



# Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union



D. Connolly<sup>a,\*</sup>, H. Lund<sup>b</sup>, B.V. Mathiesen<sup>a</sup>

<sup>a</sup> Department of Development and Planning, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen SV, Denmark

<sup>b</sup> Department of Development and Planning, Aalborg University, Vestre Havnepromenade 9, 9000 Aalborg, Denmark

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## ABSTRACT

This study presents one scenario for a 100% renewable energy system in Europe by the year 2050. The transition from a business-as-usual situation in 2050, to a 100% renewable energy Europe is analysed in a series of steps. Each step reflects one major technological change. For each step, the impact is presented in terms of energy (primary energy supply), environment (carbon dioxide emissions), and economy (total annual socio-economic cost). The steps are ordered in terms of their scientific and political certainty as follows: decommissioning nuclear power, implementing a large amount of heat savings, converting the private car fleet to electricity, providing heat in rural areas with heat pumps, providing heat in urban areas with district heating, converting fuel in heavy-duty vehicles to a renewable electrofuel, and replacing natural gas with methane. The results indicate that by using the *Smart Energy System* approach, a 100% renewable energy system in Europe is technically possible without consuming an unsustainable amount of bioenergy. This is due to the additional flexibility that is created by connecting the electricity, heating, cooling, and transport sectors together, which enables an intermittent renewable penetration of over 80% in the electricity sector. The cost of the *Smart Energy Europe* scenario is approximately 10–15% higher than a business-as-usual scenario, but since the final scenario is based on local investments instead of imported fuels, it will create approximately 10 million additional direct jobs within the EU.

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\* Corresponding author. Tel.: +45 9940 2483.

E-mail address: [david@plan.aau.dk](mailto:david@plan.aau.dk) (D. Connolly).

## 1. Introduction

There is a consensus that the energy system will need to change in the future, but there is a lot of uncertainty surrounding how it should change [1–4]. In this study, one scenario outlining how the future European energy system could evolve is presented, with a key focus on reducing carbon dioxide emissions by integrating very large penetrations of intermittent renewable energy.

The scenario proposed here is based on the Smart Energy System concept, which focuses on creating new forms of flexibility in the energy system, primarily by integrating all of the sectors with one another. This will require major changes in the technologies, regulations, policies, and institutions in today's energy system. The existing energy system in most developed countries consists of a relatively simple structure: This is presented in Fig. 1 where the structure is divided by (1) Resources, (2) Conversion processes, and (3) Demands.

There are a number of key characteristics that define how the energy system looks today. Firstly and most significantly, fossil fuels have provided very large and cheap energy storage over the past 150 years. Oil, natural gas, and coal are very energy dense fuels that can be easily stored in liquid, gas, and solid forms respectively. This means that energy can be 'called upon' by the demand side of the energy system whenever it is required. For example, if the demand for electricity increases, then more fuel is put into the power plant and more electricity is provided. This is very significant, since access to these 'on-demand' and flexible fossil fuels has meant that the rest of the energy system has become very inflexible. For example, consumers on the demand side of the energy system expect energy to be available once they need it.

Secondly, the energy system consists of very segregated energy branches. The supply chains for mobility, electricity, and cooling/heating have very little interaction with one another. From a technical perspective, this means that many of the synergies that occur across the energy system have not been utilised in the existing energy system. For example, the heat from power plants is often discarded into the sea or a river, instead of using it to supply some of the heating demand. The technical consequence of this is that the overall energy system is not as efficient as it could be [5–8]. Furthermore, due to this segregated structure, many scenarios for the future also focus on just one part of the energy system, especially the electricity sector [9–11].

Finally, there is currently no direct replacement for the fossil fuels in today's energy system, which means that the existing structure of the energy system cannot be maintained. The only direct alternative to fossil fuels identified to date is bioenergy, where oil is replaced with biofuels, gas with biogas or gasified biomass, and coal with biomass. In this situation, a large proportion of the existing energy infrastructure and institutions would be maintained since the physical and chemical properties of bioenergy are very similar to those of fossil fuels. However, the key problem is the availability of sustainable bioenergy. Based on a large variety of studies, it is forecasted that approximately 14–46 EJ of bioenergy will be available in the EU (see Fig. 2). However, already today the EU consumes approximately 60 EJ of fossil fuels so it is currently not possible to replace all of the fossil fuels with a sustainable level of bioenergy. In this study, it is assumed that a future 100% renewable energy system may consume a maximum of approximately 14 EJ/year of bioenergy, which is the minimum forecast from all of the studies identified. A conservative assumption for the availability of bioenergy has been applied here for three key reasons:

- To ensure that the solution proposed here is sustainable.
- To ensure that the EU contributes to a global sustainable energy system. A bioenergy potential of 14 EJ/year for the EU28 corresponds to  $\sim 27$  GJ/person/year of bioenergy, while the global bioenergy resource for 2050 is expected to be  $\sim 33$  GJ/person/year 14–54 GJ/person/year [12–22]. By limiting the EU28 bioenergy consumption to a similar level as the global availability, the EU28 is contributing to a sustainable global solution.
- To provide a conservative estimate of the consequences of a 100% renewable energy system. If more than 14 EJ/year of bioenergy is available in the EU28 in the future, then the 100% renewable energy scenario proposed here will be cheaper. Hence, the results in this study can be viewed as a conservative estimate of the economic viability of a 100% renewable energy system.

Future alternatives for the energy system should consider these three key characteristics and limitations in the existing energy system. In this paper, a scenario is presented for the EU energy system that accounts for these issues based on the Smart Energy System concept ([www.SmartEnergySystem.eu](http://www.SmartEnergySystem.eu)). The Smart Energy System concept has been developed by the Sustainable Energy Planning Research Group in Aalborg University, to outline how national energy systems can

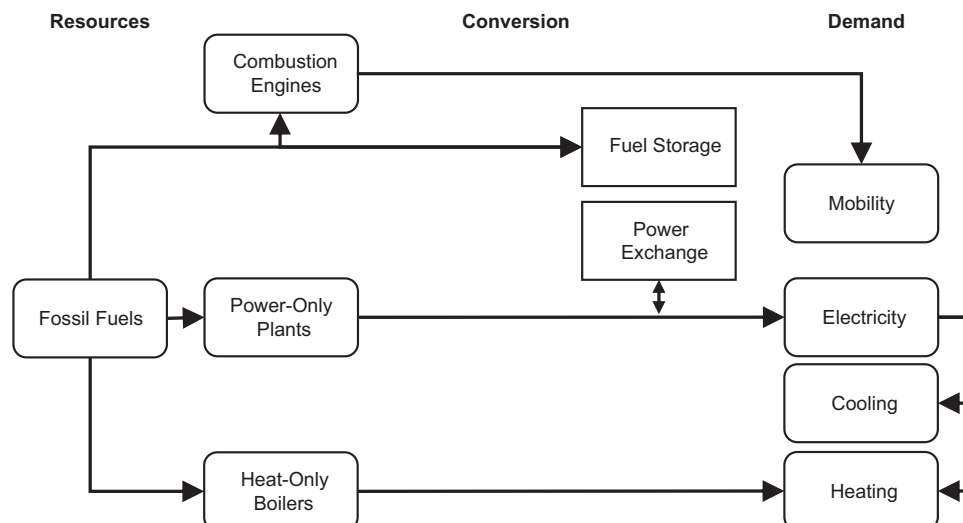


Fig. 1. Interaction between sectors and technologies in today's typical energy system.



The Smart Energy System concept is similar to the Smart Grid concept, but where the Smart Grid only focuses on the electricity sector [48,49], the benefits of the Smart Energy System are only realised when all the major sectors of the energy system are connected with one another [32,50]. Quantifying these benefits has only become possible in recent years as adequate energy tools have been developed [51]. For example, the impact of the Smart Energy System has recently been quantified for a community [52], some cities [53–55], and at a national scale [33,37], with each demonstrating how the key principal of combining energy sectors can increase renewable energy penetrations. In this study, the Smart Energy System concept is applied to a larger case study by analysing it in the context of the complete EU energy system, based on the principals displayed in Fig. 3. This study will build on existing scenarios for the European energy system, which have primarily focused on solutions in the electricity sector on its own [3,56–59]. The methodology used in this study is described in Section 2 and the results from the analysis are presented and discussed in Section 3.

## 2. Methodology

This section presents the key principles used to define the methodology in this study and afterwards, the transition simulated in this study is described. This section is supplemented by a range of cost data provided in the Appendix A.

### 2.1. Key Principles

The key principles that define how the analysis is completed are presented in detail in [30,31,33]. In brief, they are:

1. The analysis considers all sectors of the energy system, which are electricity, heat/cooling, and transport. This is clearly essential since the fundamental objective of the Smart Energy System is to utilise the synergies by combining the individual sectors of the energy system.
2. It is possible to analyse a radical change in technology. A low-carbon energy system contains some technologies which are still at the early stages of development. Hence, it is important when designing and analysing the future low-carbon energy system that these technologies can be included.
3. Accounts for short-term (hourly) fluctuations in renewable energy and demand. Intermittent resources like wind and solar power will be the primary forms of energy production in a low-carbon and sustainable energy system. Accommodating for their intermittency will be essential for the reliable operation of the future Smart Energy System.
4. The analysis is completed for a long-term time horizon. Energy technologies often have lifetimes in the region of 25–40 years, so decisions made today will affect the operation and structure of the low-carbon energy system.
5. The analysis is completed from a socio-economic perspective. Designing the energy system for the profits of any individual organisation is not the key concern for the citizens in society. Instead, it is the overall cost of energy, the type of resources used (i.e. environment), the number of jobs created, and the balance of payment for the nation that are examples of the key metrics which define a good or bad energy system from a society's perspective. Thus, future energy systems should be considered without imposing the limitations of existing institutions or regulations.

Each of these key principals helped determine how the analysis here was carried out. The first three principals are inherent in the energy modelling tool that is used. EnergyPLAN is an energy system analysis tool specifically designed to assist the design of national or regional energy planning strategies under the “Choice Awareness” theory [30]. A variety of training material, case studies, manuals, and existing models are freely available on the EnergyPLAN homepage [60]. EnergyPLAN has already been used for a wide range of analyses [61], including the development of 100% renewable energy strategies for countries such as Ireland [33], Croatia [62], Denmark [34,40,63], Hungary [64], and Italy [5]. During these projects, the model has been continuously updated to include the technologies required for the Smart Energy System, thus ensuring that the radical technological changes necessary can be simulated by the model.

EnergyPLAN also simulates the electricity, heating/cooling, and transport sectors of the energy system on an hourly basis over one year, thus accounting for the intermittency of some renewable energy resources and demands. There are some regulations built into the model to maintain grid stability on an hourly basis, which is increasingly important as more intermittent renewable energy is added. These regulations are described in detail in the model's documentation [65]. To ensure a long-term time horizon is considered, the analysis here will focus on the steps towards a 100% renewable energy system by the year 2050.

