fuels in the heavy part of transportation as well as for shipping and aviation, e-fuels are produced from gasified biomass and point source carbon capture in combination with hydrogen produced with the use of renewable electricity from wind turbines and photovoltaics.
5) The final step is to replace the remaining fuel demands in industry and power production. In the case of the smart energy Europe, the choice is to use biogas and biomass to the extent it is sustainable as these provide the most cost-efficient solution. The biomass limit is the same as the 1.5 TECH scenario, approximately 20 GJ/person, which is also in line with the limits defined in [37].

Specific capacities for each step are shown in the supplementary material alongside figures illustrating the changes.

2.3. EnergyPLAN analyses

All the energy scenarios researched in the paper are analyzed using the energy system analysis tool EnergyPLAN [38]. EnergyPLAN is a simulation tool, that simulates the energy flows of an energy system for each hour in the year and has actively been used for more than a decade [39]. It simulates a year chronologically and thus keeps track of storages, ensuring charge and discharge options throughout the year. Therefore, it is useful for investigating large implementations of renewable energy and the use of sector coupling to utilize different storages in different sectors.

EnergyPLAN includes all energy sectors. Hence, the user defines the electricity, cooling, heating, industry and transport sectors, and EnergyPLAN then balances the energy flows between the sectors. For each sector, it is possible to install a large number of different technologies, thus investigating the use of different fuels, different efficiencies and different production patterns. Overall, this allows for a detailed inclusion of the electricity, heating and gas grids as facilities for the efficient implementation of renewable energy in Europe in 2050 [38].

With EnergyPLAN having all energy sectors included, and with the possibility of modelling the energy flows between each energy sector including e.g., the use of excess heat, storages, power to heat, power to gas, power to liquid and electric vehicles, the tool is very well suited for modelling of Smart Energy Systems. Furthermore, the hourly modelling capabilities ensures that the energy flows match, including the benefits of sector coupling in each hour.

As an example, EnergyPLAN can model the consequences of production of e-methanol, by including the specific renewable energy production in each hour. EnergyPLAN identifies the excess electricity to the remaining electricity demand, as suitable for hydrogen production. That hydrogen can then either be stored or used directly for the methanol production. Alongside this normal sector coupling approach, EnergyPLAN furthermore identifies the excess heat from the electrolysers and the methanol plant. This can be delivered to a district heating grid, in which a thermal storage is also included. Thus, balancing the need for heat pumps and boilers and fulfilling the heating demand. Thus, solutions across transport, industry, heating, and electricity sectors can be identified.

EnergyPLAN models are defined by the user, in the sense that the user inputs energy demands, capacities, efficiencies, costs, fuel type and time series for demands and renewable energy production. It deterministically determines the operation of the energy system based on operation strategies and limitations also partially determined by the user. To identify suitable energy system designs, a number of runs by the user are most often required, changing parameters to achieve the necessary performance within the constraints defined.

Many research studies have utilized EnergyPLAN [39] as a modelling framework generating a large research community. Examples of EnergyPLAN analyses are on island level [40] for instance the Galapagos Islands [41], city and province level like the city of Aalborg [42], Utrecht [43] and the Sichuan region in China [21,44], country level, examples are Denmark [37], Spain [45], Germany [46] and Croatia [47] and international level like Europe [33].

The simulations of the “A Clean Planet for All” scenarios have been carried out to achieve similar primary fuel performances as in the original report based on the original models developed in PRIMES [14, 15]. From that constraint, the previously mentioned corrections have been made to achieve comparable models that can be used together with the model of the smart energy system for Europe in 2050.

For the design of the Smart Energy Europe scenario, the following constraints have been used:

- Biomass is limited to 2.71 PW h/year. This value is chosen as it is the restriction used in the 1.5 TECH scenario [16,31]. This value corresponds to the restrictions defined in the design step of approximately 20 GJ/person.
- No electricity import should be needed from outside the modelled area. This constraint is included to ensure that sufficient power production is available in the modelled area. In real-life the scenario will benefit from electricity exchange with countries such as Norway and Switzerland.

