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Smart Energy Europe – developing a renewable energy scenario for a decarbonised Europe

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ABSTRACT

The European Union has a clear target of decarbonizing the energy sector by the year 2050, necessary to mitigate climate change effects. Currently, a number of scenarios are models are developed to outline this transition, for instance the Commissions own "A Clean Planet for All" scenarios. However, the focus on the current modelling is very much towards either detailed scenario pathways that miss the need for hourly analyses, or scenarios that cannot capture the full potential for system integration, through a clear Smart Energy System approach, that utilizes not only the electricity grid, but also heating and gas grids to achieve cost efficient solutions for Europe. This paper presents a step wise approach to accomplish a renewable European energy system based on the concept of Smart Energy Systems. These steps include transforming the heating and cooling sector, as well as looking at both electrification of the transport sector and utilization of electrofuels in transport, industry and power production. Combined, the utilization of multiple grids, cheaper storage options, and a more comprehensive sector integration allows for the Smart Energy Europe scenario to be a more feasible solution than the decarbonised scenario proposed by the European Commission.

KEYWORDS

Smart Energy Systems, decarbonisation of Europe, renewable energy, energy system analysis,

1 INTRODUCTION

Working towards climate targets, reduction in carbon emissions and goals for implementation of renewable energy, energy modelling and energy system analyses provide essential knowledge to determine potential pathways a city, country or region can go to achieve decarbonization and renewable energy targets.

A number of models and tools exist [1], each with distinct features in terms of modelling framework. This includes models that focus on long term investment strategies, but can lack detail in terms of either temporal or sectoral resolution [2,3]. Other models are more detailed in time resolution and include better modelling of sector integration and storages [4–6]. Models can also differ in openness, ranging from being full open source including utilising free solvers, to be completely commercial.

For many of these models, the end-goal is to be able to model renewable and decarbonized energy systems. With the European Union having clear targets for decarbonization in the year 2050, many tools and models have suggested and work with a decarbonized Europe [7,8]. This

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includes PyPsa modelling [9], PRIMES modelling [10], elesplan-m [11] and others. Thi paper takes the PRIMES scenarios from the European Commission's "A Clean Planet for All", and investigates how these compare to an energy system designed based on the principles of Smart Energy Systems. [12,13] The "A Clean Planet for All" scenarios are shortly described in Figure 1.
The goal of this is two-fold. One is to scrutinize the scenario modelling done in PRIMES, by applying an hourly, sector integrated simulation tool, in form of EnergyPLAN. This allows for better understanding of sector integration between for instance heat and power, and how different sectors align and differ, and thus how different storages and power to X units can be used to combine the different sectors. Second, by applying such a tool, better solutions might be found than what can be achieved in an aggregated scenario model. EnergyPLAN can better investigate not only system integration, but also the application of electric grids, district heating, gas and fuel production and how co-production and utilisation of waste energy can go across the sectors and be used in various numbers of storages. In conclusion, this allows for the investigation of a Smart Energy System for Europe, a Smart Energy Europe scenario.
Thus, the paper suggests and applies steps for designing a Smart Energy Europe. These steps can in principle be used at other scales of the energy system as well. The Smart Energy Europe scenario will then be compared to the PRIMES scenarios, to discuss the different pathways.

Long Term Strategy Option								
	Electrification (ELEC)	**Hydrogen (H2)**	**Power-to-X (P2X)**	**Energy Efficiency (EE)**	**Circular Economy (CIRC)**	**Combination (COMBO**	**1.5°C Technical (1.5TECH)**	**1.5°C Sustainable Lifestyles (1.5LIFE)**
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Development of sustainable, advanced biofuels • Moderate circular economy measures • Digitalisation				• Market coordination for infrastructure development • BECCS present only post 2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system			
Power sector	Power is near decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher Recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 in targeted applications	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+ COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDV's and some for LDV's	E-fuels deployment for all modes	Increased model shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

Figure 1. Overview of the "A Clean Planet for All Scenarios" modelled in PRIMES for the European Commission [10]

2 METHODS

The research of a European renewable energy system is founded on the bases of Smart Energy System, within which a number of design steps are proposed.

2.1 Smart Energy Systems

"Smart Energy Systems" [12] is a concept towards the principal design of 100% renewable energy systems. It goes beyond the traditional focus on smart electricity grids, and includes the thermal grids and gas grids too, to create an energy system where system flexibility can be maximized across all sectors. This means utilization of cross sector technologies, like heat pumps and power-to-X production of e-fuels. The waste heat from e-fuel production and similar can then be used in the district heating grids. Figure 2 shows the overall schematic concept of a Smart Energy System.

Furthermore, storage technologies in all grids can be utilized. This includes electricity storage, but more importantly Smart Energy Systems ensure access to cheap thermal, fuel and gas storages. Figure 3 shows the economic benefit of utilization of storages across all sectors.