In relation to the socio-economic perspective, EnergyPLAN optimises the technical operation of a given system as opposed to tools that identify an optimum within the regulations of an individual sector. As a result, the tool focuses on how the overall system operates instead of maximising returns within a specified market framework or from one specific technology viewpoint. This is significant, as the structure of today's energy system will not be the same in the future, and the merging of energy sectors will increase significantly, hence markets will become intertwined. The fuel costs, investment costs, and operation and maintenance (O&M) costs used in this study are presented in the Appendix A. EnergyPLAN does not calculate the job creation and balance of payment for the region, so this was completed outside the tool: the methodology that was used is described in detail in Lund and Hvelplund [66].

### 2.2. The transition to a Smart Energy System

Using the EnergyPLAN model, a Smart Energy System, like the one displayed in Fig. 3, has been designed and analysed for the EU energy system. The design process in EnergyPLAN is typically as follows [30,31]:

1. *Reference*: Define a reference energy system to act as a starting point. This model contains energy demands and supply technologies, along with the costs associated with these. The reference model acts as a benchmark for comparing other scenarios, therefore it is usually based on a forecasted business-as-usual scenario for a future year.
2. *Alternatives*: The user can then create alternatives to compare with this reference scenario by changing the technologies in the model. The user defines the capacities and mix of supply technologies for the energy system. This is unlike many other energy tools where the supply technologies are chosen by the model itself, usually based on economic assumptions. EnergyPLAN does not include this since many of the technologies required in a Smart Energy System have much more uncertainty associated with their cost than they do with their technical performance. Hence, some benefits of a technology to the energy system could be lost if it is defined based only on its economic performance. Furthermore, the philosophy behind the EnergyPLAN

tool is to simulate the impact of a variety of options, rather than identifying one 'optimum' solution. It is important to simulate both the 'bad' solutions and the 'good' solutions, so the impact of various alternatives can be compared with one another, which is described in detail in the Choice Awareness theory behind the EnergyPLAN development [30,31].

3. *Comparison of results:* Once the user has created an alternative scenario, then the results can be compared between the reference energy system and this new starting point. Some results are automatically provided by the EnergyPLAN software (such as primary energy supply), while others require additional calculations based on the results (such as job creation).

In this section, the reference and alternatives created for the EU energy system are described, while in Section 3 the results are compared with one another.

The reference energy system for the EU is based on a business-as-usual forecast for the year 2050. It includes all 28 EU member states and it is based on the most recent energy projections by the European Commission [21]. Approximately 500 data inputs and 30 hourly distributions are required to make a complete model in EnergyPLAN therefore the EU has been modelled as one energy system in this study. This means that there is one model for the EU energy system instead of separate models for different regions or countries. Hence, there are no bottlenecks included in the electricity or gas grids in the model. Due to the amount of data required within a model, it is not practical to present all of the data that are used, so instead a summary of the key demand and supplies are presented in Table 1 and a full copy of the model can be downloaded from the EnergyPLAN homepage [60]. For all sectors, the cost of the technologies, fuels, maintenance, and carbon dioxide are included: the cost assumptions that are used are based on forecasts for the year 2050 and they are provided in the Appendix A.

The transition towards a Smart Energy System has been created in this study using the EU28 reference scenario in Table 1 as a starting point, and it is referred to here as the *EU28 Ref2050* scenario (i.e. step 1). To help explain the changes that are taking place, the transition has been divided into a number of steps. These steps are not designed to reflect how the transition should be implemented, but instead they create transparency in the results. Furthermore, the steps here are defined based on the author's perception of their political and scientific certainty rather than the current stage of development. For example, implementing electric vehicles is strongly supported for the low-carbon energy system, both politically [67] and scientifically [68–71], so it is implemented during the initial steps presented here, even though the technology is not as well established as those in later steps.

For every step, the level of intermittent renewable energy of the electricity demand (i.e. wind and solar power) is varied from 0% to 100% to identify the cheapest penetration. As the level of wind and solar increases, more electricity is produced which cannot be consumed. This is defined as Excess Electricity Production (EEP) and it is assumed here that it cannot be exported outside the EU if it occurs, hence there is no additional income from EEP (i.e. exported electricity).

To begin, the first 3 steps in the transition are implemented since they are currently getting a lot of political and scientific support. These three steps are grouped together as the 'General Consensus' steps and they include:

2. *No nuclear:* Removing nuclear power in the long run from the EU energy system due to its economic, environmental, and security concerns. In addition, nuclear power does not fit in a renewable energy system with wind and solar, since it is not

**Table 1**

Summary of the energy demand and supply in the EU28 Reference Scenario for the year 2050 (*EU28 Ref2050*).

Demand (TW h)		Supply (TW h)	
Total electricity consumed by all types of demand	4440	Total electricity production by source	4440
Electricity losses	585	Onshore wind	736
Conventional demands	3109	Offshore wind	339
Flexible electricity & EVs	255	Solar	347
Heat pumps	117	Wave and tidal	17
Electrolysis	0	Hydro	425
Electric heating	251	Geothermal	29
PHES pump	28	Nuclear	924
Electricity exports	95	CHP	234
		Power plants	913
		Industrial CHP and waste	453
		PHES turbine	23
Total heat demand by fuel	3308	Total fuel consumption for heat production	3401
District heating	278	District heating	337
Coal	43	Coal	62
Oil	433	Oil	510
Gas	1558	Gas	1640
Biomass	274	Biomass	365
Heat pump electricity	350	Heat pump electricity	117
Direct electricity	251	Direct electricity	251
Solar	118	Solar	118
		Total fuel consumption in industry	3062
		Coal	569
		Oil	434
		Gas	1400
		Biomass	658
		Total fuel consumption in transport	4321
		Jet fuel	776
		Diesel	1872
		Petrol	935
		Natural gas	3
		LPG	28
		Biodiesel	275
		Bioethanol	143
		Biojetfuel	34
		Electricity	255

very flexible. Even if these issues are resolved, there are also major challenges in relation to the safe disposal of nuclear waste and the safety of nuclear power stations.

3. *Heat savings:* Reduce the heat demand in the EU to the point where heat supply is cheaper than further savings. There is a point at which further heat savings become more expensive than a sustainable heat supply [72]. In Heat Roadmap Europe [6,8,73], it was estimated that this point occurred after a reduction of 30–50% in the heat demand in buildings compared to today. Hence, in this step the heat demand is reduced by 35% compared to the *EU28 Ref2050* scenario.
4. *Electric cars:* Convert private cars from oil to electricity. Detailed studies in Denmark have indicated that approximately 70–80% of the oil-powered private cars can be converted to electric cars [40]. A similar level has been proposed in the European Commission's Energy Roadmap scenarios: "The increase of electricity use in transport is due to the electrification of road transport, in particular private cars, which can either be plugin hybrid or pure electric vehicle; almost 80% of private passenger transport activity is carried out with these kinds of vehicles by 2050" [74]. Hence, in this step, 80% of the private cars and their corresponding energy demands are transferred from oil (i.e. petrol and diesel) to electricity.



The most important short-term issue missing from the steps under the ‘General Consensus’ group is in relation to heat pumps in the heating sector. Currently, one of the most common solutions proposed for the future heating sector in Europe are individual heat pumps [58,75]. However, recent research has indicated that a combination of heat pumps in rural areas with district heating in urban areas, is a more appropriate solution for the EU to achieve a low-carbon energy system [6,8,73]. Due to this uncertainty, a variety of heating options have been analysed in this study to estimate the impact of the various technologies available. A distinct division has been made between two modes of heating in this analysis:

- **Individual heating:** these are heating technologies that are placed individually in each building. This will be necessary in rural areas where buildings are not located close to one another, but it is unclear how much individual heating should be installed in towns and cities. For example, this includes oil boilers, biomass boilers, and individual heat pumps.
- **Network heating:** these are heating technologies which are shared among different consumers. Today, there are only two primary ‘network heating’ options: gas and water (i.e. district heating). The gas and water networks are shared across individual buildings in a similar way to other utilities such as potable water, sewage, internet, and electricity. To justify the construction of a shared heating infrastructure, there must be a sufficient heat demand (i.e. buildings must be located close to one another) and a sufficient supply of surplus heat resources (i.e. from power plants, industry and renewable energy).

In this study, four extreme versions of individual heating are analysed: 5a. Heat Pumps, 5b. Electric Heating, 5c. Oil Boilers, and 5d. Biomass Boilers. In each case, all of the heating in the EU, both rural and urban are supplied using only the individual heating technology being analysed. These extreme cases illustrate the impact of each individual heating technology on the rest of the energy system. Based on the results from this analysis, the optimum individual heating technology is then combined with both of the network heating options in step 6. This process is graphically illustrated in Fig. 4.

Once the heat supply has been defined, the next big issue is the fuel for heavy vehicles other than cars, such as trucks, ships, and aeroplanes. The fuel for these vehicles must have a high energy density, which means that batteries are unlikely to be sufficient [76]. Hydrogen is excluded due to the losses that occur during its

production and due to the cost of changing the existing infrastructure [77] and vehicles [78]. Traditional biofuels are excluded since the demand for bioenergy would be unsustainable if all the oil for trucks, ships, and aeroplanes is directly replaced with biofuels [76]. However, one of the key benefits associated with biofuels is that they can utilise existing infrastructure. For example, biofuels can be burned in existing combustion engines with very few modifications. Renewable electrofuels are proposed in this study since they also have this key benefit, but they consume much less bioenergy, thus maintaining a sustainable bioenergy demand even in a 100% renewable energy context [33,40].

Electrofuels are created by combining hydrogen and carbon with one another [76]. The fuel produced at the end of the process depends primarily on the ratio between hydrogen and carbon in the fuel. Hence, a variety of fuels can be produced by combining the correct amount of hydrogen and carbon (although this requires many other supporting components, such as suitable catalysts in the chemical synthesis). In this study, it is assumed that the renewable electrofuels are produced in the form of methanol or dimethyl ether (DME), since these are the simplest alcohol [79] and ether [80], respectively. The electrofuels produced here are defined as ‘renewable’ since both the carbon and electricity required to produce them are supplied by renewable resources. A variety of different production processes for renewable electrofuels are presented in Connolly et al. [76], four of which have been used in this study (see Table 2).

All of the electrofuel pathways involve the combination of hydrogen and carbon, but the key differences are (1) the source of carbon and (2) the type of electrofuel produced. The carbon can primarily be obtained from bioenergy or by Carbon Capture and Recovery (CCR), while the final fuel can be either liquid (methanol/DME) or gas (methane). It is assumed in step 7 that liquid fuels are used for vehicles that require energy-dense fuel, such as trucks, ships, and aeroplanes. It is assumed that half of this liquid is methanol/DME produced using biomass as a carbon source (bio-electrofuel: Fig. 5) and the other half is methanol/DME produced using carbon from a power plant or industry (CO<sub>2</sub>-electrofuel) [42,76]. For aviation, an extra loss of 15% was applied to the final fuel produced to account for additional losses when producing a higher quality fuel for aeroplanes. This data is a proxy since there is no clear evidence to suggest exactly what type of renewable electrofuel will be used in aviation in the future, even though some have previously been developed and implemented [83,84].