In each design step, variable renewable energy capacity is increased to cover the demands and fulfilling the design principle above. The specific system designs are shown in the supplementary material. The European energy system is ensured not to rely on imported electricity by having sufficient power plant capacity in the system.

In the simulation of the energy system, the technical simulation strategy has been used in EnergyPLAN. The technical simulation strategy operates the energy systems based on merit orders, ensuring the use of renewable energy, waste heat, heat pumps and CHP plants before the use of power stations and heat-only boilers. The idea is to achieve the most fuel-efficient operation of the energy system, while also minimizing the need for curtailment. Thus, this is in line with the goal of trying to maximize the use of renewable energy within Europe.

The proposed EnergyPLAN model simplifies the European Energy System as one single energy model thus having copperplate interconnection between countries. While this might overestimate potentials in terms of energy transmission, the main purpose of this paper is to compare an electrified energy system with system utilizing high degrees of sector coupling. This is in line with the conclusions of [48] highlighting that sector coupling provides a bigger benefit to the systems than electricity transmission.

To account for regional differences, heating and cooling loads have been determined based on the Heat Roadmap Europe projects [33,49]. Hence, based on GIS analyses the specific heating and cooling loads determined. These are aggregated in the EnergyPLAN model, to represent thermal energy demands in the model, and how much can be supplied by district heating both in terms of residential, commercial, and industrial demands. Furthermore, these GIS analyses also provide the basis of determining to what extent industrial excess heat and geothermal heat can be used for supplying the heating demands in the district heating grids. In terms of using excess heat from e-fuel production and electrolysers, these are assumed to be near district heating grids.

3. Analysis

The analysis is divided into two sections. Section 3.1 highlights the design of each of the three European scenarios compared, a fossil-based reference system, the 1.5 TECH scenario and finally the smart energy scenario. Section 3.2 compares the three systems in terms of primary energy and costs.

3.1. The European energy systems in 2050

The first of the three energy systems analyzed is a business-*as*-usual scenario for the European energy system in 2050. This represents previously established policies in the European energy sector from 2015 to 2050 and thus does not result in reaching European energy targets but serves as a baseline and reference point for comparison for the carbon neutral European energy system. The system is based on the Baseline 2050 scenario from the “A Clean Planet for All” scenarios [16].

When looking at Fig. 3, it can be seen that a large amount of central power stations remain in the European energy system, mainly operating on gas. Besides these, it is expected that over half of the installed capacity in the European energy system will be variable renewable energy (wind, solar and hydro energy) even in a baseline scenario. Finally, electricity is also produced from nuclear power and CHP plants in the 2050 baseline system. In the heating sector, the baseline scenario is primarily made up of boilers in individual buildings, though the energy system also includes individual heat pumps and some district heating. District heating is mostly supplied by boilers and heat from the CHP plants. Thus, the baseline system does not introduce significant sector integration principles, there are very few heat pumps in the system; and district heating is not developed to its full potential [33]. Only waste heat from waste heat from CHP plants is utilized to any significant degree with very limited excess heat from industry and electrolysis. Furthermore, the transport sector mostly relies on electrification, biofuel and fossil fuels, and as such, there needs to be a large development of electrolyzers and e-fuels to utilize variable renewable energy also in shipping, aviation and heavy transport. This is seen in Fig. 3 with the

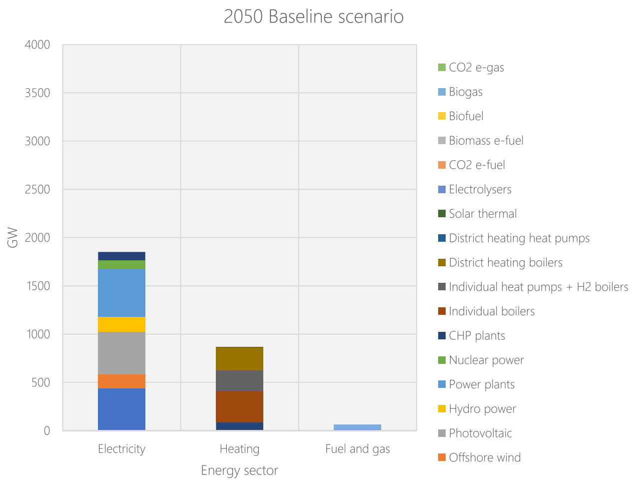

Fig. 3. Technology mix for electricity, heating (excluding industry), and fuel production in the 2050 European Energy Baseline system.