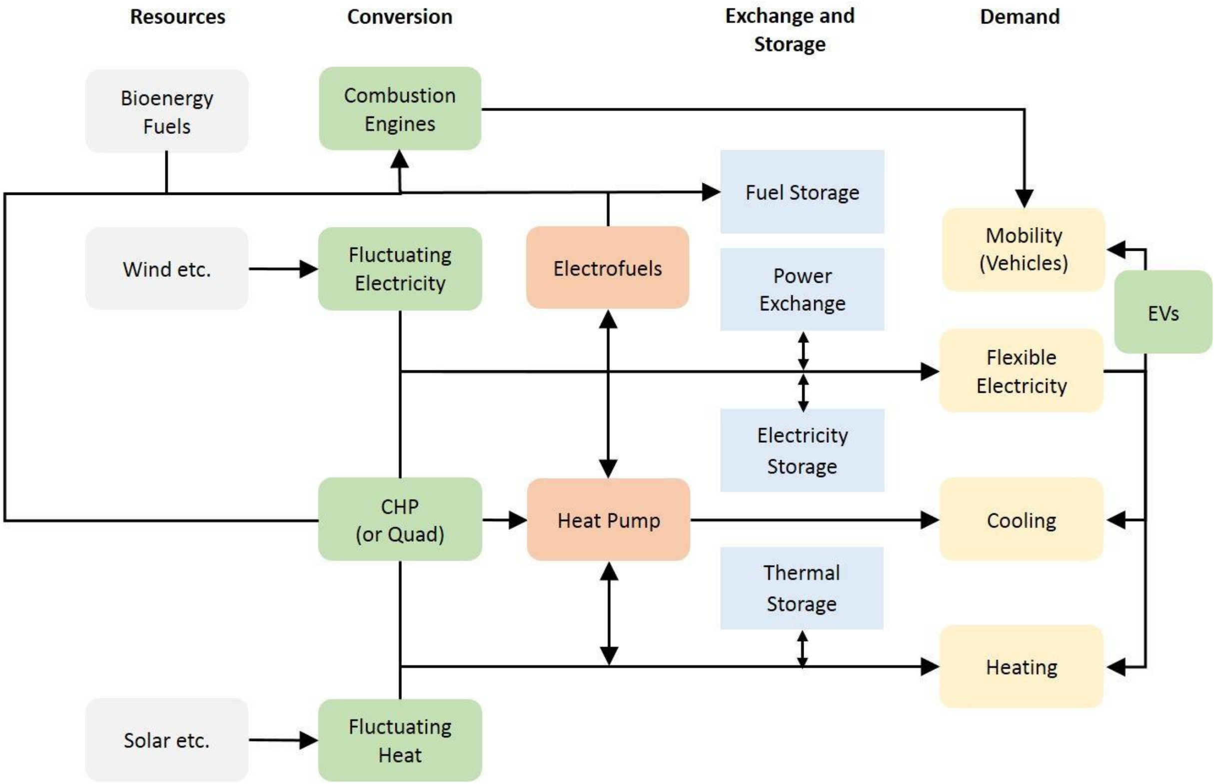


Figure 2. Schematic overview of Smart Energy Systems. [14]

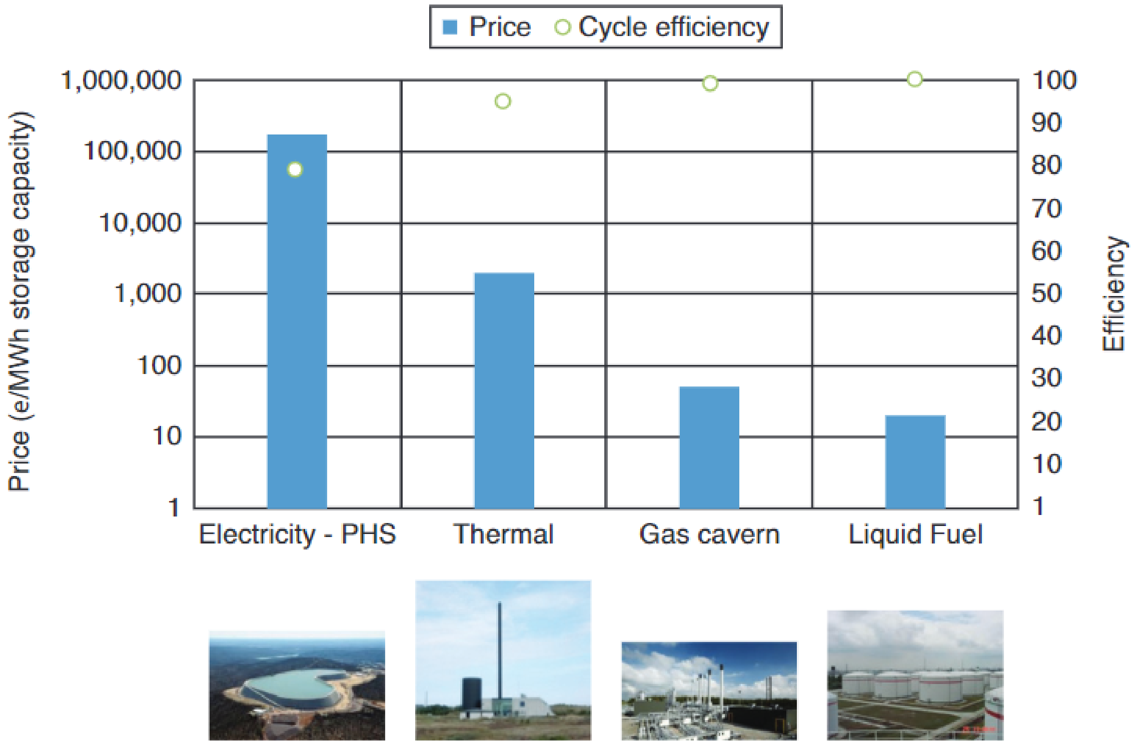


Figure 3. Investment cost and cycle efficiencies of different large scale energy storages. [15]

