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Smart Energy Europe: A 100% renewable energy scenario for the European Union

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ABSTRACT

The European Union has some of the most ambitious targets to decarbonise its energy system in the coming decades. To do so, it is likely that many countries will depend on intermittent renewable energy sources such as wind and solar power. There is still a lot of uncertainty in relation to the integration of these resources, since the current energy system is not designed to handle intermittency on the supply side. The Smart Energy System concept is one approach which can accommodate very large penetrations of these intermittent resources, with some analysis demonstrating how penetration levels in excess of 80% are possible in the electricity sector. Hence, this approach is one potential solution that will enable the European energy system to significantly reduce its carbon emissions. In this study, the Smart Energy System approach is applied to Europe, which achieves two key objectives: firstly, it demonstrates the type of technical changes required in the EU energy system by presenting the technologies and their synergies in the Smart Energy System approach and secondly, this study quantifies the scale of each technology required to achieve a 100% renewable energy system in Europe. The results indicate that a 100% renewable energy system is technically feasible in Europe using the Smart Energy System approach, assuming technologies develop according to industry's current expectations. Furthermore, the results show that the 100% renewable Smart Energy System will have similar costs as a fossil fuel alternative in Europe, but even more significant, the 100% renewable energy system will consist of much more investments instead of fuel imports. A conservative estimate suggests that this will result in the creation of approximately 10 million additional jobs in the EU. These results important in the context of decarbonising energy systems, since they indicate that 100% renewable energy can be technically achieved at an economic gain.

KEYWORDS

Smart Energy System, EnergyPLAN, Europe, 100% Renewable Energy, Heat Pumps, District Heating, Electrofuel.

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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 potentially evolve is presented, with a key focus on reducing carbon dioxide emissions.

It is important to consider the characteristics and limitations of the existing energy system before discussing how the energy system should change. The existing energy system in most developed countries consists of very simple conversion processes. These are presented in Figure 1, where the structure of today's energy system is divided by:

- Resources
- Conversion processes
- Exchange & storage
- Demands

There are a number of key characteristics that define how the energy system has evolved to this stage. 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 form 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. This is evident in Figure 1 when you compare the different supply-demand chains. The supply chains for mobility, electricity, and cooling/heating have very little interaction with one another. For example, when electricity is required it is obtained from a power plant and when heat is required it is obtained from a boiler. The only significant link to all of the sectors are the fossil fuels that supply them. Currently, 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 world, a large proportion of the existing energy infrastructure and institutions can 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, since bioenergy is often a very limited resource that competes with other sectors such as food [5]. Future alternatives for the energy system should consider these three key characteristics and limitations in the existing energy system:

- Fossil fuels have provided very large and cheap energy storage over the past 150 years
- The energy system consists of very segregated energy branches
- There is currently no direct replacement for the fossil fuels in today's energy system

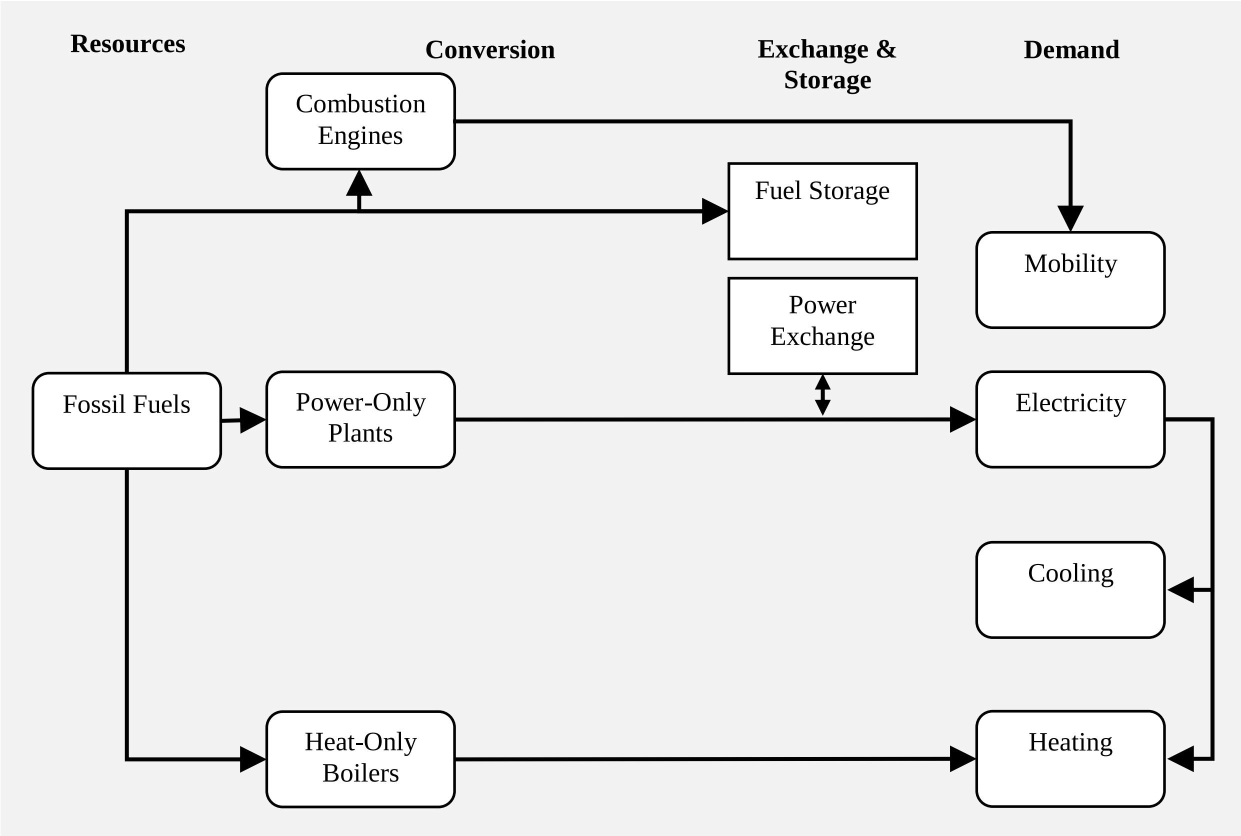

Figure 1. Interaction between sectors and technologies in today's typical energy system