During the first 7 steps, a lot of coal, oil gas, and biomass has been replaced with other energy sources so there is now much less

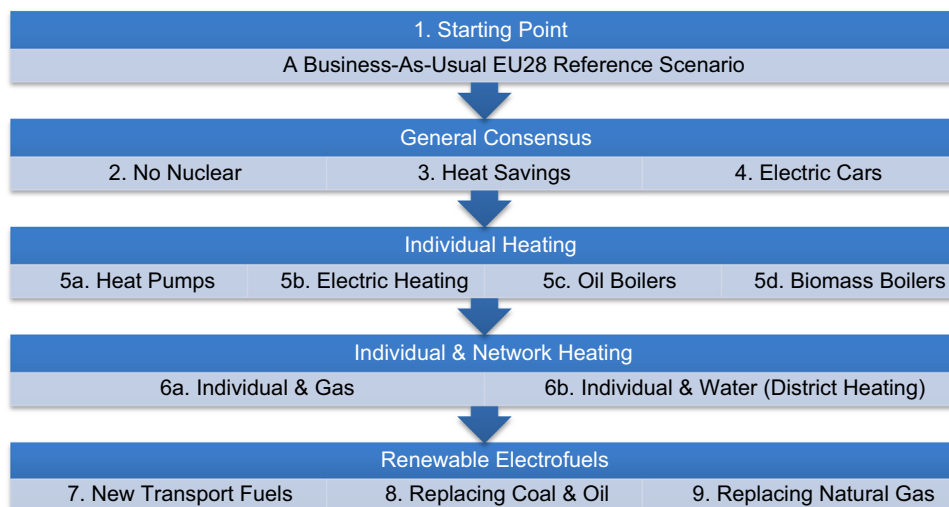


Fig. 4. Transition steps in this study from a 2050 reference energy system to a Smart Energy System for the EU.

fossil fuel and biomass in the energy system than in the *EU28 Ref2050* scenario. To reduce the carbon dioxide emissions further, in step 8 the coal and oil in the thermal plants and industry are replaced by natural gas and biomass. The biomass consumption is increased in step 8 until the same amount of biomass is being consumed as in the original *EU28 Ref2050* scenario. Afterwards, the remaining coal and oil is replaced with natural gas. As a result, the only fossil fuel remaining after step 8 is natural gas.

In the final step, step 9, this remaining natural gas is replaced by methane from renewable electrofuels, so the EU energy system is now 100% renewable. Similar to the assumptions for methanol/DME, half of the methane is produced using a bio-electrofuel (similar to Fig. 5, but for methane [42,76]) and half is produced using a CO<sub>2</sub>-electrofuel (see Fig. 6). The key motivation for using methane is to minimise the utilisation of bioenergy. Assuming that bioenergy is carbon neutral, the energy system now has no carbon dioxide emissions except for a very small amount from waste incineration.

These 9 steps outline one potential pathway to transform the EU energy system from fossil fuels to 100% renewable energy. Using the steps proposed here illustrates the impact of some key technological changes that need to be undertaken during this transition, which is presented in the next section.

**Table 2**

Electrofuel pathways used in this study [76].

Carbon source	Electrofuel produced	
	Liquid	Gas
Bioenergy	Bioenergy hydrogenation to methanol/DME (Fig. 5)	Bioenergy hydrogenation to methane [42,76]
Carbon Capture and Recycling (CCR) <sup>a</sup>	CO <sub>2</sub> hydrogenation to methanol/DME [42,76]	CO <sub>2</sub> hydrogenation to methane (Fig. 6)

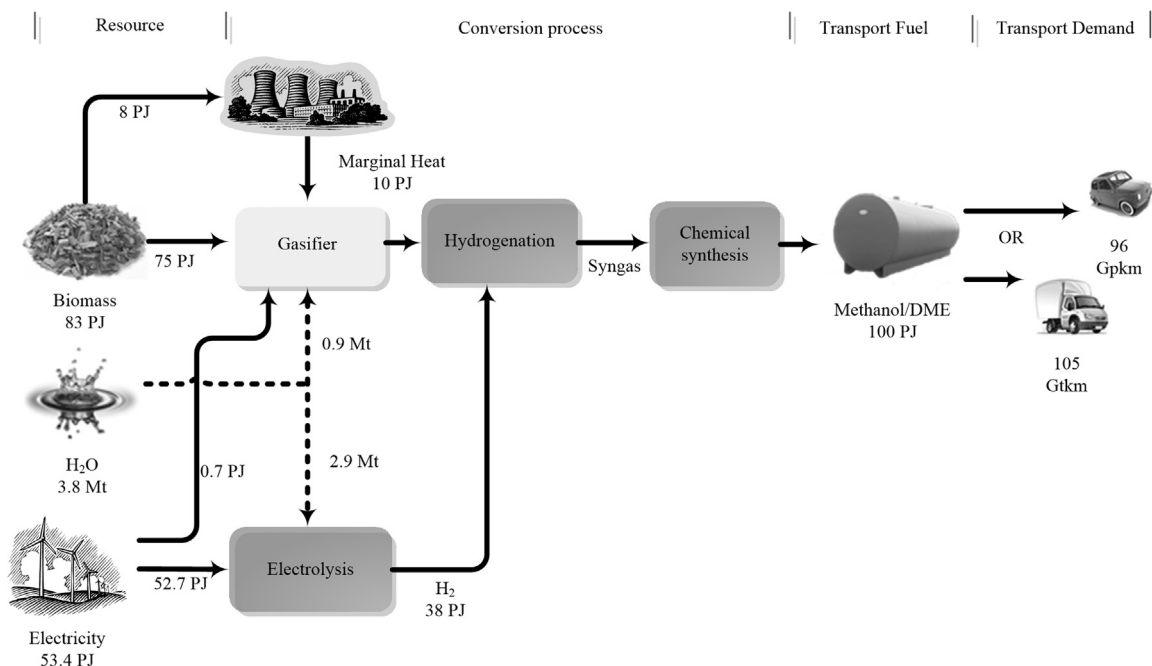
<sup>a</sup> CCR can be carried out at a power plant, industry, or even from the air using carbon trees [81,82].

### 3. Results and discussion

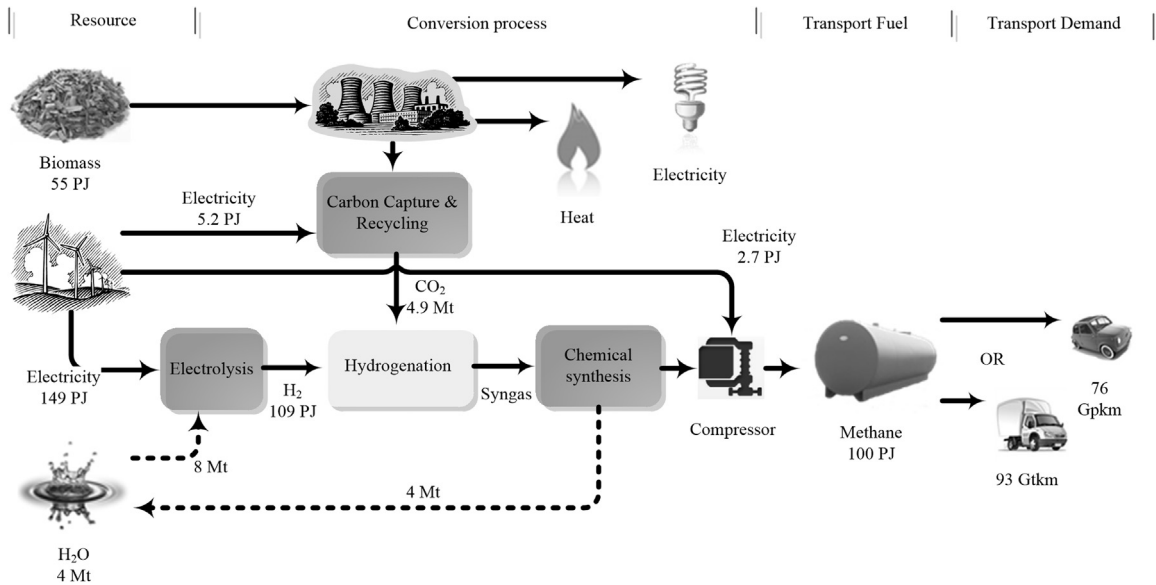
Separate results are presented for each step, starting with the *EU28 Ref2050* scenario and moving towards the Smart Energy System (step 9) for the EU. For each step, the aim is to assess the impact on energy, the environment, and the economy. To do so, the Primary Energy Supply (PES) is measured by fuel type to assess the impact on energy, the total annual carbon dioxide emissions are measured to analyse the impact on the environment, and the total annual socio-economic costs of the energy system have been calculated by sector to analyse the impact on the economy. These metrics have been chosen since the 'optimum' solution can often vary based on the initial objective, such as minimum cost or minimum CO<sub>2</sub> emissions. By measuring all three, a more balanced assessment of the impact can be carried out, although the authors recognise that many other metrics could also be used, especially in relation to health costs since some existing studies have previously highlighted their importance [34,43].

#### 3.1. General consensus

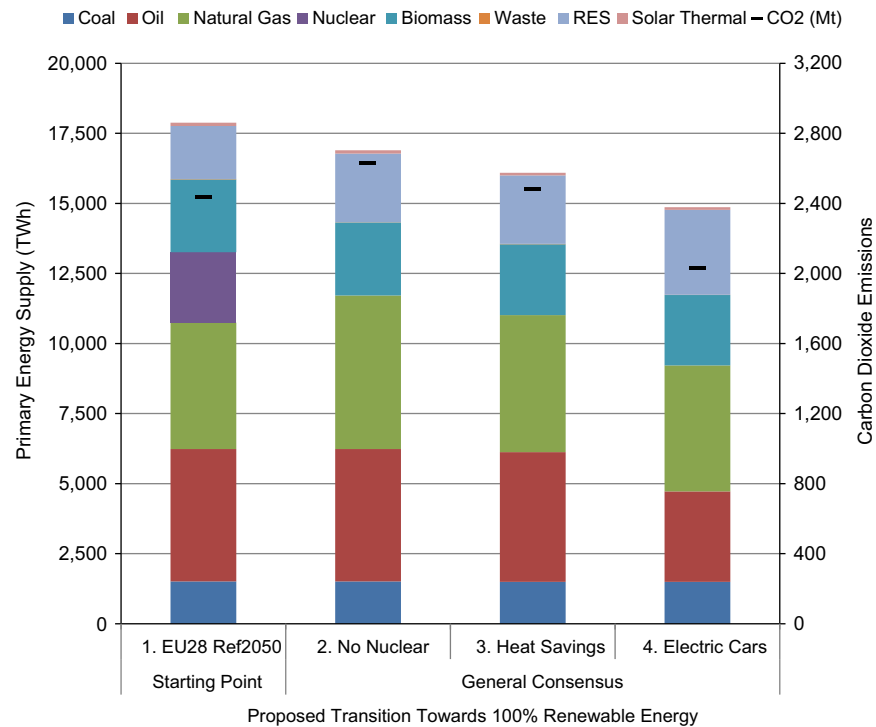
To begin, Fig. 7 displays the PES and CO<sub>2</sub> emissions for the 'General Consensus' steps. In step 2, nuclear power is removed which reduces the PES, but it increases the CO<sub>2</sub> emissions. The PES is less because nuclear power has an assumed efficiency of 33%, which is lower than the efficiency of the power plants that replace nuclear (they have an average efficiency of approximately 50%). Therefore, when power plants replace nuclear power the overall energy demand is lower. Furthermore, nuclear power is not a very flexible technology therefore when nuclear power is removed, it is possible to increase the share of intermittent renewable energy sources (IRES), such as wind and solar, from 32% to 45% of electricity production. However, the penalty is an increase in carbon dioxide emissions. Even though there is an increase in the amount of IRES, some nuclear power is replaced by power plants that use fossil fuels and so there is a corresponding increase of 8% in the total CO<sub>2</sub> emissions. There is also a cost increase of approximately 1% when nuclear power is removed from the energy system, based



**Fig. 5.** An example of a bio-electrofuel production process: biomass is gasified and the resulting gas is hydrogenated to produce methanol or dimethyl ether (DME) [42,76,108,109].