2.2 Stepwise implementation

The stepwise implementation of measures suggested in this analysis is inspired from [7]. Connolly, Lund & Mathiesen [7] highlight a number of steps, but in this paper a number of revisions are included. The new suggested stepwise implementation is as follows:

1. Starting point, reference scenario. Like [7], the offset should be a reference scenario. In this specific study a reference model based on PRIMES 2050 Business as Usual is used as a reference. Here a starting point with and without nuclear is discussed.
2. Energy savings in industry, electricity and heating. The suggestion now is to not focus on a general consensus, but to investigate potentials for energy savings. Also, the focus should not only be in heating, but should be in all demand sectors.
3. District heating. After energy savings, the goal should be to investigate what demand can be converted to district heating. Due to the potential system benefits down the road, this is now suggested to be done before assessing the individual heating sector.
4. Individual heating. After a transition to district heating, the individual heating sector needs to be addressed. This can be through electric heating and heat pumps, but other sources like biomass might have to be considered too.
5. Electrification of transport. After the heating sector, the transport sector can be transitioned. Here, the first step is to investigate the possibility for electrification as this seems most efficient.
6. E-fuels in transport. The remaining transport demand should be covered by some liquid fuel, biofuel or e-fuel, and should be investigated at this stage.
7. Replacing remaining fossil fuel with biofuels, biogas, e-gas and e-fuels. The final step of the transformation is the use of biofuels, biogas, e-gas and e-fuels to replace the remaining use of fossil fuels in industry and power plants.

Throughout these seven steps, the power sector has to be transformed as well. After each step the power sector needs to be balanced. This includes implementing renewable energy and adjusting power plant capacities, to achieve an efficient utilisation of renewable energy.
Thus, with the implementation of renewable energy, the excess electricity production should be monitored to avoid too much curtailment of wind turbines and PV solar cells. The suggestion is a maximum excess renewable production of 5% of the total electricity demand. To balance the hours where wind and PV cannot cover the demand, power stations should be implemented. As these has to be flexible, gas engines or turbines are suggested.

While this is a stepwise approach, it is important to emphasize the iterative nature within each step, and also by reassessing each step after the full transformation has been made. The approach increases the system integration throughout the system, and thus for instance, a certain heat pump capacity might be sensible in step 3 and 4, and then with the increased implementation of renewable energy in step 6 and 7, might lead to a potential higher utilisation rate of heat pumps. Thus, the steps, with iteration can be illustrated as in Figure 4.

2.3 EnergyPLAN

To conduct these analyses and ensure energy balances through out the entire year, EnergyPLAN is applied. EnergyPLAN simulates the operation of energy systems on an hourly level. The model is split into all energy sectors and therefore, it is possible to analyse sector coupling and the implementation of a Smart Energy System. EnergyPLAN is a deterministic model where the same inputs will result in the same outputs. In the analysis presented in this paper, EnergyPLAN is run in technical simulation mode. This means that the energy systems are balanced to achieve lowest fuel consumption, and utilising as much renewable energy in the European energy system as possible, compared to exporting and importing electricity. The technical simulation strategy is described more in detail in [4]. Figure 5 shows the overall concept of EnergyPLAN.

For each step presented in section 2.2 an EnergyPLAN model exists. They are all balanced on the following parameters:

- Maximum 5% CEEP. This is operationalised as a maximum of 0.05 PWh in a European energy system.
- No import, thus PP capacity is increased to fit the peak demand.
- Biomass limited to 2.5 PWh.

Offshore wind is implemented to demonstrate the need for an increase in renewable energy. In a later stage this will be balanced across the three technologies:

- Onshore wind
- Offshore wind
- Photovoltaic.

3 RESULTS AND ANALYSIS

The results and analysis will be presented by following the steps described in the methodology.

3.1 Step 1. Establishing starting point

The starting point is established by replicating the EU Commissions “A Clean Planet for all” baseline 2050 scenario developed in PRIMES. Due to the necessary further analyses, industry and heating demand are updated based on information from sEEnergies and Heat Roadmap Europe projects. This results in two adjusted baseline scenario, one that includes nuclear, and one that replaces nuclear power with offshore wind energy. The primary fuel outputs from this scenario is shown in Figure 6.