small capacities for renewable fuels and e-fuels. Thus, the baseline system illustrates some level of sector coupling without full implementation and it does not achieve a decarbonized European energy system.

From the baseline scenario, the two other European scenarios are prepared. The first is the 1.5 TECH scenario for Europe, developed in PRIMES and presented in “A Clean Planet for All” [16]. The 1.5 TECH scenario represents a future for the European energy system that can deliver on the 1.5-degree target using technological solutions. From Fig. 4, the energy system technology mix can be seen for the electricity and heating sector.

When looking at the 1.5 TECH scenario, it is clear that the capacity of variable renewable energy has increased compared to the baseline. The total capacity now is close to 2500 GW of variable renewable energy in the system. Furthermore, nuclear and central power stations still play a role, but CHP has more or less been eliminated compared to the baseline. When looking at the heating sector, it is dominated by individual heating solutions. These are individual boilers as well as heat pumps and hydrogen boilers. The district heating systems are almost removed in this scenario. Altogether, this indicates a system where the sector coupling happens either in individual houses with their own heat pumps, or through large-scale hydrogen production in electrolyzers, where waste heat cannot be utilized since the district heating grids are removed. To accommodate such a system, the 1.5 TECH scenario also implements significant heat demand reductions in households, which can be seen in the substantial reduction in heating capacity in the system. The system has a large deployment of capacities to produce green fuels such as biofuels and e-fuels. This requires a substantial electrolyzers capacity, but also a capacity for e-fuel and biofuel production, including biogas. The 1.5 TECH scenario still utilizes fossil fuels and, as such, also includes carbon capture and storage to offset the fossil carbon emissions.

To illustrate the potential benefits of going beyond the simple sector coupling of power-to-heat in individual households and power-to-hydrogen/-gas in the supply sector, a Smart Energy Europe scenario is developed, as described in section 2.2. The Smart Energy Europe scenario represents the utilization of the heating grid to explore the waste heat utilization from the various power-to-X technologies, as well as the benefits of implementing heat pumps in district heating grids, where the potential for cheap large-scale thermal storage exists [29]. Fig. 5 shows the energy system technology mix in the Smart Energy Europe scenario.

Fig. 5 shows that variable renewable energy is the main provider of power in the Smart Energy System. Nuclear energy is not needed in the energy system as it is more expensive than renewable energy solutions. The system has slightly less thermal power capacity but more CHP capacity. The reason is that the Smart Energy Europe scenario relies on district heating being build-out throughout the European energy system. This is reflected in the heating capacities shown in Fig. 4. Here, the main capacities are related to the district heating system, with heat pumps, CHP and backup boilers taking up most of the capacity. The individual heating demands are mostly provided by the utilization of heat pumps and, to a minimal degree, fuel boilers. The Smart Energy Europe scenario suggests fewer heat savings than in the 1.5 TECH scenario; instead, increased energy efficiency is mainly achieved through the implementation of district heating, which allows for waste heat utilization and a more efficient supply and storage system. The Smart Energy Europe system also has a large installed capacity for producing green gas and fuels, but unlike the 1.5 TECH, it does not dedicate any capacity to conventional biofuel productions. Instead, thermal gasification and CO_2 capture are utilized to produce the necessary e-fuels for transport, and biogas is used to produce electricity and heat in the gas turbines.