**Fig. 6.** An example of a CO<sub>2</sub>-electrofuel production process: carbon that is sequestered using CCR at a power plant and afterwards, it is hydrogenated to produce methane [42,76,108,109].



**Fig. 7.** Primary energy supply by fuel and carbon dioxide emissions for the reference EU28 Ref2050 scenario and the 'general consensus' steps in the transition to a Smart Energy System for Europe.

on the 2050 costs presented in the Appendix A. However, the costs are likely to be higher for nuclear in the real world since at present the costs reported to implement nuclear power often exceed those assumed here, particularly when delays, waste disposal, decommissioning, risk, and pollution costs are accounted for [85,86].

In the next step, the heat demand in residential and services buildings is reduced, with the introduction of energy efficiency measures such as improvements in insulation, windows, and doors. In the early stages of this development heat savings will be very cost effective, since the price to save a unit of heat will be less than the cost of supplying a unit of heat. However, at a certain

point, the cost of further savings becomes more expensive than supplying the heat. In Heat Roadmap Europe [6,8,73], this point was estimated for the EU energy system, where it was concluded that the total heat demand in the EU should be reduced by approximately 30–50% compared to today. After this point, it is cheaper to supply heat from a sustainable resource compared to reducing the heat demand. In this study, the heat demand is reduced by 35% compared to the EU28 Ref2050 scenario. As expected, these additional heat savings reduce the demand for energy, the carbon dioxide emissions (Fig. 7) and the costs of the energy system (Fig. 8).



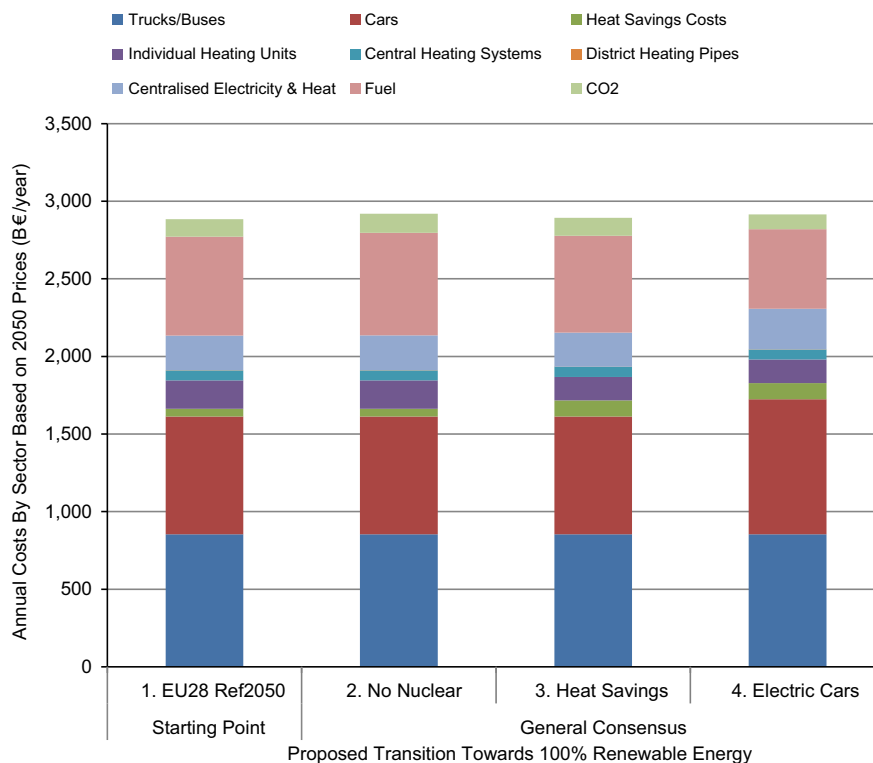


Fig. 8. Annualised costs by sector for the reference *EU28 Ref2050* scenario and the 'general consensus' steps in the transition to a Smart Energy System for Europe.

The final 'General Consensus' step is the implementation of electric vehicles. In this scenario 80% of the oil utilised for private cars is replaced with electricity, which is the penetration level forecasted for the EU energy system [74]. To make this conversion, it is assumed that electric vehicles have an efficiency of 0.5 MJ/km, while diesel and petrol vehicles have an average efficiency of 1.5 MJ/km and 1.9 MJ/km respectively. The resulting electricity demand was verified by comparing the electricity consumption here with the electricity consumption for electric vehicles in the European Commission's Energy Roadmap reports [74,75]. The additional back up capacity required for the new electricity demand for the electric vehicles is included in the modelling. When the electric vehicles are introduced, there is almost a 10% drop in the system PES for two key reasons:

- The electric vehicles are more efficient than petrol and diesel vehicles.
- The batteries in the electric vehicles create more flexibility in the energy system, which enables more wind power to be integrated and thus replaces fossil fuels in the power plants. To be more specific, the amount of IRES on the electricity grid is increased from 45% to 55% once the electric cars are added.

To estimate the impact on the vehicle costs, it is assumed that vehicles are replaced proportionally to the fuel switch. In other words, it is assumed that when replacing 80% of the fossil fuel with electricity, 80% of the vehicles are switched from internal combustion cars to electric cars. In reality, there will be a mix of combustion engines, hybrid vehicles, and pure electric cars. The costs assumed for the vehicles are presented in the Appendix A. As presented in Fig. 8, the overall costs of the system increase slightly with the introduction of electric vehicles by approximately 1%. There is a larger increase in the cost of the vehicles of approximately 15%, but this is counteracted by a reduction in the

cost of powering the vehicles, so overall there is a minor increase of 1% in the overall energy system costs.

Although there has been some minor fluctuations along the way, overall the total costs of the energy system, after implementing the General Consensus steps, are practically the same as those in the *EU28 Ref2050 scenario* (< 1% more). In comparison, there is a significant reduction of ~15% in both the PES and the CO<sub>2</sub> emissions. One key element missing from the General Consensus steps is the heat supply for buildings. This has not been included as a General Consensus step, since recent results have indicated that district heating can play a significant role in reducing the CO<sub>2</sub> emissions in the EU energy system [6–8]. In this study, various heating solutions have been analysed in the EU energy system, firstly by looking at individual heat solutions and afterwards by combining an individual and network based heating solution. The objective here is to illustrate the impact of the good and bad solutions for the heating sector in the EU, so the technical and economic impact of these solutions can be identified.

### 3.2. Individual heating

An individual heating unit is defined here as a unit that could in theory be placed in every building in Europe (i.e. rural and urban). The individual heating options that were analysed are heat pumps, electric heating, oil boilers, and biomass boilers. These are extreme scenarios where all of the heat demands in buildings are supplied for one specific type of system. In reality, there will always be a mix of heating technologies, with one specific technology likely to dominate more than the others. The extremes presented here are designed to highlight the impact of choosing the various technological solutions as this dominant solution, rather than suggesting that the EU energy system will consist solely of one heating technology in the future.

The results from the individual heating analysis are displayed in Figs. 9 and 10, along with a summary of the key observations in Table 3. Based on this comparison, electric heating and oil boilers

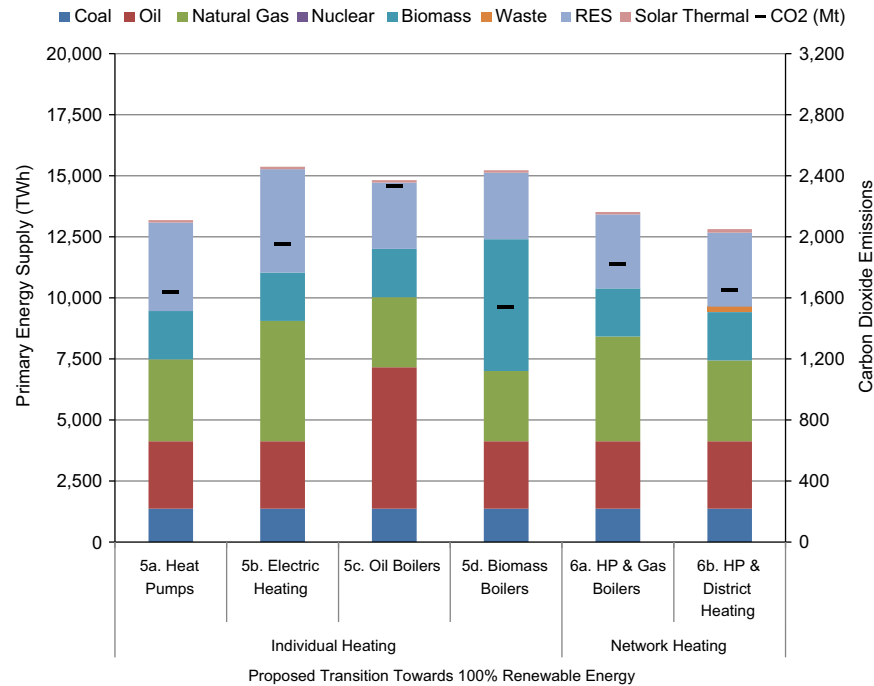


Fig. 9. Primary energy supply by fuel and carbon dioxide emissions for the individual and network heating steps in the transition to a Smart Energy System for Europe.

