Robust cost-effective 2050 investment strategies in a volatile context

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A two-dimensional interconnectivity approach

Deliverable D-3.3

Robust cost-effective 2050
investment strategies in a volatile context

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1 Introduction

Writing this, it has been 4 months since the war between Ukraine and Russia began. This sparked an attention and an awareness of the vulnerability of Europe in regards to energy security. While the Energy Union in 2015 and previous EU policies set out a path that has given Europe more renewable energy and more energy efficiency, EU has failed with the policies on natural gas. The diversion policy for having more partners to trade gas with did not change the fact that the internal production of natural gas has fallen significantly while the import of natural gas from Russia has risen.

This energy crisis comes on top of the climate crisis. The climate crisis has in many ways framed the initiatives to deal with the energy crisis in REPowerEU. In Fitfor55 EU set out a 40% renewable energy target for 2030, and a reduction of final energy consumption from 2020 until 2030 of 9%. In REPowerEU these targets have been increased to 45% and 13% respectively. The climate crisis in many ways shapes and increasingly shapes other policies. Rightly so, 2021 and 2022 has been another record-breaking weather event year, as well as effects on natural and human life. It is pivotal to limit the global warming to well below 2°C and aim at staying at 1.5°C compared to pre-industrial levels. REPowerEU in many ways accelerates the transition towards a more energy efficient and renewable energy-based system also focusing on known technologies, which can have a short-term effect.

In RE-INVEST we aim to create suggestions for a European energy system which is robust in different contexts, we aim to identify the role of different technologies in future renewable energy systems and Denmark's role in a European context. The aims in the Paris Agreement set the targets for the long term 2050 climate neutral European system. We believe Denmark can reach this target before, i.e., latest in 2045.

Robust renewable energy systems require not only "green" technologies but also the use of such technologies in a manner that enables the entire system to function while staying within the boundaries of the renewable energy potentials. Energy efficiency, electrification and renewable energy are now known technologies that can be used to a large extent in the short term for buildings (heat savings, district heating and individual heat pumps), industry (energy efficiency, symbioses, electrification, concentrated solar), transport (energy efficiency modes of transport, electrification and hydrogen-based fuels). A Smart Energy Systems approach can help utilize the different synergies between sectors and storages options. The design of such systems requires a holistic view, where not all "green" solutions are "green" enough. An example is that hydrogen should be used for small parts of industry and electrofuels in aviation and shipping, and not for low temperature purposes in industry or heating buildings. Another example is that hydrogen in power plant or batteries in buildings can create losses in the system, where other integration technologies are better at providing fuel efficient and low-cost system solutions.

Such results are based on analyses of different contexts for technologies and for Denmark in different European contexts. The current situation in Europe highlights the need to connect energy systems with energy security. It will be key to achieve a climate neutral energy system in 2050 and ensure we have the materials and skilled work force for the green transition. A clear focus on availability of resources and material, logistics as well as education is recommended.

This report aims to provide sound science-based scenarios and technology recommendations to support the green transition and reaching the European and Danish targets for 2030 and 2050. The Smart Energy Systems approach suggested here creates robust energy systems by changing to systems based on more investments and less on fuel and operation costs. Using synergies between sectors, minimizing fuel inputs from biogenic sources creates both low-cost systems that are less vulnerable to fuel price fluctuations. In order to deal faster with climate change and the current energy security situation, some investments can be accelerated.

- A robust energy system increasing energy security in potentially volatile contexts.
- A clear direction towards climate neutral energy systems based on energy efficiency and renewable energy
- Clear recommendations on the specific role for key technologies based on physics and system analyses
- A climate neutral Europe is achievable in 2050 and for Denmark in 2045
- Energy efficiency across all sectors makes the green transition more achievable and puts a lower strain on materials and key resources.

2 European pathways

The RE-INVEST project main research objective is to identify robust investment strategies of renewable energy in a Danish and European context. Therefore, during the project, scenarios has been outlined to show how a European renewable energy and decarbonisation transition can happen. In RE-INVEST we distinguish between the "A Clean Planet for All" scenarios, outlined in chapter 2.1 and a Smart Energy Europe scenario outlined in chapter 2.2.

2.1 A Clean Planet for All

"A Clean Planet for All" [1] is the latest set of scenarios from the European Commission published in 2018, with the aim of showing how to reach various levels of decarbonization by the year 2050. Not all these scenarios described in *"A Clean Planet for All"* fully decarbonize the European energy system; only the two scenarios that respect the 1.5°C ambition, i.e.,1.5 TECH and 1.5 LIFE. All scenarios are described in Deliverable 3.1 [2,3] of this project, while the present deliverable focuses on summarizing the model and results of the 1.5 TECH scenario replication in EnergyPLAN. Thus, this section critiques missing elements in the PRIMES modelling, hence motivating the creation of a Smart Energy Europe.

First, it should be clarified that only 1.5 TECH is further used as a comparison here. 1.5 LIFE relies on lifestyle changes and new consumer choices and less on implementing carbon neutral technologies. This makes it more difficult to replicate in our simulation tool (or any tool for that matter), as it assumes many of the changes come from changing behaviour. On the other hand, 1.5 TECH scenario relies on a range of technology options, biomass and carbon capture as means of achieving the 1.5°C ambition. The scenario intends to address the needs of the European energy system with the European Commission's perspective from 2018, before the COVID pandemic in 2020, the energy price hikes in 2021 and the Russian invasion in Ukraine in 2022. Although the climate urgency was already present, these events contributed to speed up the urgency of moving away from fossil fuels and also changed the way fuels as natural gas can play a role in the transition to carbon-neutral energy systems. But the 1.5 TECH scenario has not been a particularly energy and cost-efficient scenario even without considering the new geo-political context. It relies on unproven technologies, such as carbon capture and storage (CCS) and hydrogen boilers, (in cases where efficient technologies are commercially available), does not fully exploit system integration and the synergies between energy sectors – nor does it make sufficient use of the Energy Efficiency First principle, one of the core pillars for meeting the climate objectives and increase the security of supply in Europe.

More specifically, there are a number of measures and technologies that are missing or applied insufficiently, either as a choice of the modelers or due to tool limitations. For example, one of the tool limitations is the lack of hourly resolution in the simulation tools applied for the scenario design and analyses. The applied PRIMES tool operates with a low temporal resolution and therefore cannot capture the important temporal variations in the availability of variable renewable energy sources or demands and thus cannot identify production or demand peaks or troughs. Also, it cannot - nor does it require to - make full use of the potential flexibility provided by electrolysis. It is anyway not intended to operate this way, PRIMES being an investment optimisation model. Another limitation is the lack of sectorial integration, where PRIMES cannot, for example, make use of the inevitable waste heat for district heating purposes. Apart from these limitations, the modelers also decided for a technology rich energy system, but without much consideration towards the efficiency and viability of some technologies.

In the building sector, the 1.5 TECH scenario has a high level of heat savings, with over 50% heat reduction in buildings compared to 2005, a very ambitious level which incurs high capital costs and high renovation rates. From the remaining heating demand, about 40% is supplied by individual heat pumps, a welcomed measure. The model does not find any potentials for increasing the district heating share, thus keeping the 2050 share at the same 14% level as today. District heating does not include large-scale heat pumps in its production, nor does it integrate waste heat. The remaining 32% of the heat demand is supplied by a mix of individual boilers running on e-methane, natural gas and hydrogen. This is a very large gas demand for 2050, even for 2030, particularly in the context where there is a need to eliminating all gas from the heating sector as early as possible and where more efficient technologies exist. It should also be noted that E-methane and hydrogen are both subject to significant losses on the production side and thus even if close to 100% efficient boilers are available, significant source to sink energy losses will occur. There are also challenges with deployment and reconversion of hydrogen grids, plus hydrogen is a gas that does not eliminate the issue of greenhouse gas emissions[4].

Hydrogen is also used in large quantities for the transport sector, with 370 TWh/y dedicated to fuel-cell vehicles and 660 TWh/y for liquid e-fuel production. Hydrogen for liquid e-fuel production is comparatively lower, as among all liquid fuel demands in transport, about 40% comes from e-fuels, while the rest is provided by biofuels and fossil fuels. Hydrogen is also used to produce e-methane, where 50% used for the heating sector while the other half for industry and transport.

In this regard, there is still a strong dependency on fuel imports even in 2050. Natural gas remains an important fuel in 1.5 TECH and although its share in heating is small, it is used in large quantities for power production (400 TWh/y), with the majority still imported from outside Europe. On a similar note, oil dependency remains high in the 1.5 TECH model, with the energy sector still using around 500 TWh/y for jet fuel demands and industry, while much larger quantities still used for non-energy purposes (over 1500 TWh/y, but not accounted in our replication of the 1.5 TECH model).

To offset these large quantities of fossil fuel, 1.5 TECH uses CCS and bioenergy with carbon capture and storage (BECCS). Approximately 370 Mt CO_2 are captured and stored in the 2050 model to achieve negative emissions, at least for the energy sector alone, so that when considering all emissions, 1.5 TECH is a carbon-neutral scenario. Another 240 Mt CO_2 are captured for fuel production purposes, making a total of 510 Mt CO_2 captured/year.

Nuclear power is part of the 1.5 TECH scenario. The installed capacity is similar to the present level, but while many reactors will be decommissioned due to reaching end of life, new ones will be built.

With the more stringent requirements on nuclear safety and nuclear waste disposal, the costs for such power production units are rising, then reflected in the total energy system costs.

With these aspects in mind, the 1.5 TECH scenario does not represent the new European visions and targets for decarbonisation. The model does not highlight the benefits of known technologies for decarbonisation and does not benefit of a system redesign, where we move away from fossil fuels and nuclear energy, and focus on energy efficiency, renewables and sustainable biomass.

2.2 Smart Energy Europe

The Smart Energy Europe scenario was built to propose an alternative to the 1.5 TECH and 1.5 LIFE scenarios proposed in the "A Clean Planet for All" Scenarios described in section 2.1. The overall approach to designing the scenarios are as follows [3]:

1. Implementing efficiency improvements.
2. Implementing district heating and power-to-heat.
3. Electrification of vehicles.
4. Introducing E-fuels for the rest of the transport sector.
5. Eliminating any remaining use of natural gas in industry and peak load power stations.

This analytical approach was first described in [5] and refined for the specific challenge of starting with the PRIMES "A Clean Planet for All" scenarios.

Based on feedback from the RE-INVEST consortium, further improvements have been made to the model in regard to specific renewable energy potentials and the need for negative CO_2 emissions. Furthermore, analyses have shown that increased curtailment is more feasible than implementing e-methane, so compared to [3], the final Smart Energy Europe includes a higher degree of curtailment, but only uses Power-to-X, for the production of e-fuels for aviation, shipping and some heavy-duty transport. Power-to-X is not used for e-methane, and instead green gasses and direct use of hydrogen is used in the industry sector. The following subsections describes each sub-sector and show the results from the system.

2.2.1 Heating sector

The heating sector in Smart Energy Europe consists of two primary energy supplies. District heating covers 52% of the demand with individual heating covering 48% of the heating demand. Within both the individual and district heating heated buildings heat pumps are the predominant technology for heat delivery, with the district heating sector also utilizing waste heat, geothermal and solar thermal energy. Furthermore, combined heat and power from peak load power plants are also utilized in the district heating systems. The individual heated buildings are suggested to be primarily heat pumps, with few utilizing biomass boilers and even fewer with direct electric heating. Figure 2.1 shows the heat production from different technologies in the heating sector.

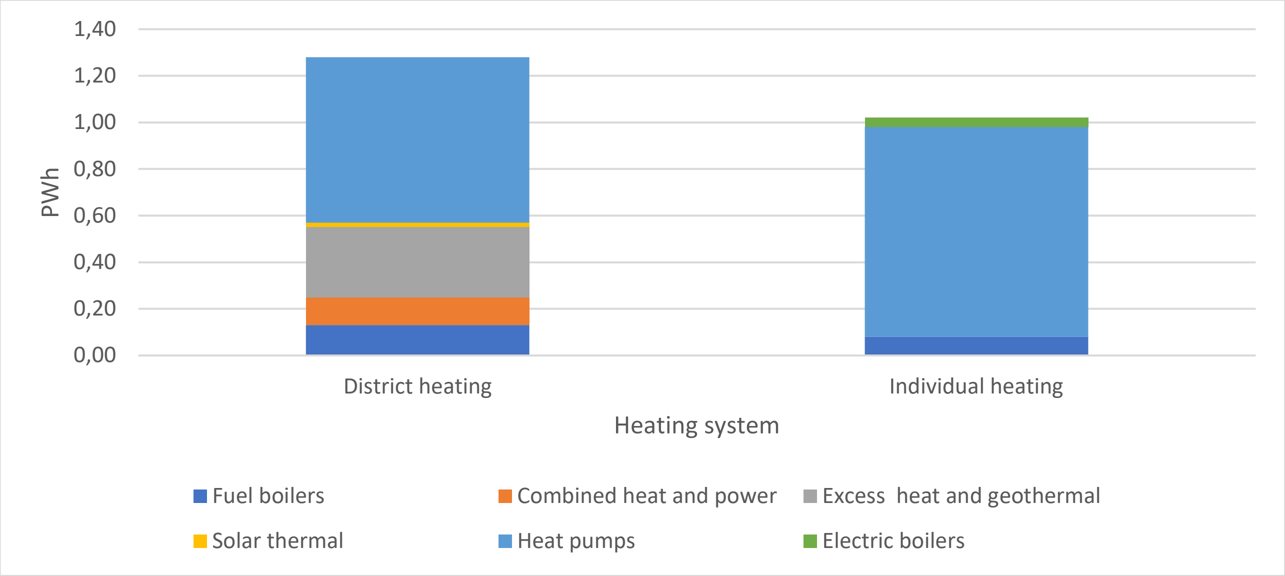


Figure 2.1. Energy production in the heating system in Smart Energy Europe.

