Smart Energy Europe

From a Heat Roadmap to an Energy System Roadmap

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SMART ENERGY EUROPE

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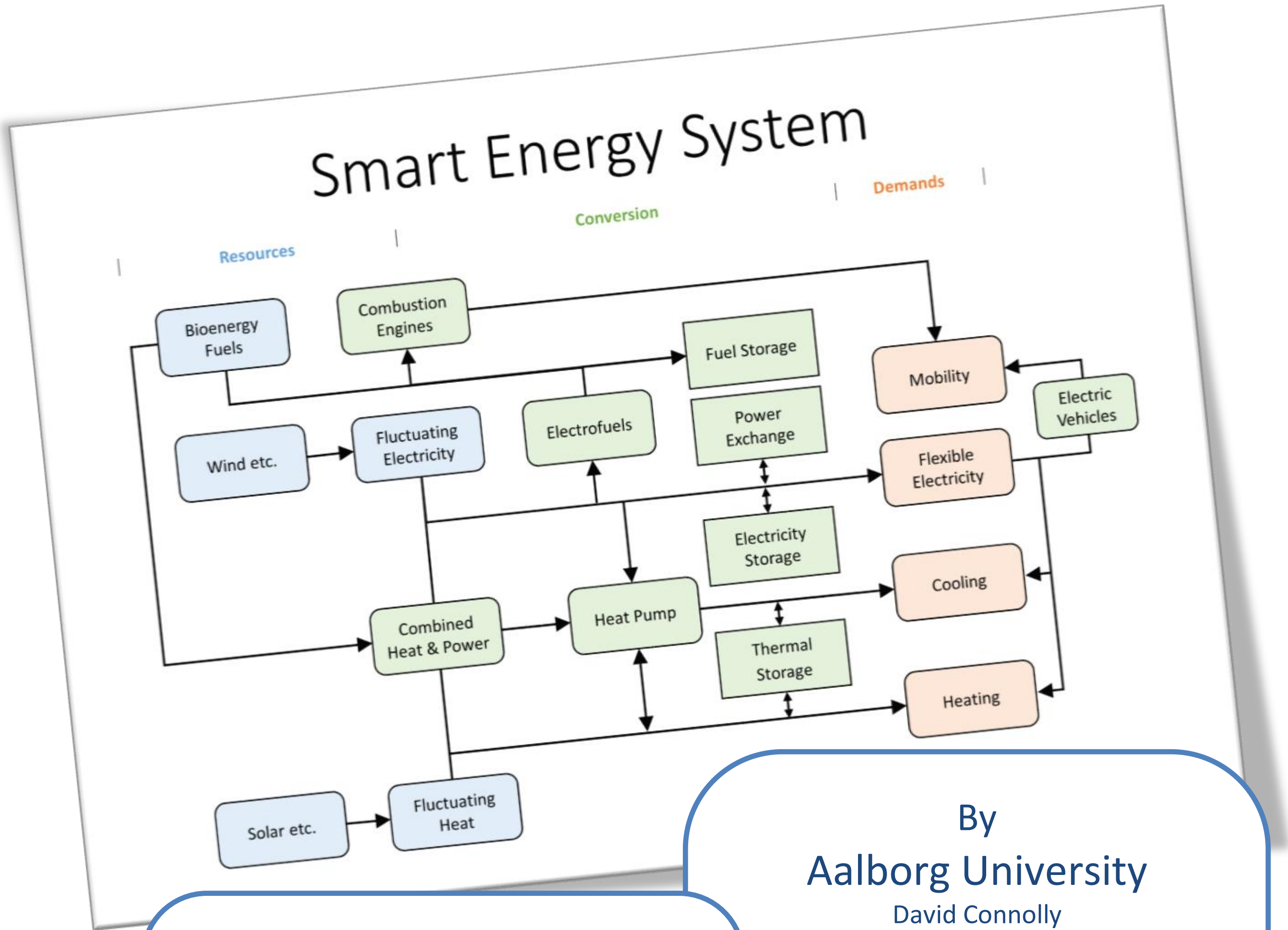

For

European Commission

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July 2015

BREAKING NEW GROUND
AALBORG UNIVERSITY

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1 DESIGNING A 100% RENEWABLE EU ENERGY SYSTEM

Today's energy system contains very large amounts of stored energy on the supply side in the form of fossil fuels. Oil, natural gas, and coal are effectively stored energy in liquid, gas, and solid form. These fossil fuels have very high energy densities, so they can be cheaply stored in tanks, reservoirs and yards. Due to this large amount of stored energy on the supply side of the energy system, there is very little need for flexibility in the rest of the energy system. In other words, historically the demand side of the energy system has been able to call on energy whenever it was required, since energy was easily accessible from the stored energy in fossil fuels. This resulted in the development of base load power plants and "peaking" power plants.

The current energy system however is subject to change due to hazarders emissions, health effects, climate change and greenhouse gas emissions, balance of payment, as well as geopolitical concerns or security of supply issues related to this centralised fossil-fuel energy system.

In theory, bioenergy could directly replace fossil fuels in the structure of today's energy system. However, looking at the biomass resources at hand, there are already suggestions today that the use of biomass can affect the food production and food prices [1]. This is the reason for a large debate on the sustainability of biomass resources and why the focus is to keep within the residual biomass resources, i.e. the bioeneryg bi-products from industry and from food production. With this in mind, these residual biomass resources are far off from being able to cover the demand currently provided by fossil fuels.

In order to make a transition away from the fossil fuels and into a system that is sustainable and based on renewable energy, more intermittent resources are needed in the energy mix. The current centralised energy system, where large production facilities provide electricity or heat and electricity can only accommodate up to 20-25% wind power or solar power. This is not enough for the transition with the biomass resources available and hence we need to re-design the energy system to accommodate more intermittent renewable electricity production.

To accommodate this intermittent electricity production, we need to identify new sources of flexibility in the energy system, so we can still meet our energy demands. These new sources of flexibility can be achieved by integrating the electricity, heat, and transport sectors with one another using a concept defined as the Smart Energy System (www.SmartEnergySystem.eu).

To help explain these new sources of flexibility, a pictorial outline of the energy flows in today's energy system is presented in Figure 1, while the energy flows in a Smart Energy System are presented in Figure 2. In Today's energy system, there is very little interaction between electricity, heat, and transport. Electricity is provided by power plants, heat is provided by boilers, and mobility is provided by combustion engines. Each of these conversion technologies primary consume fossil fuels such as coal, oil, and natural gas. This is very different to the Smart Energy System concept displayed in Figure 2, where the sectors are highly integrated with one another.

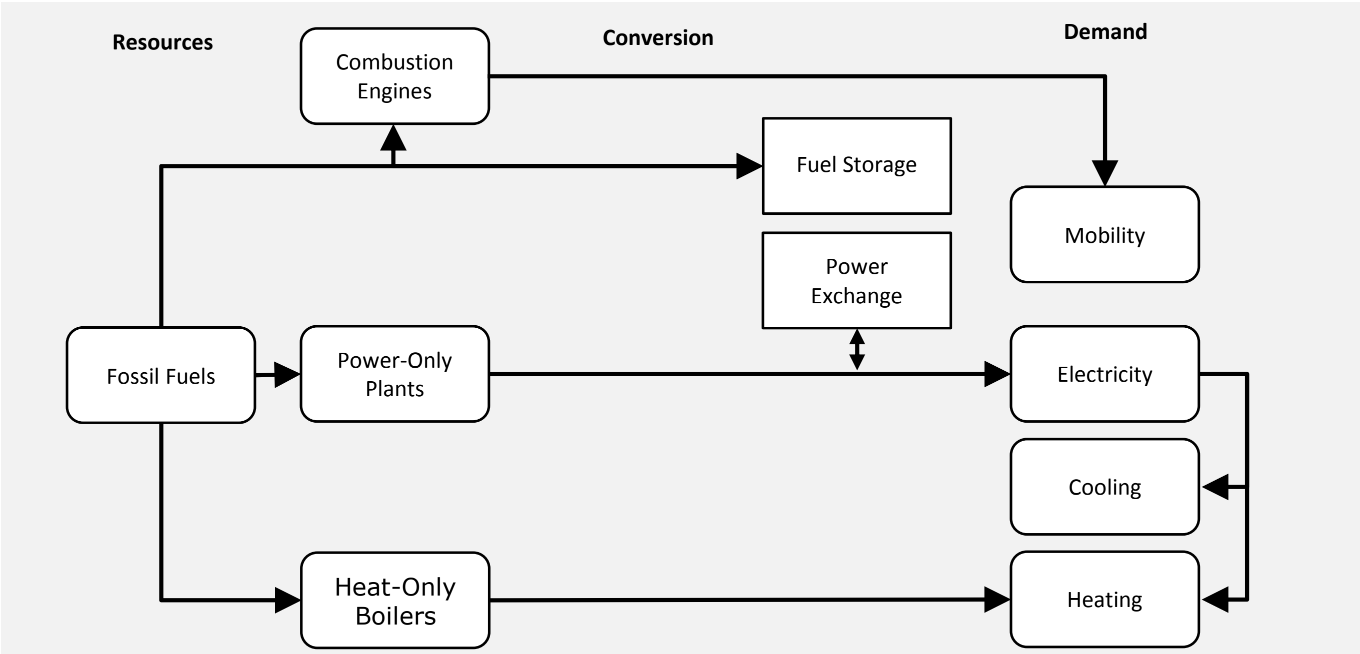

Figure 1: Interaction between sectors and technologies in today's typical energy system.

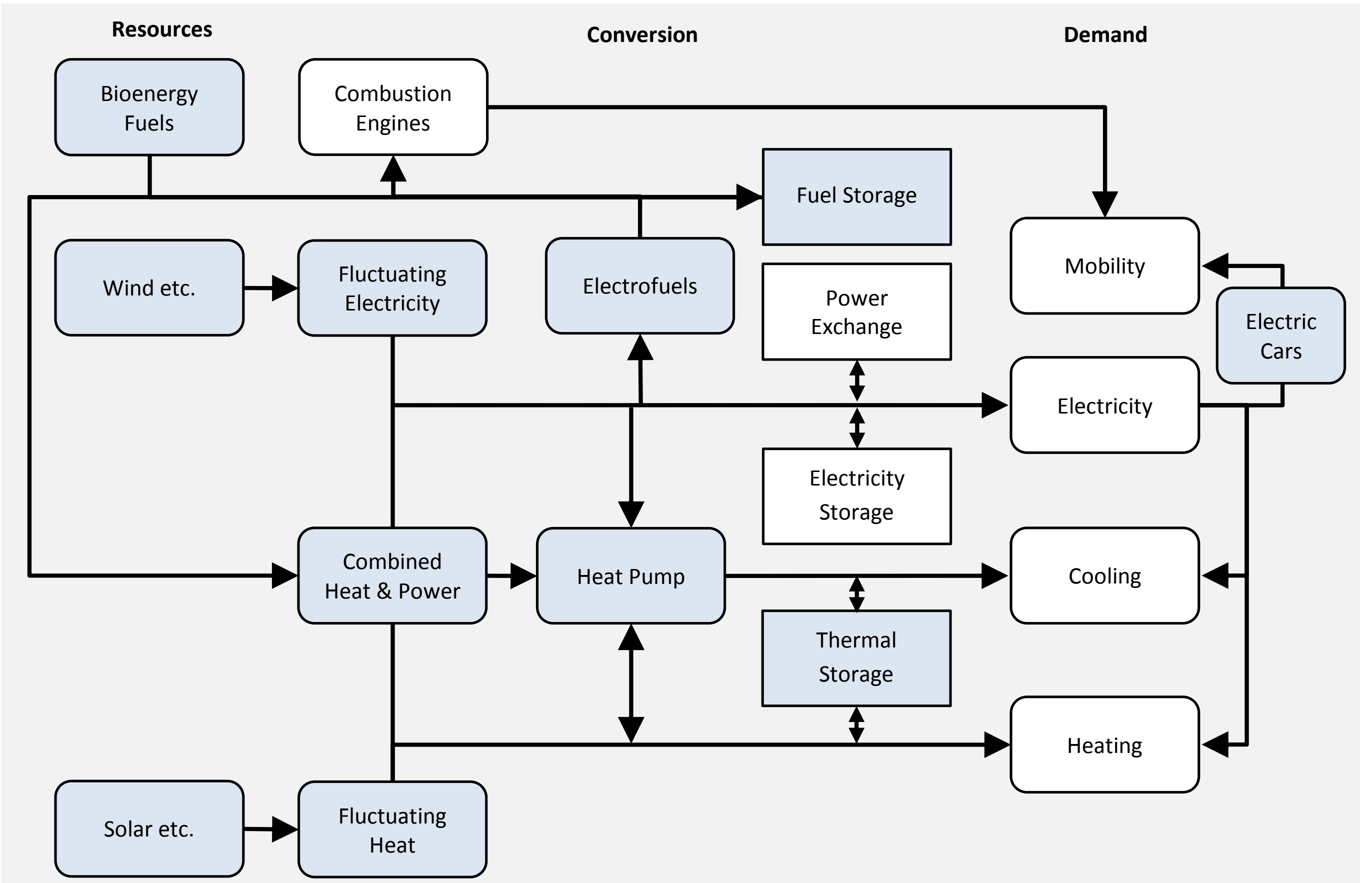

Figure 2: Interaction between sectors and technologies in a future smart energy system. The flow diagram is incomplete since it does not represent all of components in the energy system, but the blue boxes demonstrate the key technological changes required.

1.1 HEAT PUMPS: ACCOMMODATE 30-40% INTERMITTENT RENEWABLES

As already mentioned, the Smart Energy System needs to integrate the various sectors with one another to create new forms of flexibility. To highlight these, let's consider a situation where there is a very high electricity production from wind power (it could be any form of intermittent renewable energy). In other words, there is more electricity being produced from wind power than is being consumed. In this situation, large-scale heat pumps on district heating systems and individual heat pumps in the buildings can be activated in the Smart Energy System, to convert this excess electricity into heating (see Figure 3) or cooling (see Figure 4). If there is no demand for heat, then the large-scale heat pumps in the district heating systems can store heat in thermal storage tanks. Thermal storage is 50-200 times cheaper than electricity storage, which means that it is already being utilized in very large capacities today. For example, in Denmark there is approximately 50 GWh of thermal storage being used today [1], which for comparison, is almost twice as much as the amount of electricity storage in the UK [2]. These thermal storage plants are already being used in Denmark to integrate wind power, by activating electric boilers when there is excess wind power production and using it for the heat demand or storing it in thermal storage. Hence, integrating the electricity and heat sectors is something that is already being done today.

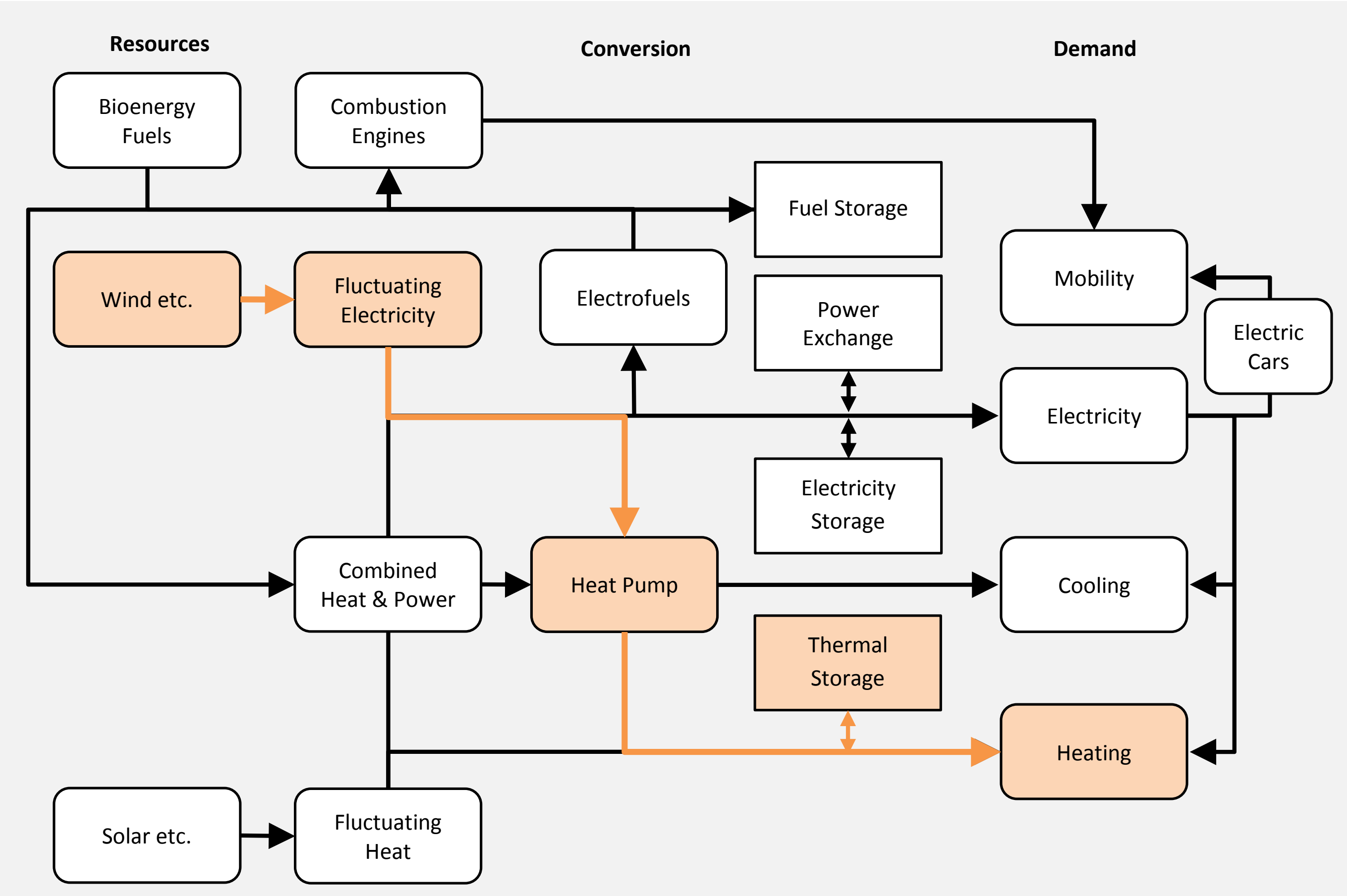

Figure 3: Interaction between sectors and technologies in a future smart energy system. The orange lines and boxes outline how surplus electricity from intermittent renewable energy, such as wind power, can be used to meet the heat demand or stored in thermal storage facilities.