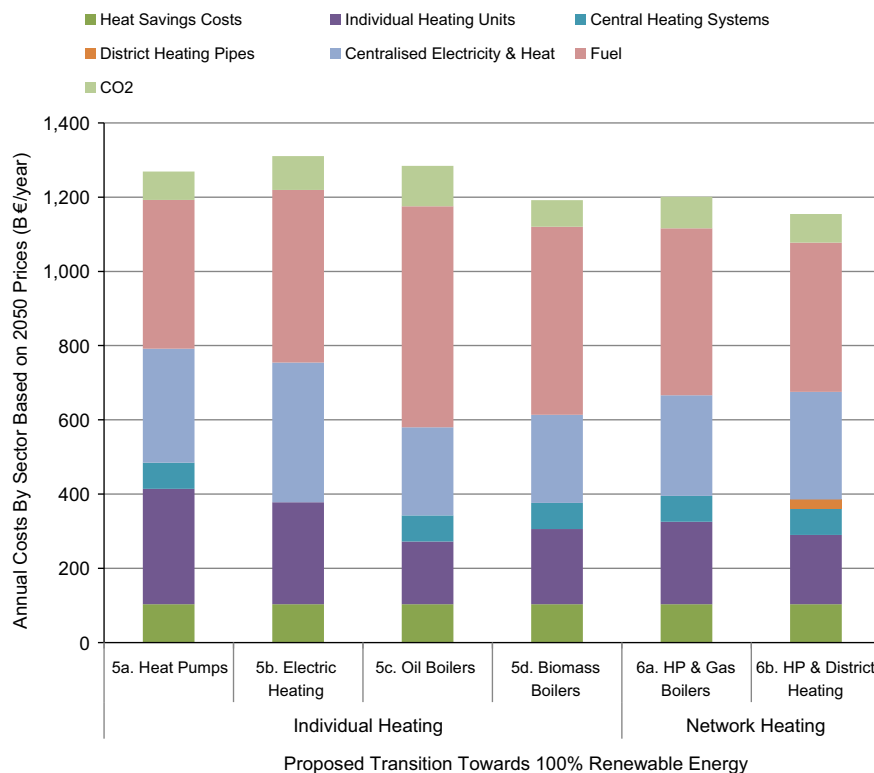


Fig. 10. Annualised costs by sector for the individual and network heating steps in the transition to a Smart Energy System for Europe. \*The transport system costs (i.e. costs for Trucks/Busses and Cars) have been removed from the costs here, since they are the same for all scenarios.

are clearly unsustainable heating solutions for the EU in the future. Electric heating can be electrified from a sustainable resource, such as wind or solar electricity, but due to its relative low efficiency, the PES for electric heating is very high. Electric heating requires a large amount of electricity, so it also requires a lot of extra power plant capacity. Although electric heating allows more wind and solar power to be utilised, there needs to be enough

power plant capacity in place to supply the heat if the wind or solar power is unavailable. This backup capacity is expensive to construct, because it has very few operation hours during the year. The cost to produce the electricity required for electric heating and to install this backup capacity is relatively high, which means that electric heating is the most inefficient and the most expensive heating solution considered.

**Table 3**

Summary of the comparison between the various individual and network heating solutions presented in Fig. 9 and Fig. 10.

Heating Unit	Sustainable Resources	Efficient	Low Cost	Robust Costs vs. Demand
Electric Heating	Yes	No	No	No
Heat Pumps	Yes	Yes	Mix	Mix
Oil Boilers	No	Mix	Mix	No
Biomass Boilers	Mix	No	Yes	No
Gas Grid	No	Mix	Mix	No
District Heating	Yes	Yes	Yes	Yes

Oil boilers are also not a suitable solution in the future since they rely on a fossil fuel, but it is included here since it is currently the dominant individual heating solution in Europe. Although it is more efficient than electric heating, it has predictably high CO<sub>2</sub> emissions so it is excluded from the scenario developed here.

Individual heat pumps and biomass boilers are the two remaining solutions available. In these results, biomass boilers are cheaper and they produce less CO<sub>2</sub> emissions. However, these results need to be considered in the context of a 100% renewable energy system and in this context, the assumptions here are unlikely to become reality for the following key reasons:

- Biomass is much more valuable in the transport sector than in the heating sector. In the biomass boiler scenario, the demand for biomass is 19 EJ/year which is more than the sustainable level defined in this study of 14 EJ/year, as discussed in the Introduction and presented later in Fig. 14. Therefore, if biomass boilers are implemented on a large-scale, then it is unlikely that there will also be enough sustainable biomass for the transport sector. In the heating sector, there is a very clear alternative to biomass, which is presented here as heat pumps, but in the transport sector, there is no obvious alternative for oil particularly for heavy-duty transport such as trucks, ships, and aviation. Therefore, it is assumed here that saving biomass for transport is more sustainable than using it in biomass boilers.
- The biomass price assumed here is unlikely to reflect the actual cost of biomass in a low-carbon EU energy system, due to the amount of additional biomass required for the boilers. Being a finite resource, the price of biomass is likely to increase as more biomass is consumed, similar to the relationship between supply and demand for oil. It is beyond this study to estimate how the biomass price will react to increases in demand, but the impact of an increase has been estimated: If the price for biomass increases by approximately 50%, then the heat pump and biomass scenarios will have the same costs. As mentioned previously, the demand for biomass in the biomass boiler scenario already exceeds the sustainable level defined in this study of 14 EJ/year, so the cost of biomass is likely to be much higher than assumed here. Based on this, the authors expect that using biomass in the heating sector is likely to be more expensive than heat pumps, especially in a 100% renewable energy system where even more biomass will be required for the transport sector [87].
- The carbon dioxide emissions for biomass are underestimated since it is assumed to be carbon neutral. Although this is true when residual resources are being utilised for energy purposes, it is unlikely that the demand for biomass will be less than the residual resources available if biomass is required in individual boilers. Hence, in a biomass boiler scenario the carbon dioxide

emissions are likely to be higher for biomass boilers than those presented in Fig. 9.

Considering these qualitative concerns surrounding the biomass boilers scenario, the additional costs and carbon dioxide emissions associated with individual heat pumps are unlikely to be as significant in reality compared with the modelling results suggested here. Furthermore, relying on electricity as the main energy source for heating is less risky than depending on the availability of sustainable biomass resources. Based on these considerations, heat pumps are deemed the most suitable individual heating solution in a 100% renewable energy system for the EU, although they are likely to be supplemented by smaller shares of biomass boilers and individual solar thermal.

### 3.3. Network heating

After concluding that heat pumps are the most suitable individual heating unit, they are then combined with two network heating solutions to see if the combination has a positive impact. The two types of network heating analysed here are gas grids and district heating. These two options are suitable in urban areas where buildings are located close to one another, so in this step the heat pumps installed in the urban areas in the previous step are replaced with heat from each of these network solutions.

Urban areas have a heat density that is high enough to justify a common heating solution. In Heat Roadmap Europe, the proportion of the heat demand in buildings in Europe that can be economically met using a network heating solution was identified as approximately 50% of the heat demand [6–8,73]. Therefore, 50% of the heat demand is converted from heat pumps to one of each of these network solutions by creating two additional scenarios:

- Heat pumps and natural gas grids: individual heat pumps in rural areas where the heat density is low and natural gas grids in the urban areas where the heat density is sufficiently high.
- Heat pumps and district heating grids: individual heat pumps in rural areas where the heat density is low and district heating in urban areas where the heat density is sufficiently high.

The results indicate that district heating is more energy efficient, produces less CO<sub>2</sub>, and costs less than the natural gas alternative based on the assumptions provided in the Appendix A. District heating is more efficient since it utilises surplus heat in the energy system, such as heat from power plants, industry, and waste incineration. This means that there is less additional fuel required for heating buildings when district heating is utilised compared to natural gas.

The carbon dioxide emissions are lower in the district heating scenario due to this lower demand for fuel and also, since the

district heating network enables the utilisation of more renewable energy (see Fig. 9). When a district heating system is in place, it is possible to use more solar thermal and direct geothermal for supplying heat to the buildings. Furthermore, the district heating network enables more wind and solar electricity to be utilised, since large-scale heat pumps can be used to supply heat on the district heating system. These new technologies for converting electricity to heat, combined with relatively cheap thermal storage, mean that the district heating system can be used to accommodate more intermittent renewable energy than the natural gas alternative. This combination of less fuel and more renewable energy mean that the total EU28 CO<sub>2</sub> emissions are reduced by 10% in the district heating scenario (or 85% less carbon dioxide if the heating sector is considered in isolation), along with lower overall costs.

There may be room for minor shares of other technologies where local conditions are suitable, such as biomass boilers, but in general the two primary solutions should be heat pumps and district heating. Finally, individual solar thermal can supplement all individual heating solutions. Here it is assumed that approximately 5% of the total heat demand in rural areas has been met using individual solar thermal panels, but this is not an optimum level. Further research is required to identify this optimum level as well as the scope of smaller shares feasible for other heating technologies.

### 3.4. Renewable electrofuels

At this stage, the two major issues that need to be resolved are the transport fuels for heavy vehicles that require energy dense fuels, and replacing fossil fuel in industry. In step 7, the first issue is resolved by introducing renewable electrofuels. As described in Section 2.2, it is assumed that the fuel produced in these pathways are methanol and DME. In step 7 of this study, half of the fuel for trucks, ships, and aeroplanes is replaced with a bio-electrofuel and half is replaced with a CO<sub>2</sub>-electrofuel.

These pathways are presented in detail in Connolly et al. [76] and in the CEESA report [42], where approximately 15 different pathways were compared with one another.

Once renewable electrofuels are introduced to replace oil in these vehicles, the structure of the energy system changes dramatically. The PES is increased for the first time in the transition proposed here, as displayed in Fig. 11, since more than one unit of bioenergy and/or electricity is required for one unit of electrofuel. For example, when producing methanol using carbon obtained from biomass, as in Fig. 5, 0.83 units of biomass and 0.53 units of electricity is required to produce 1 unit of bio-electrofuel. As a result, the PES increases by 0.33 units for every unit of methanol that is produced to replace a unit of oil.

In all of the electrofuel pathways, the hydrogen is mostly produced using electricity from intermittent resources such as wind and solar power. In other words, the renewable electrofuels move electricity from wind and solar power into the fuel tanks of heavy-duty transport such as trucks and aeroplanes. This offers three really important benefits: a) oil can be replaced in heavy vehicles, which require energy-dense fuel, with electricity from wind turbines (via an electrofuel), b) less biomass is consumed than if conventional biofuels were utilised and 3) the intermittent renewable resources now have access to gas and fuel storage. To put this in context, the EU currently has at least 1600 TWh of oil<sup>1</sup> and gas storage<sup>2</sup> [88], which is more than one-third of the total annual electricity demand in the EU28 Ref2050 scenario.

<sup>1</sup> No data was found for oil storage, so it was estimated based on the EU Directive 68/414/EEC which states that member states must have a storage equivalent to at least 90 days of average daily internal consumption.

<sup>2</sup> Gas storage in Europe equates to approximately 15–20% of the gas demand.

Furthermore, the cost of this energy storage is also relatively cheap due to the scale available. For example, the cost of pumped hydroelectric energy storage is approximately 175 €/kWh [89] whereas the cost of large-scale storage in an oil tank is approximately 0.02 €/kWh [90]. This means that intermittent renewable energy now has access to energy storage that is almost 10,000 times cheaper than electricity storage. As a result, IRES can provide approximately 75% of the electricity in the EU energy system, including the additional electricity that is required to produce the electrofuels. Therefore, even though the PES has increased, the CO<sub>2</sub> emissions are reduced by almost 40% (see Fig. 11).

It is important to emphasise that this transforms the energy system as we know it today. After implementing step 7, the energy system now has an extremely intermittent supply and a very flexible/dispatchable electricity demand (i.e. the opposite of today's energy system). The demand is extremely flexible due to thermal storage in the heat sector, electricity storage in electric vehicles, and fuel storage for the energy-dense fuels in trucks, ships, and aeroplanes.

Replacing oil in the trucks, ships, and aeroplanes increases the costs of the energy system by approximately 3% (see Fig. 12). However, renewable electrofuels also require much more investments than an oil-based energy system. This is evident in Fig. 12, where the costs for fuel have been reduced by over 30% between step 6 and step 7. Since the EU currently imports approximately 85% of its oil [91], by reducing the amount of money spent on fuel and increasing the amount of money spent on the infrastructure for electrofuels, there will be more jobs in the EU with electrofuels in place. As a result, a 3% increase in overall energy system costs may result in an overall economic gain for the EU as there will also be more EU jobs with the production of electrofuels.