2.2.2 Electricity sector

The electricity sector supplies the majority of the energy system, as different parts have been electrified. This includes parts of industry, transportation and heating including all the normal electricity demands. Power-to-X also has a high demand of electricity.

To supply the necessary electricity, Smart Energy Europe suggests a system predominantly utilizing variable renewable energy sources. There is no nuclear power in the scenario. The main flexibility in the system is achieved through sector integration utilizing smart charge and vehicle to grid in the transport sector, using heat pumps and storing heat in thermal storages used later for heating, and through Power-to-X, creating hydrogen, storing in hydrogen storage and from there generating e-fuels. For periods without variable renewable energy availability, backup power stations running on green-gas and solid biomass are used in combination with hydro storages and a few peak load battery storages. The electricity production system is described in Figure 2.2.

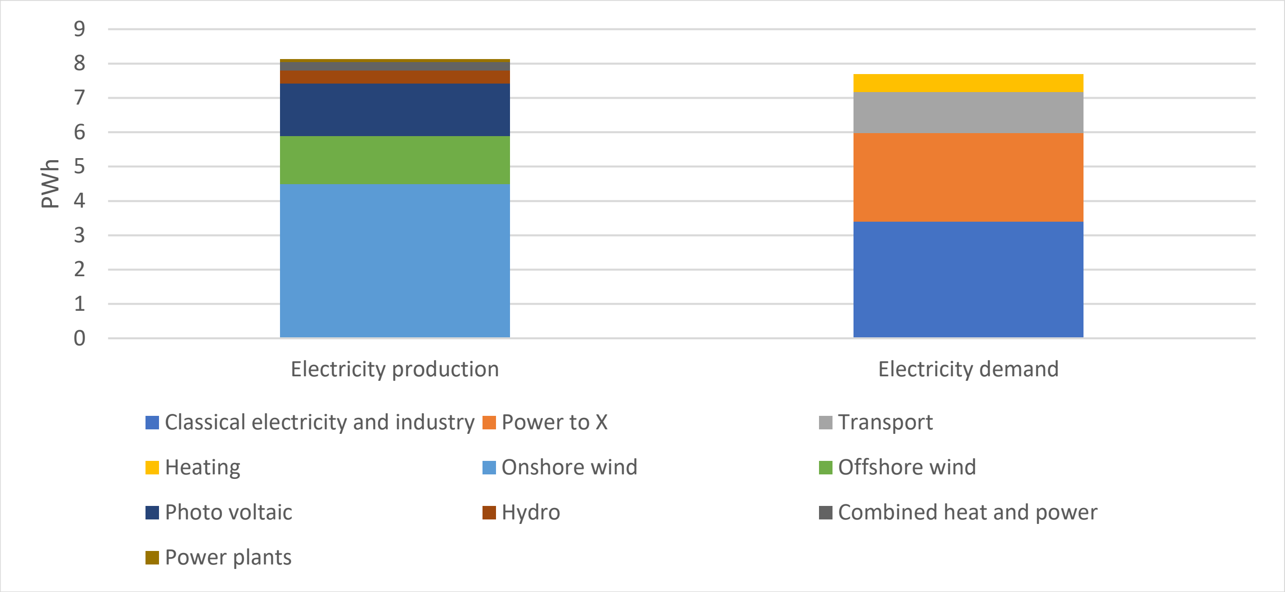


Figure 2.2. Energy production and demand in the electricity sector in Smart Energy Europe.

2.2.3 Transport sector

The transport sector in Smart Energy Europe is predominantly electrified. All personal vehicle transport is electrified, with heavy transport being a combination of electrification and the use of e-methanol produced from CCU. Furthermore, shipping and aviation is almost completely using e-fuels made from the methanol processes.

The use of different energy carriers is shown in Table 2.1.

Table 2.1. Energy demands in the transport sector in Smart Energy Europe.

	E-fuel (TWh)	Electrification (TWh)
Personal vehicles	0	557
Heavy transport, shipping and trains	502	408
Aviation	832	0

2.2.4 Industry sector

The industry sector's energy demand is to a large extent converted to electricity, and in addition, some industries are connected to the district heating network. In the industries where electrification and direct use of district heating is not possible, solid biomass, biogas and green gas from biomass gasification are used. Table 2.2 shows the use of energy carriers in the industry sector.

Table 2.2. Energy carriers used in industry in Smart Energy Europe.

	Energy carrier (TWh)
Electricity	1195
District heating	-
Biomass	710
Biogas	817
Hydrogen	0

2.2.5 Results

The transition to Smart Energy Europe provides an alternative path to a European energy transition, compared to the PRIMES-based “A Clean Planet for All” scenarios. Based on analyses conducted in EnergyPLAN, it is possible to estimate that the Smart Energy Europe scenario provides a cost efficient, potentially cheaper, transition and that it is more fuel efficient. Furthermore, the Smart Energy Europe provides a 100% renewable energy scenario, where the PRIMES scenarios still use fossil fuels offset by the implementation of CCS. Figure 2.3 and 2.4 shows the total annual costs of the Smart Energy Europe scenario compared to PRIMES scenarios, where Figure 2.5 shows the primary energy consumption.

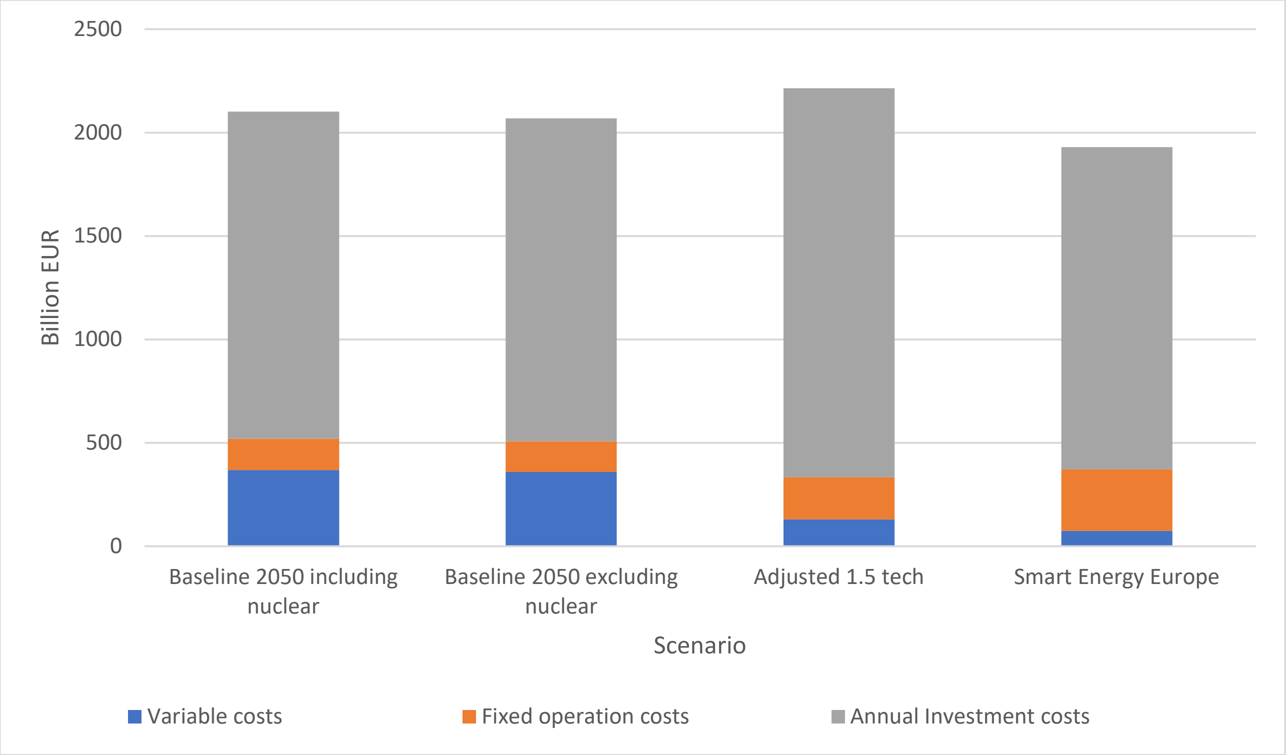


Figure 2.3 Comparison of annual costs between the four energy systems described in chapter 2. Annual costs include annualised investment costs, fixed and variable operation and maintenance costs and fuel costs.

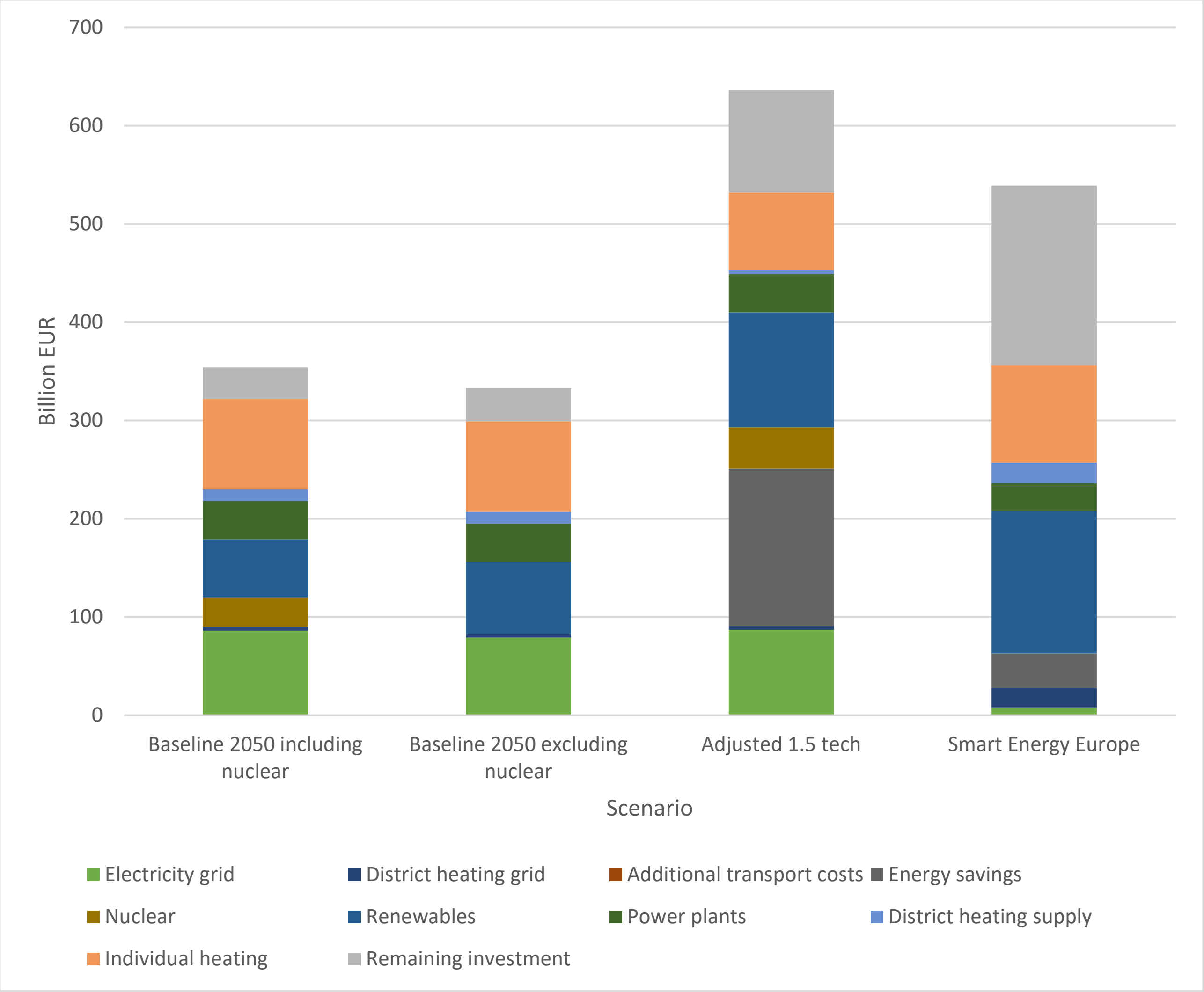


Figure 2.4. Annual investment costs excluding transport costs, detailed into subcategories.