In this paper, a scenario is presented for the EU energy system that outlines how to transform from today's segregated energy system to a **Smart Energy System** (www.SmartEnergySystem.eu), while accounting for these issues. 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 transition to 100% renewable energy while consuming a sustainable level of bioenergy. There are already numerous books [6, 7], journal papers [5, 8-12], conference proceedings [13, 14], reports [15-17], and a video (www.SmartEnergySystem.eu) about the concept published by members of the group. The scenario proposed here for the EU is not a final solution, but instead it is a snapshot of the current status and key steps required in the design of the Smart Energy System. Future work could focus on optimising and improving the scenario proposed here.

The Smart Energy System concept is similar to the Smart Grid concept, but where the Smart Grid focuses on the electricity sector only [18, 19], the benefits of the Smart Energy System are only realised with all major sectors of the energy system are connected with one another [8, 20]. Quantifying these benefits has only become possible in recent years as adequate energy tools have been developed [21].

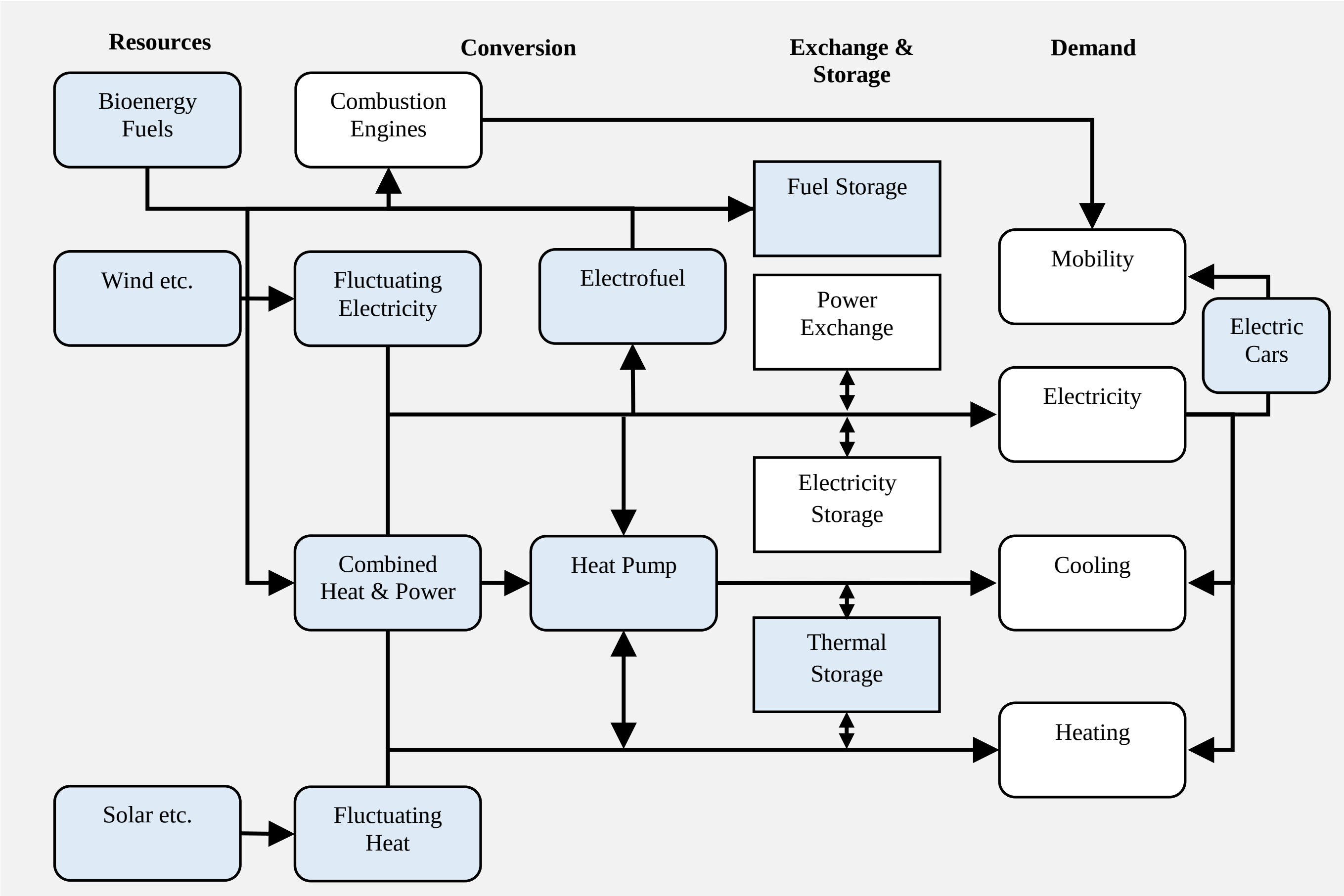

Figure 2. Interaction between sectors and technologies in a future Smart Energy System. The flow diagram is incomplete since it does not represent all of components in the energy system, but the blue boxes demonstrate the key technological changes required

METHODOLOGY

Any methodology used to develop future energy scenarios is open to deliberation, since the future is always uncertain. This section presents the key principles used to define the methodology in this study and afterwards, the transition simulated in this study is described.

Key principles

The key principles that define how the analysis is completed are presented in detail in [5-7]. In brief, they are:

1. The analysis **considers all sectors of the energy system**, which are electricity, heat, 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 today. 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 their intermittency will be essential for the reliable operation of the future Smart Energy System.