3.2. *Comparing the three energy systems*

To illustrate the potential benefits of going beyond sector coupling and to model the entire energy system, the systems are compared on three parameters: primary energy consumption, energy system costs

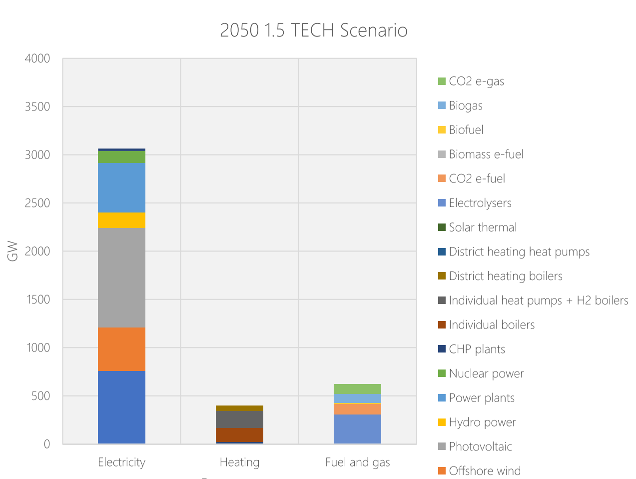

Fig. 4. Technology mix for electricity, heating (excluding industry), and fuel production in the 2050 European 1.5 TECH energy system.

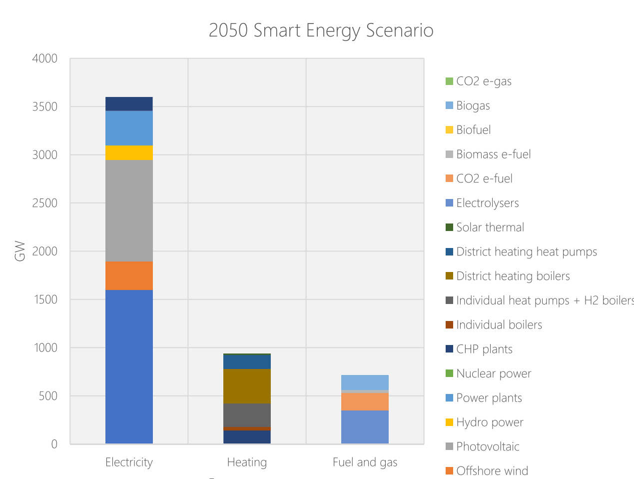

Fig. 5. Technology mix for electricity, heating (excluding industry), and fuel production in the 2050 European Smart Energy System.

(including CO_2 costs) and CO_2 emissions.

Fig. 6 shows the primary energy consumption for the three scenarios, highlighting that the Smart Energy Europe scenario has the lowest total primary energy consumption and lowers the fuel consumption most. This is due to energy efficiency gains by utilizing both the heating, gas and electricity grid and as well as energy storages across all three grids. By utilizing all grids, waste heat becomes a key resource for district heating systems. Furthermore, a heavier focus is on electrification, eliminating fossil fuel demands in transport and industry. Both the baseline and 1.5 TECH scenario include fossil fuels which in the 1.5 TECH is offset by carbon capture and storage. Nuclear is omitted in the Smart Energy System as it is more expensive than implementing more variable renewable energy with flexibility from electrolyzers and hydrogen storage. Thus, by going beyond simple sector coupling and utilizing smart grids in all energy sectors, it is possible to achieve a more fuel-efficient energy system that would be less sensitive to changes in fuel prices due to the lower fuel demands. The biomass consumption is the same between the 1.5 TECH and the Smart Energy scenario, with a consumption of around 20 GJ/person, which is within a sustainable use of biomass [37]. The biomass includes biogas, and the biomass resources are assumed to available for all countries in Europe.

When investigating the CO_2 emissions from the systems, the baseline 2050 system is not CO_2 neutral and, therefore, cannot fulfill decarbonization targets. Instead, when investigating the 1.5 TECH scenario, there is a demand for offsetting fossil carbon emissions from using natural gas and oil in the transport and industry sector. Therefore, the scenario includes a need for CCS technology which, besides offsetting fossil carbon emissions, is needed to account for missing carbon reductions in other sectors. The Smart Energy Europe energy system is completely carbon neutral; but, to reach the same negative emissions comparable to the 1.5 TECH scenario, CCS is implemented. However, this is not to offset the energy system but to allow for easier mitigation strategies in hard-to-abate sectors such as agriculture and certain industries. The baseline scenario here does not include CCS as it serves as a reference CO_2 emission level. As shown in Fig. 7, this results in similar total CO_2 emissions from the 1.5 TECH and Smart Energy Europe energy systems, with a net carbon budget of −131 Mton.