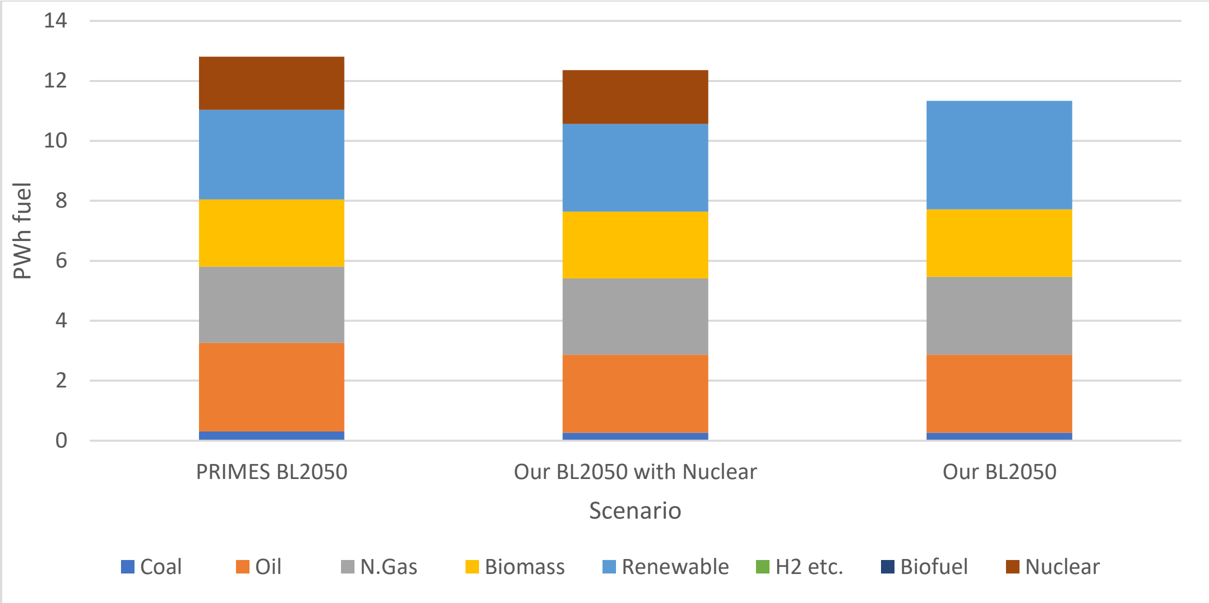


Figure 6. Baseline scenarios for the Smart Energy Europe.

3.2 Step 2. Energy efficiency

The second step is the implementation of energy savings and energy efficiency. With the data available, this is currently introduced as heat savings. The amount of heat savings implemented are related to the Heat Roadmap Europe studies, which results in an extra 10% heat savings compared to the baseline scenarios heat demand. It is important to mention that the reference baseline scenario already have established energy savings compared to a 2015 model representing our current energy system. Figure 7 shows that the fuel demand is reduced by implementing energy savings.

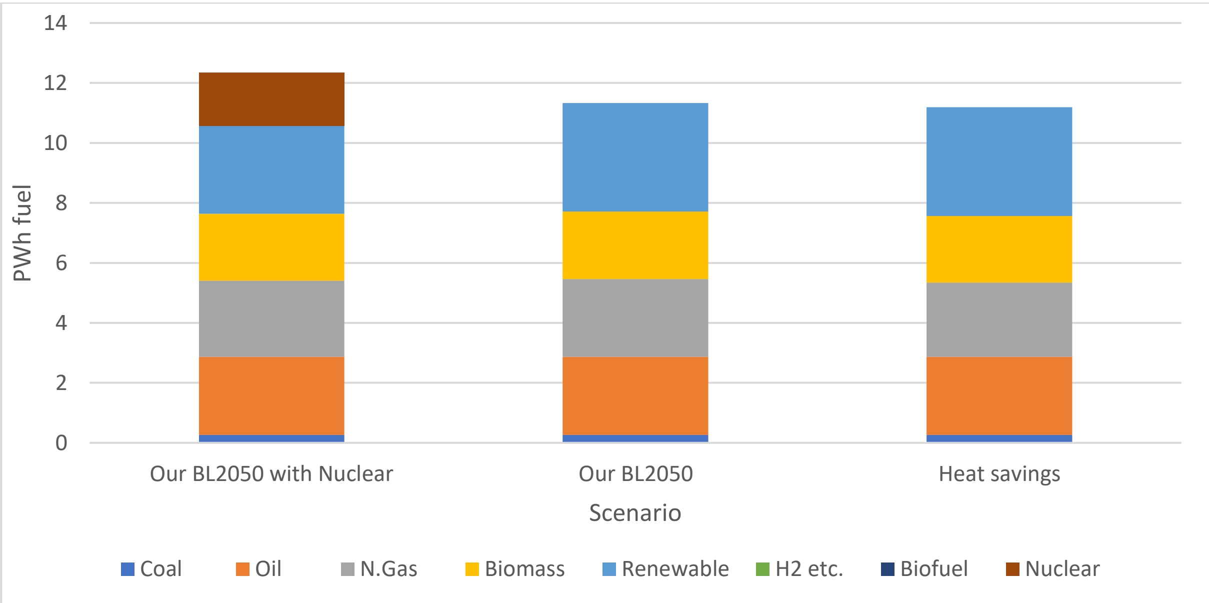


Figure 7. Implementation of energy efficiency.

3.3 Step 3. District heating

The third step is the implementation of district heating. By implementing district heating it is possible to lower the fuel demands, as shown in Figure 8. The design of the energy system here includes implementation of district heating networks covering 52% the total heat demand in Europe. Furthermore, boilers are implemented to cover peak demand in the heating grid, as well as combined heat and power plants and heat pumps both scaled to cover the average heat load in the grid. This is 144 GW thermal power. Finally, thermal storage is included, capable of storing 8 hours of the average thermal power. Industrial waste heat, geothermal energy and solar thermal energy are included based on the heat roadmap Europe study.