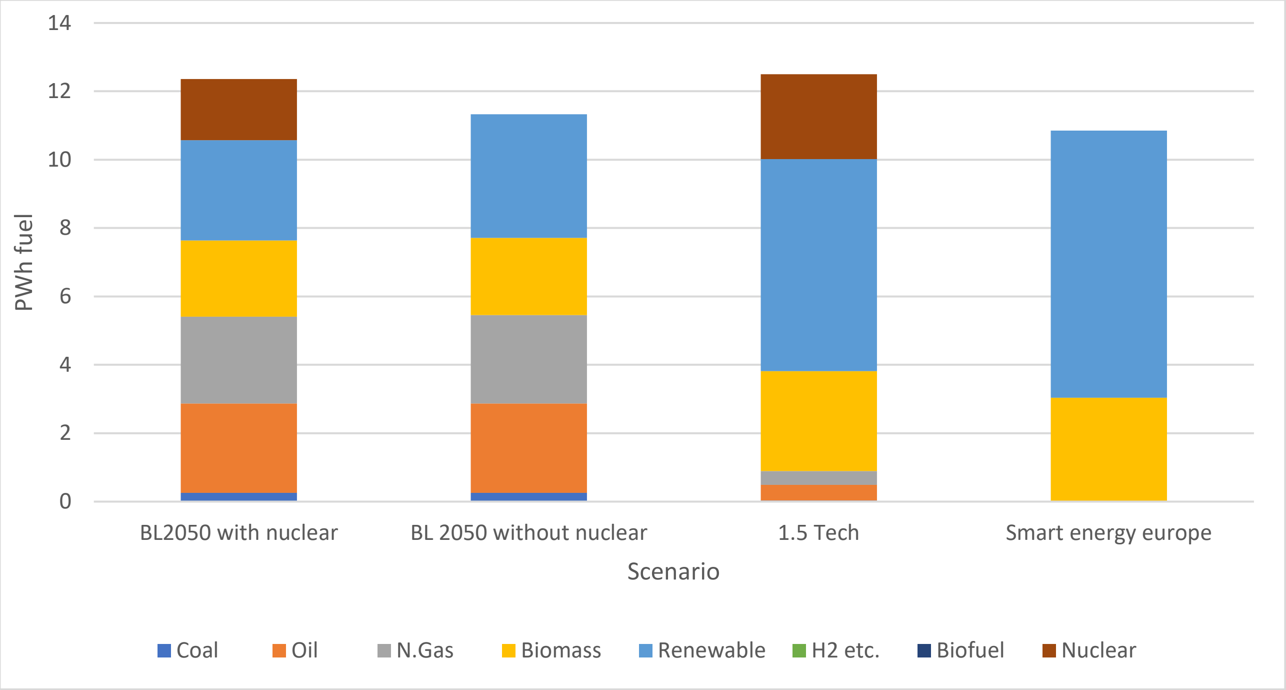


Figure 2.5. Comparison of the primary energy consumption in the four energy systems described in chapter 2.

3 Investment strategies for a robust Smart European Energy System

Large investments will be necessary for converting our existing energy system to a renewable one. Since RE-INVEST originally debuted in 2017, the perspective of energy transition has changed tremendously. In 2018, the EU Commission produced the "*A Clean Planet for All*" report, which provided the basis for comparison in this study. But in the meantime, several events occurred: a pandemic that showed us the benefits of abandoning fossil fuels, a steep increase in energy prices in 2021 caused by multiple combined factors and not least, the Russian attack on Ukraine, using gas and oil income for financing a war and making Europe make difficult decisions regarding its dependence of fossil fuels. Not least, this combines with high inflation rates and challenges with global logistics.

These events have changed the European perspective on the necessity of the transition. Europe now entered an accelerated process of reducing and replacing Russian natural gas and oil. For these reasons, even though the analysis on RE-INVEST focused on 2050, this chapter also deals with the measures that should be frontloaded by 2030. Many of these measures are inspired from a parallel project on implementing an energy efficiency roadmap, in a scenario named sEE 2030 [6,7]

Before going into the specific measures that should take place by 2030 and for the period 2030-2050, Figure 3.1 illustrates the total system costs and the distribution of costs types across several energy models: Smart Energy Europe model developed in RE-INVEST, the EU Commission's "*A Clean Planet for All*" scenarios and the 2030 scenarios in the sEEnergies project.

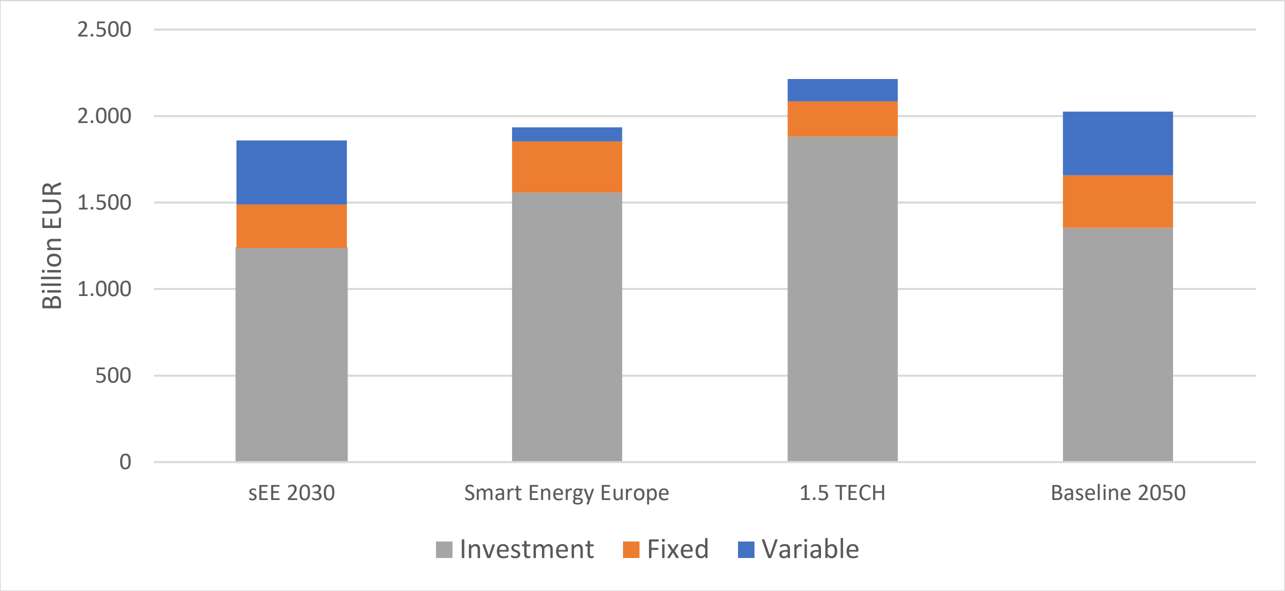


Figure 3.1: Comparison of total annual costs split including sEE 2030

All scenarios shown in the Chapter 3 entail a similar cost structure trend. A large proportion of investments and reduced costs with fuels, in opposition with the cost structure of today's energy systems i.e., large proportion of expenditures on fuels and small share of investments. The large share of investments in the scenarios in Figure 2.3 refer to the implementation of measures regarding energy efficiency and supply, critical in redesigning the fossil fuel-based energy system to an integrated smart energy system. This involves investments in heat savings, electrification of transport, industry and heat, combined with investments in large renewable capacities. Table 3.1 outlines key energy system components changes between 2020 and 2050, while Figure 3.1 highlights the investments in the energy system.

Table 3.1: Key developments in system capacities between 2020 and 2050

Key system components	**2020**	**2050**	**2020 – 2050**
Offshore wind turbines (GWe)	22	295	273
Onshore wind turbines (GWe)	169	1600	1431
Solar Photovoltaics – PV (GWe)	131	1000	869
Electric Vehicles (Million units)	2.7	366	363,3
Individual heat pumps (Million units)	14	150	136
District heat production (TWh)	0.6	1,27	0,67
Electrolyser capacity (GWe)	0	502	502
Gasification plant capacity (GWfuel)	0	123	123
Electric storage (TWh)	0	0,55	0,55
Large heat pumps (GWe)	0.5	31	30,5
Buildings – heat demand (PWh)	3.2	2,1	-1,1

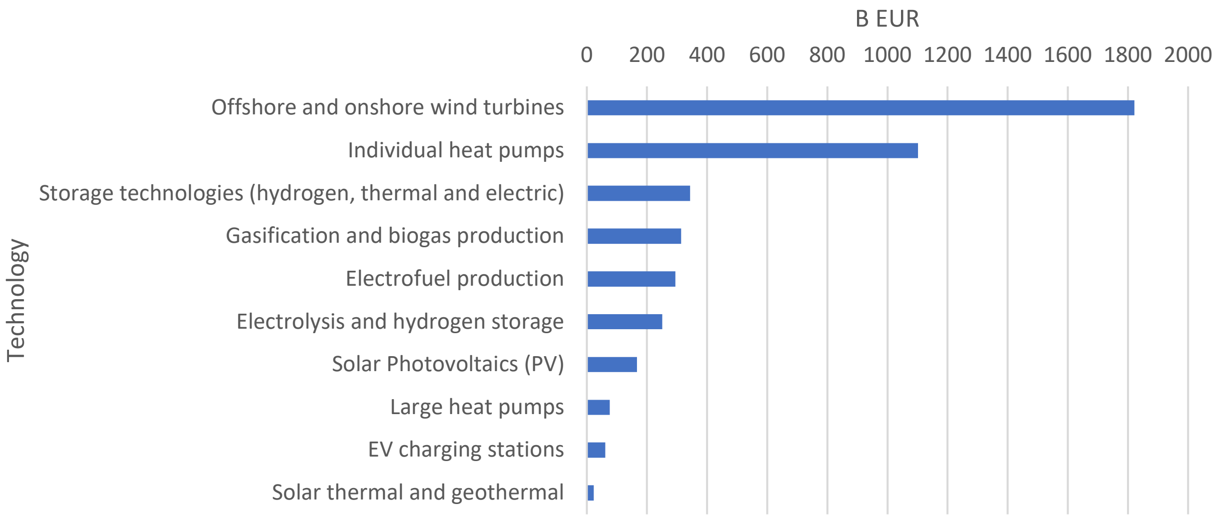


Figure 3.2: Investments in the energy system until 2050 split between the most important technologies.

3.1 No-regret measures before 2030

Towards 2030 it will be important to frontload the so-called *no-regret* measures in the energy system, those measures that we know are very effective to reduce gas, oil and CO2 emissions quickly. These measures should take place on the entire value chain of the energy system: from supply to conversion and to demand.

Energy savings in buildings is one the measures on the demand side. Smart Energy Europe proposes in general less heat savings compared to 1.5 TECH by 2050, which means that less heat savings should be achieved by 2030 as well. This does not mean heat savings are not important, as they are necessary for reducing fuel consumption, such an important metric particularly these days. For comparison, the sEE 2030 model proposes around 10% heat savings compared to today which also makes it one of the most expensive investments according to the authors [7]. For example, accelerated heat savings in the building sector, but moderate in the insulation level, that should focus on reducing the largest heat losses rather than eliminating all losses. This can keep the investment costs low.

The no-regret measures in buildings should also focus on more efficient energy conversion units, i.e., heat pumps and district heating. Heat pumps should be first deployed outside urban areas to replace fuel boilers of all types, but in careful coordination with district heating. Installing heat pumps in areas where district heating is more feasible will undermine the feasibility of district heating, which needs an "*all in*" approach to show its benefits. Therefore, a continued and steady expansion of district heating grids to cover 20% of the heat demands should also be envisioned towards 2030, with a focus on further sector integration with waste heat sources from PtX, data centres and industry. Large scale heat pumps must also replace fuel boilers, and even CHP where possible to make use of the low-grade waste heat source that are often found in the proximity of urban agglomerations. In general, large-scale and individual heat pumps will be necessary in redesigning the energy system in the short term, and this technology is not just intended for domestic applications. Industrial heat pumps can also reduce significant amounts of fuels in industry, where fossil fuels are generally used to produce low grade heat (<150°C) in industries as food and drinks production, textiles, tobacco or engineering. This should be a low-hanging fruit that can often be prioritised at a large scale, before iron and steel, metals or minerals industry which are more complex to change. The chemical industry also has a high potential of electrification, but the solutions here are more diverse than just heat pumps. In general, industry will be limited in what it can electrify, so focus will be on energy efficiency on the fuel utilization side, and to some extent diversifying the fuel mix (such as using green fuels).

The transport sector must see immediate electrification on all levels where this is technically possible. Direct electrification via e-roads and batteries in cars are no-regret measures independent on where and how they are applied. There were only 2.7 million electric cars on the European roads in 2020, but this number must get close to 100 million by 2030 if we are to reach a complete electrification of all cars and vans by 2050. This will involve a huge task on the entire value chain of mobility, but will have dramatic effects on the oil consumption, where road transport is the single largest consumer of this fuel.

Therefore, a robust smart energy system will have to prepare for electrification, which also means that the supply side must deliver in an equivalent manner. The deployment of renewables should focus on the most productive areas, such as the example from the recent North Sea Summit, where Denmark, Germany, Netherlands and Belgium collaborate on maximizing the possibilities in the North Sea. Other collaboration may take place in the Baltics, the Black Sea or Mediterranean basin for offshore wind. Similarly, the onshore wind must be deployed in larger capacities than offshore, since the potential is much higher. The sEE 2030 model identified that more than 500 GW of onshore wind must be in place by 2030, a significant leap from the 170 GW in place today. For offshore wind, 115 GW must be deployed by 2030 according the same study, which means capacities have to increase by more than 4 times compared to today. Not least, the sEE 2030 finds over 650 GW of photovoltaics in place by the same year. In other words, approximately half of the future renewable capacities must be in place by 2030, making it a no-regret measure that should not bare any delays.