4. The analysis is completed over **a long-term time horizon**. Energy technologies often have lifetimes in the region of 25-40 years, so decisions 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 one 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 has determined how the analysis here is carried out. The first three principals are incumbent in the energy modelling tool that is used. EnergyPLAN is an hour-by-hour energy system analysis tool specifically designed to assist the design of national or regional energy planning strategies under the "Choice Awareness" theory [6]. It simulates the complete energy system including electricity, heating, cooling, and transport on an hourly time resolution, which enables the short-term variations in renewable energy to be considered. 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 investments within a specified market framework or from one specific technology viewpoint. The results quantify the primary energy supply (PES), renewable energy penetration, GHG emissions, and energy system costs. In this way, various scenarios consisting of different technology mixes can be compared with one another. The fuel costs, investment costs, and operation and maintenance (O&M) costs used in this study are from the EnergyPLAN Cost Database [22]. EnergyPLAN does not calculate the job creation and balance of payment for the region, so this was completed outside the tool: the methodology used is described in detail in Lund and Hvelplund [23].

The transition to a Smart Energy System

Using the EnergyPLAN model, a Smart Energy System, like the one displayed in Figure 2, has been designed and analysed for the EU energy system. The design process in EnergyPLAN is typically as follows:

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 acts as a benchmark for comparing other scenarios, so it is usually based on a business-as-usual scenario for a forecasted 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 can be lost when it is defined based on its economic performance only. Furthermore, the philosophy behind the EnergyPLAN tool is 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 [6, 7].

3. **Comparison of Results:** Once the user has created an alternative, 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 the next section, 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 projections by the European Commission [24]. Approximately 500 inputs and 30 hourly distributions are required to make a complete model in EnergyPLAN so the EU has been modelled as one energy system in this study. This means that there is one model for the EU 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 is used so instead a summary of the key demand and supplies are presented in Table 1.

The transition towards a Smart Energy System has been created in this study using this EU28 reference scenario in Table 1 as a starting point, so it is referred to here as the *EU28 Ref2050* scenario. 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 a low-carbon energy system, both politically [25] and scientifically [26-29], 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 (i.e. wind and solar power) is varied from 0-100% of the electricity demand 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).

Table 1. Breakdown of the demand and supply in the EU28 Reference Scenario for the year 2050 (*EU28 Ref2050*). It is assumed that intermittent renewable energy sources have a conversion efficiency of 100% and nuclear power 33%.

Demand (TWh)		**Supply (TWh)**	
Electricity	4439	Electricity	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
Heat	3308	Heat	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
		Industry	3062
		Coal	569
		Oil	434
		Gas	1400
		Biomass	658
		Transport	4321
		Jet Fuel	776
		Diesel	1872
		Petrol	935
		Natural Gas	3
		LPG	28
		Biodiesel	275
		Bioethanol	143
		Biojetfuel	34
		Electricity	255

To begin, the first 3 steps in the transition are chosen 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[1]:

2. *No Nuclear*: Removing nuclear power 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 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 heat savings become more expensive than a sustainable heat supply [30]. In Heat Roadmap Europe [31-33], 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 50% compared to 2010 levels and 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 for private cars can be converted to electric cars [15]. A similar level has been proposed in the EU 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" [34]. Hence, in this step, 80% of the private cars and their corresponding 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 are in relation to the heating sector. Currently, one of the most common solutions proposed for the future heating sector in Europe are individual heat pumps [35, 36]. 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 [31-33]. Therefore, in this study these two technologies are added to the 'General Consensus' steps. Firstly, all of the heating in Europe, both urban and rural is provided by heat pumps only (i.e. step number 5 called 'Heat Pumps Only). This is based on the idea that heat pumps in theory can be installed in every building. Afterwards, in step 6, the urban heat pumps are replaced with district heating, since district heating is only viable in the urban areas where the pipes are economically viable. Therefore, the heating sector is now a mix of district heating in the urban areas and individual electric heat pumps in the rural areas. A detailed methodology about these two steps is available in the Heat Roadmap Europe reports [31-33, 37].

Once the heat supply has been defined, the next big issue is the fuel for vehicles other than cars. These vehicles include trucks, ships, and aeroplanes. The fuel for these vehicles must have a high energy density, which means that batteries are unlikely to be sufficient [38]. Hydrogen is excluded due the losses that occur during its production and due to the cost of changing the existing infrastructure [39] and vehicles [40]. Traditional biofuels are excluded since the demand for bioenergy would be unsustainable if all of the oil for trucks, ships, and aeroplanes is directly replaced with biofuels [38]. However, one of the key benefits associated with biofuels is that they can utilise existing infrastructure. For example, biofuels can be

[1] The reference is defined as 'Step 1' and hence the alternatives start at number 2.

burned in existing combustion engines with very few modifications. Renewable electrofuels are proposed here since they also have this key benefit, but they consume much less bioenergy thus maintaining a sustainable bioenergy consumption demand even in a 100% renewable energy context [5, 15].