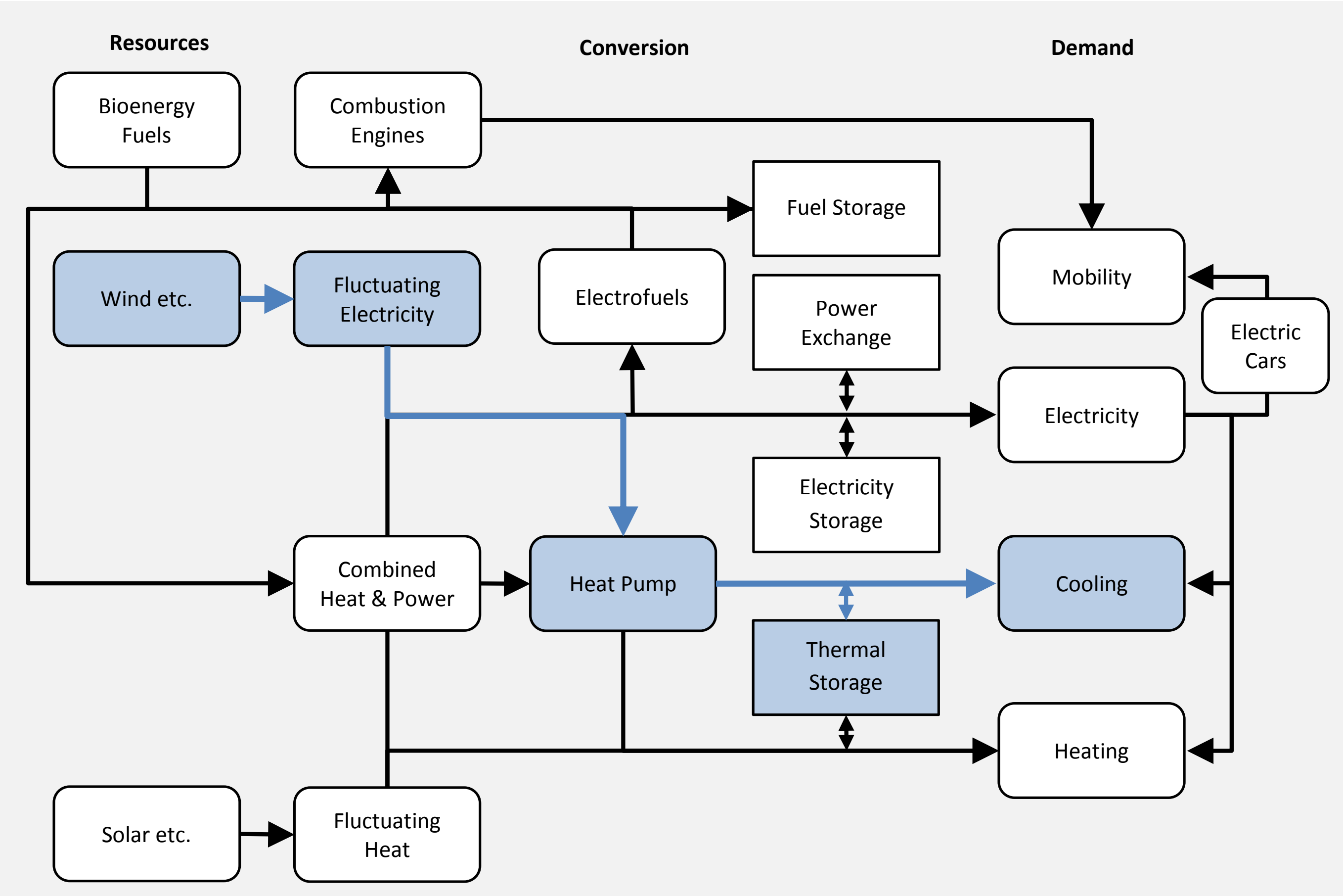

Figure 4: Interaction between sectors and technologies in a future smart energy system. The blue lines and boxes outline how surplus electricity from intermittent renewable energy, such as wind power, can be used to meet the cooling demand or stored in thermal storage facilities.

For example, Figure 5 demonstrates how the electric boilers were activated at a district heating plant in Denmark in response to low electricity prices. Since this resulted in an overproduction of heat, the thermal storage began to fill up during hours 5-8. Afterwards, the electricity price increased again so the electric boilers stopped and the heat in the thermal storage was used (hours 8-11), thus demonstrating the flexibility that already exists today by connecting the electricity and heat sectors.

In an European context, the Heat Roadmap Europe scenarios which included district heating, had approximately 500 GWh of thermal storage when 50% of the heat demand in buildings was met with district heating [2,3]. The average hourly electricity consumption in Europe today is approximately 400 GWh/hour [3], so by introducing thermal storage it is possible to create daily flexibility in the energy system. When this is analysed in an energy systems model [4-7], the results indicate that it is now possible to supply approximately 40% of the electricity demand with intermittent renewable energy such as wind and solar power. This will lead to reductions in carbon dioxide emissions and fuel consumption, but the exact reductions depend on the system being evaluated.

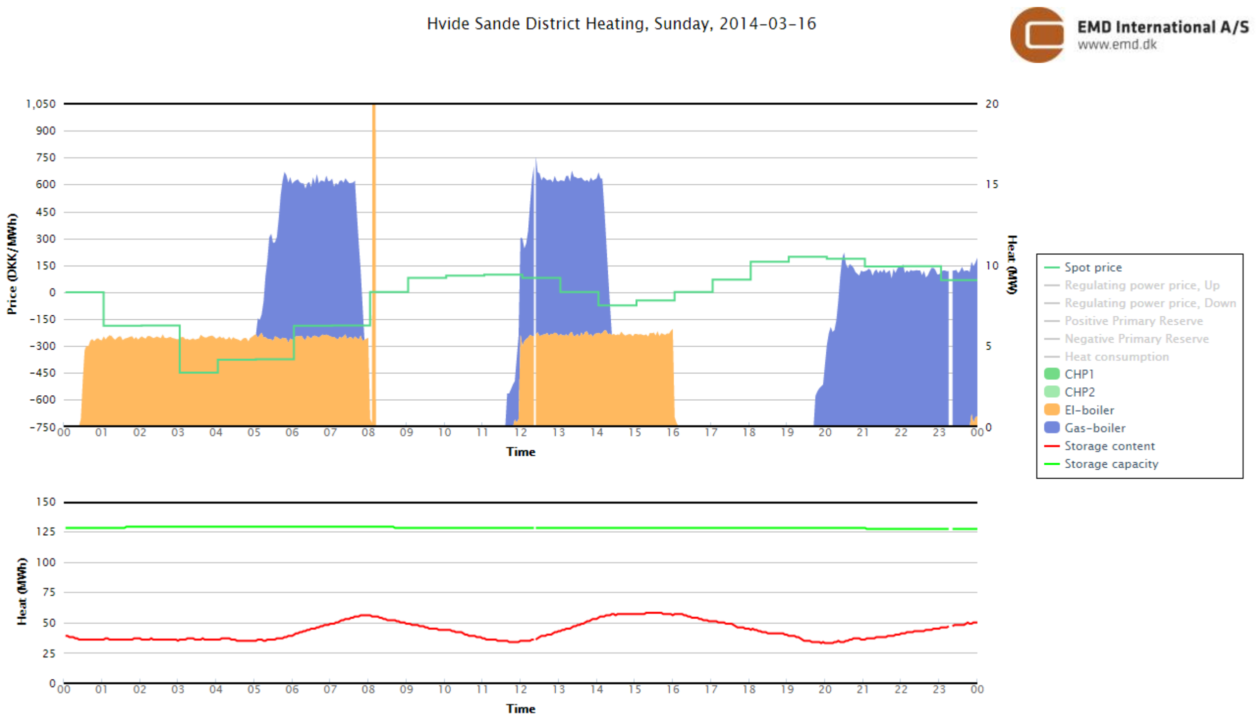

Figure 5: Operation of CHP unit, electric boilers, and thermal storage in Hvide Sande district heating plant (Denmark), in response to a low price on the electricity spot market (www.emd.dk). This demonstrates how thermal storage can be activated by low electricity prices, which often occur in hours of high wind penetrations.

1.2 ELECTRIC VEHICLES: ACCOMMODATION 50-60% INTERMITTENT RENEWABLES

Another excellent source of flexibility in the Smart Energy System is created when electric vehicles are introduced (see Figure 6). By replacing combustion engines with electric vehicles, intermittent renewable energy such as wind power gains access to the transport sector. This enables renewable electricity to replace oil. These electric vehicles have a very large electricity storage capacity when they are aggregated together. For example, a typical electric vehicle today has approximately 25 kWh of battery storage [8]. There are approximately 250 million cars in Europe, so if 80% of these cars are converted to electricity, then it will create an aggregated electricity storage of 5 TWh. The average daily electricity consumption in Europe is almost 10 TWh/day [3], so these electric vehicles increase the flexibility for the electricity sector from daily (i.e. with thermal storage) to weekly. Hence, the electricity demand can be adjusted to match the intermittent production from renewables such as wind and solar power. Furthermore, some of the electric vehicles can be fitted with vehicle-to-grid (V2G) technology, which enables the cars to become electricity providers also [9, 10]. By combining these electric cars with the integration of the electricity and heat sectors discussed previously, it is possible to provide approximately 50-60% of electricity with intermittent renewable resources. Electric vehicles are already commercially available, although the consumer cost will need to be reduced and more charging infrastructure will need to be in place before a large-scale uptake can be expected.

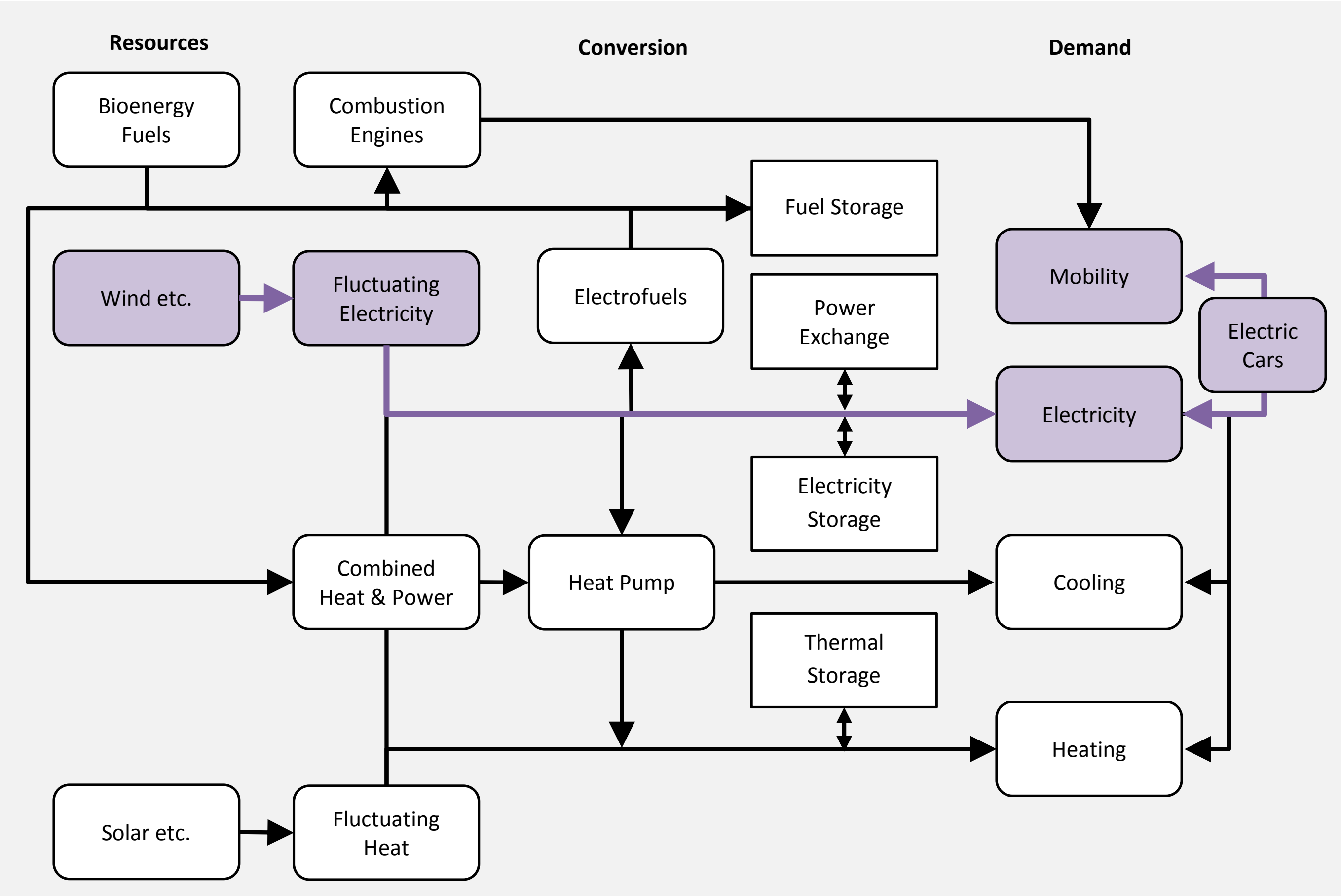

Figure 6: Interaction between sectors and technologies in a future smart energy system. The purple lines and boxes outline how surplus electricity from intermittent renewable energy, such as wind power, can be used to meet the transport demand or stored as electricity.

1.3 ELECTROFUELS: ACCOMMODATE >80% INTERMITTENT ELECTRICITY

The next key form of flexibility that is created in the Smart Energy System has not been proven on a large-scale yet. Some of the components required are available at a large-scale, but others are still at the demonstration/pilot stage. In this step, the electricity sector is connected to the production of fuel, which can be used in industry or in vehicles that require energy dense fuel such as trucks, ships, and aeroplanes (see Figure 7). There is no specific name for these fuels, but here they are referred to as electrofuels. These electrofuels are produced by combining hydrogen and carbon together, which is the same as the natural process which occurs in the production of existing hydrocarbons such as coal, oil, and gas. The ratio between hydrogen and carbon in the final fuel, defines what fuel it is. Hence, it is possible to get liquid and gaseous fuels during this process. In the Smart Energy System, the fuels we promote are methanol and dimethyl ether (DME) when a liquid fuel is required, and methane when a gaseous fuel is required.

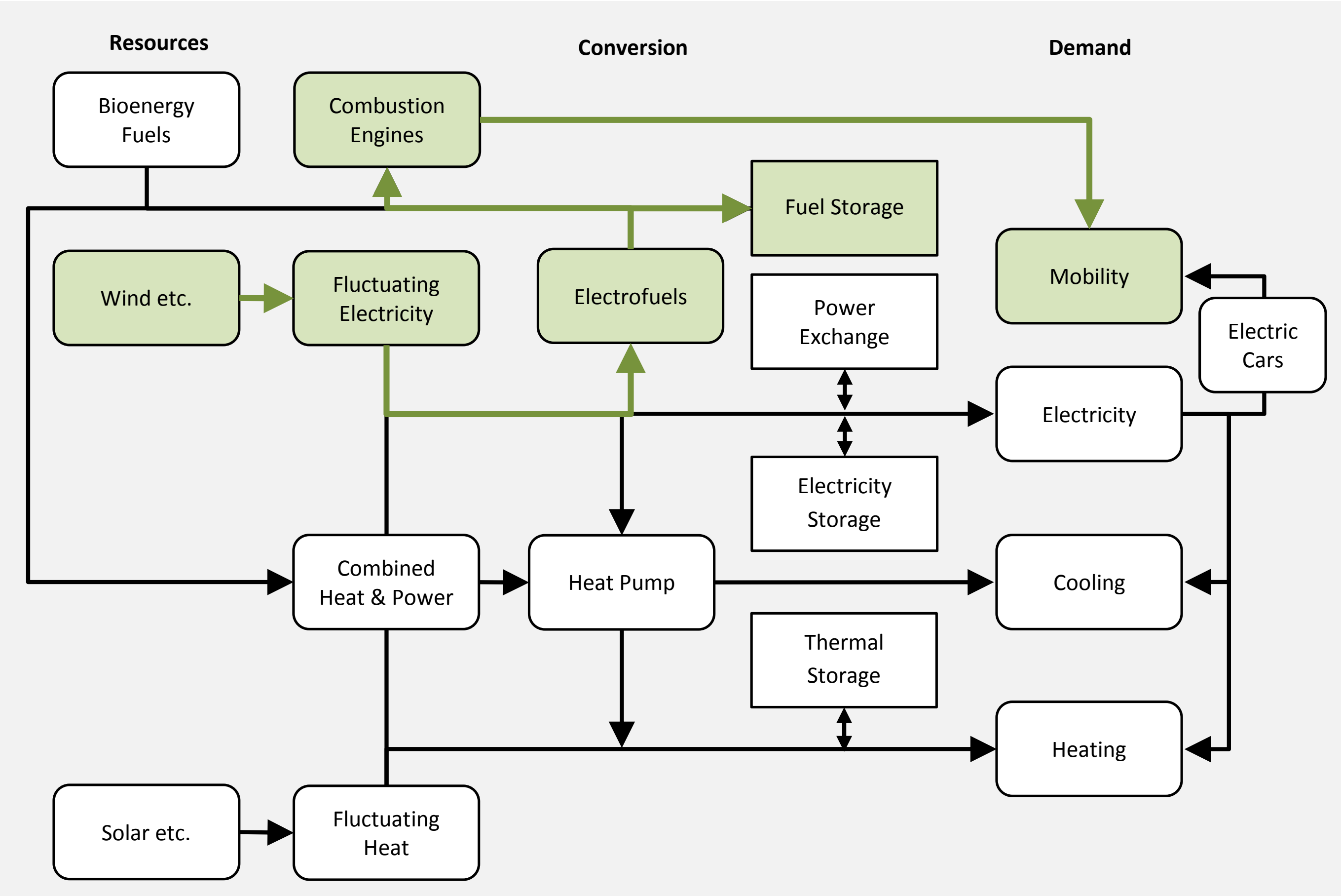

Figure 7: Interaction between sectors and technologies in a future smart energy system. The green lines and boxes outline how surplus electricity from intermittent renewable energy, such as wind power, can be used to meet the transport demand or stored as fuel.

Methanol is discussed here in more detail, to further explain the production process of an electrofuel. To create 1 TWh of methanol, approximately 1.15 TWh of hydrogen and 250,000 t of CO_2 are required. As displayed in Figure 8, there are a variety of different sources for the carbon in a Smart Energy System: it can be obtained from biomass using a gasifier, from a power plant or an industrial process using carbon capture & recycling (CCR), or it can be obtained from the air using carbon trees. To date, biomass gasification [11] and CCR [12] have been demonstrated on a small-scale, but carbon trees have only been proven in the laboratory [13].