After step 7 there is now much less coal, oil, gas, and biomass being utilised in the EU energy system, compared to the original EU28 Ref2050 scenario. There is 140 TWh less coal, 4150 TWh less oil, 1400 TWh less natural gas, and 280 TWh less biomass. In step 8, these fuels are reorganised so that the cleanest fuels are prioritised.

- Firstly, either natural gas or biomass replace coal and oil in industry and in the power plants.
- Secondly, carbon capture and storage (CCS) power plants are removed from the electricity system. CCS is not very suitable for a 100% renewable energy system that is based on intermittent renewable energy since these plants operate as baseload production and they consume additional fuel, which is very expensive in a 100% renewable energy context [92]. Once CCS is removed, then the electricity system becomes more flexible so more wind and solar power can be introduced. However, CCR is still an important part of the energy system for electrofuel production.
- There is still less biomass being consumed than in the EU28 Ref2050 scenario. Therefore, the biomass consumption is increased until it is the same as in the EU28 Ref2050 scenario, by gasifying the biomass and using it to replace natural gas.

After implementing these changes, the results indicate that both the PES and CO<sub>2</sub> emissions are reduced (see Fig. 11), while the overall energy system costs remain the same as in step 7 (see Fig. 12). The EU energy system no longer contains any coal or oil so the only remaining fossil fuel is natural gas. As a result, the CO<sub>2</sub> emissions are now 78% lower than those recorded in 1990, which is only 2% less than the current EU target of an 80% reduction in CO<sub>2</sub> by the year 2050. It is unlikely that all of the biomass produced in this scenario will be carbon neutral, so in reality, the CO<sub>2</sub> emissions could be more than reported here. Therefore, in the final

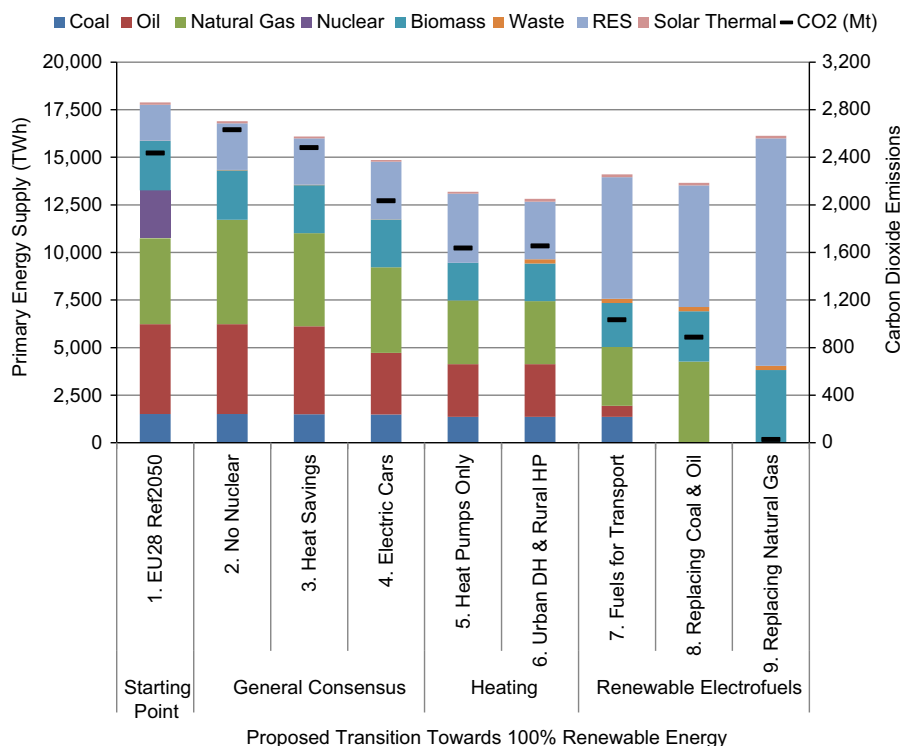


Fig. 11. Primary energy supply by fuel and carbon dioxide emissions for all steps in the transition to a Smart Energy System for Europe.

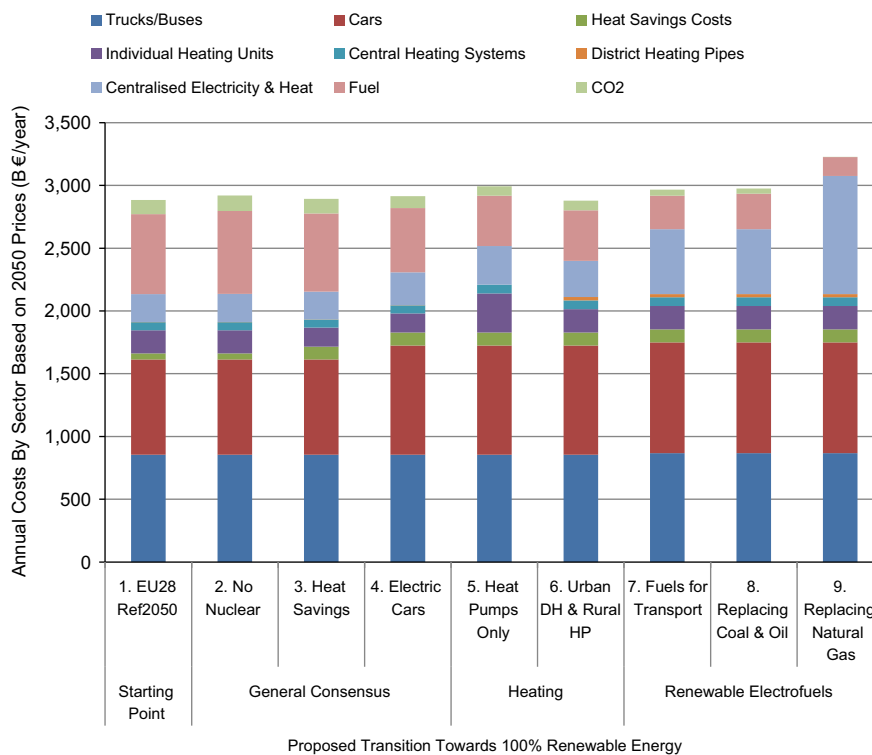


Fig. 12. Annualised costs by sector for all steps in the transition to a Smart Energy System for Europe.

step, to demonstrate the consequences of a zero carbon and 100% renewable EU energy system, natural gas is also replaced.

To replace the remaining natural gas, in step 9, electrofuels are produced once again. However, this time, to replace natural gas, methane is produced instead of methanol/DME. The energy flow diagram for producing methane as a CO<sub>2</sub>-electrofuel is presented in Fig. 6, where the carbon dioxide is captured from the power

plant or industry. It is assumed in this scenario that 50% of the natural gas is replaced with methane as a bio-electrofuel and 50% with methane as a CO<sub>2</sub>-electrofuel.

Once again, these renewable electrofuels connect intermittent renewable energy to large-scale and relatively cheap energy storage, but this time in the form of gas storage. Gas storage costs approximately 0.05 €/kWh [93], which is more expensive than oil/



methanol storage, but it is still much cheaper than electricity storage (€175/kWh). As a result, once the methane is introduced to replace natural gas, it is possible to supply over 80% of the electricity demand with IRES (83%). Following a similar trend as methanol/DME replacing oil, the PES increases when methane replaces natural gas. Once again this is due to the fact that more biomass and/or electricity is required when methane is produced, no matter whether it is as a bio-electrofuel or as a CO<sub>2</sub>-electrofuel. Hence, the PES increases as each unit of natural gas is replaced with methane.

There is a significant cost when replacing natural gas with methane, and the overall energy system costs increase by 8% (see Fig. 12). This is similar to the cost increases reported for high renewable energy scenarios for the EU in other studies [58,74,94]. However, there are additional steps that could be included here to reduce the costs of the final scenario, such as increasing the sustainable bioenergy limit (see Fig. 2), adding biogas plants, optimising the mix of electrofuels, and making modal shift measures in the transport sector. Other studies have concluded that by including these additional measures, the cost of a 100% renewable energy scenario can be the same or less than a business-as-usual scenario, as presented for Denmark in Lund et al. [40]. However, optimising the 100% renewable energy system is beyond the scope of this work and so it could be a focus in future research. Furthermore, as discussed earlier in relation to step 7 (methanol/DME), electrofuels result in more investment-based costs which are likely to create much more local jobs in the EU, thus potentially offsetting the additional energy cost. Similarly, there is also a security of supply aspect to consider, because in the final step 9, all of the energy for the EU will be provided domestically. There is no economic value placed on energy independence in this study so this is an external factor that should also be considered.

### 3.5. Important changes in the final scenario

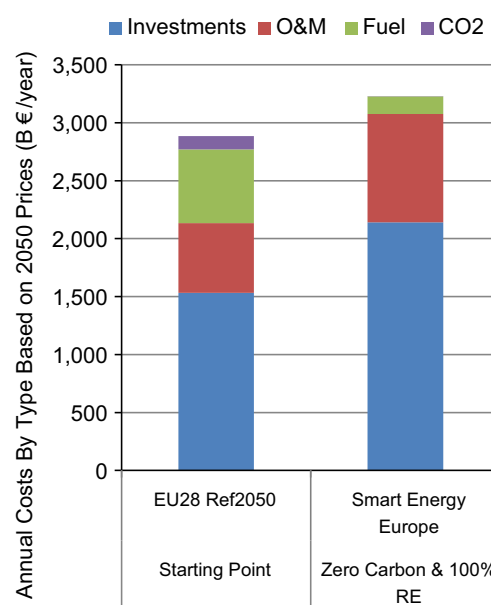
The scenario proposed here outlines the energy, environmental, and economic impacts of one potential transition for the EU energy system to 100% renewable energy. The purpose of this study is not to define the optimum transition, so the solution proposed here should not be viewed as a final plan. Instead, the *Smart Energy Europe* scenario (step 9) provides one comparison between a 100% renewable energy system and a fossil fuel alternative (i.e. the *EU28 Ref2050* scenario).

**Table 4**

Changes that occur for each step in terms of energy, environment, and economy compared to the *EU28 Ref2050* scenario.

Metric (vs. <i>EU28 Ref2050</i> ): Scenario	Energy (PES)	Environment		Economy (Total annual costs)
		(CO <sub>2</sub> Emissions)	(CO <sub>2</sub> vs. 1990 Levels <sup>a</sup> ) (%)	
1. <i>EU28 Ref2050</i>	n/a	n/a	–40	n/a
2. No nuclear	–5%	8%	–35	1%
3. Heat savings	–10%	2%	–38	0%
4. Electric cars	–17%	–16%	–50	1%
5. Heat pumps only	–26%	–33%	–59	4%
6. Urban DH & rural HP	–28%	–32%	–59	0%
7. Fuels for transport	–21%	–58%	–74	3%
8. Replacing coal & oil	–24%	–64%	–78	3%
9. Replacing natural gas	–10%	–99%	–99	12%

<sup>a</sup> Assuming that energy related CO<sub>2</sub> emissions in 1990 were 4030.6 Mt [74]. The EU target is to reduce CO<sub>2</sub> emissions by 80% compared to 1990 levels [95].



**Fig. 13.** Annual energy system costs by type of cost for the *EU28 Ref2050* scenario and the *Smart Energy Europe* scenario.