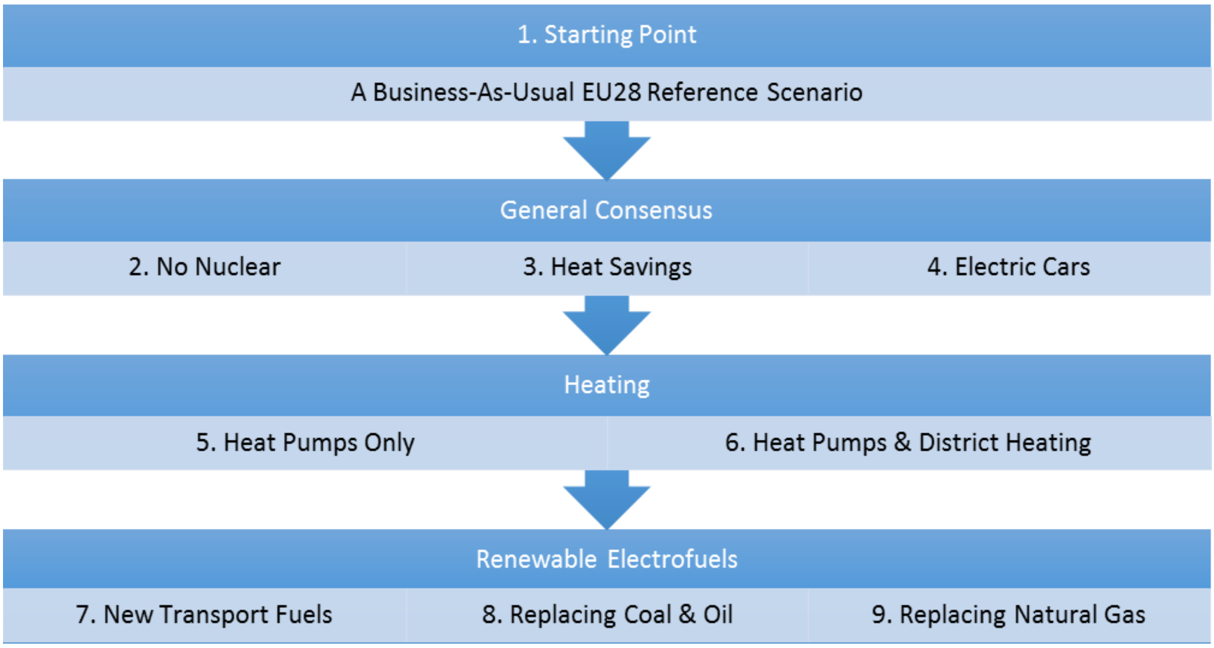

Figure 3. Transition steps in this study from a 2050 reference energy system to a Smart Energy System for the EU

Electrofuels are created by combining hydrogen and carbon with one another. 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 simplest alcohol [41] and ether [42] 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 process for renewable electrofuels are presented in Connolly *et al.* [38], four of which have been used in this study including the example displayed in Figure 4.

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 large vehicles which require energy-dense fuel with electricity from wind turbines (via an electrofuel), b) less bioenergy is consumed than if conventional biofuels were utilised and 3) the intermittent renewable resources now has access to gas and fuel storage. To put this in context, the EU currently has at least 1600 TWh of oil[2] and gas storage[3] [43], which is more than one-third of the total

[2] 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.
[3] Gas storage in Europe equates to approximately 15-20% of the gas demand.

annual electricity demand in the *EU28 Ref2050* scenario. 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, planes, and ships.

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 fossil fuel and biomass in the energy system than in the *EU28 Ref2050* scenario. To reduce the carbon dioxide emissions further, coal and oil in the thermal plants and industry are replaced by natural gas and biomass. In step 8, the biomass consumption is increased 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 in 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 and half is produced using a CO_2-electrofuel. 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.