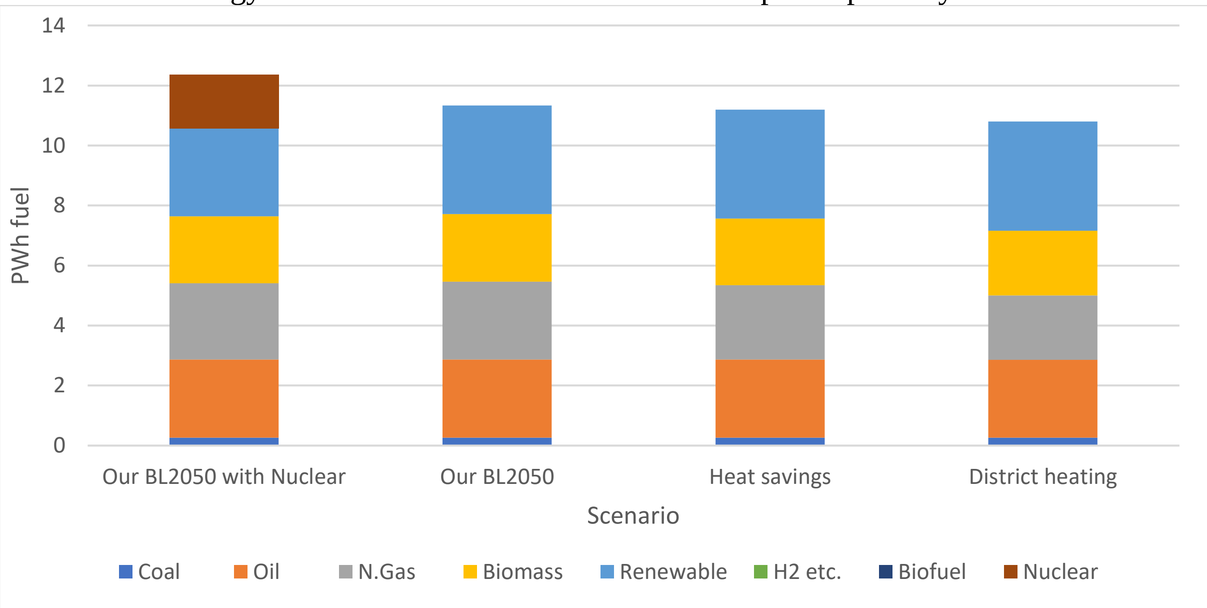


Figure 8. Implementation of district heating towards a smart energy Europe.

3.4 Step 4. Individual heating

After transitioning approximately half of the heat demand to district heating, the effect of transitioning the individual heating sector is assessed. Based on the previous smart energy Europe study, heat pumps are the most efficient technology, and by implementing heat pumps in the majority of the individual heated buildings, it is possible to keep reducing the total fuel use in the European energy system as shown in Figure 9. As the individual heating sector most likely will remain diverse in the future, a small amount of biomass boilers and electric boilers are kept in the system, to reflect this diversity. Thus, individual heat pumps covers 42% of the total heat demand, with biomass boilers and electric boilers covering the last 6% of the heat demand.

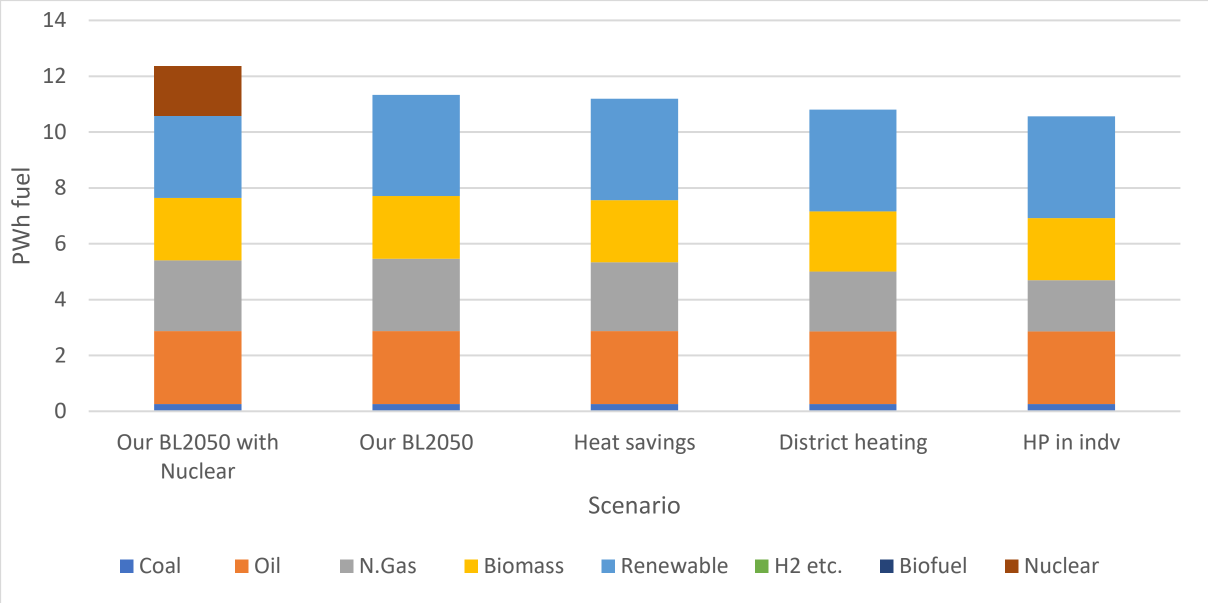


Figure 9. Fuel demand after transitioning the individual heating sector.