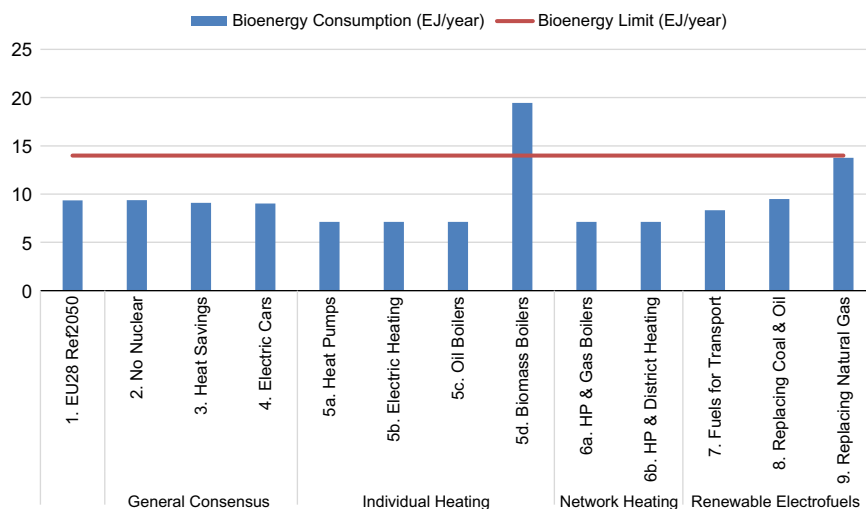
**Table 5**

Import shares assumed for the job creation estimates for the *EU28 Ref2050* scenario and the *Smart Energy Europe* scenario.

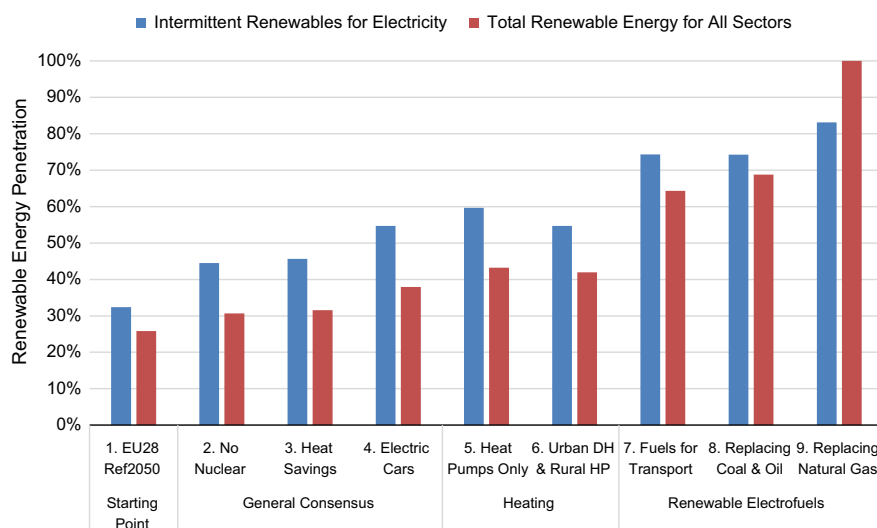
Assumed import factors	Assumed import factors	
	<i>EU28 Ref2050</i> (%)	<i>Smart Energy Europe</i> (%)
Investments	40	30
O&M	20	20
Fossil fuel	75	0
Uranium	100	0
Biomass fuel	10	10
Fuel handling	10	10
CO <sub>2</sub>	0	0

The changes that occurred during each step in the study are summarised in Table 4. During the transition, the PES is lower in every step in comparison to the *EU28 Ref2050* scenario, while the carbon dioxide emissions are reduced to practically zero. There are some emissions remaining from the waste incineration and although it is not evident here in the modelling results, it is likely that there will be some indirect CO<sub>2</sub> emissions from the production of bioenergy. In terms of economy, the overall costs of the energy system do not change by more than  $\pm 5\%$  in all scenarios, except for the final step when natural gas is replaced by methane. This means that an 80% reduction in CO<sub>2</sub> emissions, which is the official target in Europe [95], can be achieved without a significant increase in the overall cost of energy (i.e. 3%). These costs are naturally very dependent on the cost assumptions in the study, which have been reported in the Appendix A to enable the reader to interpret the robustness of this conclusion. It is also important to recognise that even though the total energy costs are the same or slightly higher in all scenarios, the proportion of investment increases with each step (see Fig. 13). Hence, these increases in costs will most likely be counteracted by local job creation in the EU.

For example, the breakdown in costs between the *EU28 Ref2050* and *Smart Energy Europe* scenarios are compared with one another by the type of cost (see Fig. 13). This comparison outlines how the level of investment and O&M costs increase in the *Smart Energy Europe* scenario compared to the *EU28 Ref2050* scenario. These



**Fig. 14.** Bioenergy consumption for each scenario analysed during the transition to a 100% renewable energy system. The limit suggested in this figure is based on the data from Fig. 2.



**Fig. 15.** Penetration of renewable energy for each step in the transition from the EU28 Ref2050 to the Smart Energy Europe scenario.

costs replace fuel costs, and since the EU is an importer of fuel, this will have a very positive effect on the balance of payment for the EU. Less money will leave the EU in the form of importing fuel, while more money will stay within the EU in the form of investments and O&M costs, especially if the EU takes a leading role in developing the Smart Energy System concept. The impact on job creation has been estimated here by assuming the import shares outlined in Table 5. The import share is an estimate of the proportion of each expenditure type that is imported into the EU. Historical data has previously been used to estimate these for the Danish economy [96]. These have been used as a starting point here, but then they are reduced to reflect the larger industrial portfolio of the EU compared to Denmark. Based on these assumptions, the Smart Energy Europe scenario would result in almost 10 million additional jobs compared to the EU28 Ref2050 scenario. These are only direct jobs associated with the EU energy system, so it does not include indirect jobs in the other industries that would service these new jobs, such as shops and restaurants, and it does not include potential jobs from the export of new technologies.

A key consideration defining the design of the scenarios in this study is the amount of bioenergy deemed sustainable. As outlined in the Introduction, it is likely that the bioenergy resource will be very scarce in the future when there is a large demand for energy dense fuel, especially in the transport sector. A limit of approximately 14 EJ/year has been used as a guide during the design of the scenarios here, and Fig. 14 summarises the scale of biomass utilised for each scenario. As already discussed during the results, when biomass boilers are introduced as the sole technology for heating buildings in the EU, the amount of biomass consumed exceeds the bioenergy resource available by over 50%, even before the consumption of bioenergy in the transport sector is considered. This is why the consumption of biomass needs to be minimised where economic alternatives are available, such as in the heat sector. The Smart Energy Europe scenario proposed here is just under (2%) the 14 EJ/year bioenergy limit set at the beginning of the study, which is very likely to be a sustainable consumption based on the literature presented in the Introduction (see Fig. 2). However, if the biomass demand exceeds a sustainable level in the Smart Energy Europe scenario, there are some additional options available to reduce the biomass demand, such as:

- More CO<sub>2</sub>-electrofuel can be produced to replace bio-electrofuel, by using the hydrogenation of carbon dioxide emissions from a power plant/industry (such as in Fig. 6). CO<sub>2</sub>-electrofuel is more expensive than bio-electrofuel, so the overall costs of the energy system will increase. There will be a balance here between extra costs and reducing the biomass demand.
- Methane could be utilised in the transport sector instead of methanol/DME. When methane is produced, it requires less carbon per unit of energy produced than methanol/DME [42,76]. Hence, if methane is used in the transport sector instead of methanol/DME, then less carbon will be required and thus less biomass. However, this is likely to increase the costs of the energy system and reduce the driving range of the vehicles.
- Some fossil fuels can be utilised in the system, preferably natural gas. This however will increase the carbon dioxide emissions.

A balance will need to be established between the additional cost of the electrofuels, the impact of more CO<sub>2</sub> emissions from fossil fuels, and the sustainable level of bioenergy consumption, which is dependent on a number of additional factors such as land use, residual resources, and food production.

It has been possible to minimise the bioenergy consumption due to the amount of intermittent renewable electricity that can be integrated onto the electricity grid. As outlined in Fig. 15, the renewable energy penetration increases in all of the steps proposed here, and it is mirrored by a corresponding increase in renewable electricity in almost all of the steps. Intermittent electricity production in the form of wind and solar power is the main source of energy production in the *Smart Energy System* scenario. The increase in the installed electricity capacity is very large, with the final *Smart Energy Europe* including approximately 2750 GW of offshore wind, 900 GW of onshore wind, and 700 GW of solar PV. This is not an optimal mix, but it represents the scale of the intermittent electricity required for one potential 100% renewable energy system for Europe.

#### 4. Limitations

The future is never certain, especially when considering a timeframe as far away as the year 2050. As a result, there are always significant limitations and uncertainties associated with any study when modelling the future energy system.

In relation to the methodology, the EnergyPLAN tool has been used to model a single EU energy system. Hence, internal bottlenecks in the electricity system are not considered, which is likely to result in an underestimation of the electricity grid costs assumed. On the contrary, there is a lot of uncertainty in relation to the location of the electrolyser plants for electrofuels in the future. For example, these plants could be located close to large wind and solar plants, which means electricity does not need to be transferred over long distances. If this is the case, then the electricity grid costs assumed here may be overestimated.

Also in relation to the methodology, all of the assumed costs are also open to debate and further consideration. These costs have been presented in the Appendix A to enable the reader to judge each cost assumption on an individual basis. Due to the wide variety of opinions about different costs, a very large number of alternatives could be simulated by adjusting any of the costs assumed here. To facilitate this, the EnergyPLAN tool and the models developed in this study are freely available from [www.EnergyPLAN.eu/smartenergyeurope](http://www.EnergyPLAN.eu/smartenergyeurope). The costs, capacities, and demands can be varied in these models to test how sensitive the results are.

All technologies in the scenarios under the General Consensus steps and the Heating Options are currently available today. The only major exception is that the cost of electric cars assumed in the scenario does not reflect the cost of the technology today, but rather in the year 2025. Hence, many of the steps proposed here can be implemented using existing technologies and techniques. However the Renewable Electrofuel steps have some technological barriers that need to be overcome. All of the technologies presented in the energy flow diagrams, which are presented in Figs. 5 and 6, exist and have been demonstrated, but some of them are only at a relatively small-scale. The key technologies which need to be demonstrated on a large scale are biomass gasification, CCR, and electrolyzers. Furthermore, the interactions between these technologies also needs to be developed, since some of them can gain from the bi-products of others. For example, the surplus heat from the chemical synthesis could be used as a heat source for electrolyzers. Due to these uncertainties and the fact that the technologies required for electrofuels are not fully established yet, these steps are unlikely to be developed on a large-scale in the next 10 years.

In the future, there may be a carbon shortage in the energy system if electrofuels are utilised. For example, if bioenergy is limited to a sustainable level, then very little bioenergy will be utilised in centralised plants, such as power plants and CHP plants. Hence, it might not be possible to capture enough carbon from the power plants to create the electrofuels necessary for the transport sector, as presented previously in Wenzel [97]. If there is an extreme shortage of carbon when producing CO<sub>2</sub>-electrofuels, then CO<sub>2</sub> may need to be captured from the air [82], instead of power plants. A carbon balance is not included here, so this is another opportunity for further research.