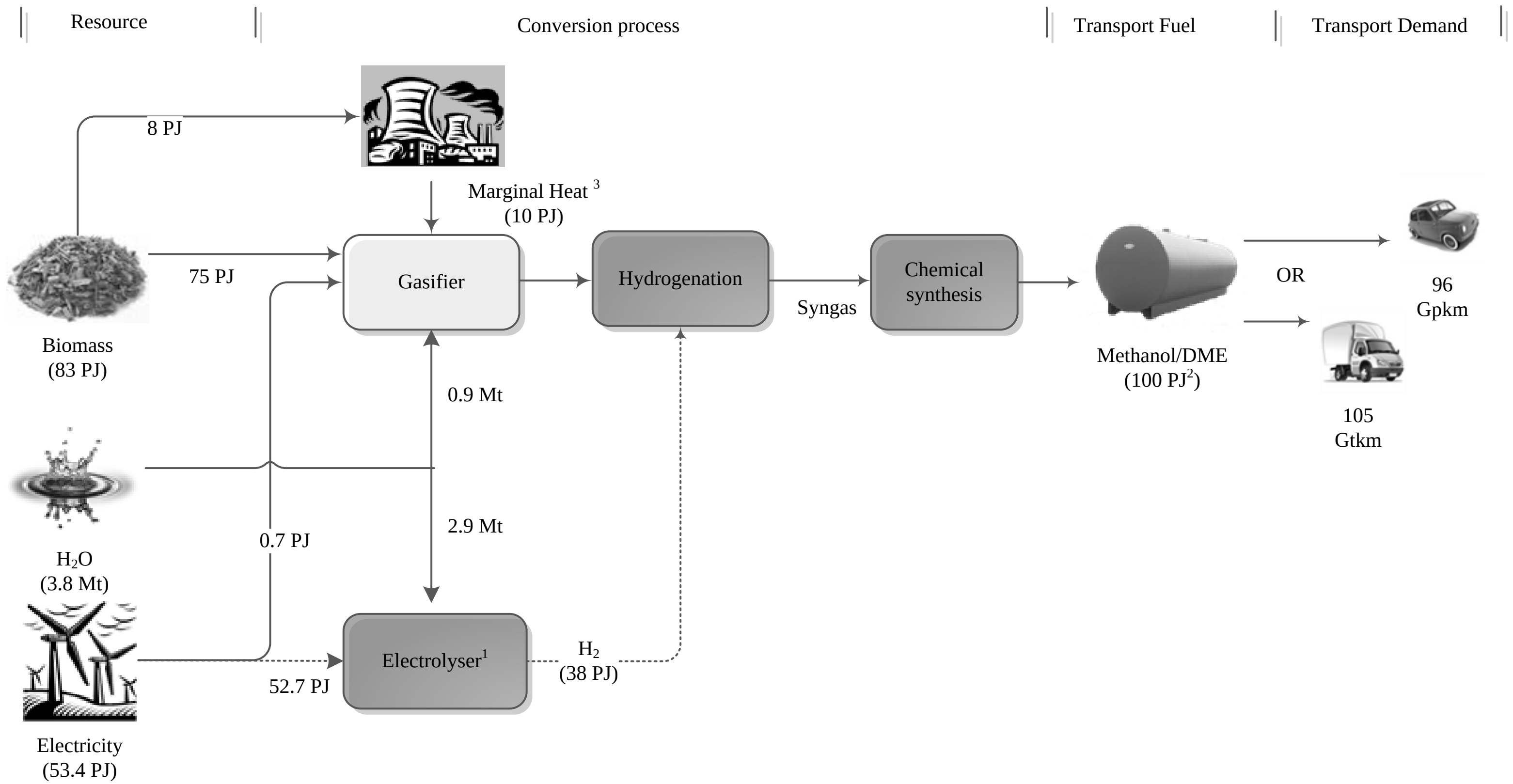

Figure 4. An example of a bio-electrofuel production process: biomass is gasified and the resulting gas is hydrogenated to produce methanol or dimethyl ether (DME) [38, 44]

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, environment, and economy (Figure 5 and Figure 6). 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 socio-economic costs of the energy system have been calculated by sector to analyse the impact on the economy.

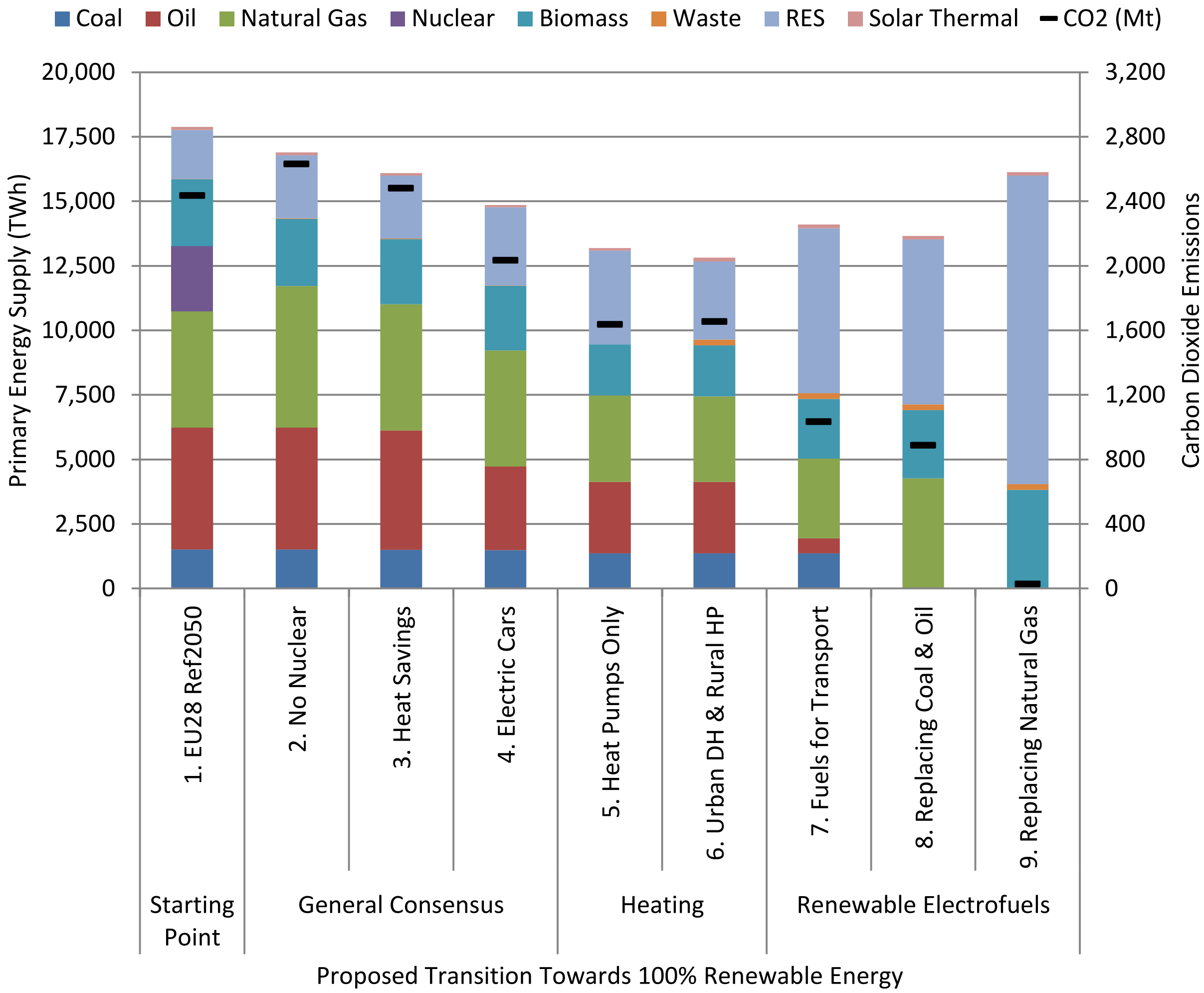

Figure 5. Primary energy supply by fuel and carbon dioxide emissions for all steps in the transition to a Smart Energy System for Europe

General consensus

To begin, Figure 5 displays the PES and carbon dioxide (CO_2) emissions for the steps. In step 2, nuclear power is removed which reduces the PES, but it increases the CO_2 emissions. Furthermore, nuclear power is not a very flexible technology so 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. There is also a cost increase of approximately 1% when nuclear power is removed from the energy system, based on the 2050 costs from the EnergyPLAN Cost Database [22]. However, this should be viewed with caution since the costs reported for nuclear power can often exceed those assumed here, particularly when delays, waste disposal, decommissioning, risk, and pollution costs are accounted for [45, 46].