The hydrogen should be produced using an electrolyser, which uses electricity to convert water into hydrogen and oxygen. Electrolysers are commercially available today in the form of alkaline electrolysers, but these are not expected to be utilised in the future. Instead, a new form of electrolyser which is under development, known as a solid oxide electrolyser (SOEC) is expected to become the primary form of hydrogen production since they are more efficiency and cheaper to produce [14]. The key benefit of electrofuel production from a flexibility perspective is the connection that is now created between electricity production and fuel storage. If intermittent renewable energy is used as the electricity source for the electrolyser, then these resources are now connected to very large-scale and relatively cheap fuel storage. To put this in context, an estimate of Europe's existing fuel storage today indicates that there is approximately 900 TWh of oil storage and 700

TWh of gas storage. In contrast the total annual electricity demand in Europe today is approximately 3500 TWh, so by connecting the electricity sector to fuel storage, the scale of flexibility has moved from weekly to monthly. Furthermore, the cost of storing 1 kWh of energy in a fuel storage facility is almost 10,000 times less than the price of storing 1 kWh of energy in electricity storage. Therefore, introducing fuel storage in combination with electrofuels connects intermittent electricity production to large-scale and affordable energy storage. When this fuel storage is combined with thermal storage and battery storage in electric vehicle, our hourly energy system analysis work indicates that over 80% of the electricity demand can now be supplied with intermittent electricity resources. This is evident from the Smart Energy Europe scenario presented in the Appendix, which has been designed by implementing this Smart Energy System concept.

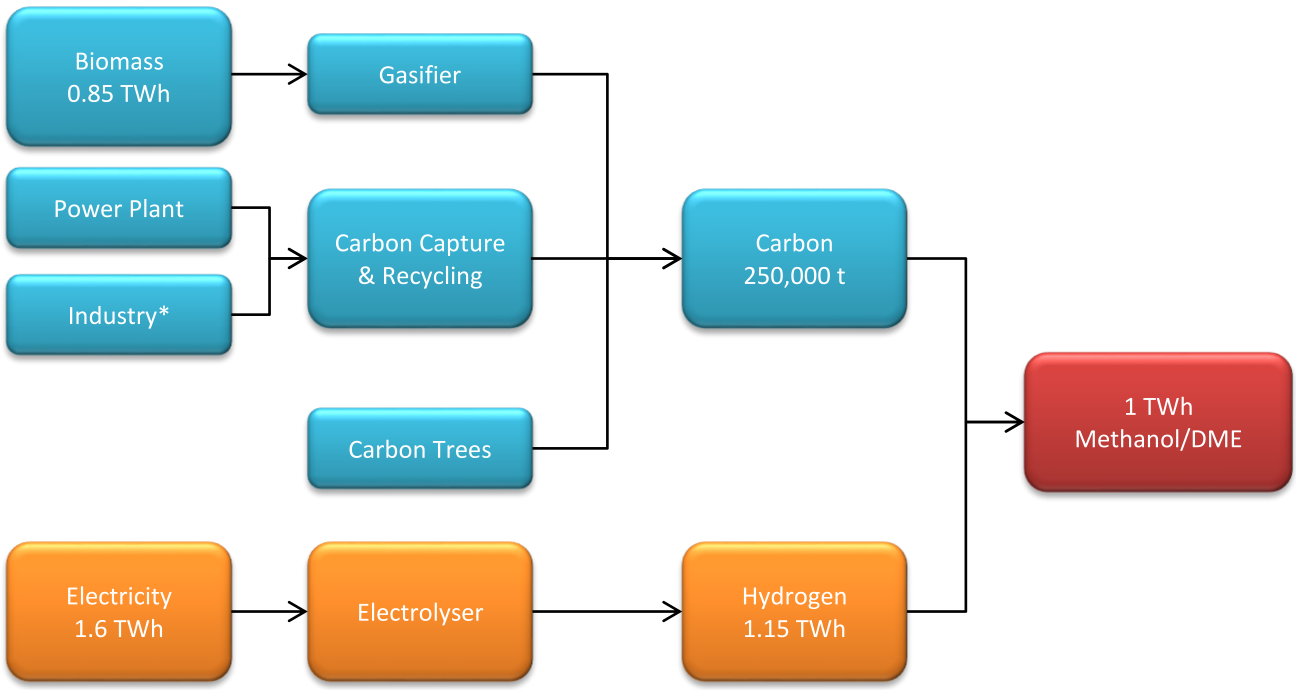

Figure 8: Carbon and hydrogen required to produce electrofuel in the form of methanol or dimethyl ether (DME). A variety of different carbon options are displayed here to illustrate the options available. *Cement production is one very good example of an industrial process with surplus carbon.

A number of options are currently being investigated to integrate even more than 80% intermittent renewable energy into the energy system. The costs to be considered in this type of energy system are different to those currently considered today. Today, energy costs are very dependent on fuel costs, as power plants, boilers, and vehicles use significant amounts of fuel. However, the amount of fuel being consumed in the Smart Energy System is approximately 75% less than today's energy system. For example, the fuel previously burned in a power plant has been replaced by electricity from a wind turbine. This means that almost all of the energy produced in the Smart Energy System is from an investment-based piece of infrastructure, instead of a fuel-based infrastructure. Therefore, in the Smart Energy System, choosing technologies is very dependent on investment costs, rather than on fuel costs. To beyond an 80% wind penetration will require a comparison between the investment costs in options such as:

- Installing an over-capacity of intermittent renewable electricity such as wind power. This will result in high levels of curtailment, but even with this lower capacity factor, wind and solar power may continue to be the cheapest investment.
- Adding electricity storage on the electric grid. Then the additional electricity can be stored for a few days, or sold on international markets.
- Adding more electric heating (electric boilers or heat pumps) on district heating systems. Then the additional heat can be stored for another season.
- Adding more electrolyser capacity and hydrogen storage. Then the additional hydrogen can be stored for another year, or sold on international markets.
- Adding more carbon capture and chemical synthesis capacity, along with fuel storage. Then the additional fuel can be stored for another year, or sold on international markets.

It is not clear which one or combination of these options is most suitable in the Smart Energy System, but the key point is that many of the options available require an economic comparison of investments, rather than primarily fuel costs.

To summarise, the key focus in the description above relates to creation of flexibility to accommodate intermittent renewable electricity by integrating the electricity, heat, and transport sectors to form the Smart Energy System. However, there are numerous other improvements in efficiency, which are also taking place during this transition also. Here are some examples in the heat sector:

- When district heating is in place, then surplus heat from the power plants, industry, and waste incineration can be used in the buildings instead of waste in a river or the sea.
- Similarly, surplus heat from the biomass gasification and electrolysers can be used in the buildings.
- Heat networks also enable new sources of renewable energy to be utilised, which would otherwise not be possible, such as large-scale solar thermal, direct geothermal heat, and renewable electricity via large-scale heat pumps.
- District heating and cooling networks enable centralised thermal storage to be utilised. It is cheaper to construct these central storage facilities than providing individual storage units in each building. For example, existing thermal storage facilities can be constructed for approximately €0.5-3/kWh, whereas an individual thermal storage tank cost €300/kWh.
- Heat pumps are also much more efficient than boilers, so the energy required to heat buildings is reduced by replacing boilers with heat pumps.

And here are some examples from the transport sector:

- Electric vehicles are more efficient than combustion engines, so introducing electric cars reduces the energy demand for cars.
- Replacing oil with electrofuels means that existing vehicles and infrastructure can be utilised

There are a number of key technologies required to develop the Smart Energy System concept, which are presented in Table 1. It is clear that the integration of the electricity and heat sectors can be done today, since all of the key technologies required are already available. It is possible to begin integrating the electricity and mobility sectors with electric vehicles, but further developments are required in battery technology to reduce the price and increase the range of an electric car. Hence, the integration of electricity and heat can be seen as a short-term target within the next 5-10 years, while the electricity and mobility sectors is a medium-term target over the next 10-20 years. Finally, there are a number of key technologies required to integrate the electricity & fuel sectors, which are only at the demonstration phase such as biomass gasification and electrolysers. Hence, this is a long-term target which can be achieved in the next 20-40 years.

Table 1: Key technologies required to integrate the electricity, heat, and transport sectors of the energy system. There are a number of other technologies in the Smart Energy System which are not mentioned here, since the focus here is on those for integrating the sectors.

	Electricity & Heat/Cooling*	Electricity & Mobility*	Electricity & Fuel*
Commercially Available	• District heating networks • District cooling networks • Combined Heat & Power plants • Centralised compression heat pumps • Centralised absorption heat pumps • Centralised thermal storage • Individual heat pumps • Others for energy efficiency gains: - Heat savings in buildings - Recycling industrial surplus heat - Utilise waste incineration heat - Centralised and individual solar thermal - Direct geothermal heat (absorption heat pumps)	• Electric cars • Charging infrastructure for electric cars	• Chemical synthesis (converts carbon and hydrogen to the final fuel) • Centralised fuel storage • Methanol and dimethyl ether vehicles
Needs further development		• Batteries for electric cars • Vehicle-to-grid (V2G)	• Biomass gasification • Carbon capture & recycling • Solid oxide electrolysers

***All of these technologies assume a major increase in intermittent renewable electricity production, such as wind and solar power.**

2 QUANTIFYING THE IMPACT OF A 100% RENEWABLE EU ENERGY SYSTEM

The Smart Energy System concept described previously has been analysed in an EU context to create a scenario called Smart Energy Europe. The results of this scenario are presented in this section. A business-as-usual scenario for the European energy system in 2050, called EU28 Ref2050, is compared to alternative 100% renewable energy scenario for Europe, called Smart Energy Europe. This scenario has been constructed in a series of 9 steps which are:

1. **EU28 Ref2050:** This is the starting point for the analysis. It is a business-as-usual forecast for the European energy system and it includes all 28 member states. It is based on the Reference scenario from the latest EU Energy Roadmap report [3].
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.
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 that a sustainable heat supply. In Heat Roadmap Europe [15, 16], 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 [17, 18]. 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" [19]. Hence, in this step, 80% of the private cars and their corresponding demands are transferred from oil (i.e. petrol and diesel) to electricity.

5. **Individual Heating:** a variety of different individual heating solutions are analysed, which include heat pumps, electric boilers, biomass boilers, and oil boilers. After comparing the energy, environmental, and economic implications of these, individual heat pumps are chosen as the most suitable solution for the Smart Energy System. In theory, this individual solution could be installed in all buildings in Europe, but in the next step various network heating solutions are also investigated to see if they compliment these individual heat pumps.
6. **Network Heating:** this is only suitable in areas with a high heat density and so it is only feasible in urban areas. The two commercially available network heating solutions today are based on gas and water. In this step, two scenarios are considered: one where individual heat pumps are combined with gas networks and another where they are combined with water networks (i.e. district heating). The results indicate that district heating is more efficient, enables more renewable energy, and costs less than both gas networks and the use of individual heat pumps on their own. Hence, individual heat pumps in the rural areas of Europe and district heating in the urban areas is deemed the most sustainable for the future.
7. **New Transport Fuels:** due to limitations in the energy density of batteries, electricity can only replace oil in light transport such as cars. Other modes of transport require fuels with higher energy densities, such as trucks, ships, and aeroplanes. To replace the oil in these vehicles, electrofuels are used, more specifically methanol and DME. These fuels are produced by combining carbon and hydrogen to one another. The carbon can be obtained from power plants, industry, or the air, while the hydrogen can be produced by the electrolysis of water in an electrolyser. The electrolyser needs electricity to function and so, by implementing electrofuels, the electricity sector is connected to large-scale and cheap energy storage, in the form of fuel storage. As a result, this step enables two key changes: 1) oil is being replaced in heavy duty transport and 2) connecting the electricity sector to fuel storage enables over 80% of the electricity demand to be provided by intermittent renewable resources.
8. **Replacing Coal & Oil:** Biomass, natural gas, oil and coal consumption is reduced significantly compare to the EU28 Ref2050 scenario in the steps already discussed. In this step, coal and oil are replaced with biomass and natural gas. After implementing this, the level of biomass and natural gas consumed is almost the same as in the EU28 Ref2050 scenario. The rest is being provided by other forms of renewable energy. This means that natural gas is the only form of fossil fuel remaining in the energy system.
9. **Replacing Natural Gas (*Smart Energy Europe* scenario):** in the final step, the remaining natural gas is replaced using methane. Similar to methanol and DME, the methane is produced as an electrofuel by combing carbon and hydrogen with one another. After replacing natural gas with this methane, the energy system is practically carbon free and 100% renewable.

These steps have been analysed in detail for the EU28 energy system. The impact of each step in terms of energy, environment, and economy are summarised here, but presented in detail in the Appendix of this report. The energy impact is measured based on the Primary Energy Supply (PES), the environmental impact is measured in terms of carbo dioxide emissions, and the economic impact is measured in terms of total annual socio-economic costs. The results for each step are summarised in Table 2, which indicates that the PES is reduced for all steps up until step 7 when the first electrofuels are introduced. The PES increases in this step since 0.83 units of biomass and 0.53 units of electricity is required to replaced 1 unit of oil with an electrofuel. However, even though the PES increases in step 7 and step 9, with the introduction of electrofuels, the overall PES is still 10% less than the initial *EU28 Ref 2050* scenario.

Table 2: Changes that occur for each step in terms of energy, environment, and economy compared to the *EU28 Ref2050* scenario.

Metric (vs. *EU28 Ref2050*):	Energy	Environment		Economy
Scenario	(PES)	(CO_2 Emissions)	(CO_2 vs. 1990 Levels*)	(Total Annual Costs)
1. EU28 Ref2050	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%

***Assuming that energy related CO_2 emissions in 1990 were 4030.6 Mt [65]. The EU target is to reduce CO_2 emissions by 80% compared to 1990 levels [84].**

The aim in all steps has been to maximise the integration of renewable, primarily via wind and solar power. As a result, the carbon emissions are reduced in every step, until eventually in step 9 there is practically no carbon emissions remaining: there is only a very small amount from waste incineration. However, it is important to note that it is assumed here that biomass is carbon neutral, which is optimistic since some biomass may come from processes that are not carbon neutral especially when the biomass demand is high.

Finally, the cost is approximately the same (<5% difference) in all scenarios until the final one step. This means that the EU carbon emissions are reduced by 78% compared to 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, without significantly increasing the cost of the energy system. In the final step, natural gas is replaced with electrofuel gas (power-to-gas) which does increase the costs significantly. Therefore at this point in the transition, there will be a balance between the additional cost of the electrofuels, the impact of more CO_2 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.

The final Smart Energy Europe scenario is a 100% renewable energy and carbon free scenario that consumes a sustainable level of bioenergy. It represents an extreme scenario where there is very high penetration of intermittent renewable energy (>80% in the electricity sector), and the global energy system does not exceed a bioenergy consumption of 25 GJ/person. This may be necessary to avoid serious indirect climate change (see Appendix). As displayed in Figure 9, almost all of the energy in the Smart Energy Scenario is from renewable electricity or bioenergy.

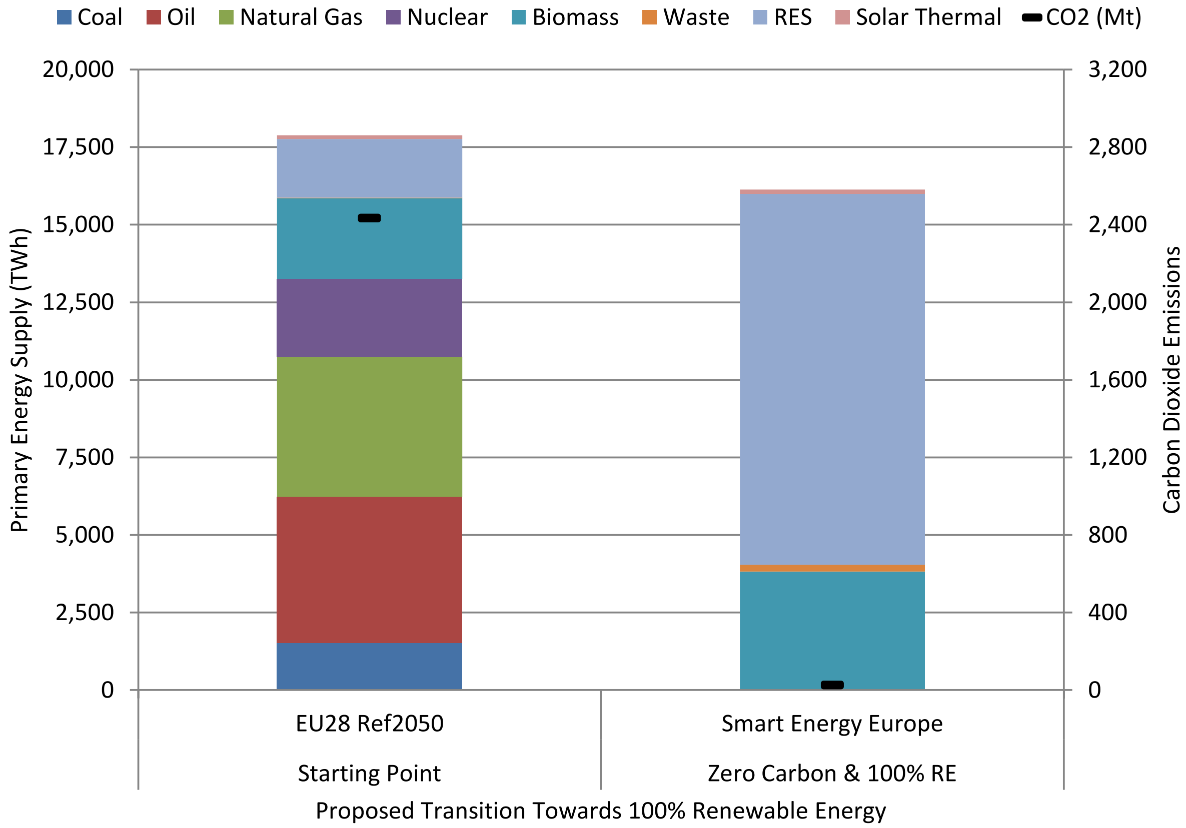

Figure 9: Primary energy supply by fuel and carbon dioxide emissions for the reference EU28 Ref2050 scenario and the Smart Energy Europe scenario.

Finally, it is also important to recognise that even though the total energy costs in the *Smart Energy Europe* scenario are slightly higher than the original *EU Ref2050 scenario*, the proportion of investment is higher in the *Smart Energy Europe* scenario (see Figure 10). Hence, these increases in costs will most likely be counteracted by local job creation in the EU.

The investments in the Smart Energy Europe scenario primarily replace fossil 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 and **based on the assumptions described in the Appendix, 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.