The impact of energy systems on air pollution is not considered in this study, but previous work has demonstrated that this can be significant in terms of people's well-being and the corresponding health costs [43,98]. It is particularly important to evaluate the impact of bioenergy in relation to air pollution, to ensure that replacing fossil fuels with the sustainable level of bioenergy defined in this study will not result in damaging levels of air pollution.

Also, some key technologies have also not been described in detail during the steps discussed in this paper. These include individual solar thermal panels, large-scale solar thermal, geothermal, large-scale heat pumps, flexible electricity demands, biomass gasification, and biogas. These technologies are very important for the *Smart Energy Europe* scenario, but they are not mentioned here since they are often bi-products within one of the steps proposed. Furthermore, this study has focused on the changes required from a technical perspective, but it does not deal with the implementation challenges that lie ahead [99,100]. This is an area that will require a lot of further research, especially considering the wide variety of policies and traditions across the 28 Member States in Europe.

Even with these limitations, this study is still novel since it quantifies for the first time the impact of a 100% renewable energy system for all of Europe in terms of energy demands, carbon dioxide emissions, and costs. It thus demonstrates the scale and type of technological development that is necessary to create a 100% renewable energy system in Europe.

#### 5. Conclusions

This study has presented one potential pathway to 100% renewable energy for the EU energy system by the year 2050. The transition is presented in a series of 9 steps, where the EU energy system is converted from primarily fossil fuels to 100% renewable

energy. The corresponding impact is quantified for each step in terms of energy (PES), the environment (carbon emissions), and economy (total annual socio-economic cost). It should not be viewed as a final solution, but instead as an option for debate on the impact of various technologies and their impact on reaching a 100% renewable energy system in Europe. These steps are based on hourly modelling of the complete energy system (i.e. electricity, heating, cooling, industry, and transport) and they are designed to enable the EU to reach its final goal of a decarbonised energy system.

The results in this study indicate that to reach the EU targets of 80% less CO<sub>2</sub> in 2050 compared to 1990 levels, the total annual cost of the EU energy system will be approximately 3% higher than the fossil fuel alternative, and 12% higher to reach a 100% renewable energy system. However, considering the uncertainties in relation to many of the cost assumptions for the year 2050, these differences could be considered negligible. Also, there are additional steps which could be implemented to reduce the cost of the 100% renewable energy system, such as increasing the sustainable biomass limit. But these were beyond the scope of this study [40]. Furthermore, the change in the type of system costs is much more significant than the total energy system costs reported. Due to a radical change in the technologies on the energy system, the major cost will be converted from imported fuel to local investments, which results in a major increase in jobs created in the EU in a low carbon energy system. The total number of additional direct jobs from this transition is estimated here as approximately 10 million, which could result in an overall gain for the EU economy in the *Smart Energy Europe* scenario, even though it is more costly.

Furthermore, in the final *Smart Energy Europe* scenario, there are no fossil fuels, no energy imports, and no carbon dioxide emissions (< 1%). The key technological changes required to implement the *Smart Energy Europe* scenario are: wind power, solar power, electric vehicles, heat savings, individual heat pumps, district heating, large-scale thermal storage, biomass gasification, CCR, electrolyzers, chemical synthesis, and fuel storage (i.e. for electrofuels). Many of these technologies are already at a mature enough development to be implemented today, especially those in the electricity and heat sectors.

Based on existing policies, the EU energy system is likely to be somewhere between the *Smart Energy Europe* scenario proposed here and where it is today. The results in this study suggest that the progress towards a 100% renewable energy system will most likely be defined by political desire and society's ability to implement suitable technologies, rather than the availability of cost-effective solutions.

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## Appendix A. Cost assumptions

The costs assumed for the year 2050 in the analysis here are outlined in the tables below. This includes the costs assumed for

**Table 6**

Fuel costs and fuel handling costs assumed for 2050 [101].

Fuel	Fuel costs <sup>a</sup> (€/GJ)	Fuel handling costs (€/GJ)		
		Centralised power plants	Decentralised power plants & industry	Consumer
Natural gas	10.9	0.4	2.0	3.1
Coal	3.2	–	–	–
Fuel Oil	14.3	0.3	–	–
Diesel/ petrol	17.6	0.3	1.9	2.1
Jet fuel	17.6	–	–	0.5
Straw	7.2	1.8	1.2	2.7
Wood chips	7.2	1.5	1.5	0.0
Wood pellets	7.2	–	0.5	3.3
Energy crops	5.6	1.5	1.5	0.0
Nuclear	1.8	–	–	–

<sup>a</sup> Based on a forecasted oil price of \$127/bbl [74,95].

**Table 7**

Investment, lifetime, and operation & maintenance (O&M) costs assumed for the centralised electricity and heating plants [6, 8, 90, 93,102–107].

Production type	Unit	Investment (M €/unit)	Lifetime (Years)	Fixed O&M (% of investment)
Heat plants				
Combined heat & power (CHP) plants	MWe	0.8	25	3.8%
Decentral CHP plants	MWe	1.2	25	3.8%
Waste CHP plants	TW h/year	216	20	7.4%
Electric heat pump	MWe	2.9	25	2.0%
Absorption heat pump	MWth	0.4	20	4.7%
Industry surplus heat	TW h	40	30	1.0%
Solar thermal	TW h/year	307	30	0.2%
Wood chip boiler	MWth	0.8	20	1.4%
Gas boiler	MWth	0.1	35	3.7%
Electricity plants				
Coal steam plant	MWe	1.9	40	3.3%
Additional cost of CCS for a coal plant	MWe	0.8	40	2.2%
Biomass steam plant	MWe	1.9	40	3.3%
Combined cycle gas turbine	MWe	0.8	25	3.8%
Open cycle gas turbine	MWe	0.6	25	0.0%
Gas engine	MWe	1.3	22.5	0.0%
Nuclear	MWe	3.0	30	2.0%
Renewable electricity				
Onshore wind	MWe	1.2	30	3.2%
Offshore wind	MWe	2.1	30	3.2%
Photovoltaic	MWe	0.9	40	1.2%
Wave power	MWe	1.6	30	2.0%
Tidal	MWe	3.2	20	3.7%
CSP solar power	MWe	3.5	25	8.2%
River hydro	MWe	3.3	50	2.0%
Hydro power	MWe	3.3	50	2.0%
Hydro storage	GW h	7.5	50	1.5%
Geothermal PP	MWe	2.4	20	3.5%

**Table 7** (continued)

Production type	Unit	Investment (M €/unit)	Lifetime (Years)	Fixed O&M (% of investment)
<b>Electrofuels</b>				
SOEC electrolyser	MWe	0.3	15	3.0%
Hydrogen storage	GW h	20	30	0.5%
Chemical synthesis MeOH	MW-Fuel	0.6	20	3.5%
Carbon capture costs for CO <sub>2</sub> -electroFuel	Mt	30	25	0.0%
<b>Energy storage</b>				
Thermal storage	GW h	3.0	20	0.7%
Pumped hydro-electric energy storage	MWe	1.2	50	1.5%
Pumped hydro-electric energy storage	GW h	7.5	50	1.5%
Oil storage	TW h	23	50	0.6%
Methanol storage	TW h	52	50	0.6%
Gas storage	TW h	48	50	1.0%
<b>Bioenergy conversion</b>				
Gasification plant	MW Syngas	0.3	25	7.0%
Gasification gas upgrade	MW Gas Out	0.3	15	18.8%
Biodiesel plant	MW-Bio	1.9	20	3.0%
Bioethanol plant	MW-Bio	0.4	20	7.7%
Biojetfuel plant	MW-Bio	0.4	20	7.7%

**Table 9**

District heating pipeline costs [102].

District heating pipes	Conventional DH network	Low-temperature DH network
Specific investment costs (1000 €/TW h)	72,000	522,000
Technical lifetime (years)	40	40
Average fixed O&M (€/TW h/year)	900,000	3,960,000
Variable O&M (€/MW h)	0	0

**Table 10**

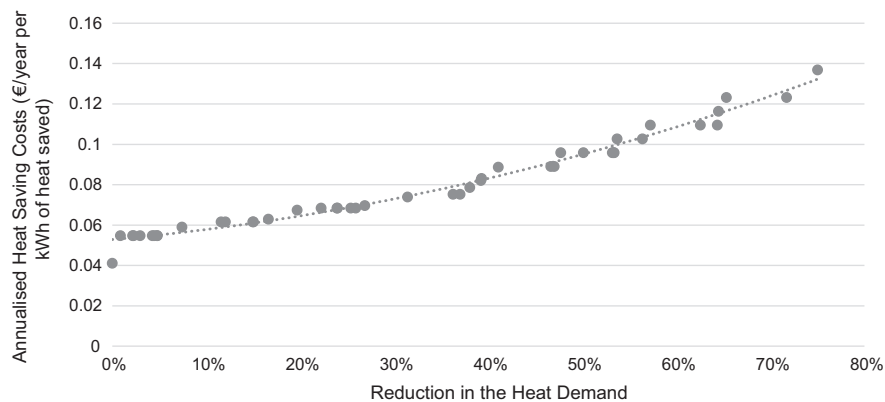
Vehicle costs assumed for 2050 [106].

Vehicle	Fuel	Investment (€/vehicle)	Annual operation & maintenance (% of Invest)
Cars	Diesel	12,822	7.2%
	Petrol	11,480	8.2%
	Battery electric vehicles <sup>a</sup>	12,971	11.2%
	Bio-methanol	14,104	6.6%
Busses & trucks	Diesel	161,074	1.2%
	Petrol	163,960	1.2%

<sup>a</sup> The battery costs are included in the annual O&M costs.**Table 11**

Other key economic assumptions in this study.

Interest rate for annualising investments	3.0%
CO <sub>2</sub> price (€/t)	46.6
Assumed lifetime of heat savings (years)	30

**Fig. 16.** Unit costs assumed for reducing the heat demand in buildings. These costs are based on the Danish building stock and extrapolated to the EU energy system in Heat Roadmap Europe [6,8].**Table 8**

Individual heating unit costs and central heating system costs for the individual buildings [102].

Cost	Oil boiler	Natural gas boiler	Biomass boiler	Heat pump (air-to-water)	Heat pump (brine-to-water)	Electric heating	District heating substation	Central heating system
<b>Residential buildings</b>								
Specific investment (1000 €/unit)	6.6	5	6.75	12	16	8	5.5	5.4
Technical lifetime (years)	20	22	20	20	20	30	20	40
Fixed O&M (€/unit/year)	270	46	25	135	135	50	150	70
Variable O&M (€/MW h)	0	7.2	0	0	0	0	0	0
<b>Services buildings</b>								
Specific investment (1000 €/unit)	40	20	108.5	160	176	266	21.5	15
Technical lifetime (years)	20	25	20	20	20	30	20	40
Fixed O&M (€/unit/year)	1000	1540	3465	400	400	4000	150	70
Variable O&M (€/MW h)	0	7.2	0	0	0	0	0	0



fuel (Table 6), centralised electricity and heating plants (Table 7), costs of implementing heat savings in the buildings (Fig. 16), individual heating unit costs (Tables 8 and 9), vehicle costs (Table 10), and some key economic assumptions (Table 11).

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