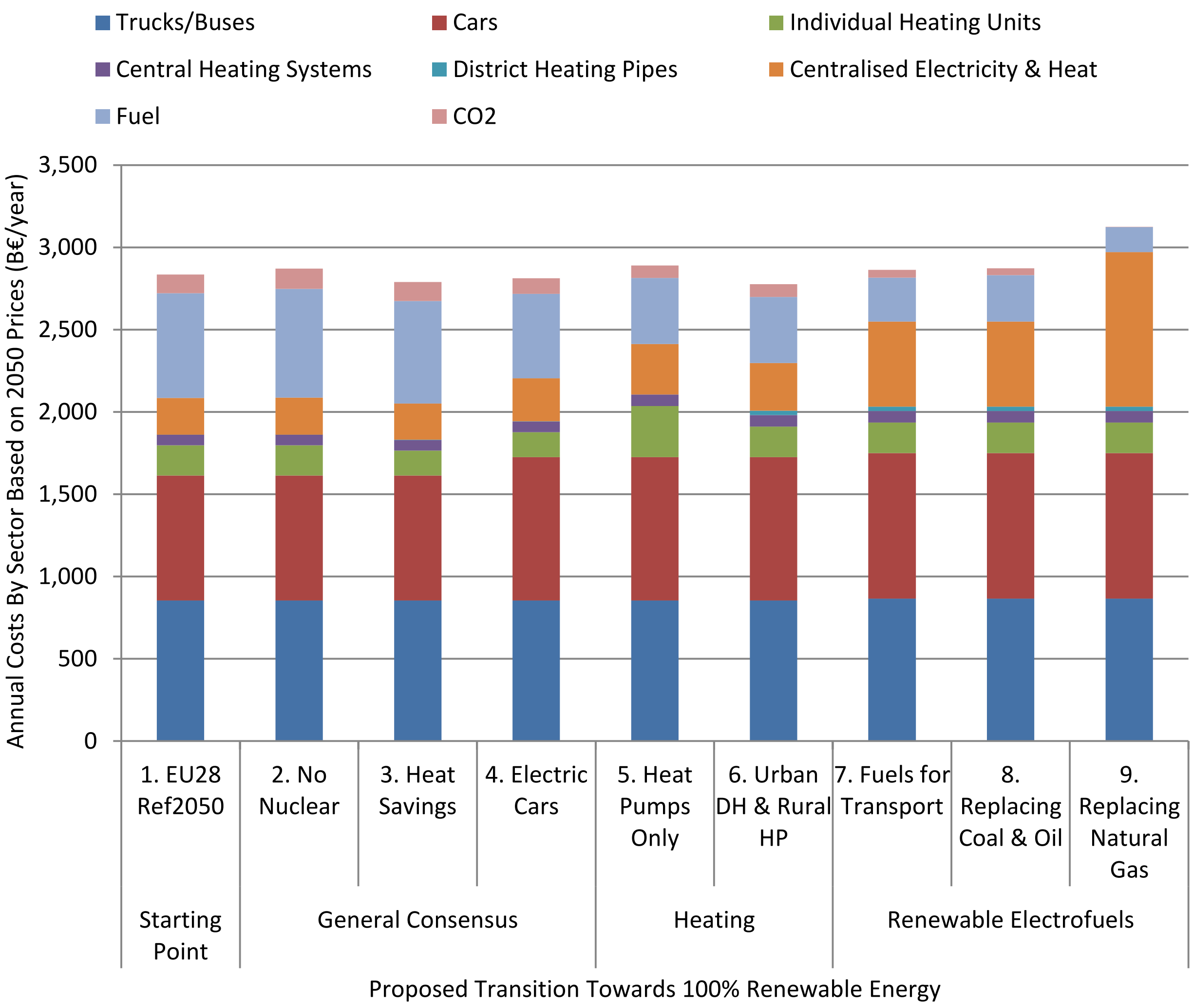

Figure 6. Annualised costs by sector for all steps in the transition to a Smart Energy System for Europe

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 Heat Roadmap Europe [31-33], 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. Therefore, here the heat demand is reduced by 35% compared to the year 2010[4], which is almost twice as much as the 18% reduction in the *EU28 Ref2050* scenario. As expected, these additional heat savings reduce the demand for energy, the carbon dioxide emissions (Figure 5) and the costs of the energy system (Figure 6).

[4] Compared to the 2010 reference scenario in the EU Energy Roadmap 2050 report.

The final 'General Consensus' step is the implementation of electric vehicles. In this scenario 80% of the oil in private cars is replaced with electricity, which is the penetration level forecasted for the EU energy system [34]. When the electric vehicles are introduced, there is almost a 10% drop in the PES for two key reasons:

- The electric vehicles are more efficient that 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 replacing 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.

As presented in Figure 6, the overall costs of energy 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. These two factors combined mean that the additional cost in the electric vehicles is eliminated by a reduction in the cost of powering the cars, so overall there is a minor increase of 1% in the overall energy system costs.

There have been some minor fluctuations along the way, but overall the total costs of the energy system after the General Consensus steps have been implemented 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_2 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 a combination of district heating in the urban areas and individual heat pumps in the rural areas are the most sustainable alternatives when reducing the CO_2 emissions in the EU energy system [31, 32, 37]. Based on these results, these heating solutions have been analysed here in the EU energy system.

Heating

In Heat Roadmap Europe [31, 32] and STRATEGO [47], it was concluded that a combination of heat pumps and district heating are the most economically viable way to decarbonise the energy system. To begin, heat pumps are used here to supply all of the heating in Europe, both in the rural and urban areas. By doing so the PES is reduced significantly due to their high efficiency, but the costs of the energy system are increased since the heat pumps have a relatively high upfront cost. Therefore, in step 6, the urban heat pumps which are the most expensive, are replaced by district heating.