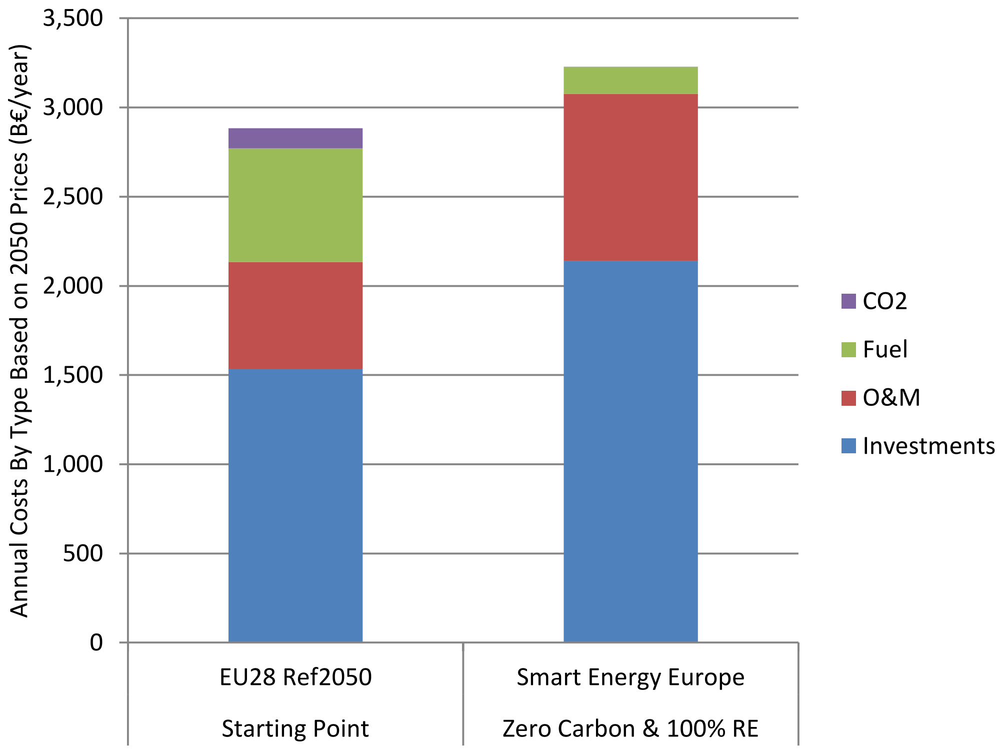

Figure 10: Annualised costs by sector for the reference EU28 Ref2050 scenario and the Smart Energy Europe scenario.

3 CONCLUSIONS

The *Smart Energy Europe* work has presented one potential pathway to 100% renewable energy for the European 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, the environment (carbon emissions), and economy (total annual socio-economic cost). 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. These steps are based on hourly modelling of the complete energy system (i.e. electricity, heat, 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 the total annual cost of the EU energy system will be approximately 3% higher than the fossil fuel alternative 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 these were beyond the scope of this study [37]. 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 a major increase in the 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, no and carbon dioxide emissions (<1%). The key technological changes required to implement the *Smart Energy Europe* scenario are (see Table 1): wind power, solar power, electric vehicles, heat savings, individual heat pumps, district heating, large-scale thermal storage, biomass gasification, carbon capture and recycling, electrolysers, 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, 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 availability of cost-effective solutions.

4 REFERENCES

[1] PlanEnergi, Teknologisk Institut, GEO, and Grøn Energi. Udredning vedrørende varmelagringsteknologier og store varmepumper til brug i fjernvarmesystemet. Danish Energy Agency, 2013. Available from: http://www.ens.dk/.

[2] McKay DJC. Sustainable Energy - Without the Hot Air. UIT Cambridge Ltd, Cambridge, England, 2009. ISBN: 978-0-9544529-3-3.

[3] E3M Lab, National Technical University of Athens. EU28 Reference scenario: Summary Report using the PRIMES Version 4 Energy Model. European Commission, 2013.

[4] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems - A market operation based approach and understanding. **Energy** 2012;42(1):96-102.

[5] Lund H. Renewable Energy Systems: The Choice and Modeling of 100% Renewable Solutions. Academic Press, Elsevier, Burlington, Massachusetts, USA, 2010. ISBN: 978-0-12-375028-0.

[6] Lund H. Renewable Energy Systems: A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions. Academic Press, Elsevier, Massachusetts, USA, 2014. ISBN: 978-0-12-410423-5.

[7] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. **International Journal of Sustainable Energy Planning and Management** 2014;1:7-28.

[8] Nissan. New Leaf Technical Specifications and Prices. Nissan, 2014. Available from: http://media.nissan.eu/.

[9] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. **Energy Policy** 2008;36(9):3578-3587.

[10] Kempton W, Tomic J. Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. **Journal of Power Sources** 2005;144(1):280-294.

[11] Ridjan I, Mathiesen BV, Connolly D. A review of biomass gasification technologies in Denmark and Sweden. Aalborg University, 2013. Available from: http://vbn.aau.dk/.

[12] Carbon Recycling International. George Olah Renewable Methanol Plant. Available from: http://www.carbonrecycling.is/ [accessed 28 September 2012].
[13] Lackner KS. Capture of carbon dioxide from ambient air. **Eur. Phys. J. Special Topics** 2009;176:93-106.
[14] Mathiesen BV, Ridjan I, Connolly D, Nielsen MP, Hendriksen PV, Mogensen MB, Jensen SH, Ebbesen SD. Technology data for high temperature solid oxide electrolyser cells, alkali and PEM electrolysers. Aalborg University, 2013. Available from: http://vbn.aau.dk/.
[15] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, Persson U, Werner S, Grözinger J, Boermans T, Bosquet M, Trier D. Heat Roadmap Europe: Second pre-study. Aalborg University, Halmstad University, Ecofys Germany GmbH, PlanEnergi, and Euroheat & Power, 2013. Available from: http://vbn.aau.dk/.
[16] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, Boermans T, Trier D, Østergaard PA, Nielsen S. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. **Energy Policy** 2014;65:475–489.
[17] Lund H, Mathiesen BV, Hvelplund FK, Østergaard PA, Christensen P, Connolly D, Schaltz E, Pillay JR, Nielsen MP, Felby C, Bentsen NS, Meyer NI, Tonini D, Astrup T, Heussen K, Morthorst PE, Andersen FM, Münster M, Hansen L-LP, Wenzel H, Hamelin L, Munksgaard J, Karnøe P, Lind M. Coherent Energy and Environmental System Analysis. Aalborg University, 2011. Available from: http://www.ceesa.plan.aau.dk.
[18] Mathiesen BV, Connolly D, Lund H, Nielsen MP, Schaltz E, Wenzel H, Bentsen NS, Felby C, Kaspersen P, Hansen K. CEESA 100% Renewable Energy Transport Scenarios towards 2050. Aalborg University, 2014. Available from: http://www.ceesa.plan.aau.dk/.
[19] European Commission. Impact Assessment Accompanying the document Energy Roadmap 2050 (Part 2/2). European Commission, 2011. Available from: http://ec.europa.eu/.

APPENDIX

SMART ENERGY EUROPE: THE TECHNICAL AND ECONOMIC IMPACT OF ONE POTENTIAL 100% RENEWABLE ENERGY SCENARIO FOR THE EUROPEAN UNION

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

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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.

Keywords

100% renewable energy; Jobs; Europe; EnergyPLAN

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 potentially 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

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presented in Figure 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 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.

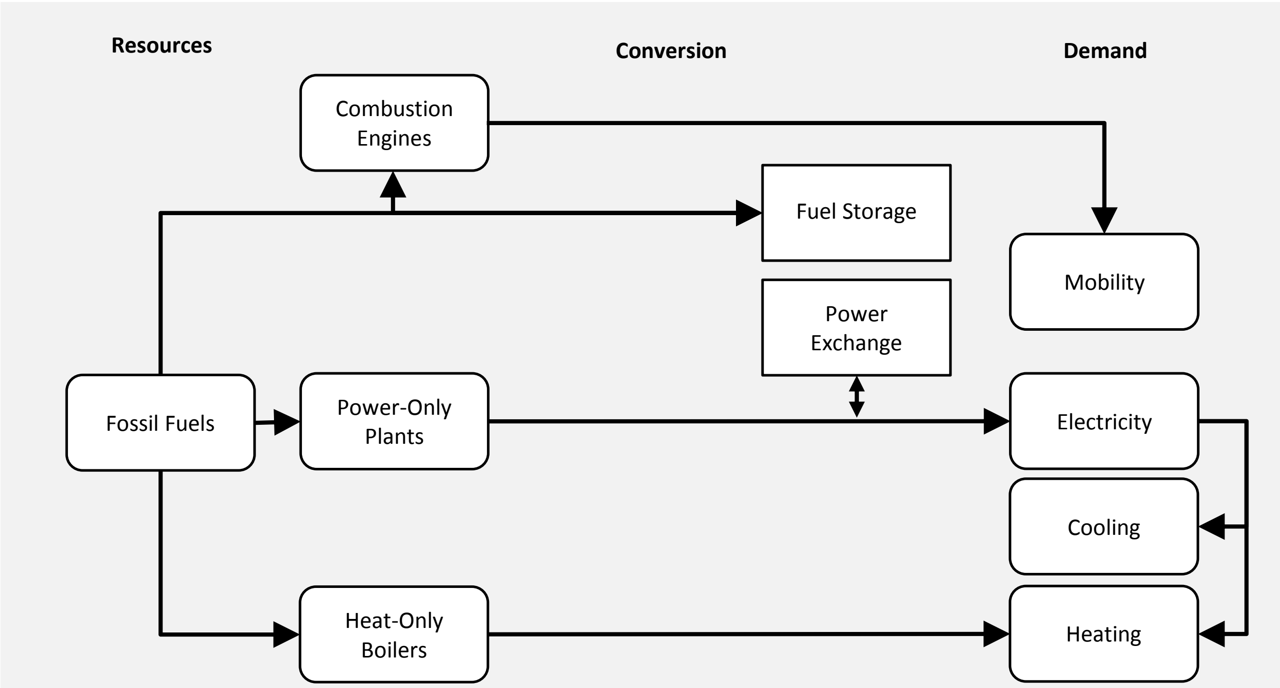

Figure 1: Interaction between sectors and technologies in today's typical energy system.

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 rather, 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 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. As outlined in Figure 2, it is forecast that approximately 14-46 EJ of bioenergy will be available in the EU, which is based on a large variety of studies (see Figure 2). However, already today the EU already 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 must consume a maximum of approximately 14 EJ/year of bioenergy, which is the minimum average 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 a 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 ~27 GJ/person/year of bioenergy, while the global bioenergy resource for 2050 is expected to be ~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.

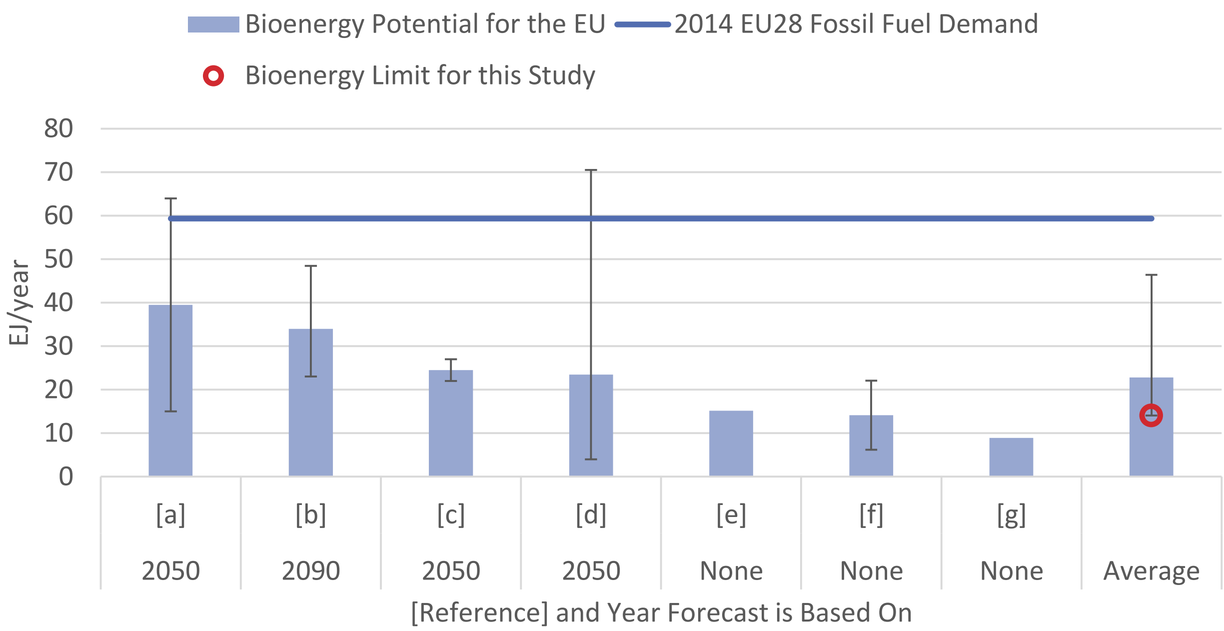

Figure 2: EU28 fossil fuel consumption in 2011 [23, 24], compared with various forecasts for the EU bioenergy potential: [a][25], [b][26], [c][27], [d][26], [e][28], [f][29], and [g][14].

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). 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 [30, 31], journal papers [32-37], conference proceedings [38, 39], reports [40, 41], and a video (www.SmartEnergySystem.eu) about the concept. In brief, with the Smart Energy System it is possible to supply all of the energy demands using only renewable energy, while at the same time the consumption of bioenergy is limited to a sustainable level [33, 40, 42-44]. This paper is the first study to apply the Smart Energy System concept at an EU level: it outlines the type of technologies and the scale of the renewable resources required during the decarbonisation of the EU energy system. This is important since the transition in Europe will be a combined effort across Member States, rather than isolated efforts within the national boundaries. 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 fundamental difference between the Smart Energy System and today's energy system is the source of flexibility.

As already mentioned, flexibility in the energy system today is almost exclusively available due to the large amounts of stored energy in fossil fuels. Fossil fuels are not available in the Smart Energy System, so the flexibility required to ensure demand and supply always match must be obtained elsewhere. This is achieved by creating flexibility in the conversion sector of the energy system, which is possible by integrating the individual branches of the energy system with one another, which is something many other studies have also moved towards in recent times also [45-47]. This is illustrated in Figure 3 where a variety of new resources and conversion process have been added. By integrating the electricity, heating/cooling, and transport sectors with one another, it is possible to utilise very large amounts of wind and solar power. This reduces the pressure on the bioenergy resource, which makes a 100% renewable energy system feasible without consuming an unsustainable level of bioenergy. This is in contrast to some existing studies which have removed the demand for bioenergy altogether [47].

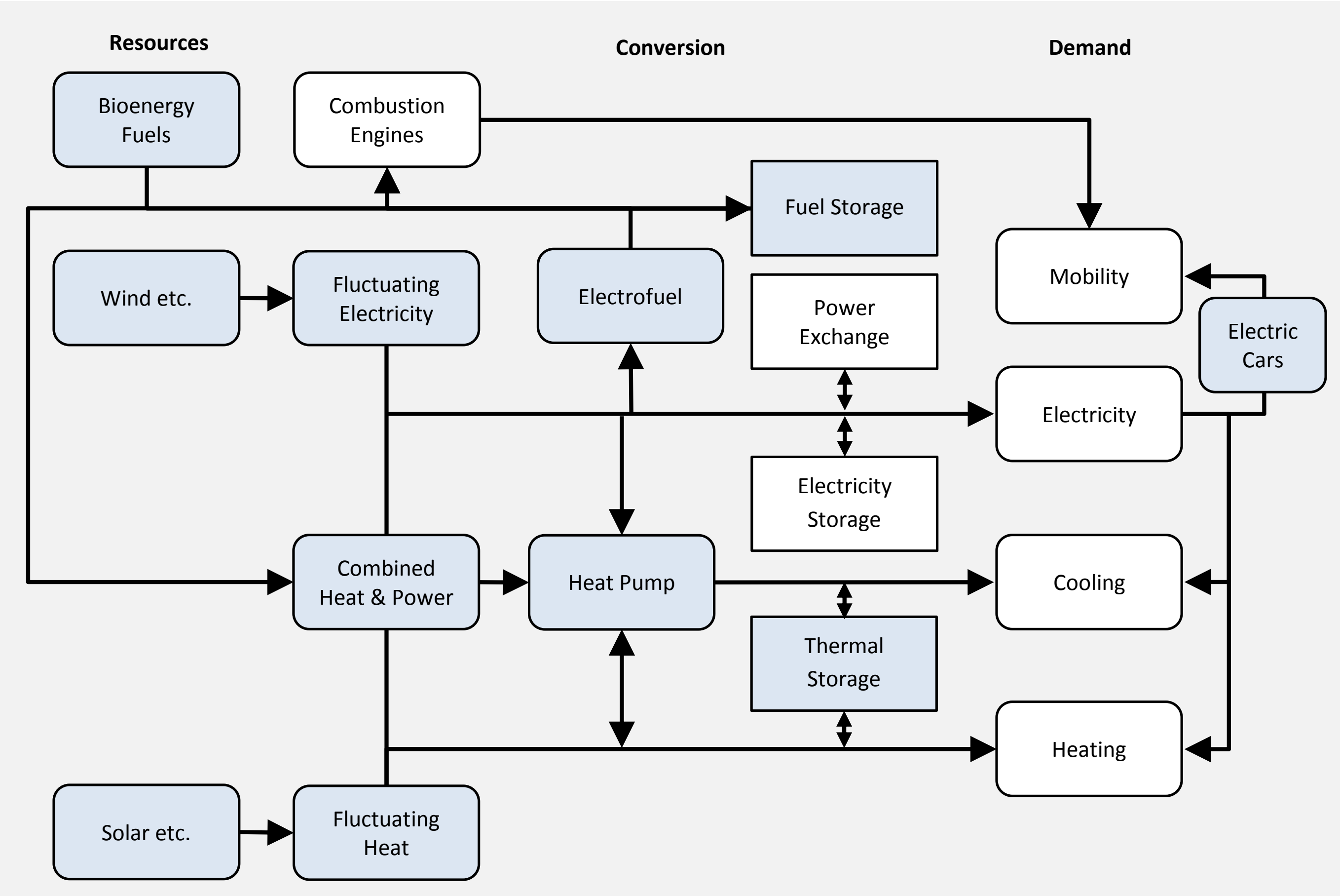

Figure 3: Interaction between sectors and technologies in a future Smart Energy System. The flow diagram is incomplete since it does not represent all of components in the energy system, but the blue boxes demonstrate the key technological changes required.

There are many technical differences between today's energy system in Figure 1 and the Smart Energy System displayed in Figure 3. The Smart Energy System concept is similar to the Smart Grid concept, but where the Smart Grid focuses on the electricity sector only [48, 49], the benefits of the Smart Energy System are only realised with all 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 Figure 3. This 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

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. This section is supplemented by a range of cost data provided in the Appendix.