3.5 Step 5. Electrification of transport

After transitioning the heat sector, the transport sector is the next in line. Here figure 10 illustrate the energy efficiency benefits of electrifying the transport sector. The transport sector is electrified by converting all personal vehicles to electricity, 50% of the light duty vehicles and 20% of the heavy duty vehicles. These numbers are estimates based on previous studies[16,17], but the latest research shows that potentially a further electrification is possible. To cover these increased electricity demands, the renewable capacity is increased as well as the power plant capacity.

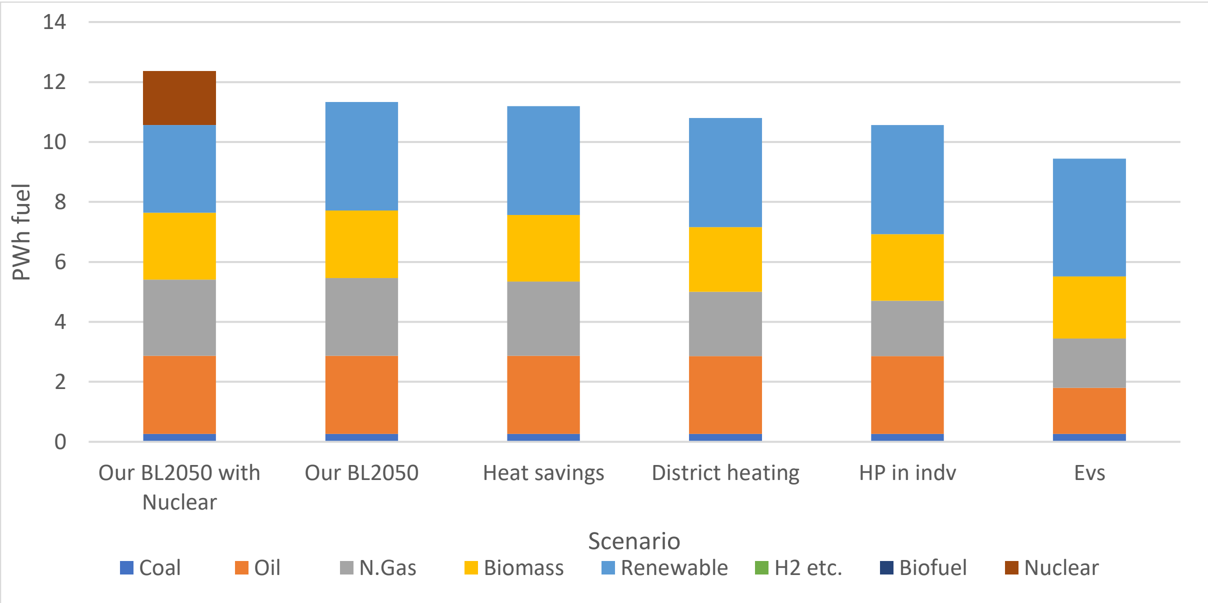
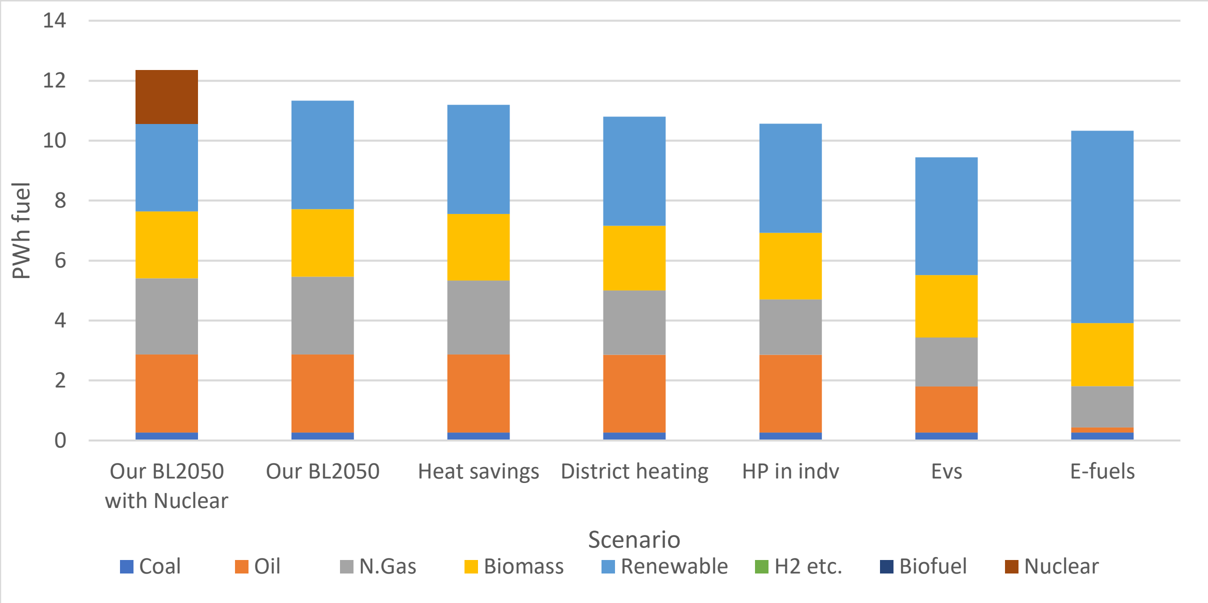