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% using detailed mapping in Heat Roadmap Europe [31-33, 37]. This means that the heat density is high enough in urban areas in Europe, so that approximately 50% of the heat demand in buildings can be met using a water grid (i.e. district heating). Once district heating is used in the urban areas, the energy system becomes more efficient, produces less CO_2, and has lower costs. District heating is more efficient since it utilises surplus heat in the energy system, such as heat from power plants, industry, and waste incineration. These means that there is less additional fuel required for heating buildings when district heating is utilised compared to natural gas. The results demonstrate two key findings: firstly that district heating in the urban areas is more suitable than individual heat pumps, but secondly, that a combination of district heating and individual heat pumps improves the efficiency and cost of the energy system compared to step 4, which had the business-as-usual heating sector. This is in line with the more thorough analysis carried out in the Heat Roadmap Europe studies, which can be found in the existing reports [31, 32].

Renewable electrofuels

At this point, the two major issues that need to be resolved are the transport fuels for vehicles that require energy dense fuels, and replacing fuel in industry. In step 7, the first issue is resolved by introducing renewable electrofuels. In this paper, electrofuels are defined as those that are created from the combination of carbon and hydrogen. The hydrogen is produced using electrolysers, which convert water into hydrogen and oxygen using electricity. The carbon can be obtained from a variety of sources including bioenergy, industrial process, power plants, and the air via carbon trees [48, 49]. In this study, two different carbon sources are considered: carbon from biomass and carbon captured from the exhaust of the power plants. It is assumed that the fuel produced in these pathways are methanol and dimethyl ether (DME). Methanol is very suitable as a replacement for petrol while DME is very suitable as a replacement for diesel. These pathways are presented in detail in the CEESA report, where approximately 15 different pathways were compared with one another [38, 44].

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_2-electrofuel. 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 planes. This 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 [50, 51].

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 Figure 5. Also, by connecting wind and solar to fuel storage, 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_2 emissions are reduced by almost 40% (see Figure 5). Replacing oil in the trucks, ships, and aeroplanes increases the costs of the energy system by approximately 3% (see Figure 6).

There is now much less coal, oil, gas, and biomass being utilised in the EU energy system after step 7, 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 as follows:

- 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 [52]. Once CCS is removed, then the electricity system becomes more flexible so more wind and solar power can be introduced. However, carbon capture and recycling (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_2 emissions are reduced (see Figure 5), while the overall energy system costs remain the same as in step 7 (see Figure 6). 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_2 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_2 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_2 emissions could be more than report here. Therefore, in the final step, natural gas is also replaced to demonstrate the consequences of a zero carbon and 100% renewable EU energy system.

To replace the remaining natural gas, in step 9 electrofuel is produced once again. However, this time methane is produced to replace natural gas, instead of methanol/DME. There is a significant cost when replacing natural gas with methane, since the overall energy system costs increase by 8% (see Figure 6), which is similar to the cost increases reported for high renewable energy scenarios for the EU in other studies [34, 35, 53]. 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, adding biogas plants, optimising the mix of electrofuels, and 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 is the same or less than the business-as-usual scenario [15]. However, optimising the 100% renewable energy system is beyond the scope of this work and so it could be a focus in future research.

Important changes during the transition

The PES is lower in every step during the transition 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_2 emissions from the production of bioenergy.

The renewable energy penetration increases in all of the steps proposed here, and it is mirrored by a corresponding increasing 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 and it is displayed in Figure 7. The Smart Energy Europe scenario indicates that to reach a 100% renewable energy Europe, we will need approximately:

- 2750 GW of offshore wind
- 900 GW of onshore wind
- 700 GW of solar PV
- 3800 TWh of bioenergy

This is not an optimal mix. It simply represents the scale of the development required for this one potential scenario of how Europe can develop a 100% renewable and carbon free energy system.