The final comparison is based on the total annual costs of the three energy systems. The costs include investments, calculated as annuity payments based on lifetimes and a discount rate of 3% (within the 1–7% range suggested by [50], fixed and variable operation and maintenance costs, fuel costs and CO_2 costs. The comparison can be seen in Fig. 7, which highlights the total annual costs, and also shows the comparison when not taking into account the investments and operation and maintenance in the transport sector.

In Fig. 8 the systems have similar total annual costs, around 2000 billion Euros. However, the Smart Energy Europe scenario comes out with the cheapest system both when including the transport costs and when only looking at the costs for the energy system. The reason is the increased energy efficiency in the supply by smart utilization of all energy grids. By going beyond simple sector coupling, and not focusing on individual solutions requiring either power-to-heat or direct use of hydrogen, but instead utilizing the potentials of all energy grids, it is possible to reap the benefits of the smart energy system. The implementation of large-scale heat pumps in district heating, waste heat use from electrolysis and fuel storage, all possible to store using cheaper thermal storages, offsets the need for more expensive individual solutions and a requirement for massive renovations in the building sector. By making the supply system cheaper, it is possible to not only lower investment costs but also achieve a system with lower fuel demands and, therefore, lower fuel costs. This highlights how important it is for energy system models and tools to include the entire scope of sector coupling and go beyond only including direct electrification in the heating and transport sector. In the cost comparison it is important to note that infrastructure costs for expanding electricity grids and district heating grids are included across the scenarios.