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, 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 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, case studies, manuals, and existing models are freely distributed on the EnergyPLAN homepage [60]. It has already been used for a wide range of analysis [61], including the development of 100% renewable energy strategies for many 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. 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 investments 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. 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 [66].

2.2 The Transition to a Smart Energy System

Using the EnergyPLAN model, a Smart Energy System, like the one displayed in Figure 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 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 [30, 31].
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 section 3 the results are compared with one another.

Table 1: Summary of the demand and supply in the EU28 Reference Scenario for the year 2050 (*EU28 Ref2050*).

Demand (TWh)		Supply (TWh)	
Electricity Consumed by Type of Demand	4440	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
Heat Demand by Fuel	3308	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
		Fuel Consumption in Industry	3062
		Coal	569
		Oil	434
		Gas	1400
		Biomass	658
		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

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 [21]. 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 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 used are based on forecasts for the year 2050 and they are provided in the Appendix.

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 (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 a 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 (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).

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:

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 [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 for 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 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 [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 types of heating in this analysis:

- Individual heating: these are heating technologies that are individually placed 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 placed 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). These gas and water networks are shared across individual buildings in a similar way to other utilities such as cold 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 renewables).

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 to form step 6. This process is graphically illustrated in Figure 4.

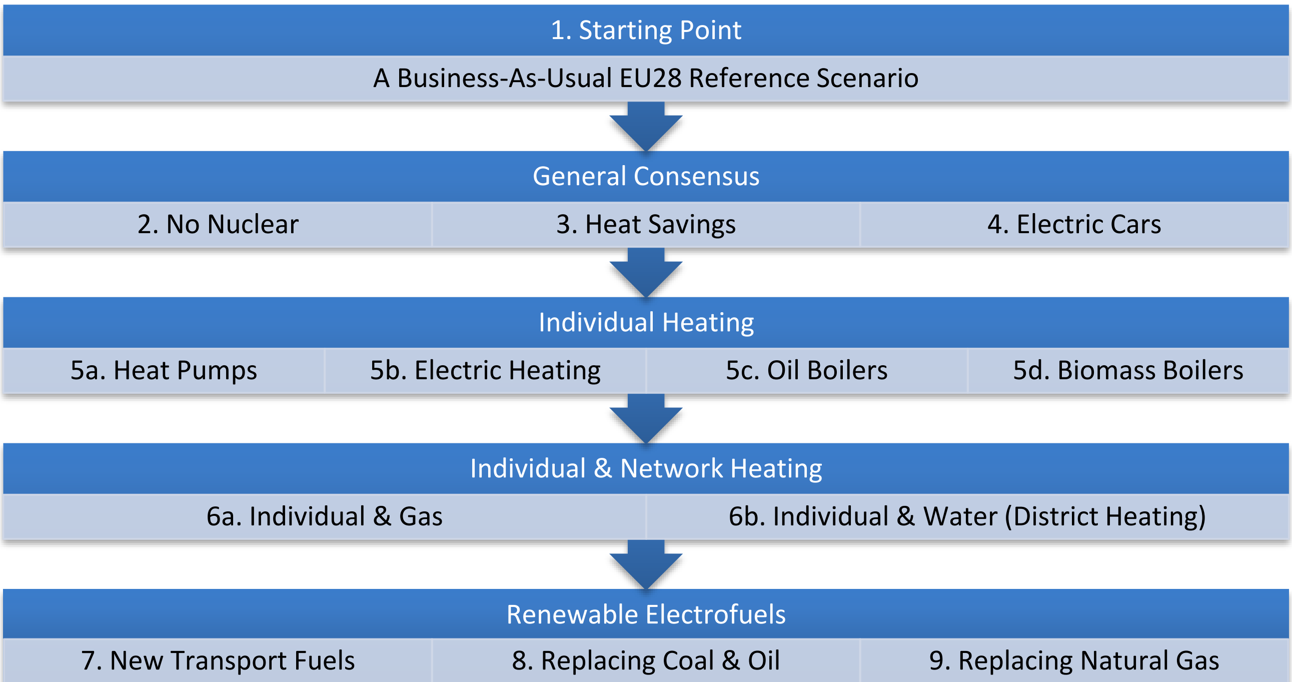

Figure 4: Transition steps in this study from a 2050 reference energy system to a Smart Energy System for the EU.

Once the heat supply has been defined, the next big issue is the fuel for 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 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 of 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 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 [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 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 process for renewable electrofuels are presented in Connolly *et al.* [76], four of which have been used in this study (see Table 2).

Table 2: Electrofuel pathways used in this study [76].

	Electrofuel Produced	
Carbon Source	**Liquid**	**Gas**
Bioenergy	Bioenergy hydrogenation to methanol/DME (Figure 5)	Bioenergy hydrogenation to methane [42, 76]
Carbon Capture and Recycling (CCR)*	CO_2 hydrogenation to methanol/DME [42, 76]	CO_2 hydrogenation to methane (Figure 6)

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

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 CCR, while the final fuel can be either liquid (methanol/DME) or gas (methane). It is assumed in step 7 of this study 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 bioenergy as a carbon source (bio-electrofuel: Figure 5) and the other half is methanol/DME produced using carbon from a power plant (CO_2-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 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 [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 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.

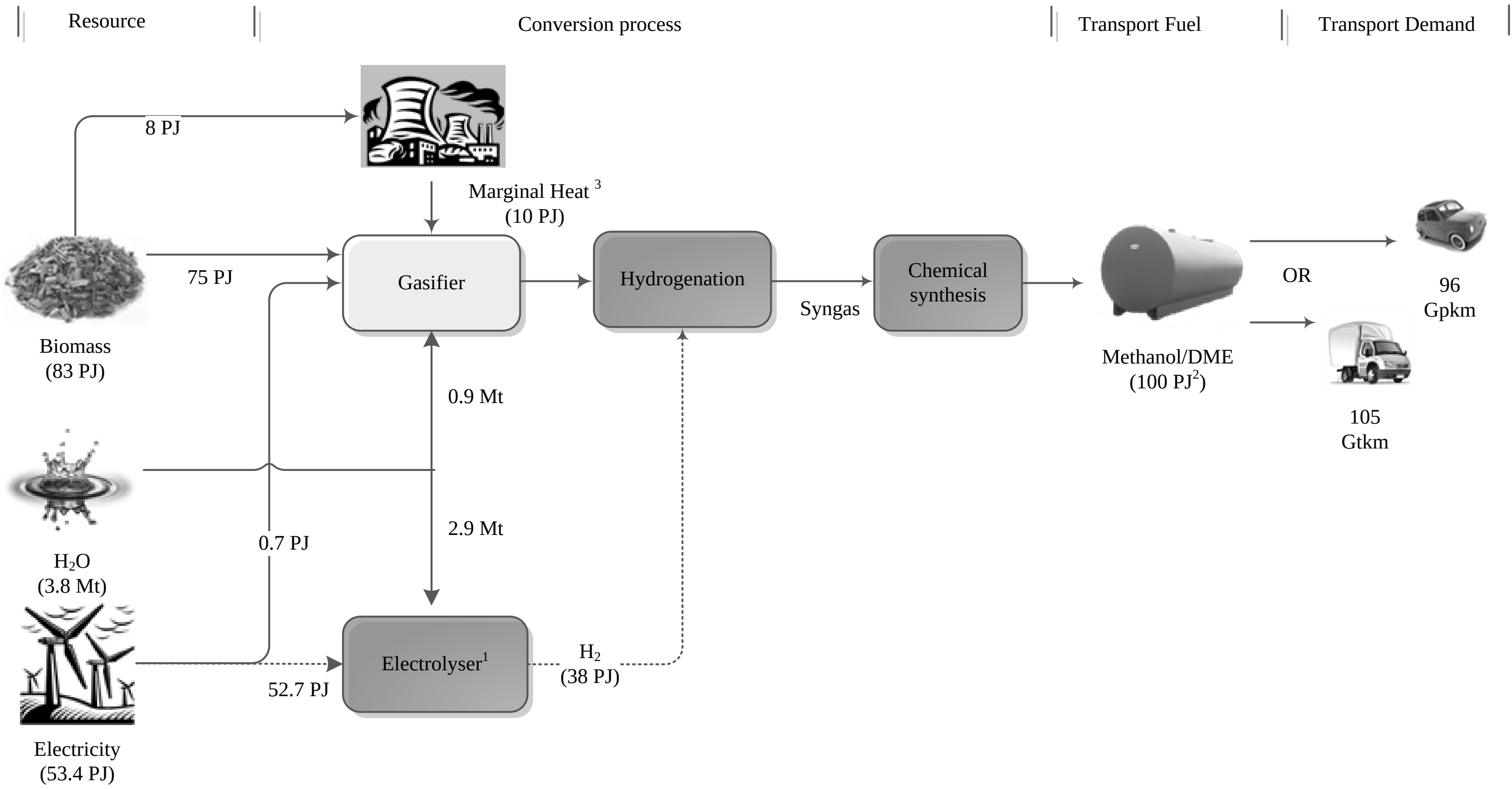

Figure 5: An example of a bio-electrofuel production process: biomass is gasified and the resulting gas is hydrogenated to produce methanol or dimethyl ether (DME) [42, 76].

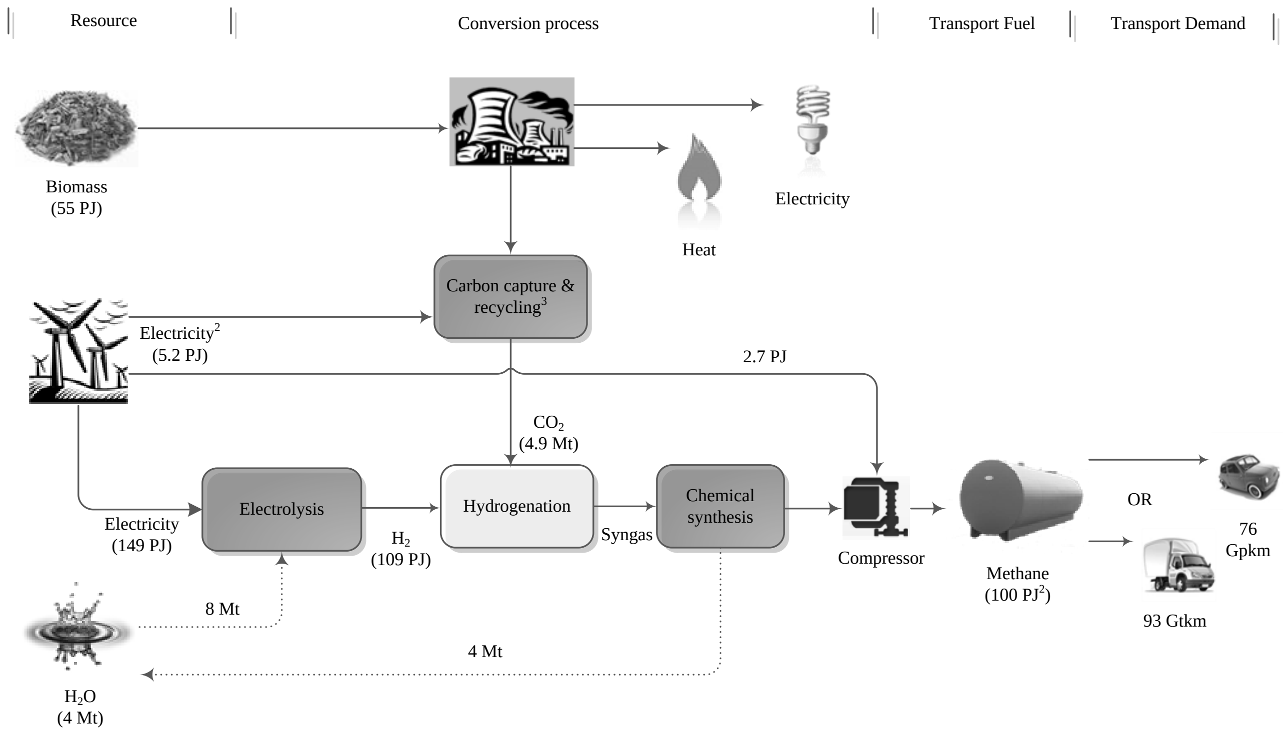

Figure 6: An example of a CO_2-electrofuel production process: carbon that is sequestered using CCR at a power plant and afterwards, it is hydrogenated to produce methane [42, 76].

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 Figure 5, but for methane [42, 76]) and half is produced using a CO_2-electrofuel (see Figure 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 how 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.

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_2 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 be used also, especially in relation to health costs since some existing studies have previously highlighted their importance [34, 43]. In each step, the intermittent renewable energy penetration is increased to the cheapest level, primarily by increasing the wind power capacity. This is to illustrate how each step increases the flexibility of the energy system.

3.1 General Consensus

To begin, Figure 7 displays the PES and carbon dioxide (CO_2) emissions for the 'General Consensus' steps. In step 2, nuclear power is removed which reduces the PES, but it increases the CO_2 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 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. 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 which use fossil fuels and so there is a corresponding increase of 8% in the total CO_2 emissions. There is also a cost increase of approximately 1% when nuclear power is removed from the energy system, based on the 2050 costs presented in the Appendix. However, the costs are likely to be higher for nuclear since the costs reported to implement nuclear power at present 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 (Figure 7) and the costs of the energy system (Figure 8).

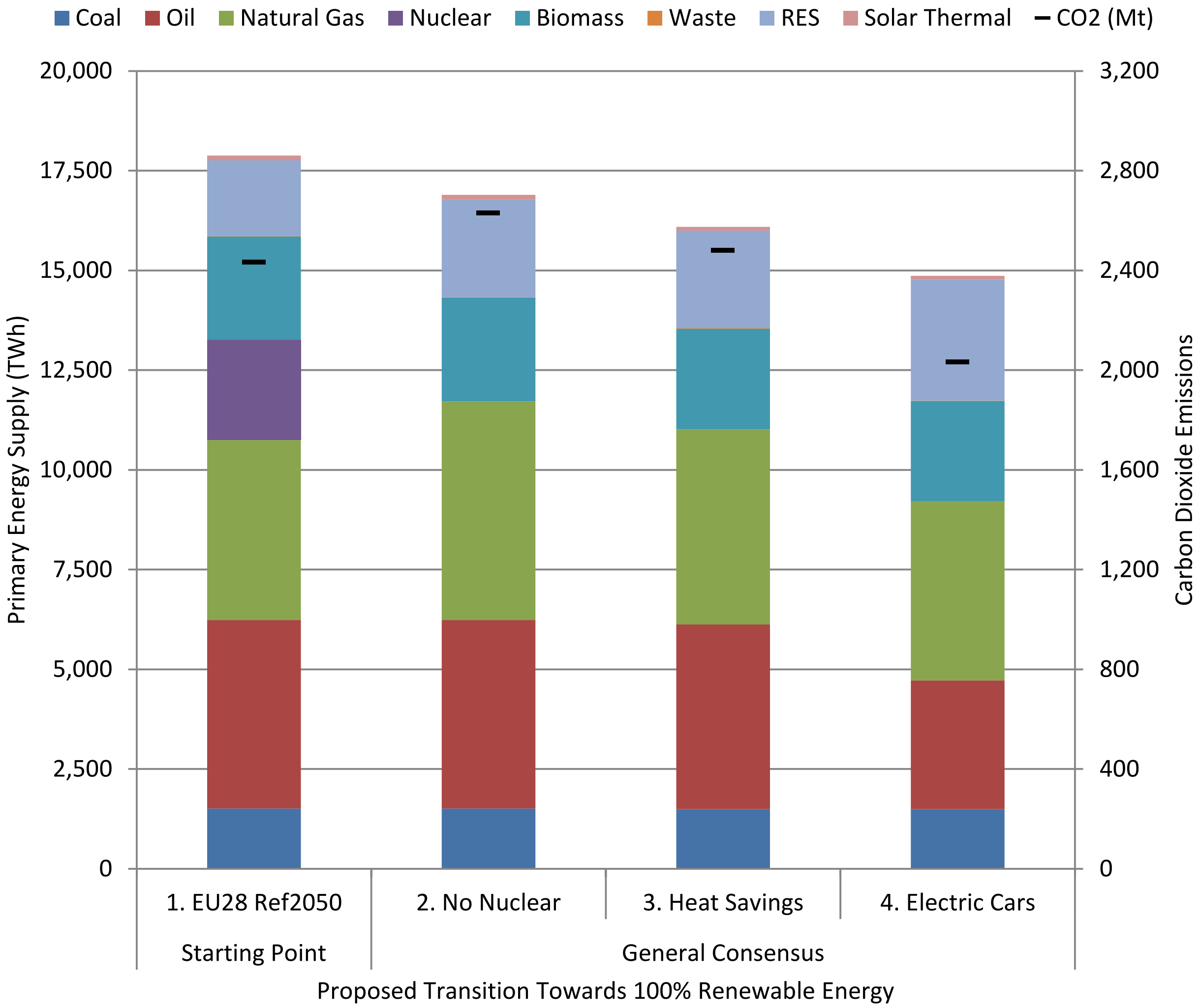

Figure 7: Primary energy supply by fuel and carbon dioxide emissions for the reference *EU28 Ref2050* scenario and the 'general consensus' steps in the transition to a Smart Energy System for Europe.

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 [74]. To make this conversion, it is assumed here 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 with the introduction of a 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 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.