Other measures in the energy system exist, but their implementation in the energy system by 2030 should be limited. On the other hand, these technologies should involve a steep learning curve, so that they can be implemented in full scale after 2030. One of these groups of technologies is hydrogen. Hydrogen will be part of the future energy systems, but hydrogen is not a silver bullet that can achieve much by 2030. It is expensive to produce and is subject to significant losses. For these reasons it should not be the major focus of the system transition before 2030. Electrolysis should be deployed in gradually larger scale to improve the learning curves and know-how rather than focus the transition on it. Most electrolysis capacity should be deployed after 2030.

In a similar manner, large parts of the hard-to-abate industries should see major changes beyond 2030, where electrification takes over more and fossil fuels are eliminated. Here, renewable hydrogen may have a larger role, both as feedstocks and energy vector. For these reasons, and because technology is less prepared for large-scale decarbonisation for the hard-to-abate industries, it is recommended that efforts are directed towards implementing first what we know works, and learn in smaller demonstration and commercial projects hydrogen technologies and their application in industry.

3.2 Measures in the 2050 outlook

If measures as the ones describes above are implemented by 2030, then large amounts of the fossil fuels will be offset by that time. This leaves the more difficult measures to be implemented by 2050 and expand the ones already started before 2030.

First, heat savings must continue and make another 20% on top of the savings to be achieved by 2030, to reduce the total heat demand in the EU27+UK to 2,110 TWh by 2050. Even though more time should be available to achieve this level of savings, it will also become more expensive the more the buildings with the lowest heat efficiency are insulated. District heating should continue its expansion where it can eventually cover about 50% of the heating demand. Because district heating is a heavy investment infrastructure and takes time to deploy the expansion and construction of new grids should not be delayed. Instead, with the new investments reducing heat demands and supply temperatures in pipes, waste heat can play a larger role, essentially further reducing the necessity of burning fuels for heating. This means that some CHP and fuel boilers will become obsolete and heat pumps can contribute more to the heat supply. Household heat pumps should not compete with district heating; therefore, it is important to lay plans starting today on which areas should be district heating and which should be dedicated to heat pumps.

After 2030 more focus should be directed towards the electrification and fuel switch in industry. The hard-to-abate sectors should be able to rely on new technologies that do not use fossil fuels, so that in 2050, the only fuels in industry will be green methane, biomass and electricity.

Hydrogen will play an increasingly important role in the energy system, but in the Smart Energy Europe model it is not used directly in any of the energy sectors, but instead it is intended as feedstock for the production of liquid fuels for road transport, shipping and aviation in the form of methanol and respectively jet fuel. Around 500 GW of electrolysis will be necessary to sustain these demands by 2050 (depending on the efficiency of electrolysis), reason why hydrogen should not compete with any of the more efficient technologies that do not require hydrogen, as a large part of the road transport, heating or electricity production. Hydrogen could also be used in industry as alternative to biomass and fossil fuels in the processes that are more difficult to electrify. By 2030 it should only be deployed in limited quantities, while the majority of capacity should come online after 2030.

When deploying hydrogen, electrolysis must be used flexibly. In Smart Energy Europe this has about 4500-5500 full load hours per year, which can be achieved in combination with hydrogen storage or CO_2 storage. The latter appears to bring more economic benefits as it can be scaled easier and for a lower cost than H_2 tank storage. Hydrogen can also be stored in caverns, which can mean a lower cost per stored GWh, but these require complete conversions of cavern systems and large-scale hydrogen production and transport in designated regions. The Smart Energy Europe scenario approaches e-fuel production at a more local level, with complete production plants focusing primarily on methanol (with ammonia as alternative) that can make use of local resources and benefit of the low-cost transport and storage of liquid e-fuels. Fuels should be produced locally where possible, but very large-scale projects as the energy islands in the North Sea will require different solutions as hydrogen grids or overhead electricity lines to shore if not producing fuels on the islands themselves. In all cases though, the cost of energy transport becomes less significant than the cost of producing energy, and the choice of energy transport should be a matter of making use of best available technologies on land and on sea that focus on energy efficiency. Smart Energy Europe has a high level of electrification in all energy sectors, so liquid e-fuels are only necessary for heavy-duty long-distance transport that cannot be electrified.

To support the increase in electricity demands from all the electrification efforts our modelling shows that the onshore wind capacity necessary in the EU28 system will be at least 4 time higher than offshore, i.e., 1300 GW, which also makes it the largest type of renewable in the Smart Energy Europe model. Together with offshore wind they make one of the largest investments in the energy system. Photovoltaics must also be deployed with priority on the largest roofs and on grid scale installations, as photovoltaics will need to achieve more than 1000 GW installed capacity in 2050.

All the measures presented above entail a complete system redesign, where the majority of expenditures go towards investments and only a fraction on fuels. The new energy system is more integrated, robust and flexible than 1.5 TECH. The strategic deployment of technologies enables synergies between sectors and energy grids. The energy system is more robust, not reliant on few sources of energy (or imports), but benefits of a distributed generation that makes it more secure to internal and external disruptions. Not least, the energy system is flexible, with low full load hours on key technologies as large heat pumps and electrolysis and benefits of extensive storages of all types: thermal, gaseous, electric and liquid.

4 Smart Energy Denmark in a European Context

The investment choice of a Smart Energy Denmark [8–10] is analysed in the context of the European energy system. Concretely, the interplay between Denmark and Europe is investigated, both if Europe develops along the 1.5 TECH pathway or if it develops along the Smart Energy Europe Pathway. Furthermore, Smart Energy Denmark is investigated in combination with the neighbouring Nordic countries and Germany.

4.1 Methods

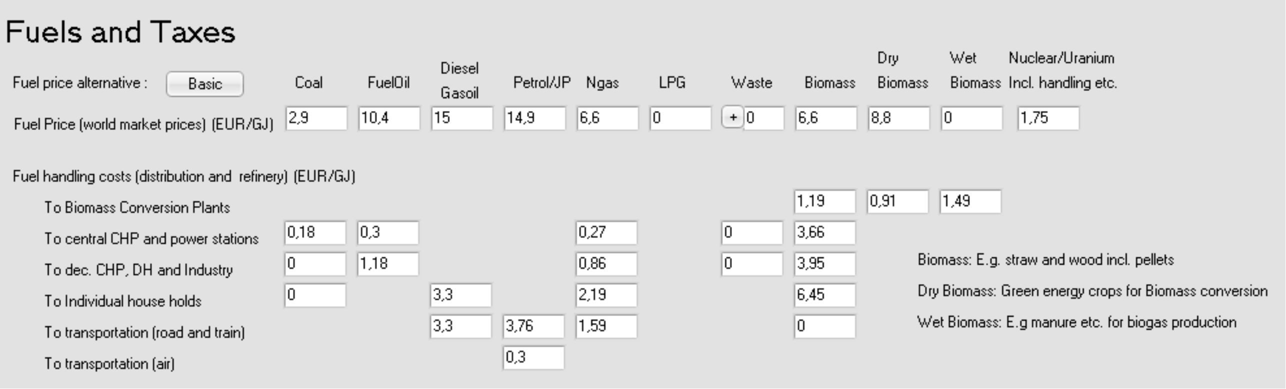
The studies are made with the help of the EPlanFlow extension for EnergyPLAN, described in deliverable 1.2 [11]. To run the tool EnergyPLAN is needed alongside the Powerflow python script and the access to a solver. In principle, the tool identifies marginal electricity producers in EnergyPLAN based on different electricity prices. Based on these prices and modelled network of nodes and edges, exogenously defined capacity limits on transmission lines, the Powerflow extension identifies the operation of the power grid between the different systems. This allows for interconnection being used to lower the marginal operation costs of the energy system. The final outcome of the simulation are updated EnergyPLAN models for each simulated system.

Within this chapter two different cases are analysed using the described EPlanFlow approach. The first is to investigate how the 1.5TECH and the Smart Energy Europe are impacted and might impact the performance of the Smart Energy Denmark scenario. To do this, Denmark is modelled with interconnection to the European models.

The second scenario is a more specific zoom in to Denmark and its neighbouring countries. Here the connections are made between Denmark and the Nordic countries modelled as one EnergyPLAN model as well as a model of Germany. The Nordic model and the German model are made from a combination of RE-INVEST, SENTINEL and sEEnergies works, with the Smart Energy Europe model being split into 27+1 EU countries. These are combined with an existing model of Norway [12]. The subsections below highlight the important outlines of the different models and transmission network modelled.

4.1.1 Economic assumptions

In the scenarios, the investment costs are kept constant between the scenarios, but to be able to compare the different scenarios and ensure the same economic operation, the same variable costs are used throughout the scenarios. Figure 5.1 shows the fuel costs and Table 4.1 the variable operation costs of the scenarios.



Fuels and Taxes

Fuel price alternative : Basic

	Coal	FuelOil	Diesel Gasoil	Petrol/JP	Ngas	LPG	Waste	Biomass	Dry Biomass	Wet Biomass	Nuclear/Uranium Incl. handling etc.
Fuel Price (world market prices) (EUR/GJ)	2,9	10,4	15	14,9	6,6	0	0	6,6	8,8	0	1,75
Fuel handling costs (distribution and refinery) (EUR/GJ)											
To Biomass Conversion Plants								1,19	0,91	1,49	
To central CHP and power stations	0,18	0,3			0,27		0	3,66			
To dec. CHP, DH and Industry	0	1,18			0,86		0	3,95			
To Individual house holds	0		3,3		2,19			6,45			
To transportation (road and train)			3,3	3,76	1,59			0			
To transportation (air)				0,3							

Biomass: E.g. straw and wood incl. pellets

Dry Biomass: Green energy crops for Biomass conversion

Wet Biomass: E.g manure etc. for biogas production

Figure 4.1. Fuel costs used in the scenarios.

Table 4.1. Variable operation and maintenance costs

Technology	EUR/MWh
District heating boiler	3.4
Combined heat and power plants	3.1
District heating heat pumps	3.9
District heating electric boilers	1.0
Hydro power	4.0
Power plants	2.7

4.1.2 German model

The German model is based on splitting the RE-INVEST Smart Energy Europe scenario, the models have then been further re-worked in the sEEnergies project, which might reflect small differences, with green gas being replaced by hydrogen e.g.. These are documented here [13]. It has then further been refined in the sEEnergies project, to arrive at the model scenario described here. Table 4.2 to 4.3 has the key inputs, and Figure 4.2 shows the primary energy consumption. The model has been adjusted with 170 GW extra PP capacity to ensure that peak electricity can be met with national production units, the power flow model will however still prioritize import and export if possible and more cost efficient than the marginal production cost of power from the gas turbines.

Table 4.2. Energy demands in the German 2050 model.

Sectors	Demand [TWh]

Electricity, classical	282
Electricity, industry	364
Heating, individual bio boilers (0.79 efficiency)	17
Heating, individual electric boilers (COP: 1)	17
Heating, individual heat pumps (COP: 3)	153
Cooling demand	113
Hydrogen, industry	125
Biomass, industry	70
Transport, E-JP	109
Transport, E-methanol	29
Transport, electricity	286

Table 4.3. Energy production units in the German 2050 model.

Technology	Capacity [MW]	Electric efficiency	Thermal efficiency
Power plant	240000	0.55	-
CHP plant	21543	0.45	0.45
Onshore wind turbines	86000	0.23 capacity factor	-
Offshore wind turbines	85000	0.55 capacity factor	-
PV	440000	0.17 capacity factor	-
Hydro	4081	0.64 capacity factor	-
DH boilers	55249	-	0.95
DH heat pumps (thermal)	21543	-	4
Electrolysers	97800	0.7	-

Detailed inputs can be found here: https://zenodo.org/record/6827561

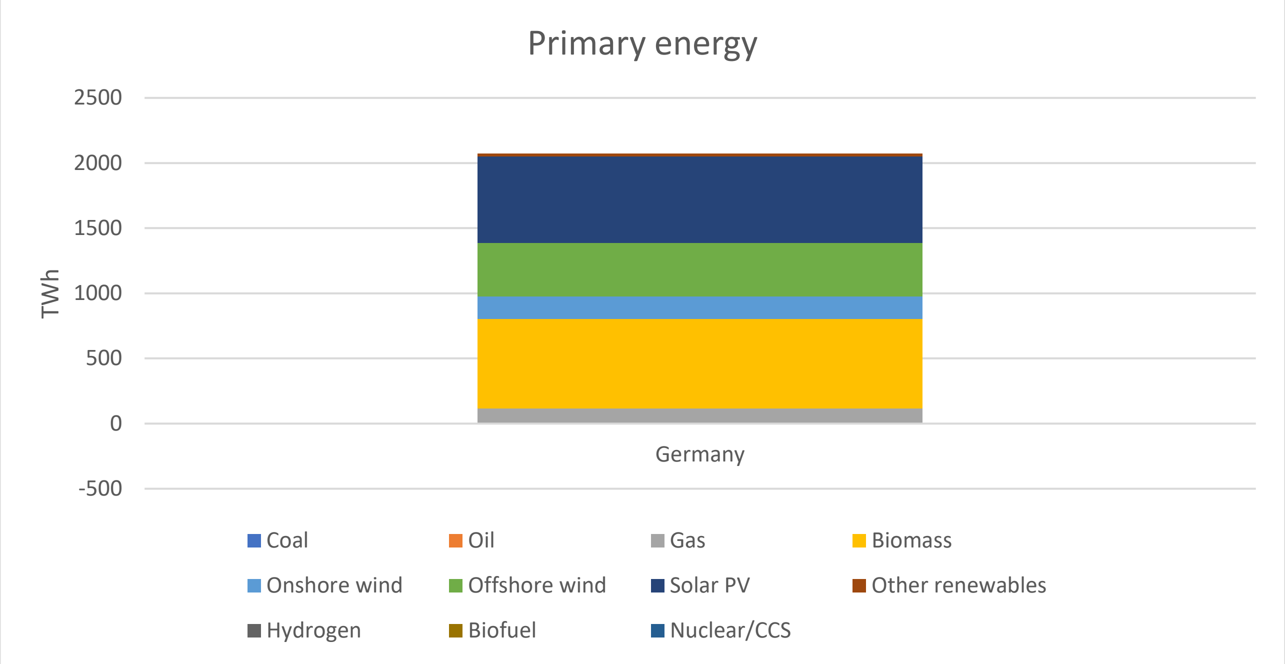


Figure 4.2. Primary energy consumption in the German 2050 model.