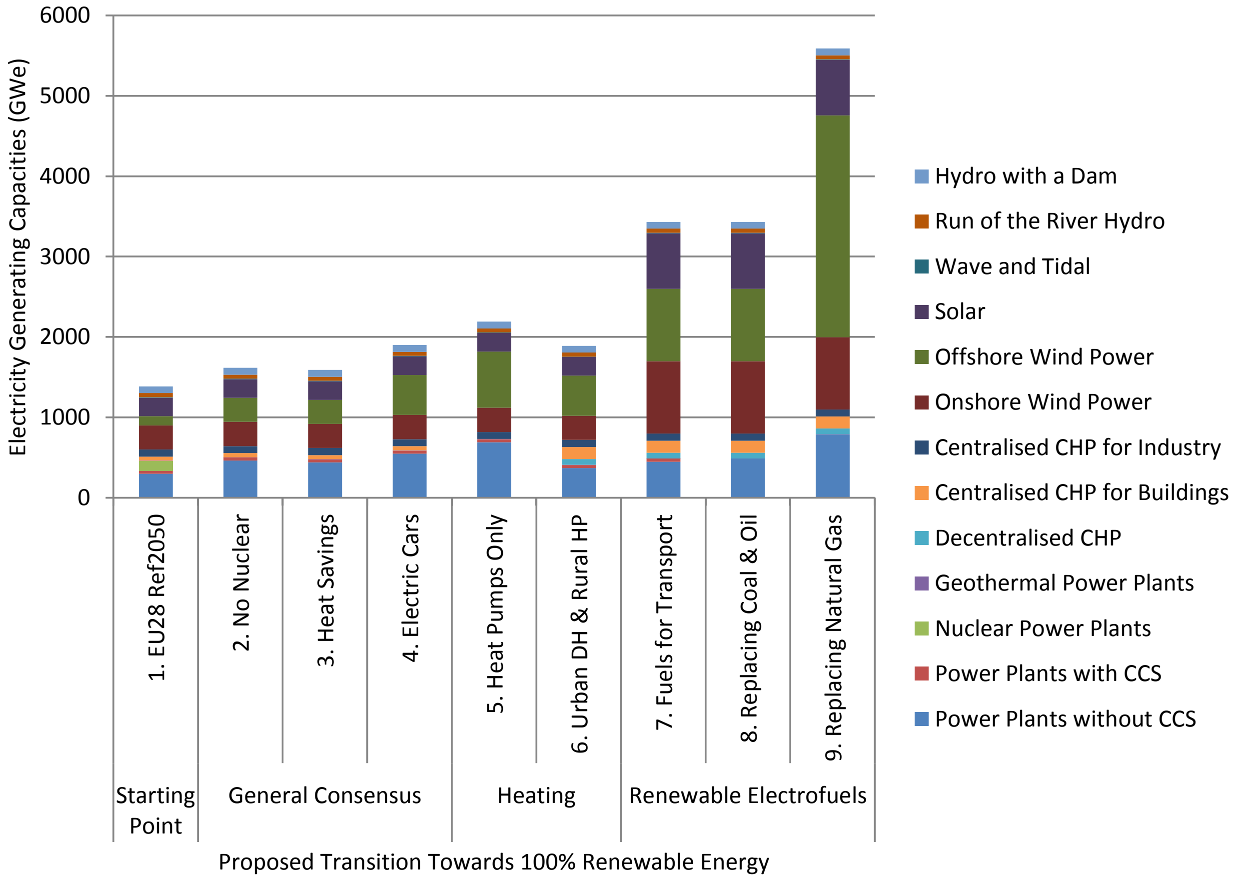

Figure 7. Installed electricity capacities for each step in the transition from the *EU28 Ref2050* to the Smart Energy Europe scenario

In terms of economy, the overall costs of the energy system do not change by more than +/-5% in all scenarios, except for the final step when natural gas is replaced by methane. This means that an 80% reduction in CO_2 emissions, which is the official target in Europe [54], can be achieved without a significant increase in the overall cost of energy (i.e. 3%). 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 is increasing with each step. Hence, these increases in costs will most likely be counteracted by local job creation in the EU.

For example, here the breakdown in costs between the *EU28 Ref2050* and *Smart Energy Europe* scenarios are compared with one another by the type of cost (see Figure 8). This comparison outlines how the level of investment and O&M costs increases in the *Smart Energy Europe* scenario compared to the *EU28 Ref2050* scenario. These 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 2. The import share is an estimate for 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 [55]. These have been used as a starting point here, but then 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.

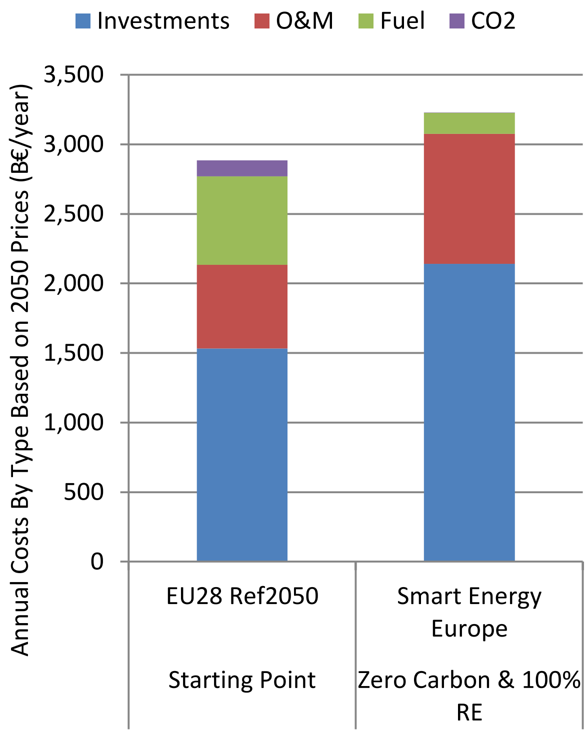

Figure 8. Annual energy system costs by type of cost the EU28 Ref2050 scenario and the Smart Energy Europe scenario.

Table 2. Import shares assumed for the job creation estimates for the *EU28 Ref2050* scenario and the Smart Energy Europe scenario

Assumed Import Factors		
	EU28 Ref2050	Smart Energy Europe
Investments	40%	30%
O&M	20%	20%
Fossil Fuel	75%	0%
Uranium	100%	0%
Biomass Fuel	10%	10%
Fuel Handling	10%	10%
CO_2	0%	0%

CONCLUSIONS

The results in this study indicate that the total annual cost of the EU energy system will be approximately 3% higher to reach the EU targets of 80% less CO_2 in 2050 compared to 1990 levels, 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 bioenergy limit, but they were beyond the scope of this study [15]. Furthermore, the change in the type of 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 has been converted from imported fuel to local investments, which results in an estimated 10 million additional jobs in the EU in a low carbon energy system.

This has been demonstrated here by presenting one potential pathway to 100% renewable energy for the European energy system and its corresponding impact on energy, the environment, and economy. It should not be viewed as a final solution, but instead as a palette for debate on the impact of various technologies and their impact on reaching a 100% renewable energy system in Europe. In the final *Smart Energy Europe* scenario, there are no fossil fuels, no energy imports, no carbon dioxide emissions (<1%), and the total annual costs of the energy system are increased by approximately 10-15% (although there are additional options not considered here which could reduce and even eliminate extra costs). In 2050, the EU energy system is likely to be somewhere between this extreme and where it is today, which will be defined by political desire, innovative policies, and the development in the technologies promoted here.

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