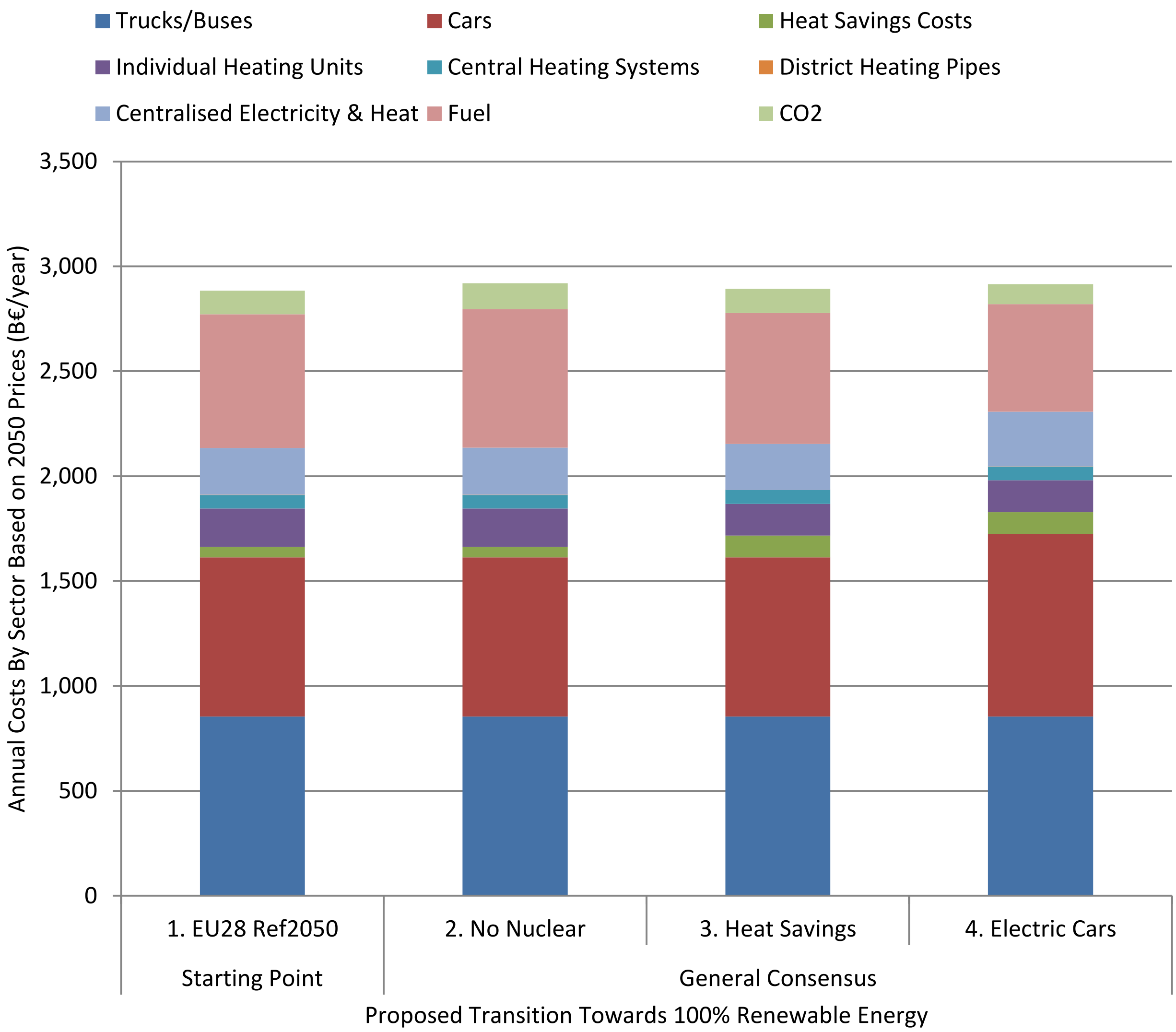

Figure 8: Annualised costs by sector for the reference *EU28 Ref2050* scenario and the 'general consensus' steps in the transition to a Smart Energy System for Europe.

To estimate the impact on the vehicle costs, it is assumed that vehicles are replaced proportionally to the fuel replaced. In other words, it is assumed that when replacing 80% of the fossil fuel with electricity, 80% of the vehicles are converted from combustion engines 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. As presented in Figure 8, 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, 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 district heating can play a significant role in reducing the CO_2 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 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 Figure 9 and Figure 10, along with a summary of the key observations in Table 3. Based on this comparison electric heating and oil boilers are clearly unsustainable heating solutions for the EU in the future. Electric heating can be provided 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 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 not available. This backup capacity is expensive to construct, even if 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.

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 dominate individual heating solution in Europe. Although it is more efficient than electric heating, it has predictably high CO_2 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_2 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 Figure 14. Therefore, if biomass boilers are implemented on a large-scale, then it is unlikely that there will be enough sustainable biomass for the transport sector also. 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 here are underestimated since it is assumed here 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, the carbon dioxide emissions are likely to be higher for biomass boilers than those presented in Figure 9 in a biomass boilers scenario.

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 as the modelling results here suggest. Furthermore, relying on electricity as the main fuel 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.

Table 3: Summary of the comparison between the various individual and network heating solutions presented in Figure 9 and Figure 10.

Heating Unit	Sustainable Resources	Efficient	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

3.3 Network Heating

After concluding that heat pumps are the most suitable individual heating unit, here they are combined with some network heating solutions to see if the combination has a positive impact. 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 in urban areas in the previous step are replaced with each of these network solutions.

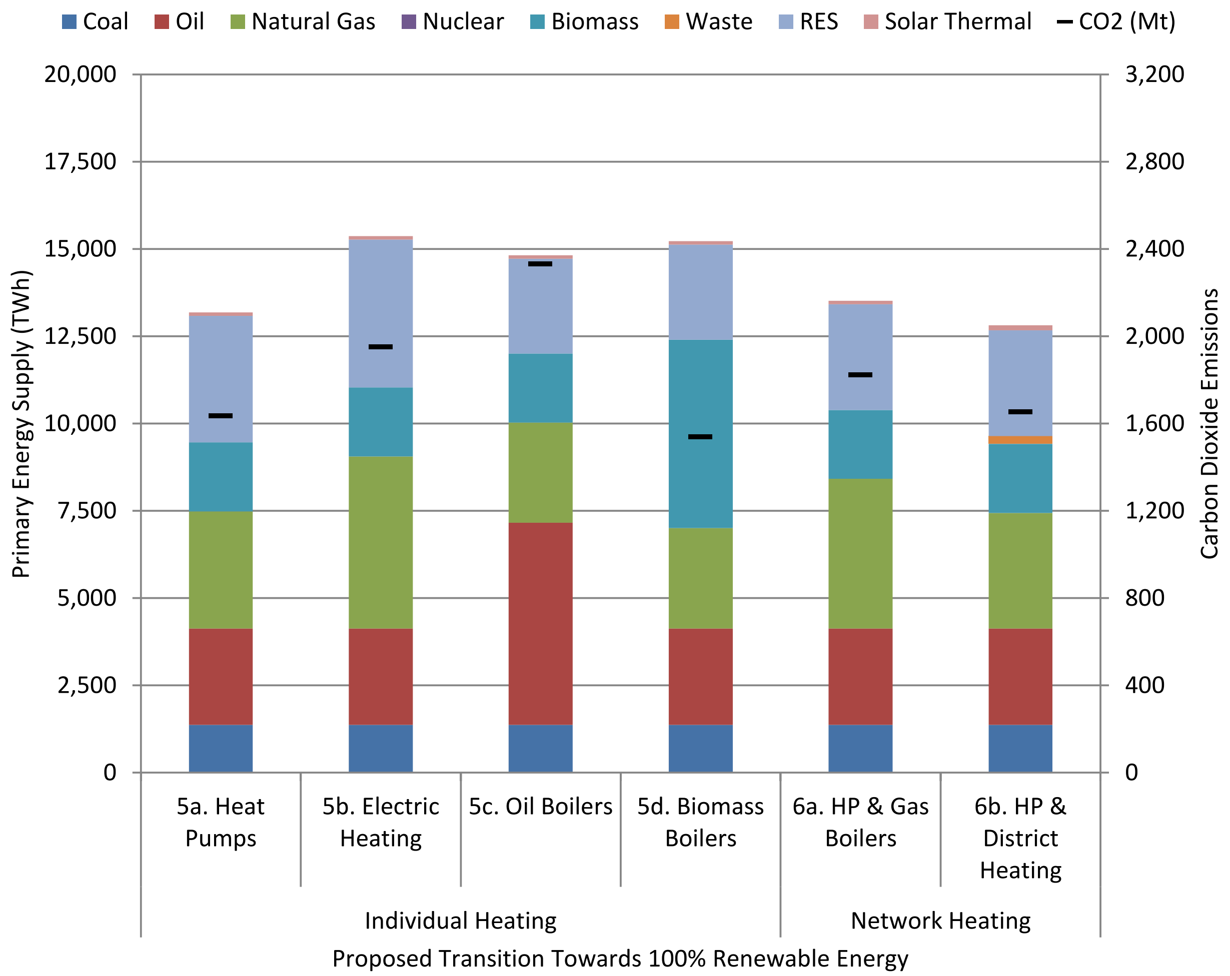

Figure 9: Primary energy supply by fuel and carbon dioxide emissions for the individual and network heating steps in the transition to a Smart Energy System for Europe.

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 solutions was identified as approximately 50% of the heat demand [6-8, 73]. Therefore, 50% of the heat demand is converted from heat pumps to 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 efficient, produces less CO_2, and costs less than the natural gas alternative based on the assumptions provided in the Appendix. 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.

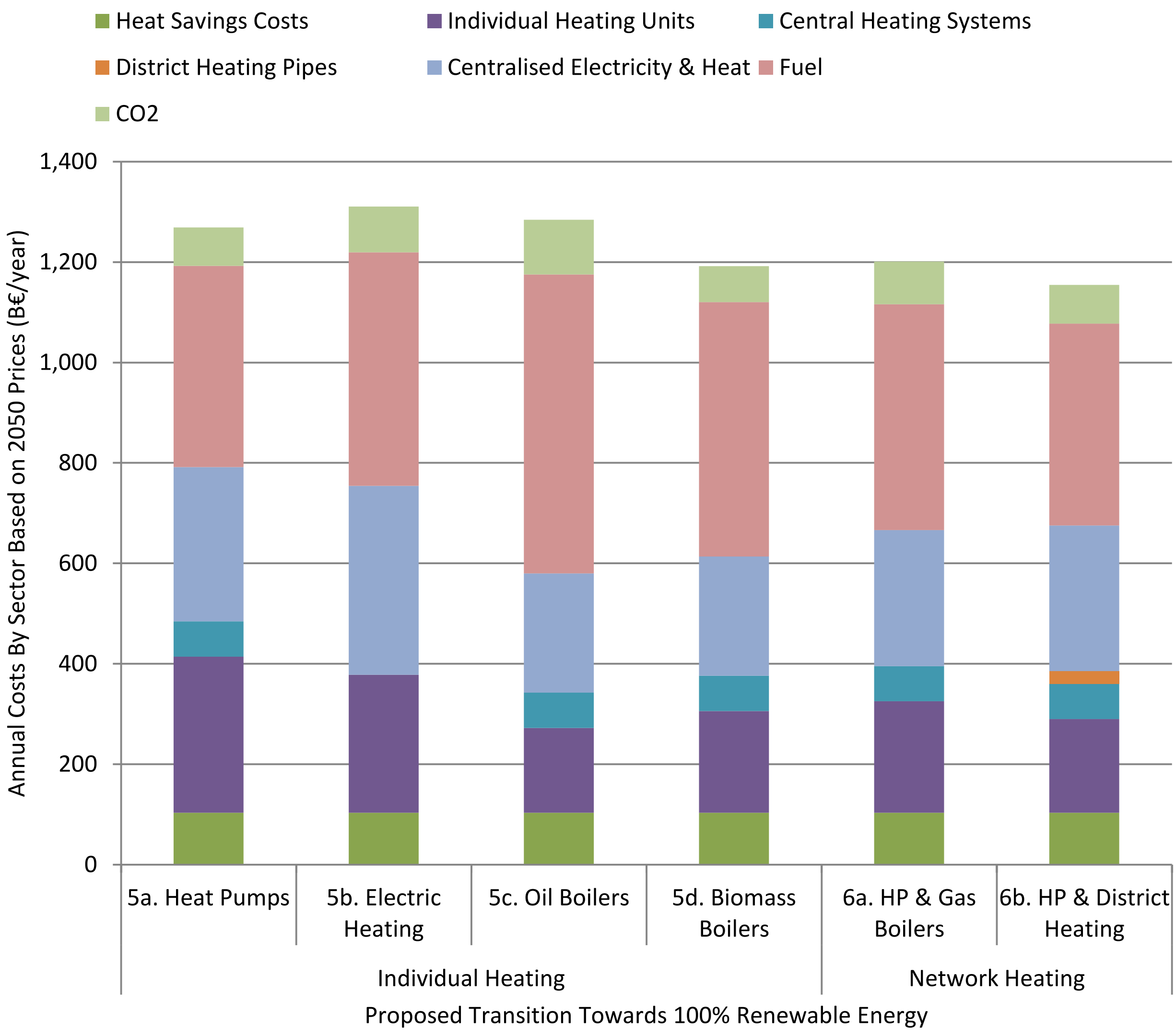

Figure 10: Annualised costs by sector for the individual and network heating steps in the transition to a Smart Energy System for Europe. *The transport system costs (i.e. costs for Trucks/Busses and Cars) have been removed from the costs here, since they are the same for all scenarios.

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 Figure 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_2 emissions are reduced by 10% the district heating scenario (or 85% less carbon 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 assumed that approximately 5% of the total heat demand in rural areas has been met using individual solar 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 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. 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_2-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 Figure 11, since more than one unit of bioenergy and/or electricity is required for one unit of electrofuel. For example, producing methanol using carbon obtained from bioenergy, as in Figure 5, then 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 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[1] and gas storage[2] [88], which is more than one-third of the total annual electricity demand in the *EU28 Ref2050* scenario. 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

[1] 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.
[2] Gas storage in Europe equates to approximately 15-20% of the gas demand.

required to produce the electrofuels. Therefore, even though the PES has increased, the CO_2 emissions are reduced by almost 40% (see Figure 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, planes, and ships.

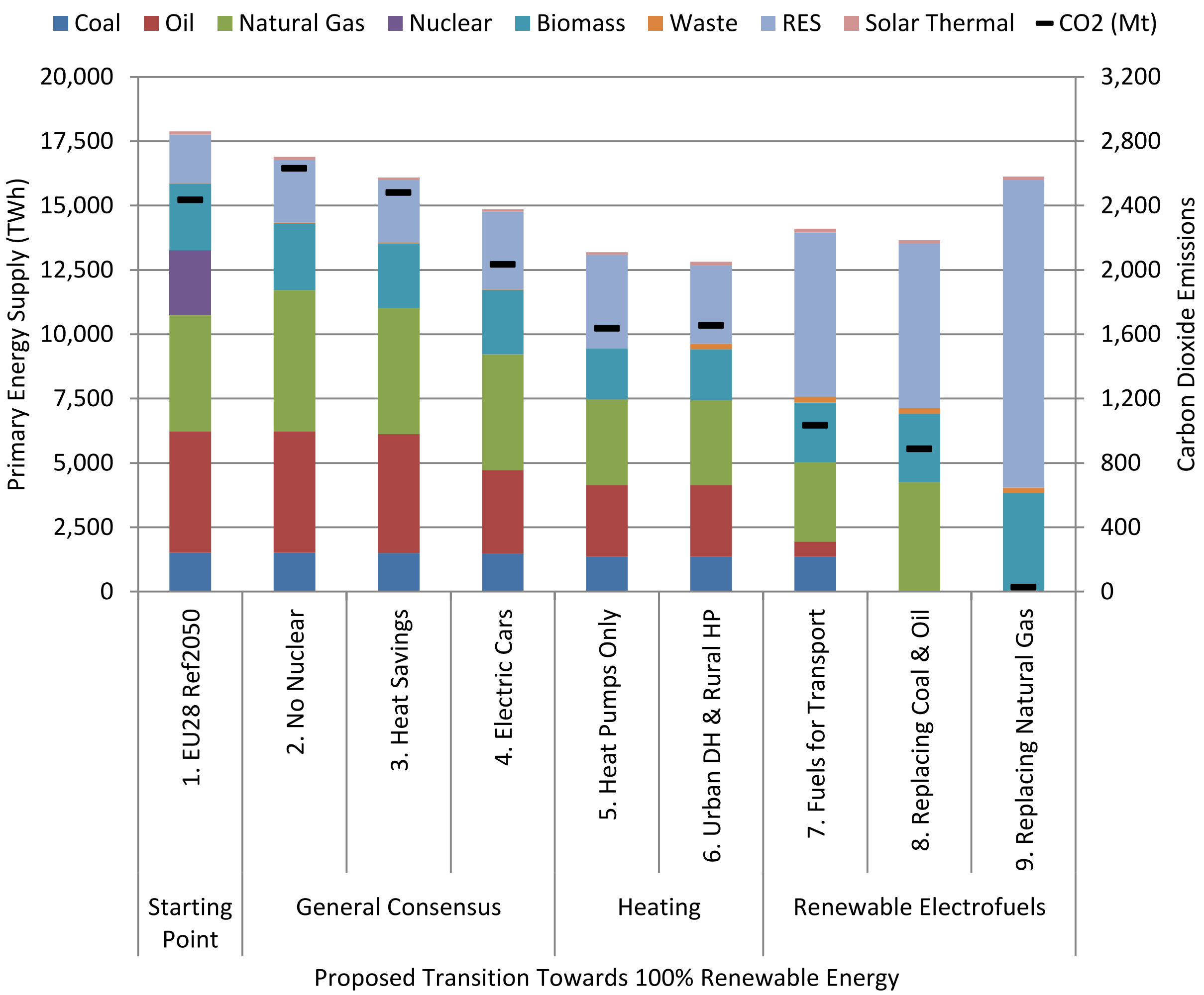

Figure 11: Primary energy supply by fuel and carbon dioxide emissions for all steps in the transition to a Smart Energy System for Europe.

Replacing oil in the trucks, ships, and aeroplanes increases the costs of the energy system by approximately 3% (see Figure 12). However, renewable electrofuels also consists of much more investments than an oil-based energy system. This is evident in Figure 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 on fuel and increasing the amount of money 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 results in an overall economic gain for the EU as there will also be more EU jobs with the production of electrofuel.