4.1.3 Nordic model

The Nordic model is made from a combination of Sweden and Finland models from RE-INVEST, SENTINEL [14] and sEEnergies[6], combined with technologies and time series from a previous Norwegian model created as part of RE-INVEST [12]. Electricity, heating, and cooling demands are based on the SENTINEL models HEB [15] and DESSTINEE[16,17] , whereas the technology mixes are based on sEEnergies and RE-INVEST. The model has been adjusted with 17 GW extra PP capacity to ensure that peak electricity can be met with national production units.

The basic result for a Smart Energy Nordics is highlighted below in Tables 4.4 to 4.5. The primary energy consumption can be seen in Figure 4.3

Table 4.4. Energy demands in the Nordic 2050 model.

Sectors	Demand [TWh]
Electricity, classical	135
Electricity, industry	122
Heating, individual bio boilers (0.79 efficiency)	11

Heating, individual electric boilers (COP: 1)	68
Heating, individual heat pumps (COP: 3)	9
Cooling demand	19
Hydrogen, industry	71
Biomass, industry	19
Transport, E-JP	64
Transport, E-methanol	8
Transport, electricity	93

Table 4.5. Energy production units in the Nordic 2050 model.

Technology	Capacity [MW]	Electric efficiency	Thermal efficiency
Power plant	43000	0.55	-
CHP plant	12500	0.45	0.45
Onshore wind turbines	45000	0.31 capacity factor	-
Offshore wind turbines	49000	0.45 capacity factor	-
PV	50275	0.15 capacity factor	-
Hydro	46250	0.64 capacity factor	-
DH boilers	22500	-	0.95
DH heat pumps (thermal)	18000	-	3
Electrolysers	30000	0.7	

Detailed inputs can be found here: https://zenodo.org/record/6827561

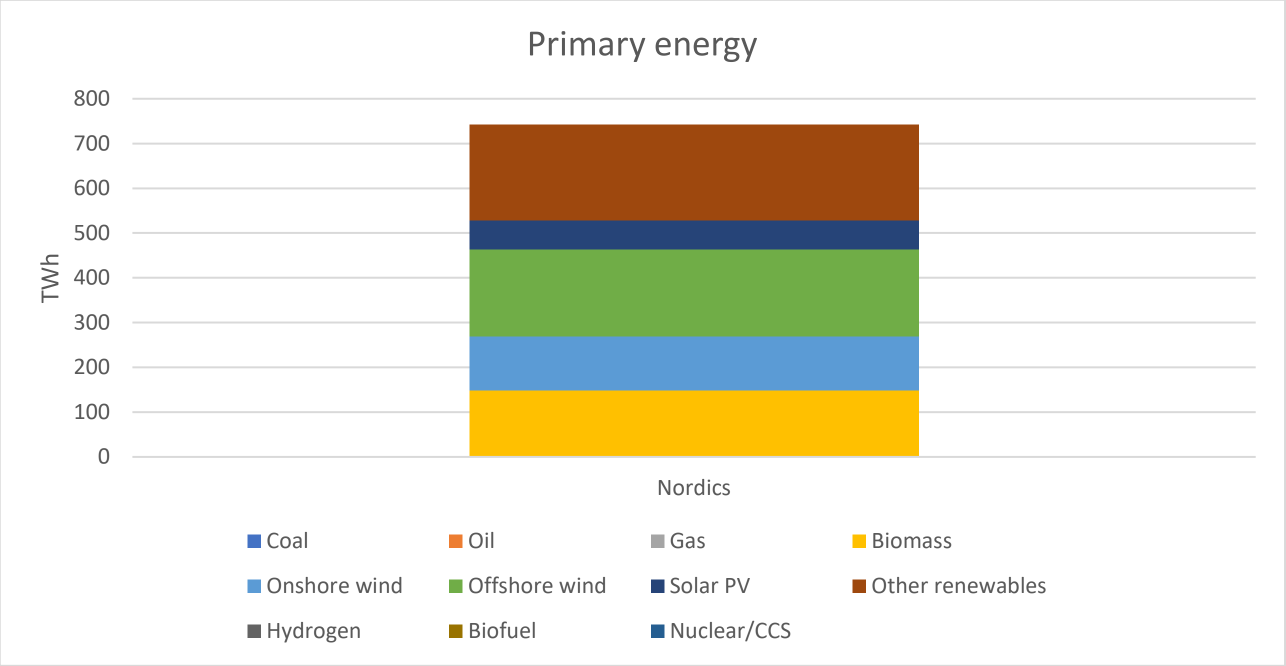


Figure 4.3. Primary energy consumption in the Nordic 2050 model.

4.1.4 Transmission scenarios

The transmission scenarios investigated are based on the different consequences of various transmission capacity constraints. The first scenario reflects island mode operation as a reference, then the current transmission capacity constraint sizes, and finally the two year 2050 scenarios for transmission grid expansion from the *Ten-Year Network Development Plan 2022*[18], developed by the European association for the cooperation of transmission system operators for electricity (referred to as TYNDP). These are highlighted in Table 4.6.

For the Denmark-Europe scenario, the list below shows the links between Denmark and Europe included, whereas for the Nordics-Denmark-Germany scenario, only lines between Denmark, the Nordics, and Germany are included.

For Denmark-Europe, connections included are from Denmark to:

- Sweden
- Norway
- Germany
- Poland
- Netherlands
- UK

Table 4.6. Distribution scenarios between Denmark, Europe, and Denmark and Germany and Denmark and the Nordics as highlighted in the Ten-Year Network Development Plan.[18]

[MW]	Zero	Current	TYNDP 1: Distributed energy	TYNDP: Global ambition
Denmark-Europe	0	10655	18255	13355
Denmark-Nordics	0	4055	8055	5840
Denmark-Germany	0	4500	5700	4700
Germany-Nordics	0	2015	4915	3415

4.2 Denmark and Europe

With the goal of investigating Denmark's renewable energy transition pathways in a European context, the figures below show the primary energy consumption in Denmark if it connects to a Smart Energy Europe scenario or a 1.5 TECH scenario for Europe. The goal is to see how different technology outlooks potentially could impact the Danish Smart Energy pathway.

From the analyses it can first and foremost be seen that a Danish smart energy system path is not impacted significantly whether Europe decides for a smart energy approach or the approach of the 1.5 TECH. This is shown in Figure 4.4, where the primary energy consumption is similar across the different scenarios.

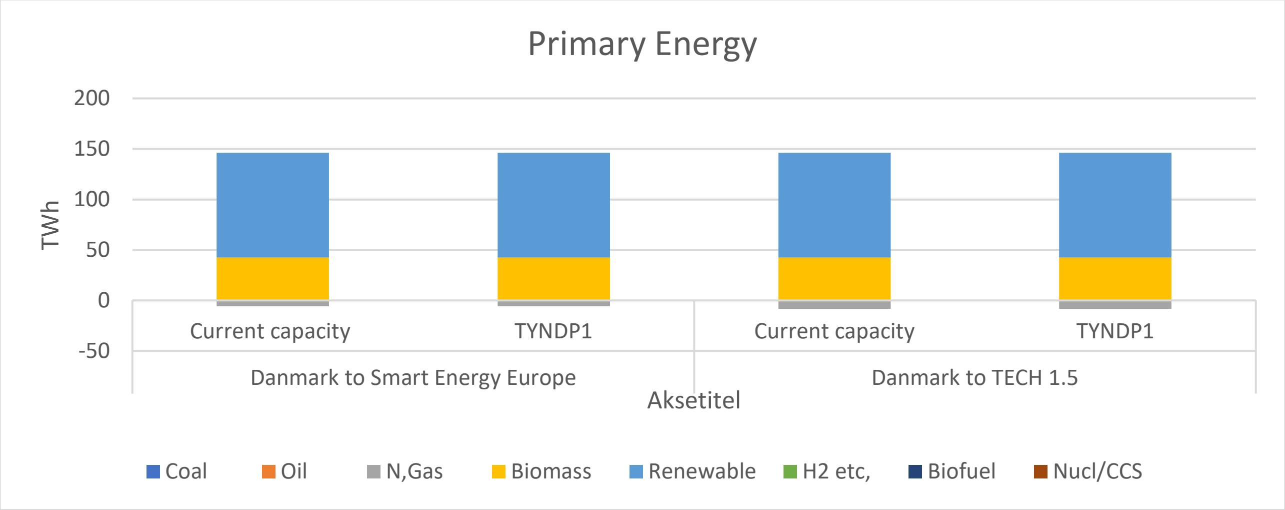


Figure 4.4. Primary energy consumption in Denmark, connected with either current or TYNDP1 interconnection capacity.

The investments will allow to interplay with the European development. However, the results do show that with the 1.5 TECH scenario, which relies on more direct electrification, less system integration and less utilization of waste heat, a higher reliance is on electricity exchange. This means that the 1.5 TECH link results in higher utilisation of the electricity interconnectors, as well as a bigger export of biogas from Denmark. Here, the smart energy system approach offers solutions that to a large extent allows for designing low-cost solutions where the individual regions can handle their own energy system balancing

4.3 Denmark interconnected to the Nordics and Germany

The second analysis focuses on Denmark's connection to its Nordics neighbours and Germany. These represents the majority of the interconnections Denmark will have to the rest of Europe according to the TYNDP scenarios. For both the Nordics and Germany, a smart energy system approach is assessed.

What can be seen is that Denmark will rely on imports from the Nordic countries, in terms of hydro power from Norway and Sweden predominantly. EPLANFlow cannot capture the synergy that it is also possible to send excess electricity back to Norway in hours with no use in Denmark thus it does underestimate the potential synergy. Furthermore, Norway and Denmark can also provide electricity to Germany and vice versa. This is shown in Figure 4.5. Figure 4.6 shows the primary energy consumption in Denmark, with the different TYNDP scenarios.

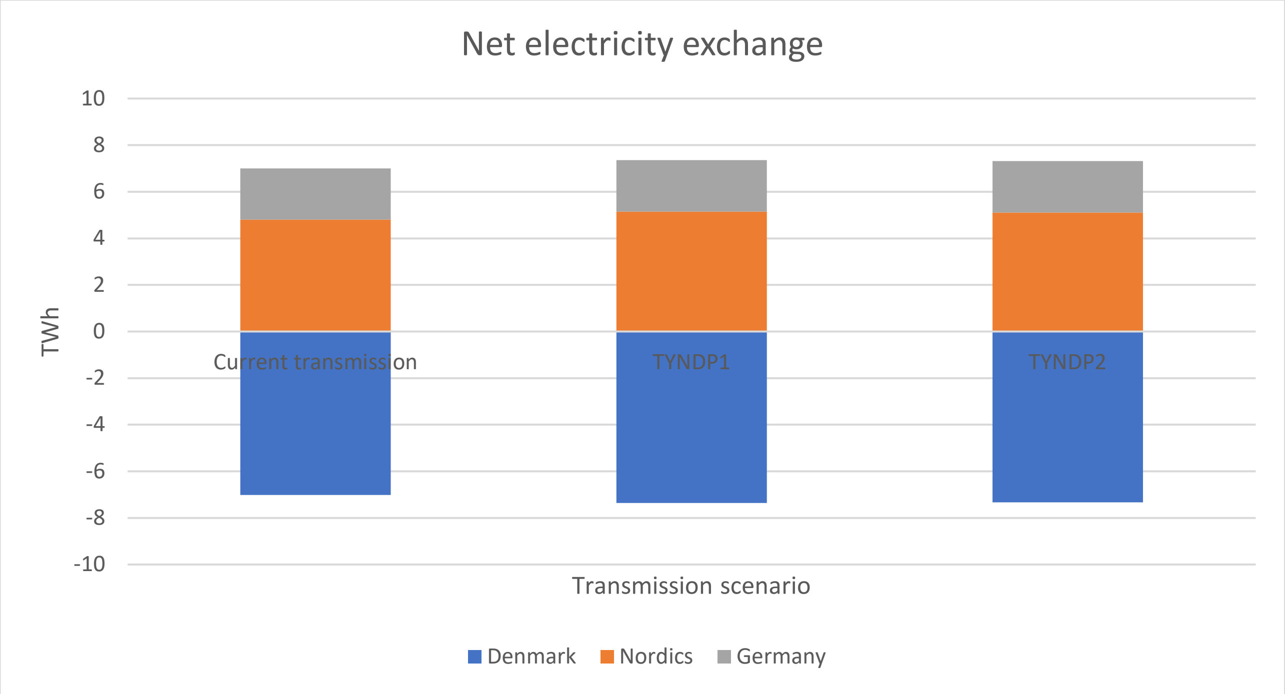


Figure 4.5. Export (positive) / Import (negative) net balance in the three systems.