4. Conclusions

The analyses investigate the benefits of going beyond a simple

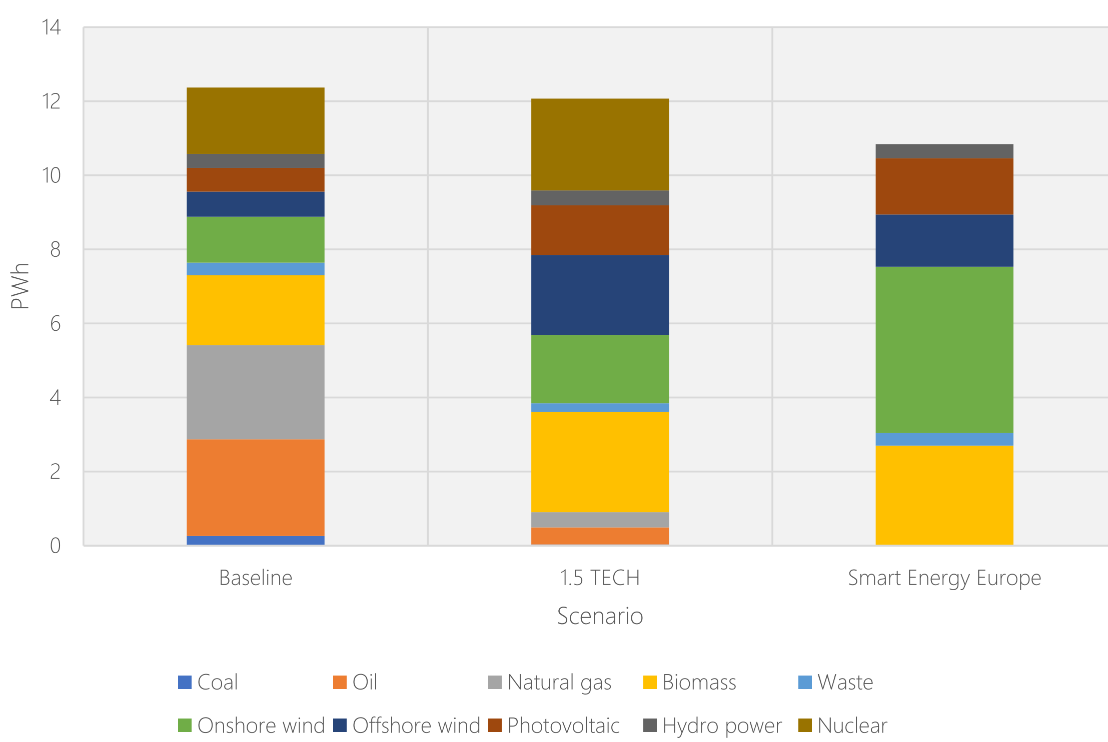

Fig. 6. Primary energy consumption in the three energy systems.

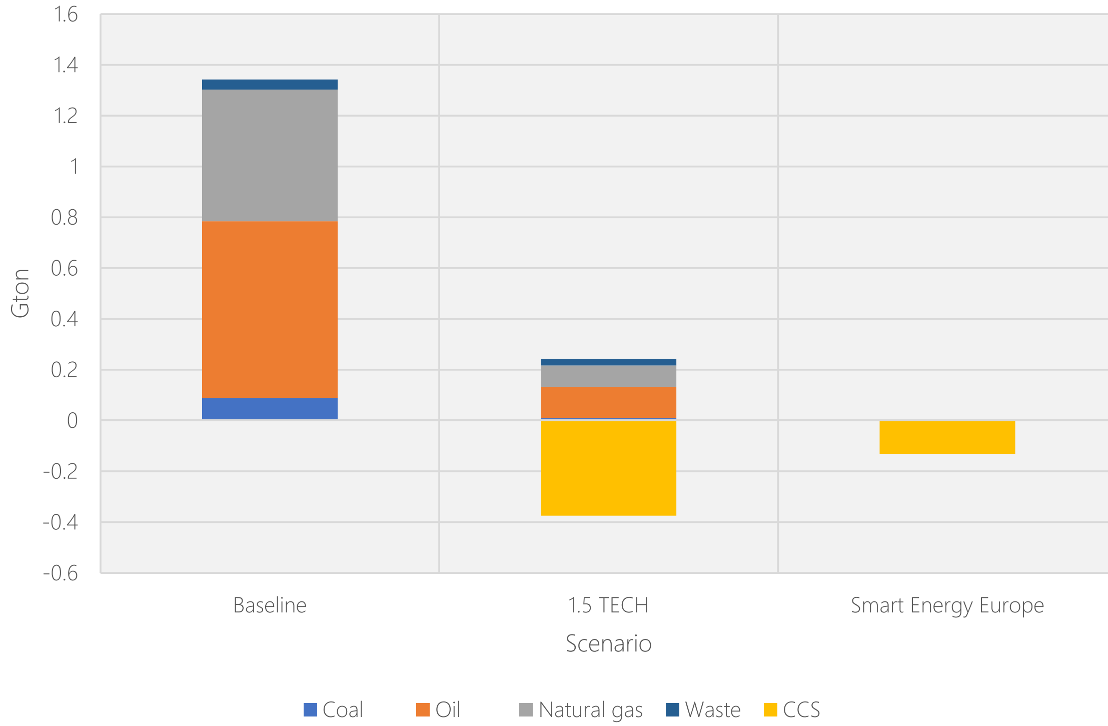

Fig. 7. CO_2 emissions and carbon capture and storage in the three energy systems.