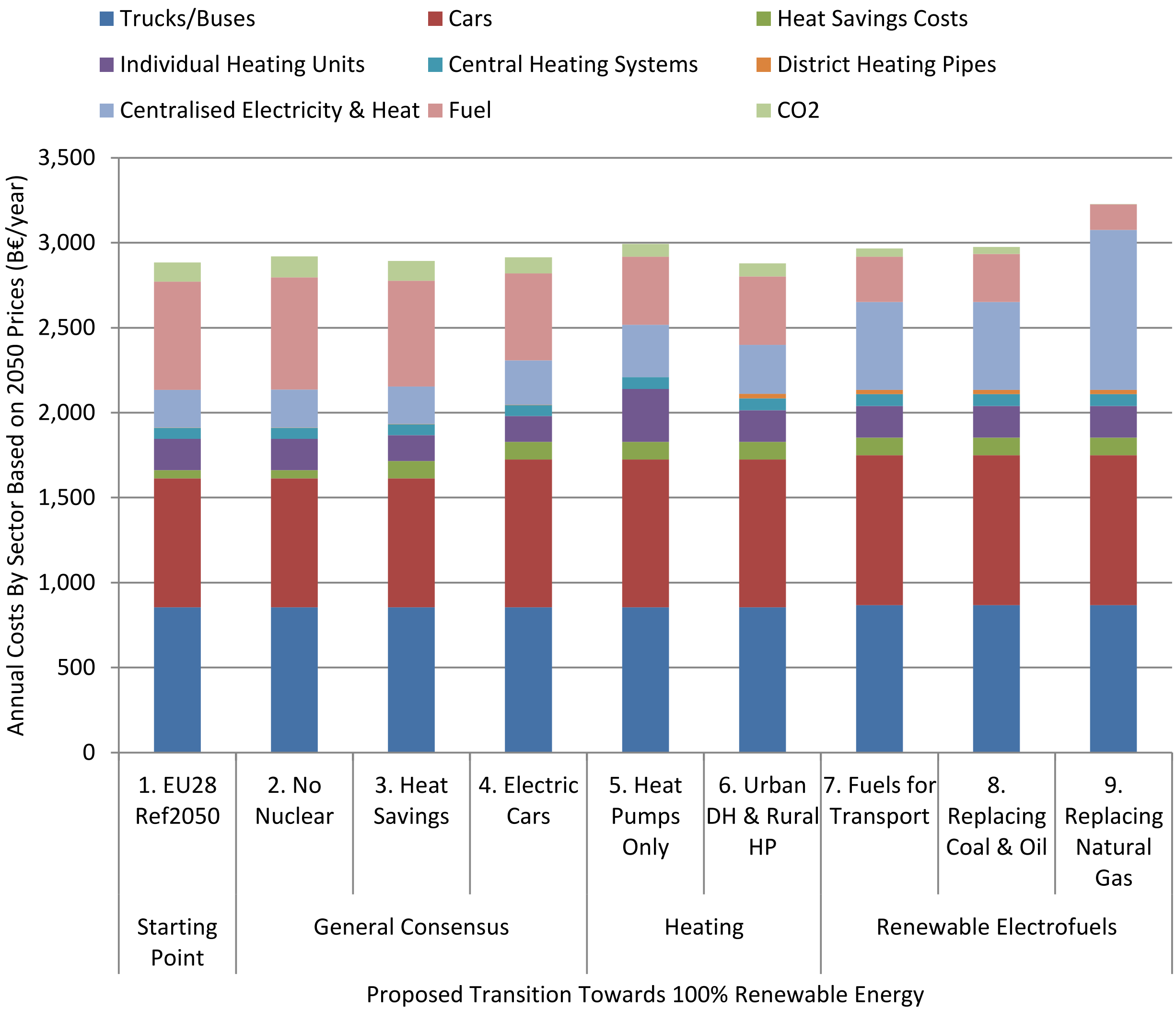

Figure 12: Annualised costs by sector for all steps in the transition to a Smart Energy System for Europe.

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.

- 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, 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 11), while the overall energy system costs remain the same as in step 7 (see Figure 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_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 reported 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. The energy flow diagram for producing methane as a CO_2-electrofuel is presented in Figure 6, where the carbon is captured from the exhaust fumes of a power plant. 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_2-electrofuel.

Once again, these renewable electrofuels connect intermittent renewable energy to large-scale and relatively cheap energy storage, 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 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 when methanol/DME replaced 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_2-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, since the overall energy system costs increase by 8% (see Figure 12), which 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 Figure 2), 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 can be the same or less than a business-as-usual scenario, such as 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, since in the final step 9, all of the energy for the EU will be provided domestically. There is no economic value placed on energy dependence 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).

The changes that occurred during each step are summarised in Table 4. 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. 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 [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 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 is increasing with each step (see Figure 13). Hence, these increases in costs will most likely be counteracted by local job creation in the EU.

Table 4: Changes that occur for each step in terms of energy, environment, and economy compared to the *EU28 Ref2050* scenario.

Metric (vs. *EU28 Ref2050*):	Energy	Environment		Economy
Scenario	(PES)	(CO_2 Emissions)	(CO_2 vs. 1990 Levels*)	(Total Annual Costs)
1. EU28 Ref2050	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%

***Assuming that energy related CO_2 emissions in 1990 were 4030.6 Mt [74]. The EU target is to reduce CO_2 emissions by 80% compared to 1990 levels [95].**

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 13). 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 5. 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 [96]. 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.

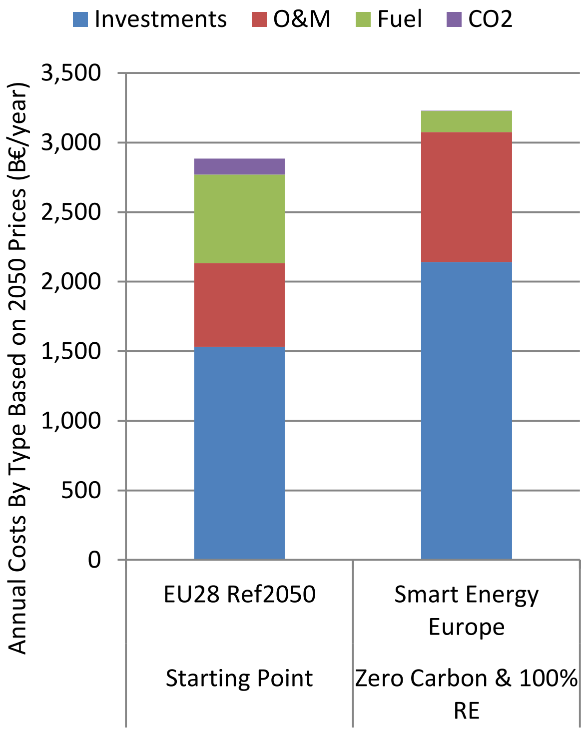

Figure 13: Annual energy system costs by type of cost the *EU28 Ref2050* scenario and the *Smart Energy Europe* scenario.

Table 5: Import shares assumed for the job creation estimates for the *EU28 Ref2050* scenario and the *Smart Energy Europe* scenario.

Assumed Import Factors		
	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%

A key consideration defining the design of the scenarios in this study is the level 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, so Figure 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 Figure 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 bioenergy demand such as:

- More CO_2-electrofuel can be produced to replace bio-electrofuel, by using the hydrogenation of carbon dioxide emissions from a power plant/industry (such as in Figure 6). CO2-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 bioenergy 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 bioenergy. However, this is likely to increase the costs of the energy system and reduce the driving range of 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_2 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.

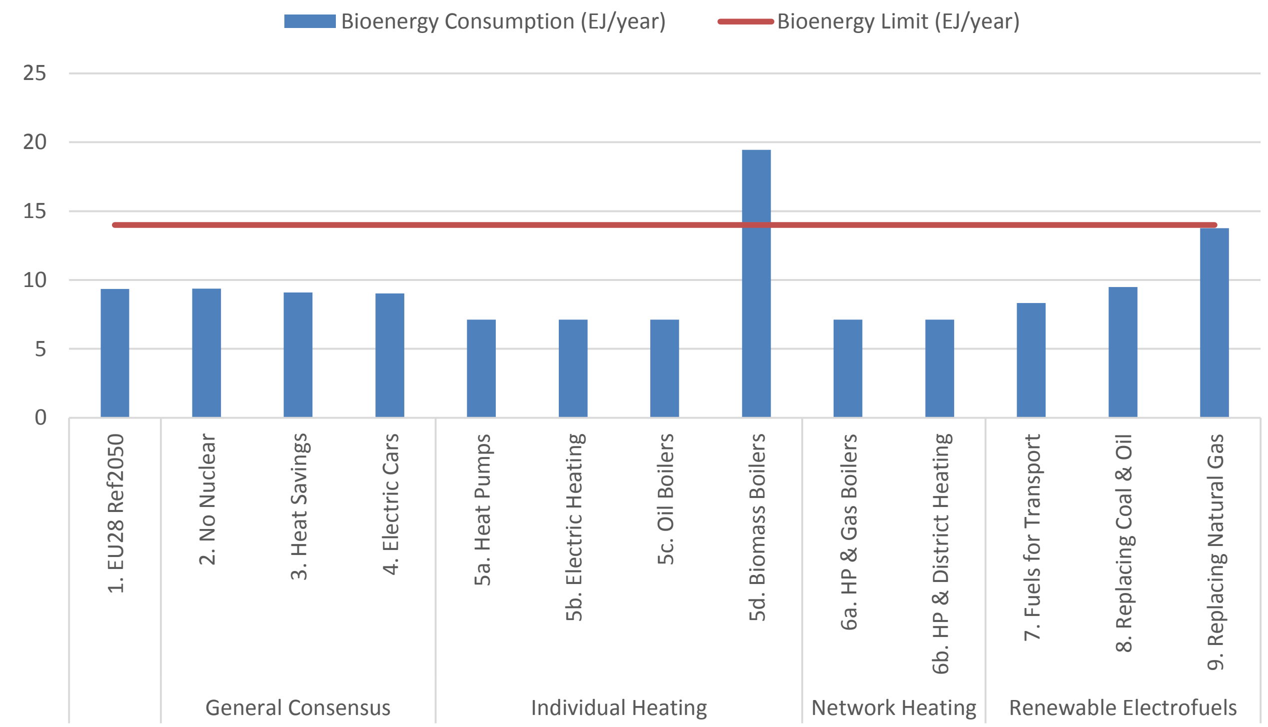

Figure 14: Bioenergy consumption for each scenario analysed during the transition to a 100% renewable energy system. The limit suggested in this Figure is based on the data from Figure 2.

It has been possible to minimise the bioenergy consumption due to the amount of intermittent renewable electricity that can now be integrated onto the electricity grid. As outlined in Figure 15, 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, 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.

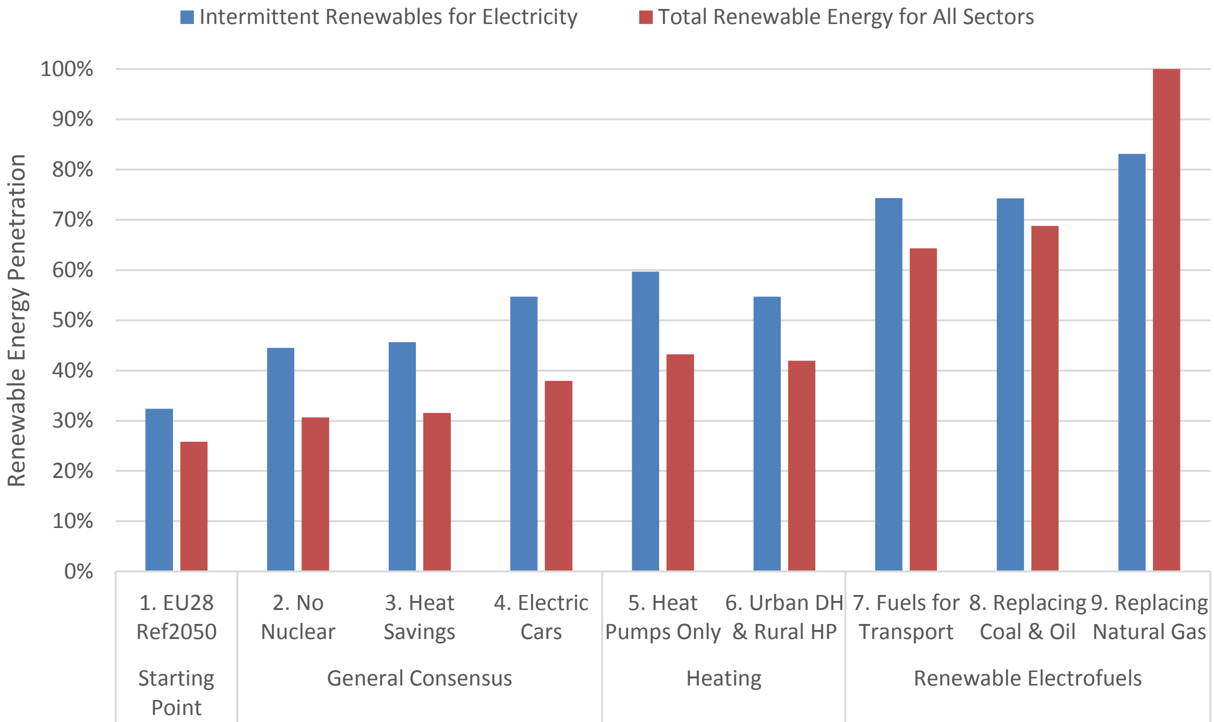

Figure 15: Penetration of renewable energy for each step in the transition from the *EU28 Ref2050* to the *Smart Energy Europe* scenario.

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 here 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 costs assumed here are also open to debate and further consideration. These costs have been presented in the Appendix 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. The costs, capacities, and demands can be varied in these models to test how sensitive the results are.

In relation to the scenarios, all technologies 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 in the year 2025. Hence, many of the steps proposed here can be implemented using existing technologies and techniques. The Renewable Electrofuel steps do however have some technological barriers that need to be overcome. All of the technologies presented in the energy flow diagrams, which are presented in Figure 5 and Figure 6, exist and have been demonstrated, but some of these are only at a relatively small-scale. The key technologies which need to be demonstrated on a large scale are biomass gasification, carbon capture, and electrolysers. 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 biomass gasification could be used as a heat source for electrolysers. 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 then CO_2 may need to be captured from the air [82], instead of power plants when producing CO_2-electrofuels. A carbon balance is not included here, so it is another opportunity for further research.

The energy systems impact 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.

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 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 consider 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 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 European 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, the environment (carbon emissions), and economy (total annual socio-economic cost). 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. These steps are based on hourly modelling of the complete energy system (i.e. electricity, heat, 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 the total annual cost of the EU energy system will be approximately 3% higher than the fossil fuel alternative 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 these were beyond the scope of this study [40]. 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 a major increase in the 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, no and 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, carbon capture and recycling, electrolysers, 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, 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 availability of cost-effective solutions.

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7 References

[1] Elliston B, MacGill I, Diesendorf M. Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market. **Renewable Energy** 2014;66(0):196-204.

[2] Glasnovic Z, Margeta J. Vision of total renewable electricity scenario. **Renewable and Sustainable Energy Reviews** 2011;15(4):1873-1884.

[3] Spiecker S, Weber C. The future of the European electricity system and the impact of fluctuating renewable energy – A scenario analysis. **Energy Policy** 2014;65(0):185-197.

[4] Steinke F, Wolfrum P, Hoffmann C. Grid vs. storage in a 100% renewable Europe. **Renewable Energy** 2013;50(0):826-832.

[5] Connolly D, Hansen K, Drysdale D, Lund H, Mathiesen BV, Werner S, Persson U, Möller B, Wilke OG, Bettgenhäuser K, Pouwels W, Boermans T, Novosel T, Krajačić G, Duić N, Trier D, Møller D, Odgaard AM, Jensen LL. (Heat Roadmap Europe 3 and STRATEGO WP2 Main Report) Enhanced Heating and Cooling Plans to Quantify the Impact of Increased Energy Efficiency in EU Member States: Translating the Heat Roadmap Europe Methodology to Member State Level. Aalborg University, Halmstad University, University of Flensburg, Ecofys, University of Zagreb, and PlanEnergi, 2015. Available from: http://www.heatroadmap.eu.

[6] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, Persson U, Werner S, Grözinger J, Boermans T, Bosquet M, Trier D. Heat Roadmap Europe: Second pre-study. Aalborg University, Halmstad University, Ecofys Germany GmbH, PlanEnergi, and Euroheat & Power, 2013. Available from: http://vbn.aau.dk/.

[7] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, Trier D, Persson U, Nilsson D, Werner S. Heat Roadmap Europe: First pre-study for EU27. Aalborg University, Halmstad University, and Euroheat & Power, 2012. Available from: http://vbn.aau.dk/.

[8] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, Boermans T, Trier D, Østergaard PA, Nielsen S. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. **Energy Policy** 2014;65:475–489.

[9] Kloess M, Zach K. Bulk electricity storage technologies for load-leveling operation – An economic assessment for the Austrian and German power market. **International Journal of Electrical Power & Energy Systems** 2014;59(0):111-122.

[10] Loisel R. Power system flexibility with electricity storage technologies: A technical–economic assessment of a large-scale storage facility. **International Journal of Electrical Power & Energy Systems** 2012;42(1):542-552.

[11] Jacobson MZ, Delucchi MA. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. **Energy Policy** 2011;39(3):1154-1169.

[12] World Energy Council. Survey of Energy Resources. World Energy Council, 2010. Available from: http://www.worldenergy.org.

[13] IEA Bioenergy. Potential Contribution of Bioenergy to the World's Future Energy Demand. IEA Bioenergy, 2007. Available from: http://ieabioenergy.com/.

[14] Offermann R, Seidenberger T, Thrän D, Kaltschmitt M, Zinoviev S, Miertus S. Assessment of global bioenergy potentials. **Mitigation and Adaptation Strategies for Global Change** 2011;16(1):103-115.

[15] Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC. A bottom-up assessment and review of global bio-energy potentials to 2050. **Progress in Energy and Combustion Science** 2007;33(1):56-106.

[16] Berndes G, Hoogwijk M, van den Broek R. The contribution of biomass in the future global energy supply: a review of 17 studies. **Biomass and Bioenergy** 2003;25(1):1-28.

[17] Fischer G, Schrattenholzer L. Global bioenergy potentials through 2050. **Biomass and Bioenergy** 2001;20(3):151-159.

[18] Hoogwijk M, Faaij A, de Vries B, Turkenburg W. Exploration of regional and global cost–supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. **Biomass and Bioenergy** 2009;33(1):26-43.

[19] Haberl H, Erb K-H, Krausmann F, Bondeau A, Lauk C, Müller C, Plutzar C, Steinberger JK. Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. **Biomass and Bioenergy** 2011;35(12):4753-4769.

[20] Gregg J, Smith S. Global and regional potential for bioenergy from agricultural and forestry residue biomass. **Mitigation and Adaptation Strategies for Global Change** 2010;15(3):241-262.
[21] E3M-Lab, IIASA-GAINS model, IIASA-GLOBIOM model, and EuroCARE. EU Energy, Transport, and GHG Emissions Trends to 2050: Reference Scenario 2013. European Union and European Commission, 2014. Available from: http://ec.europa.eu/.
[22] United Nations. Department of Economic and Social Affairs, Population Division, Population Estimates and Projection Section. World Population Prospects: The 2012 Revision. Available from: http://esa.un.org/ [accessed 14 May 2014].
[23] International Energy Agency. Energy Balances of OECD Countries. International Energy Agency, 2011. Available from: http://www.iea.org/.
[24] International Energy Agency. Energy Balances of Non-OECD Countries. International Energy Agency, 2011. Available from: http://www.iea.org/.
[25] Smeets EW, Faaij AC. Bioenergy potentials from forestry in 2050. **Climatic Change** 2007;81(3-4):353-390.
[26] Bentsen NS, Felby C. Biomass for energy in the European Union - a review of bioenergy resource assessments. **Biotechnology for Biofuels** 2012;5(25).
[27] Shell Oil Company. The Evolution of the World's Energy Systems. Shell International Limited, Group External Affairs, SIL Shell Centre, London, United Kingdom, 1996.
[28] Hall D, Rosillo-Calle F, Williams R, Woods J, Biomass for energy: Supply prospects, in: T Johansson, et al. (Eds.), Renewable energy: sources for fuels and electricity, Island, Washington D.C, 1993
[29] de Wit M, Faaij A. European biomass resource potential and costs. **Biomass and Bioenergy** 2010;34(2):188-202.
[30] Lund H. Renewable Energy Systems: The Choice and Modeling of 100% Renewable Solutions. Academic Press, Elsevier, Burlington, Massachusetts, USA, 2010. ISBN: 978-0-12-375028-0.
[31] Lund H. Renewable Energy Systems: A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions. Academic Press, Elsevier, Massachusetts, USA, 2014. ISBN: 978-0-12-410423-5.
[32] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems - A market operation based approach and understanding. **Energy** 2012;42(1):96-102.
[33] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. **International Journal of Sustainable Energy Planning and Management** 2014;1:7-28.
[34] Mathiesen BV, Lund H, Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. **Applied Energy** 2011;88(2):488-501.
[35] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, Mathiesen BV. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. **Energy** 2014;68(0):1-11.
[36] Lund H, Mathiesen BV, Connolly D, Østergaard PA. Renewable Energy Systems - A Smart Energy Systems Approach to the Choice and Modelling of 100 % Renewable Solutions. **Chemical Engineering Transactions** 2014;39.
[37] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, Nielsen S, Ridjan I, Karnøe P, Sperling K, Hvelplund FK. Smart Energy Systems for coherent 100% renewable energy and transport solutions. **Applied Energy** 2015;145(0):139-154.
[38] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B. The design of Smart Energy Systems for 100% renewable energy and transport solutions. In: Proceedings of the 8th Dubrovnik Conference for Sustainable Development of Energy, Water and Environment Systems. Dubrovnik, Croatia, 22-27 September, 2013.
[39] Mathiesen BV, Lund H, Connolly D. Heating technologies for limiting biomass consumption in 100% renewable energy systems. In: Proceedings of the 6th Dubrovnik Conference for Sustainable

Development of Energy, Water and Environment Systems. Dubrovnik, Croatia, 25-29 September, 2011.