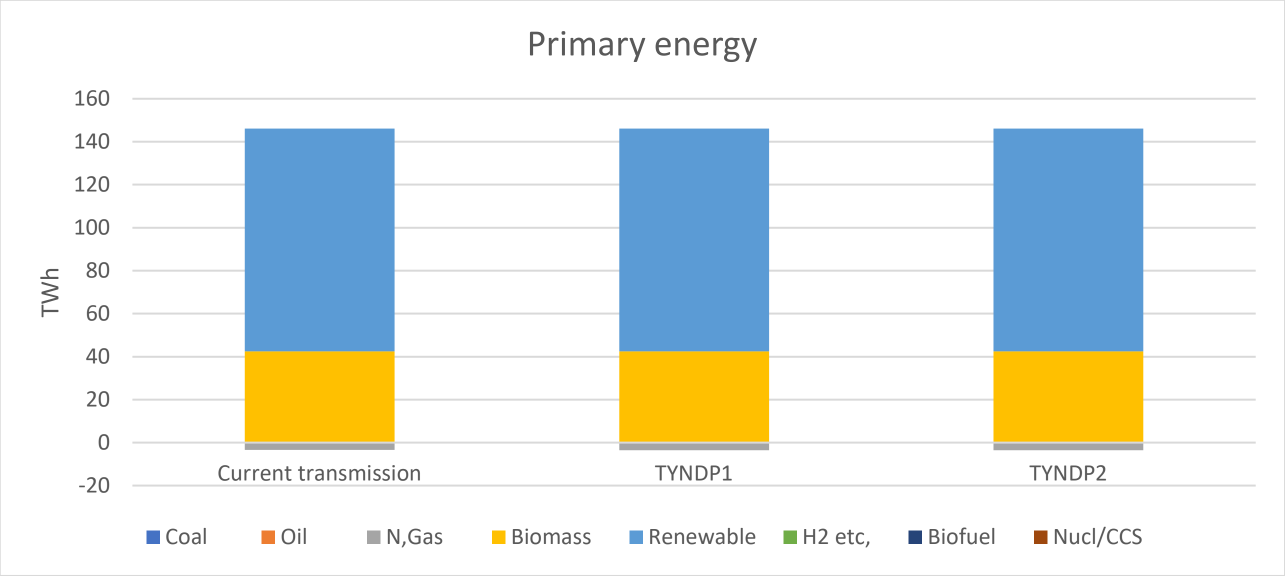


Figure 4.6. Primary energy consumption in Denmark with different transmission scenarios.

While these effects can be seen from the results, the results also show there is no reason to expand electricity grids, as the effect does not change with higher interconnection capacities than what is there today from Denmark to Germany and the Nordics. While increased wind power can be implemented in Denmark, and will make higher use of interconnection in terms of export from Denmark, lowering the total net import. This is shown in Figure 4.7, with an increase of 20GW extra offshore wind in Denmark.

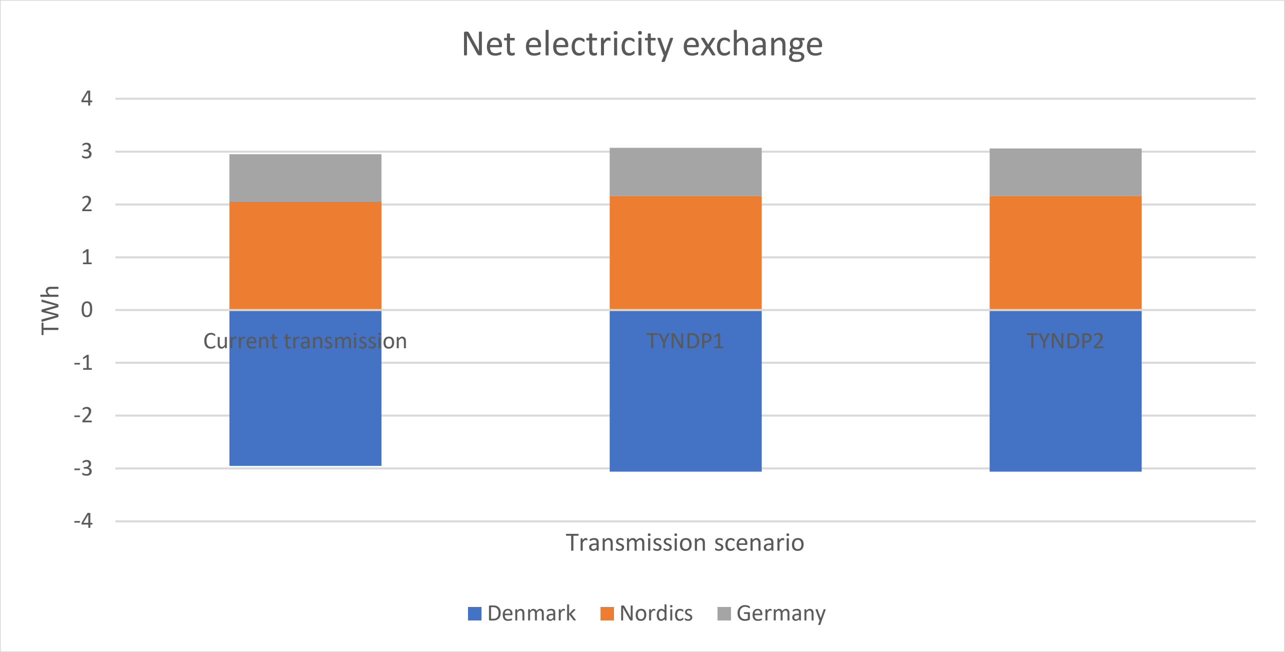


Figure 4.7. Export (positive) / Import (negative) net balance in the three systems with 20GW extra offshore wind in Denmark

Throughout this analysis the energy system is kept constant, mainly changing the different interconnection scenarios and the effect they have on the Danish smart energy system. The current setup specifically investigates a scenario design where Denmark is able to cover its domestic demand based on smart energy systems. These systems are then seen in relation to a number of regions which has also been given the opportunity to cover their own demands. Here it is seen that the transmission lines do improve the performance of the system, but the sizes do not have to be higher than the current setup under the given system designs. However, the analysis does not investigate potential synergies if most of the production was placed in one country, having surrounding countries being dependent on import/export. Potentially a more cost-efficient solution could be found here, but it is important to point out, that the smart energy system does already show a system with costs similar to alternative, non-carbon neutral scenarios.

5 Investment Strategies for Denmark

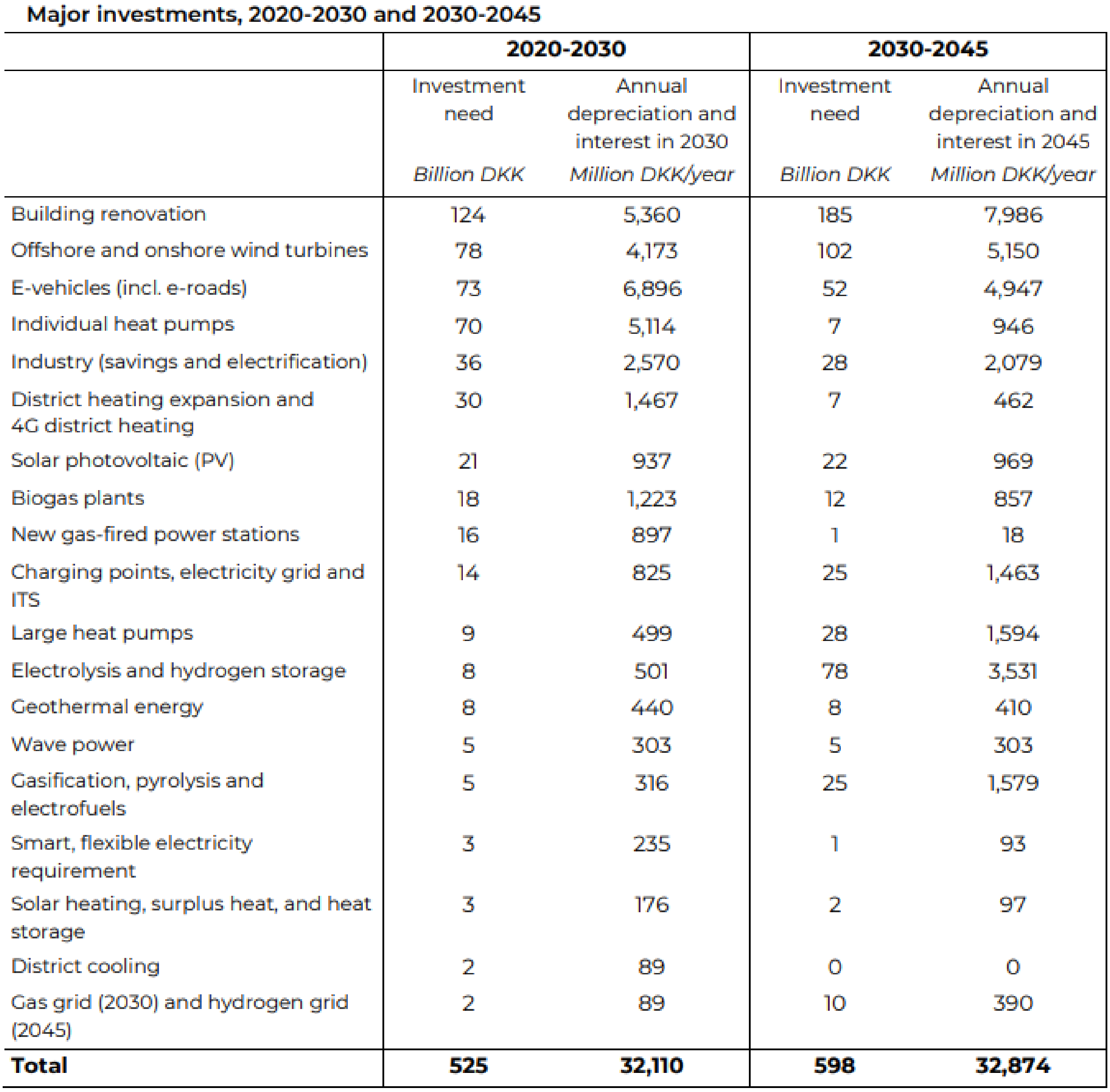
RE-INVEST focuses on the Danish renewable energy investment strategies required for the decarbonisation of the Danish energy system and a transition to 100% renewable energy.

Thus, this chapter highlights the Smart Energy Denmark scenario, which was developed in RE-INVEST alongside a parallel activity in the form of IDA's Climate Response. It proposes a concrete scenario for 100% renewable energy supply in Denmark in 2045.

The Smart Energy Denmark scenario suggests a solution for Denmark to be climate neutral in the energy and transport sector, with the following key investments:

1. Continuing focus on energy efficiency measures, both in households, industry, and energy production. Concretely Smart Energy Denmark suggests lowering current buildings heating demand with 30%.
2. Expansion of wind and solar power. Smart Energy Denmark includes 19 GW of wind power capacity, with approximately 14 GW offshore. Photovoltaic should reach 10 GW installed capacity in 2045.
3. 4800 MW of electrolysis in 2045, producing hydrogen for e-fuels and direct use of hydrogen in transport.
4. Excess heat from industry, data centres and power-to-X production facilities must be used in district heating systems. This increases the system efficiency and allows for district heating to cover up 63% of the heating demand.
5. Only individual heat pumps and district heating for heat supply in 2045.
6. Carbon capture is necessary to produce e-fuels. This capture can be at biogas plants, and point source from industry and power stations. There should only be a long-term priority to CCS, as circular solutions are preferred to end of pipe solutions.
7. Biomass is primarily used for producing green fuels either from biogas, thermal gasification, pyrolysis and hydrothermal liquefaction (HTL). Direct combustion of biomass should be avoided.
8. Busses, cars, trains, and vans are fully electrified. 35% of trucks are expected to be battery powered in 2045 as wells as an investment in 400 km of e-roads to further electrify the heavy transport sector.
9. E-fuels are used for the remaining transport demand in shipping, aviation and heavy transport.

These steps major investments are highlighted in Table 5.1 [8].