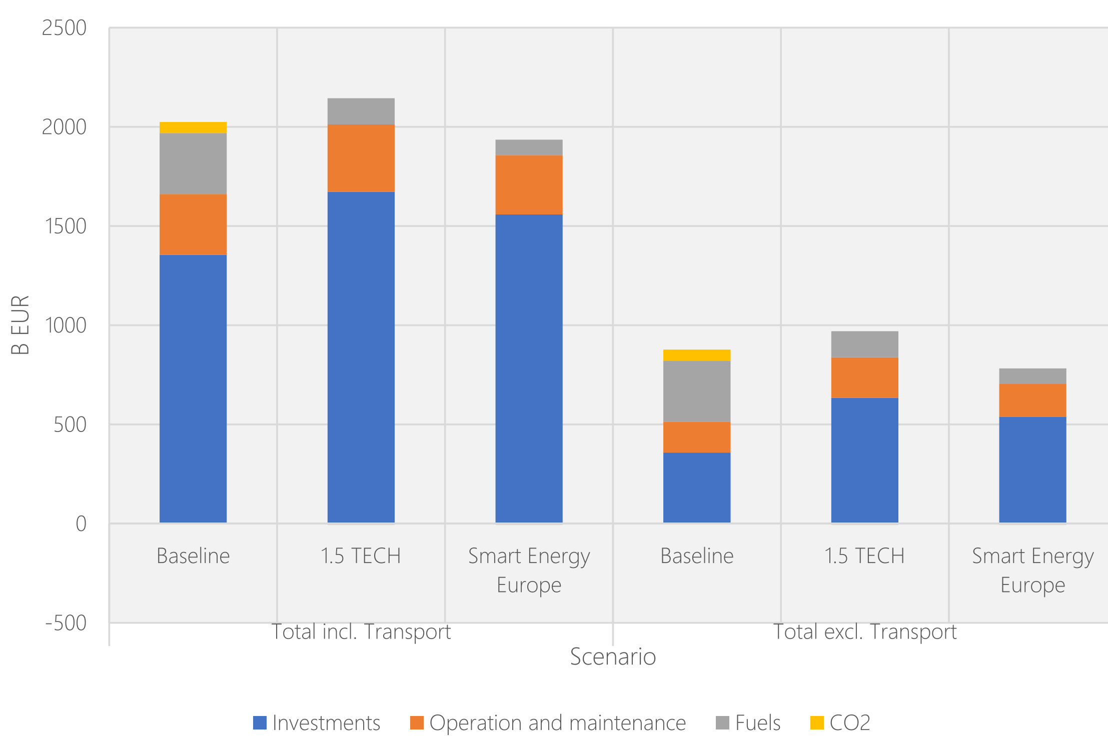

Fig. 8. Total annual costs in the three energy systems, one including transport costs and one excluding transport costs.

understanding of sector coupling, identifying improved energy system performance by utilizing the concept of Smart Energy Systems in the context of a European energy transition. The study emphasizes the need to fully investigate all energy grids and the synergies between the grids.

From comparing the three systems, the 2050 baseline, the 1.5 TECH scenario and the Smart Energy Europe scenario, it is seen that by utilizing all system benefits, including waste heat from industry, e-fuel production and power-to-heat, in combination with cheap thermal and fuel storages, it is possible to find a decarbonized energy system that is cheaper and more fuel efficient than the comparable 1.5 TECH scenario, which mostly uses electrification as a mean of sector coupling.

The reason behind achieving this result is that increased sector coupling i.e., the smart energy system, changes energy efficiency from focusing only on the end-use heating demand to being a holistic principle, both in the supply and demand sides. This means, that we are not reducing the end-use heating demand to the same extent as the 1.5 TECH scenario, but by implementing sector coupling in all grids and utilizing the energy more efficiently in the supply system, we achieve an overall more efficient energy system.

Consequently, for modelling pathways for future energy systems, this highlights that current scenarios might be missing crucial sector coupling benefits simply due to a modelling scope that captures many but not all potential sector coupling between electricity, heating, transport, and industry. It is crucial to include the entire energy system, not only to include all demands but also to enable an analysis of the links within the energy system, between the grids and to utilize different types of cheap energy storages in the different sectors to create necessary flexibility in an energy system relying on large renewable energy. In this study, EnergyPLAN is used as a tool capable of these focus points, but these focus points can – of course – be included in other energy system analysis tools and models to further the modelling of smart energy systems that goes beyond the simple understanding of sector coupling as electrification. If these are not included potential suboptimal solutions might be identified simply due to lack of modelling capacities.

Declaration of competing interest

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

Data availability

I have shared data with link in the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2023.100116.

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