Figure 10. Fuel demands in the energy system after electrification of the transport system.

3.6 Step 6. E-fuels in the transport sector

With the electrification of the transport sector and the heating sector, the last remaining steps revolves around solving issues where fuels need to be replaced with new green fuels. Thus, energy efficiency is hard to achieve as these fuels needs to be reduced from electricity converted to e-fuels by the way of electrolysis. Thus, as seen in Figure 11, the fuel demand now increases as well as the demand for variable renewable energy and power plants increase. By replacing fossil fuels in the remaining road transport, as well as shipping and aviation with e-fuels, the renewable energy share increases, but also the total primary energy demand increases. This is an important step towards the Smart Energy System, which also delivers waste heat to the district heating system.



3.7 Step 7. E-fuels in the remaining energy sector

The final demands in the energy sector are industry and power stations. In industry solid fossil fuel is substituted with solid biomass and fossil oil and gas is replaced with biogas and green e-methane. This again requires an increase in electrolysis, biomass gasification and CO2 capture, all to ensure the necessary production of the needed fuels. To supply these processes the variable renewable energy is again increased alongside the backup power plant capacity. Finally, the gas fired power stations have their fossil natural gas replaced with biogas and e-methane. Figure 12 shows the consequences of replacing the system either with biogas, or with green e-methane from carbon capture and utilization. The biogas solution requires no extra power plant capacity or renewable energy, however increases the biomass demand. To lower the biomass demand, an option with more renewable energy and carbon capture can be chosen instead to produce e-methane.

Figure 13 and Figure 14 show respectively the primary energy consumption and the annual total costs. Here two final Smart Energy Europe systems for Europe are suggested, one with higher biomass consumption utilizing green gas from biogas and one relying on green gas from e-methane to supply the power stations. Due to the biomass restrictions mentioned in the methods chapter, the latter system is defined as the Smart Energy Europe scenario. In the figures, the system is compared to the 2050 Business as usual scenario and the "A Clean Planet for All" 1.5 TECH scenario. From here it can be seen that the Smart Energy Europe scenario represent a cheaper transition than the 1.5 TECH scenario, primarily due to the increase in system efficiency achievable by the implementation of a Smart Energy System. The 1.5 TECH scenario gains most of the efficiency increases from massive renovations of the building stock, which is more expensive than the potential system efficiency. Furthermore, the 1.5 TECH scenario still have nuclear investments as well as higher fuel costs. Both systems are more expensive than the business as usual scenarios, but neither of these fulfill the carbon emission targets and have not transitioned to renewable energy.