Major investments, 2020-2030 and 2030-2045

	2020-2030		2030-2045	
	Investment need *Billion DKK*	Annual depreciation and interest in 2030 *Million DKK/year*	Investment need *Billion DKK*	Annual depreciation and interest in 2045 *Million DKK/year*
Building renovation	124	5,360	185	7,986
Offshore and onshore wind turbines	78	4,173	102	5,150
E-vehicles (incl. e-roads)	73	6,896	52	4,947
Individual heat pumps	70	5,114	7	946
Industry (savings and electrification)	36	2,570	28	2,079
District heating expansion and 4G district heating	30	1,467	7	462
Solar photovoltaic (PV)	21	937	22	969
Biogas plants	18	1,223	12	857
New gas-fired power stations	16	897	1	18
Charging points, electricity grid and ITS	14	825	25	1,463
Large heat pumps	9	499	28	1,594
Electrolysis and hydrogen storage	8	501	78	3,531
Geothermal energy	8	440	8	410
Wave power	5	303	5	303
Gasification, pyrolysis and electrofuels	5	316	25	1,579
Smart, flexible electricity requirement	3	235	1	93
Solar heating, surplus heat, and heat storage	3	176	2	97
District cooling	2	89	0	0
Gas grid (2030) and hydrogen grid (2045)	2	89	10	390
Total	**525**	**32,110**	**598**	**32,874**

Table 5.1. Major investments included in the decarbonization of Denmark towards 2045 [8].

The overall consequences of the energy system are highlighted in Figure 5.1 which shows the primary energy consumption and Figure 5.2 which shows the total annual costs. In both figures, the Smart Energy Denmark scenario is compared to a reference 2045 scenario only obtaining a 70% reduction in CO_2 emissions, as wells as a 2020 reference and 2030 scenario. These scenarios can be further studied here [8–10].

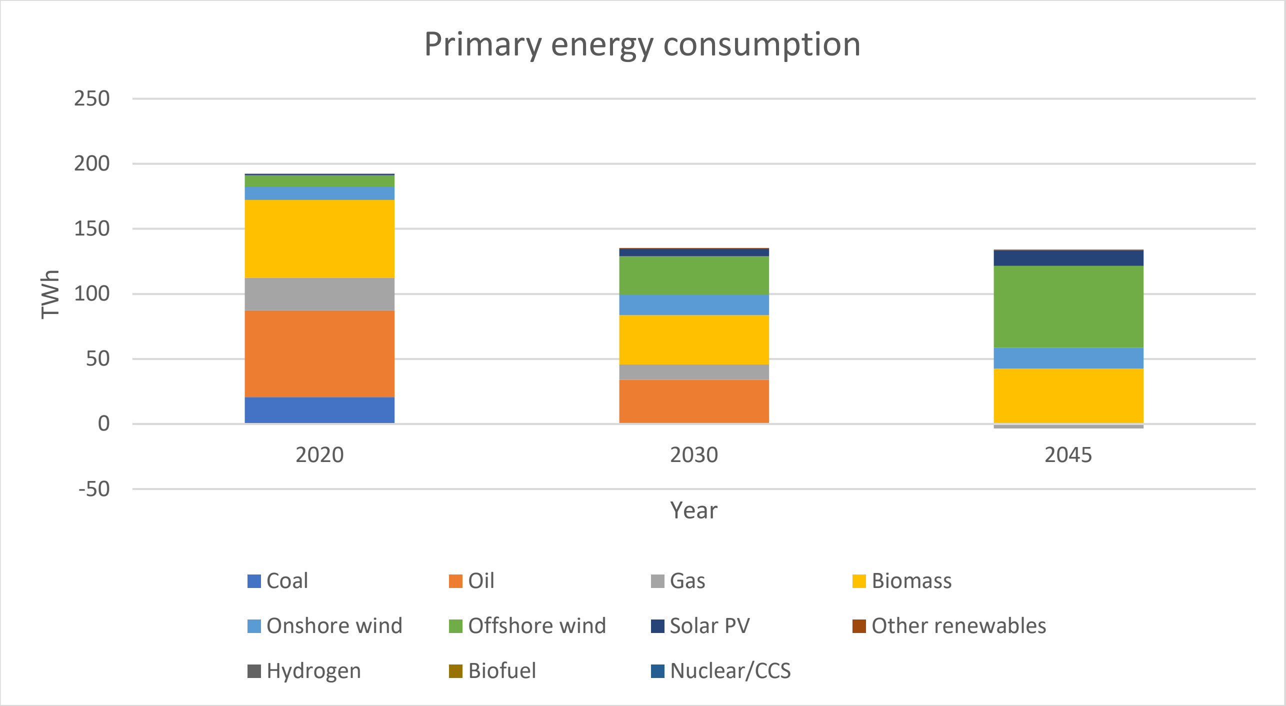


Figure 5.1. Primary energy consumption in three scenarios for Denmark, with 2045 being the fully decarbonized scenario.

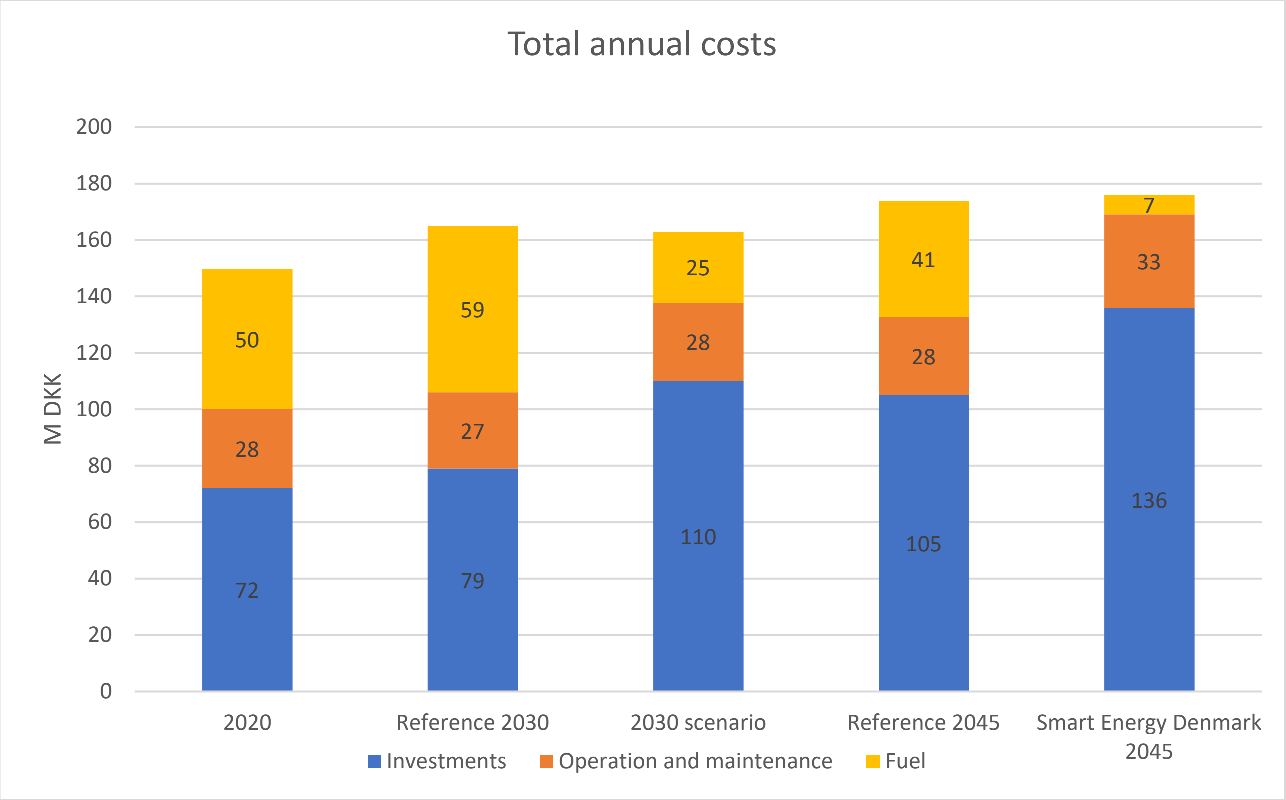


Figure 5.2. Total annual costs for the different scenarios for Denmark.

From looking at Figure 5.1 and 5.2, it is shown that the renewable energy transition as modelled in the Smart Energy Denmark scenario also lowers the biomass consumption compared to today[10], and allows for a renewable energy transition with comparable costs to other alternative scenarios, which does not provide 100% renewable energy [8].

6 Employments Effects of Investing in Smart Energy Europe

It is a fundamental question not only how transitioning to carbon neutral energy supply could be implemented in the EU but also how to unravel the possible effects and/or consequences. Some of the consequences are of an economic nature and to politicians especially the employment effect in the short term is of special relevance as the degree of unemployment is a crucial parameter for the well-being and voting of the electorate.

To the comfort of the politicians most studies do according to an older review [19] show that the net employment effect of investing in specific renewable technologies or conducting renewable energy policies is positive. These studies did, however, focus on either the local, regional, and national level while only two of the reviewed studies were concerned with studying the effects in the EU-area.

In this chapter we, however, have managed to identify far more than two studies of the employment effect in EU. But first, we discuss the relevance of analysing employment effects of renewables rather than treating this as self-evident. Second, we present a critical review of some of the previous EU-studies focusing on the results only. Thirdly, we review the methods applied in earlier EU-studies thereby positioning our newly developed method. Fourthly and finally, we present our own results.

6.1 Why we look at employment

Generally, one major reason is, as indicated above, that politicians would always tend to emphasize that large public investments do also have a significant and positive impact on employment. That is a way of politically defending and justifying such investments. In most countries the well-being of the economy is crucial for becoming re-elected or de-selected. So, doing effect studies is in essence to take the concerns and visions of politicians seriously.

There is, however, different perspectives on employment effects of renewables – assuming that they are positive – all depending on the context. During times with high rates of unemployment it could be argued that we do not run into problems of shortage of labour and resulting inflationary pressure due to such investments. Furthermore, from a typical Keynesian perspective the argument is that during recessions we need to do deficit spending and hereby we can also afford the financing of large public investments into renewables while at the same time bringing down unemployment. One of the major rationales underlying this type of policy is that hereby we avoid loss of potential production as well the misery stemming from being unemployed. This policy makes us richer as a society as well as individuals.

In the opposite situation during a boom the estimated employment effects tell us something about the degree of restructuring needed to take place. To avoid bottlenecks and over-heating we must either open for import of foreign labour or we need to re-allocate labour force from other sectors to renewables. The larger the size of the employment effects, the larger the challenge. This paves the way for a discussion about what not to produce in the future and which measures to apply to accelerate and accommodate the reallocation of the already existing labour force.

Still, from a neoclassical economic perspective (some would maybe even say a mainstream perspective) it could be argued that this emphasis on employment effects is beside the point for various reasons. First, for a long time the argument was that we could not economically afford to transition to renewable energy. Emphasizing the positive employment effects has been a way of pointing to some of the benefits of incurring additional cost to society.

Along the same lines it has also been argued that it might well be that renewables require more labour than, e.g., oil, but that this indicates that renewables are a comparatively less efficient source of energy. This might do damage to employment in the longer run as this would undermine the competitiveness of firms being dependent on cheap energy and remove labour from other lines of employment.

In a Danish context it has also been argued that studies of economic effects of public investments should exclude the impact on employment in notably the guide from the Ministry of Finance [20] about how to assess and justify a public investment or a change in regulation. The implicit argument being that in the long run the Danish economy would be characterized by full employment anyway due to the supposed self-regulating forces of the labour market[20].

Relatedly, economists have also in a Danish context argued that investments into renewables are no better than investments in anything else. In essence, it does not matter what and how an economy produces if it produces something and enough of this to create full employment. Possible positive long-term consequences in the form of exports of renewables are ignored.

This indicates that most studies of employment effects are probably not conducted by mainstream economist but by people from other occupations having a more pragmatic and less theoretically biased attitude towards the question of employment effects on investing into renewables. This does, however, not imply that studies of employment effects are unproblematic as they involve several methodological intricacies (for an elaborated argument, cf. below).

6.2 Previous studies of the employment effect in EU

In this review we have managed to identify nine different publications published after the year of 2000 concerned with quantifying the relation between employment effects and renewable energy for EU as a separate coherent entity. The focus has been on studies conceiving renewable energy as a system rather than focusing on the impact on employment of one specific technology like, e.g., wind turbines (with one exception: Blanco, & Rodrigues, 2009). The nine studies are very different for various reasons and consequently also very difficult to compare directly as will become apparent in the following.

6.2.1 What is EU?

As some of the studies are quite new and forward looking rather than historical, the dominant definition of EU in the studies is EU-27 but one of the five historical studies [21] goes as far back as 1990 and as a logical consequence their study is confined to EU-15. As the only study Markandya et al [22]does also present results for individual member states.

6.2.2 What is renewable energy?

In the studies renewable energy is defined, conceptualized, and measured very differently. Three of the studies focus on renewable energy *policy* as their point of departure [21,23,24]. In these studies, the idea is that a renewable energy policy might increase the growth of the economy and then next as a logical consequence also employment.

It is, however, more common in this and other contexts to focus on either the production or consumption of renewable energy. When focusing on *production*, technologies such as wind turbines [25] or the number of employed in the production of renewable energy are in focus[26]. Renewable technology is defined either narrowly as already indicated or more broadly as in [27]: "primary production of solar energy, biomass energy and wastes, geothermal energy, hydraulic energy, wind energy and marine energy"

When the focus is on *consumption* of renewable energy a term like 'renewables' emphasizing the 'output' of renewable technology is applied. It could be electricity, 'capacity', or biofuels.