[40] Lund H, Mathiesen BV, Hvelplund FK, Østergaard PA, Christensen P, Connolly D, Schaltz E, Pillay JR, Nielsen MP, Felby C, Bentsen NS, Meyer NI, Tonini D, Astrup T, Heussen K, Morthorst PE, Andersen FM, Münster M, Hansen L-LP, Wenzel H, Hamelin L, Munksgaard J, Karnøe P, Lind M. Coherent Energy and Environmental System Analysis. Aalborg University, 2011. Available from: http://www.ceesa.plan.aau.dk.

[41] Connolly D, Lund H, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Ridjan I, Hvelplund F, Sperling K, Karnøe P, Carlson AM, Kwon PS, Bryant SM, Sorknæs P. Smart Energy Systems : Holistic and Integrated Energy Systems for the era of 100% Renewable Energy. Sustainable Energy Planning Research Group, Aalborg University, 2013. Available from: http://vbn.aau.dk/.

[42] Mathiesen BV, Connolly D, Lund H, Nielsen MP, Schaltz E, Wenzel H, Bentsen NS, Felby C, Kaspersen P, Hansen K. CEESA 100% Renewable Energy Transport Scenarios towards 2050: Technical Background Report Part 2. Aalborg University, 2014. Available from: http://www.ceesa.plan.aau.dk/.

[43] Delucchi MA, Jacobson MZ. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. **Energy Policy** 2011;39(3):1170-1190.

[44] Jacobson MZ, Delucchi MA, Ingraffea AR, Howarth RW, Bazouin G, Bridgeland B, Burkart K, Chang M, Chowdhury N, Cook R, Escher G, Galka M, Han L, Heavey C, Hernandez A, Jacobson DF, Jacobson DS, Miranda B, Novotny G, Pellat M, Quach P, Romano A, Stewart D, Vogel L, Wang S, Wang H, Willman L, Yeskoo T. A roadmap for repowering California for all purposes with wind, water, and sunlight. **Energy** 2014;73(0):875-889.

[45] Lienert M, Lochner S. The importance of market interdependencies in modeling energy systems – The case of the European electricity generation market. **International Journal of Electrical Power & Energy Systems** 2012;34(1):99-113.

[46] Erdener BC, Pambour KA, Lavin RB, Dengiz B. An integrated simulation model for analysing electricity and gas systems. **International Journal of Electrical Power & Energy Systems** 2014;61(0):410-420.

[47] Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. **Proceedings of the National Academy of Sciences of the United States of America** 2015;112(49).

[48] Connor PM, Baker PE, Xenias D, Balta-Ozkan N, Axon CJ, Cipcigan L. Policy and regulation for smart grids in the United Kingdom. **Renewable and Sustainable Energy Reviews** 2014;40(0):269-286.

[49] Phuangpornpitak N, Tia S. Opportunities and Challenges of Integrating Renewable Energy in Smart Grid System. **Energy Procedia** 2013;34(0):282-290.

[50] Orecchini F, Santiangeli A. Beyond smart grids – The need of intelligent energy networks for a higher global efficiency through energy vectors integration. **International Journal of Hydrogen Energy** 2011;36(13):8126-8133.

[51] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. **Applied Energy** 2010;87(4):1059-1082.

[52] Chai DS, Wen JZ, Nathwani J. Simulation of cogeneration within the concept of smart energy networks. **Energy Conversion and Management** 2013;75(0):453-465.

[53] Lund PD, Mikkola J, Ypyä J. Smart energy system design for large clean power schemes in urban areas. **Journal of Cleaner Production** (0).

[54] Mathiesen BV, Lund RS, Connolly D, Ridjan I, Nielsen S. Copenhagen Energy Vision: A sustainable vision for bringing a Capital to 100% renewable energy. Aalborg University, 2015. Available from: http://vbn.aau.dk/.

[55] Østergaard PA, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. **Energy** 2010;35(12):4892-4901.

[56] Bussar C, Moos M, Alvarez R, Wolf P, Thien T, Chen H, Cai Z, Leuthold M, Sauer DU, Moser A. Optimal Allocation and Capacity of Energy Storage Systems in a Future European Power System with 100% Renewable Energy Generation. **Energy Procedia** 2014;46(0):40-47.
[57] Schaber K, Steinke F, Mühlich P, Hamacher T. Parametric study of variable renewable energy integration in Europe: Advantages and costs of transmission grid extensions. **Energy Policy** 2012;42(0):498-508.
[58] McKinsey & Company, KEMA, The Energy Futures Lab at Imperial College London, and Oxford Economics. Roadmap 2050: A practical guide to prosperous low-carbon Europe. The European Climate Foundation, 2010. Available from: http://www.roadmap2050.eu/.
[59] German Advisory Council on the Environment. Pathways Towards a 100% Renewable Electricity System: Summary for policy makers. German Advisory Council on the Environment, 2014. Available from: http://www.umweltrat.de/.
[60] Aalborg University. EnergyPLAN: Advanced Energy System Analysis Computer Model. Available from: http://www.energyplan.eu/ [accessed 8 September 2014].
[61] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. **Applied Energy** 2015;154(0):921-933.
[62] Krajačić G, Duić N, Zmijarević Z, Mathiesen BV, Vučinić AA, da Graça Carvalho M. Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction. **Applied Thermal Engineering** 2011;31(13):2073-2083.
[63] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems--The case of Denmark in years 2030 and 2050. **Energy** 2009;34(5):524-531.
[64] Sáfián F. Modelling the Hungarian energy system – The first step towards sustainable energy planning. **Energy** 2014;69(0):58-66.
[65] Lund H, Aalborg University. EnergyPLAN Documentaiton: Version 12. Aalborg University, 2015. Available from: www.EnergyPLAN.eu.
[66] Lund H, Hvelplund F. The economic crisis and sustainable development: The design of job creation strategies by use of concrete institutional economics. **Energy** 2012;43(1):192-200.
[67] European Commission. R&D involvement in the EU Economic Recovery Plan: focus on the three Public Private Partnerships: The Energy-efficient buildings, Factories of Future and European Green Cars Initiatives European Commission, 2009. Available from: http://ec.europa.eu/.
[68] Richardson DB. Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. **Renewable and Sustainable Energy Reviews** 2013;19(0):247-254.
[69] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. **Energy Policy** 2008;36(9):3578-3587.
[70] Turton H, Moura F. Vehicle-to-grid systems for sustainable development: An integrated energy analysis. **Technological Forecasting and Social Change** 2008;75(8):1091-1108.
[71] Andersen PH, Mathews JA, Rask M. Integrating private transport into renewable energy policy: The strategy of creating intelligent recharging grids for electric vehicles. **Energy Policy** 2009;37(7):2481-2486.
[72] Lund H, Thellufsen JZ, Aggerholm S, Wittchen KB, Nielsen S, Mathiesen BV, Möller B. Heat Saving Strategies in Sustainable Smart Energy Systems. Aalborg University, 2014. Available from: http://vbn.aau.dk/en/.
[73] Persson U, Möller B, Werner S. Heat Roadmap Europe: Identifying strategic heat synergy regions. **Energy Policy** 2014;74:663-681.
[74] European Commission. Impact Assessment Accompanying the document Energy Roadmap 2050 (Part 2/2). European Commission, 2011. Available from: http://ec.europa.eu/.
[75] European Commission. Impact Assessment Accompanying the document Energy Roadmap 2050 (Part 1/2). European Commission, 2011. Available from: http://ec.europa.eu/.
[76] Connolly D, Mathiesen BV, Ridjan I. A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. **Energy** 2014;73:110-125.

[77] Semelsberger TA, Borup RL, Greene HL. Dimethyl ether (DME) as an alternative fuel. **Journal of Power Sources** 2006;156(2):497-511.
[78] COWI. Alternative drivmidler i transportsektoren (Alternative Fuels for Transport). Danish Energy Agency, 2013. Available from: http://www.ens.dk/.
[79] European Biofuels Technology Platform. Biofuel Fact Sheet: Methanol from biomasss. European Biofuels Technology Platform, 2011. Available from: http://www.biofuelstp.eu/.
[80] European Biofuels Technology Platform. Biofuel Fact Sheet: Dimethyl ether (DME). European Biofuels Technology Platform, 2011. Available from: http://www.biofuelstp.eu/.
[81] Graves C, Ebbesen SD, Mogensen M, Lackner KS. Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy. **Renewable and Sustainable Energy Reviews** 2011;15(1):1-23.
[82] Lackner KS. Capture of carbon dioxide from ambient air. **Eur. Phys. J. Special Topics** 2009;176:93-106.
[83] Yan Q, Yu F, Liu J, Street J, Gao J, Cai Z, Zhang J. Catalytic conversion wood syngas to synthetic aviation turbine fuels over a multifunctional catalyst. **Bioresource Technology** 2013;127:281-290.
[84] Moses CA, Roets PNJ. Properties, Characteristics, and Combustion Performance of Sasol Fully Synthetic Jet Fuel. **Journal of Engineering for Gas Turbines and Power** 2009;131(4).
[85] Lovins AB, Sheikh I. The Nuclear Illusion. Rocky Mountain Institute, 2008. Available from: http://www.rmi.org.
[86] Harris G, Heptonstall P, Gross R, Handley D. Cost estimates for nuclear power in the UK. **Energy Policy** 2013;62(0):431-442.
[87] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. **Energy** 2012;48(1):160-168.
[88] European Federation of Energy Traders. Gas Storage in Europe. European Federation of Energy Traders, 2009. Available from: http://www.efet.org/.
[89] Electric Power Research Institute. Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. Electric Power Research Institute, 2010. Available from: http://www.epri.com/.
[90] Dahl KH, Oiltanking Copenhagen A/S, 2013: Oil Storage Tank. Personal Communication, Received 30 September 2013.
[91] European Commission. Energy production and imports. Available from: http://epp.eurostat.ec.europa.eu [accessed 15 May 2014].
[92] Lund H, Mathiesen BV. The role of Carbon Capture and Storage in a future sustainable energy system. **Energy** 2012;44(1):469-476.
[93] Federal Energy Regulatory Commission. Current State Of and Issues Concerning Underground Natural Gas Storage. Federal Energy Regulatory Commission, 2004. Available from: http://www.ferc.gov/.
[94] Gracceva F, Zeniewski P. A systemic approach to assessing energy security in a low-carbon EU energy system. **Applied Energy** 2014;123(0):335-348.
[95] European Commission. Energy Roadmap 2050. European Commission, 2011. Available from: http://ec.europa.eu/.
[96] Lund H. A Green Energy Plan for Denmark. **Environmental and Resource Economics** 1998;14(3):431-439.
[97] Wenzel H. Breaking the biomass bottleneck of the fossil free society. CONCITO, 2010. Available from: http://www.concito.dk/.
[98] Zvingilaite E. Human health-related externalities in energy system modelling the case of the Danish heat and power sector. **Applied Energy** 2011;88(2):535-544.
[99] Hvelplund F, Möller B, Sperling K. Local ownership, smart energy systems and better wind power economy. **Energy Strategy Reviews** 2013;1(3):164-170.

[100] Sperling K, Hvelplund F, Mathiesen BV. Centralisation and decentralisation in strategic municipal energy planning in Denmark. **Energy Policy** 2011;39(3):1338-1351.
[101] Danish Energy Agency. Forudsætninger for samfundsøkonomiske analyser på energiområdet (Assumptions for socio-economic analysis on energy). Danish Energy Agency, 2011. Available from: http://www.ens.dk.
[102] Danish Energy Agency and Energinet.dk. Technology Data for Energy Plants: Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. Danish Energy Agency and Energinet.dk, 2012. Available from: http://www.ens.dk/.
[103] Mathiesen BV, Blarke MB, Hansen K, Connolly D. The role of large-scale heat pumps for short term integration of renewable energy. Department of Development and Planning, Aalborg University, 2011. Available from: http://vbn.aau.dk.
[104] Gonzalez A, Ó'Gallachóir B, McKeogh E, Lynch K. Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland. Sustainable Energy Authority of Ireland, 2004. Available from: http://www.seai.ie/Grants/Renewable_Energy_RD_D/Projects_funded_to_date/Wind/Study_of_Elec_Storage_Technologies_their_Potential_to_Address_Wind_Energy_Intermittency_in_Irl.
[105] Mathiesen BV, Ridjan I, Connolly D, Nielsen MP, Hendriksen PV, Mogensen MB, Jensen SH, Ebbesen SD. Technology data for high temperature solid oxide electrolyser cells, alkali and PEM electrolysers. Aalborg University, 2013. Available from: http://vbn.aau.dk/.
[106] COWI. Alternative drivmidler i transportsektoren (Alternative Fuels for Transport). Danish Energy Agency, 2012. Available from: http://www.ens.dk/.
[107] Joint Research Centre. Technology Map of the European Strategic Energy Technology Plan (SET-Plan): Technology Descriptions. European Union, 2011. Available from: http://setis.ec.europa.eu/.

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

Table 6: Fuel costs and fuel handling costs assumed for 2050 [101].

Fuel	Fuel Costs* (€/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	-	-	-

***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	TWh/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	TWh	40	30	1.0%
Solar Thermal	TWh/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	GWh	7.5	50	1.5%
Geothermal PP	MWe	2.4	20	3.5%
Electrofuels				
SOEC Electrolyser	MWe	0.3	15	3.0%
Hydrogen Storage	GWh	20	30	0.5%
Chemical Synthesis MeOH	MW-Fuel	0.6	20	3.5%
Carbon Capture Costs for CO_2-ElectroFuel	Mt	30	25	0.0%
Energy Storage				
Thermal Storage	GWh	3.0	20	0.7%
Pumped Hydroelectric Energy Storage	MWe	1.2	50	1.5%
Pumped Hydroelectric Energy Storage	GWh	7.5	50	1.5%
Oil Storage	TWh	23	50	0.6%
Methanol Storage	TWh	52	50	0.6%
Gas Storage	TWh	48	50	1.0%
Bioenergy Conversion				
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%

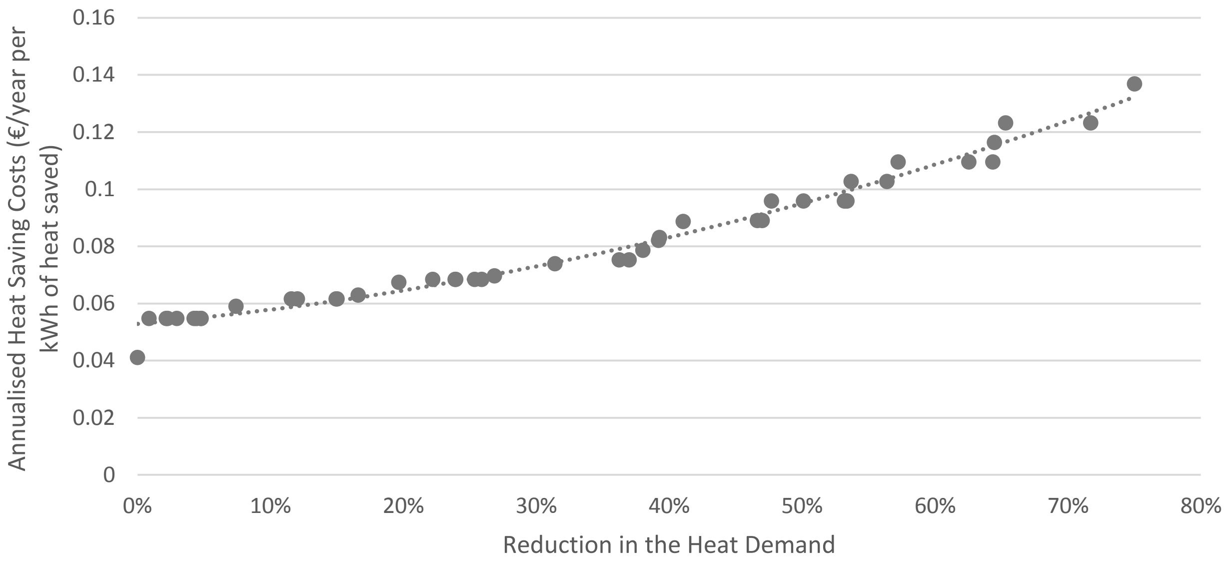

Figure 16: Unit costs assumed for reducing the heat demand in buildings. These costs are based on the Danish building stock and extrapolated to the EU energy system in Heat Roadmap Europe [6, 8].

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
Residential Buildings								
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 (€/MWh)	0	7.2	0	0	0	0	0	0
Services Buildings								
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 (€/MWh)	0	7.2	0	0	0	0	0	0

Table 9: District heating pipeline costs [102].

District Heating Pipes	Conventional DH Network	Low-Temperature DH Network
Specific Investment costs (1000 €/TWh)	72,000	522,000
Technical lifetime (years)	40	40
Average Fixed O&M (€/TWh/year)	900,000	3,960,000
Variable O&M (€/MWh)	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*	12,971	11.2%
	Bio-methanol	14,104	6.6%
Busses & Trucks	Diesel	161,074	1.2%
	Petrol	163,960	1.2%

*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_2 Price (€/t)	46.6
Assumed Lifetime of Heat Savings (years)	30