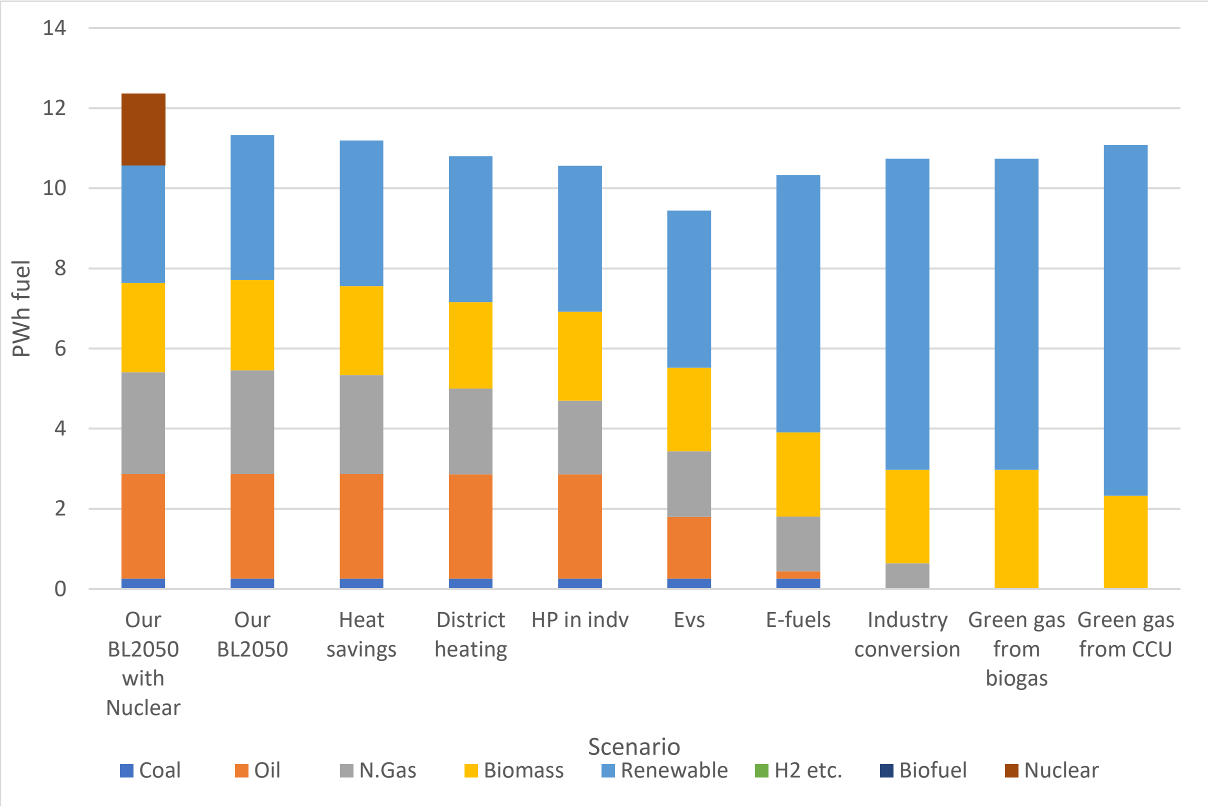


Figure 13. Final energy balance across all scenarios.

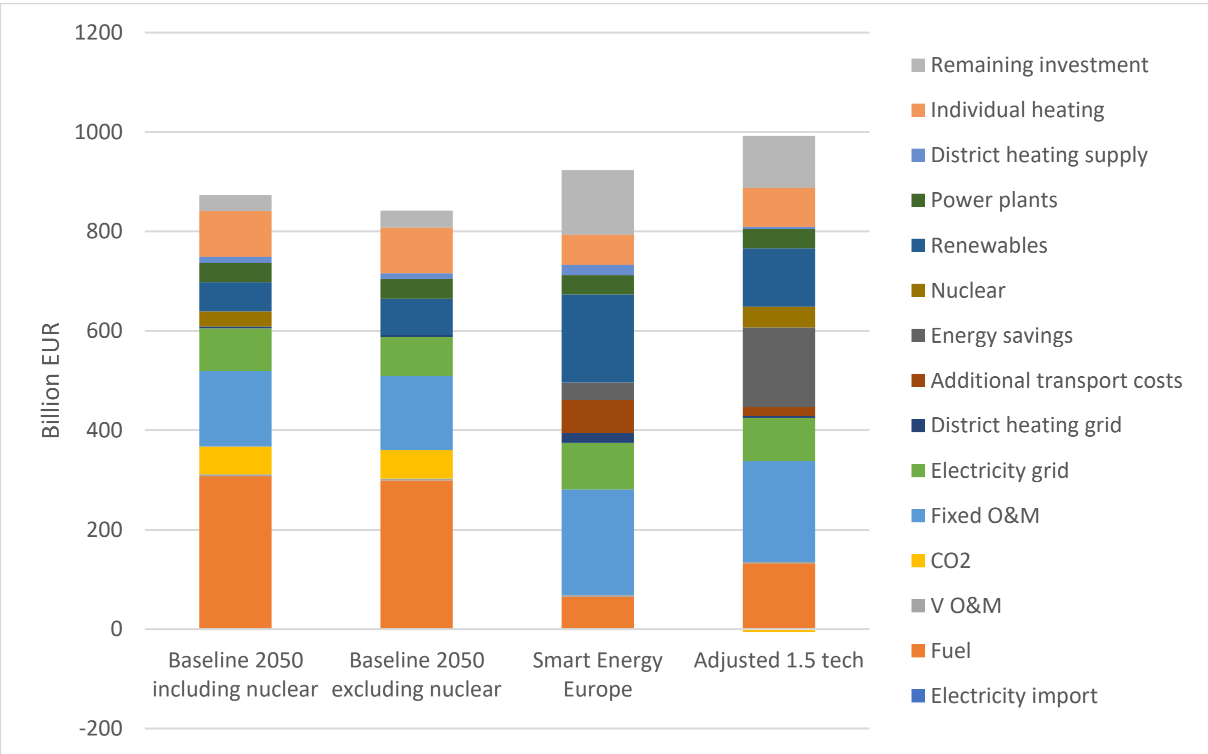


Figure 14. Total annual costs compared to baselines and the 1.5 TECH scenario.

4 CONCLUSIONS

Based on the steps above it is shown that it is possible to identify a pathway for Europe based on a Smart Energy System approach. Furthermore, the method described is potentially applicable for individual countries and other regions as it follows an analytical approach, changing and investigating different elements of the energy system one at a time. Thus, it operationalises a renewable energy transition that is complex and iterative by nature.

Furthermore, when comparing the smart energy Europe to the 1.5 TECH scenario from the European Commission, it is possible to see that a cheaper and more fuel-efficient scenario is possible to find. Furthermore, the Smart Energy Europe scenario eliminates fossil fuel completely, not only being carbon neutral, but also 100% renewable. The 1.5 TECH scenario still uses fossil fuels in the transport and industry sector.

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