6.2.3 How do the studies conceptualize and measure the impact on employment of renewable energy?

The most tricky and complicated issue in the studies is, however, the discussions about the impact on employment of investing in renewable energy. The simplest and straight-forward conceptualization is 'direct employment'. The concept of *direct employment* covers those being employed in:

- The production of renewable technology
- The installation
- The operation
- The maintenance.

Indirect employment is employment that follows from 'supply chain effects'[26]. Renewable energy is not an island but involves deliveries from subcontractors etc. who also benefit from the development of a new technology area. The possible beneficiaries are broadly defined by[26] as "equipment supply, extraction and processing of raw materials (e.g., to produce copper and steel for wind turbines), marketing and selling, administration, or the work performed by regulatory bodies, consultancy firms and research organisations"[26]. Compared to direct employment it is not possible to directly measure indirect employment as this also involves a multiplier effect which produces first, second round and so on effects.

Two other related effects are gross and net employment. *Gross employment* is "direct and indirect employment effects derived from investments in RES[1] without taking negative employment effects in other sectors into account"[24].In other words, this measure tells us how much labour renewable energy would require when seen in isolation not taking the replacement of previous sources of energy.

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[1] An abbreviation used in at least two of the studies: Renewable Energy Source.

Studies of the *net employment* effect do also attempt to take negative effects of investing into renewables on employment into account. A typical example is the production of coal which quite naturally is expected to become reduced partly as a reaction to an increased supply of energy from renewable technology which would diminish the general employment effect and could lead to local and regional problems of unemployment.

The next concept is *induced* employment effects[26]– also called ‘induced effects’ by Ortega-Izquierdo & del Río [28] and ‘cost effects’ in Proença & Fortes [29]. The word ‘induced’ is not directly defined in either of the papers and is ambiguous. The understanding of the research team is that we have to do with effects that do not follow directly or indirectly from the introduction of renewable technology but as a derived effect e.g., increased competition within the delivery of electricity and heating. IEA [30] defines induced as: “Jobs created by wages earned from the projects and spent in other parts of the economy, thereby creating additional jobs” [30]. They also add ‘Cost savings re-spend’. Energy cost might increase or decrease due to investments in renewables and hereby influence spending and hence jobs elsewhere in the economy.

In the last two mentioned papers it is assumed that induced effects are mainly negative. Of the three papers the most thorough treatment of the induced effect is to be found in Fragkos & Paroussos [26] and here we get a much more complex but also self-contradictory understanding. In the first quote from this text the induced effects sound entirely positive: “Induced jobs are created due to the total economic impacts of RES expansion. They arise from economic activities of direct and indirect employees, shareholders and governments, as their increased spending stimulates other industries which are not connected with RES. The consistent estimation of induced jobs requires the use of a macroeconomic model capturing both income and price-induced changes in the economic structure driven by RES” [26].

In the next quote from the same text, negative induced effects might also be a part of the picture: “induced employment impacts are subject to the overall macro-economic effects and crucially depend (among others) on: (i) whether climate policies are EU-specific or global (as global policies would tend to mitigate the negative competitiveness impacts), (ii) the financial scheme used that implies limited or high crowding-out effects, (iii) policies to mitigate negative impacts on vulnerable and (iv) the assumed carbon revenue recycling scheme” [26].

So far, the conceptualization of employment has been static but one of the studies [28] does also take a dynamic factor like ‘learning’ due to technological into account (cf. Table 6.1). This phenomenon is not discussed at great length but with reference to two studies by IEA and IRENA. The idea is simply that the technologies are gradually improved, and the work force get more experienced in working with these technologies.

Table 6.1: Learning rates used to define the dynamic employment factors [28]

	Onshore wind energy	Offshore wind energy
From 2008-2014	7 %	9 %
Since 2015	21 %	15 %

In previous studies by the research team an additional consequence has also been considered but without attempting to quantify it. It is so-called dynamic effects which refers not only to employment but to the implications for the overall industrial development by paving the way for the development of new products and services and sometimes even for the establishments of whole new industries as exemplified by the wind turbine adventure of Denmark. Such consequences might be essential to national and industrial competitiveness on the export and home market.

6.2.4 What is the method?

There is no general consensus concerning choice of method when quantifying employment effects but three of the studies that emphasize the indirect effects of renewable energy apply input-output analysis (cf. Table 6.2). Studies that regard induced effects to be important typically apply an economic CGE-model (computable general equilibrium model). More important in this context is, however, how the employment effect is specified in the different studies (cf. Table 6.3). As can be seen from table 2 very different methods are used – often of a more indirect character.

Table 6.2: How is the employment effect estimated?

Study	**Specific method**
(Azretbergenova et al, 2021)	Specification a model in which employment is assumed to be dependent on renewable energy production, GDP per capita, and fixed capital formation (investments)
(Blanco & Rodrigues, 2009)	Inductive method compiling data from each member country
(Fragkos & Paroussos, 2018).	”combining Eurostat Labour Force Survey (LFS5) and Structural Business Statistics (SBS6)- with information obtained from literature review to estimate **current employment levels** in all energy-related sectors and activities”. Manufacturing, plant construction and O&M”. “**Estimate labour intensities** in the entire chain of activities related to RES and fossil fuels”. “Employment factors are expected to reduce over time as technologies and production techniques mature and labour productivity increases”. But constant in the study.
(Jaraite et al, 2015)	Estimate how employment correlate with increases in e.g., wind capacity. Do also try to check for causality
(Markandya et al, 2016)	Comparing the level of employment keeping the input structure of the electricity and gas supply sector constant.

(Neuwahl et al, 2008)	"Sectoral employment coefficients are used to quantify the employment levels". "employment coefficients, were constructed based on process chain data derived from the WTW study"
(Ortega-Izquierdo & del Río, 2020).	See table 1 above
(Proença & Fortes 2020).	Employment is modelled as dependent on renewable power generation capacity, energy consumption per capita, and dependency on import of energy
(Ragwitz et al, 2009)	Employment coefficients from EU-KLEMS database. Sectoral share of employment in SME from Eurostat data. A comparison of the labor intensities and the import shares of the value chains of RES products provides a first impression of the probable structural effects on growth and employment.

6.2.5 What are the main results of interest to our study?

Four of the studies argue in favour of a positive *net employment* effect of transforming the EU energy sector into relying much more on renewable energy. Two of these studies are historical and have for the EU-area calculated that:

- 530,000 jobs were created in the period 1995-2009 [22]. An important proviso is that this positive development is limited to 21 of the member states.
- Based on data from 2006-2019 Azretbergenova et al [27]have established the following causality: A "1% increase in primary production of renewable energy in the long term increases the workforce by 0.08%" (p. 24).[2]

The future-oriented studies suggest the same order of magnitude net employment:

- 200,000 in 2050 for EU-28 [26]
- 187,000 – 656,000 in 2030 in EU-27 [24].

6.3 Our method and main results

Based on the Smart Energy Europe scenario, a potential employment estimate has been made. This takes as a starting point concrete investment costs and costs involved in operating and maintaining the capital equipment within energy production. These costs have been estimated for each of the three different scenarios depictured in Figure 6.1, and the estimated employment coefficients determining the annually employment following directly from the total investment. Indirect or induced effects of the investment are not considered. But learning effects are included in our calculations by assuming

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[2] They do not discuss whether this result could also be applied in studies of the future development.

a yearly productivity growth. Individual member countries of EU are, hence, assumed to gradually become more efficient in producing or using renewable energy.

The employment effects are currently based on Danish assumptions, which may result in an underestimation when transferred to a European level. As some of the activity might be based on imports the share of imports has to be considered. We do not have access to European data on imports within renewables and has therefore applied Danish data from some of our previous research. However, Denmark is a far more open economy than the EU-area and a major part of Danish imports are from EU. So, the employment coefficients in Table 6.3 do underestimate the direct employment impact of an increased renewable activity in EU.[3]

Table 6.3: Employment coefficients used to calculate annual employment in the different scenarios.

Employment when investing in machinery	600 person years/b EUR
Employment when investing in district heating and energy savings	700 person years/b EUR
Employment from the fossil fuel industry	100 person years/b EUR
Employment from biomass industry	800 person years/b EUR
Employment tied to operation and maintenance	800 person years/b EUR

When applying these coefficients to investments in respectively the baseline scenario, the Smart Energy Europe scenario, and the 1.5 TECH scenario the cumulative potential employment is estimated. The results are shown in Figure 6.1. The net employment effect of a smart energy scenario is around 2.5 million employed compared to a baseline scenario based on oil and gas. The figure should be interpreted as the difference in the level of employment by 2050 when comparing the two scenarios. This figure is, however, much higher than in previous studies reviewed above. This may probably be explained by our more encompassing definition and operationalisation of ‘renewables’.

It must be emphasized this relatively higher demand for labour would only be turned into actual jobs if there is a sufficient supply of labour – both in quantitative and qualitative terms. This could turn out to be a very different problem in Northern Europe compared to Southern Europe. The North is close to overemployment while the South has large unemployment rates and an idle workforce having an academic degree and, thus, not being tailormade to work in the renewable sector.

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[3] Compared to the employment coefficients applied in OECD (2020) our coefficients do also appear rather small. The IEA does, however, take the indirect effect into account and probably also more realistic import coefficients.

A current re-education of the workforce in both parts of Europe would, hence, have to be an inherent part of the future development combined with a current restructuring of the Northern European workforce. The positive net employment might, hence, be partially obstructed by a shortage of labour in Northern Europe and lacking competences especially in the Southern part of Europe.

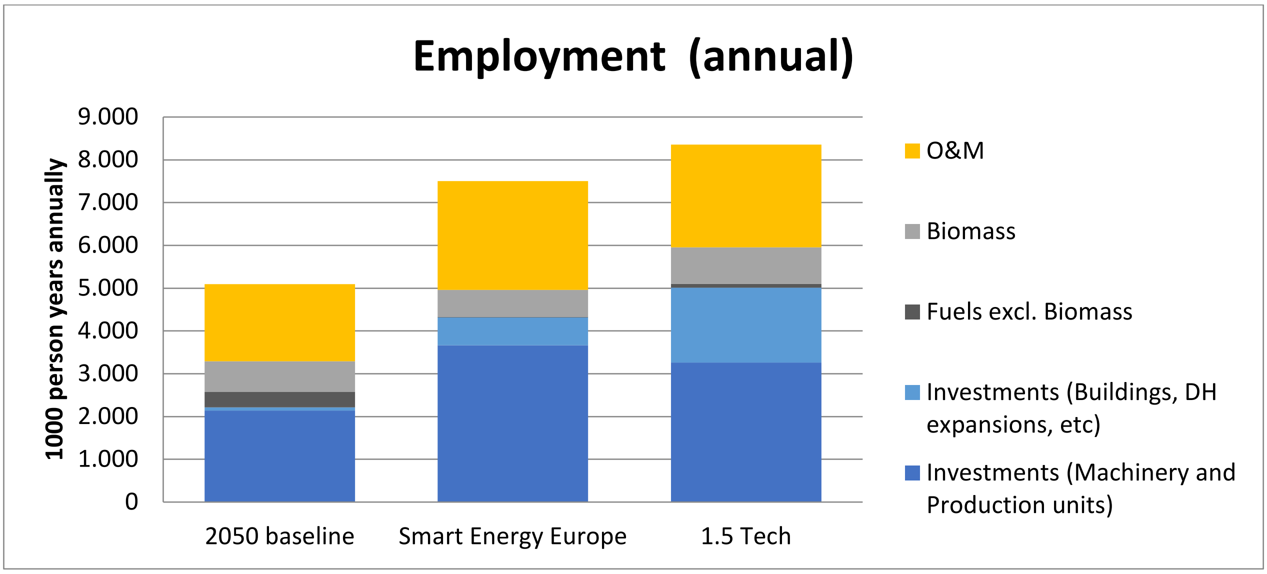

Figure 6.1: Annual employment in the three scenarios measured in person years.[3]

The employment generation in the baseline scenario is mostly tied to fossil fuel industry. These types of jobs would almost evaporate in the Smart Energy Europe scenario as well as the 1.5 TECH scenario. Most of the employment would become tied to investments in renewable energy and other production units, but in the Smart Energy Europe scenario most of the newly created workplaces would be in the renewable energy sector. Large amounts of heat savings in the 1.5 TECH scenario would, however, generate more employment in the building sector, compared to the Smart Energy Europe scenario, in which there would be fewer investments in heating, due to efficiency being implemented also in the district heating sector.

All three scenarios have a comparable employment in the biomass sector, whereas the Smart Energy Europe and the 1.5 TECH scenario have employment numbers of the same magnitude for the operation and maintenance of the entire energy system. When comparing the Smart Energy Europe scenario and the 1.5 TECH scenario to the baseline scenario, it would be possible to generate much more employment in the energy sector by a transition to renewable energy.

But Figure 6.1 does not tell us anything about the distribution of employment through time. Figure 6.2 does demonstrate how this distribution might be all depending on the timing and speed of the investments in renewables and renewable activity. The figure depictures respectively an early and steady energy transition, and a late and rapid. The conclusion is that both paths will ensure almost the same amount of employment within the solar, wind and biomass sectors. An early transition path will ensure a more stable employment creation pathway, compared to the late and rapid which shows more sensitivity towards timing. This smoothening of the temporal distribution of the employment generation also lessens potential bottleneck issues in the labour force.

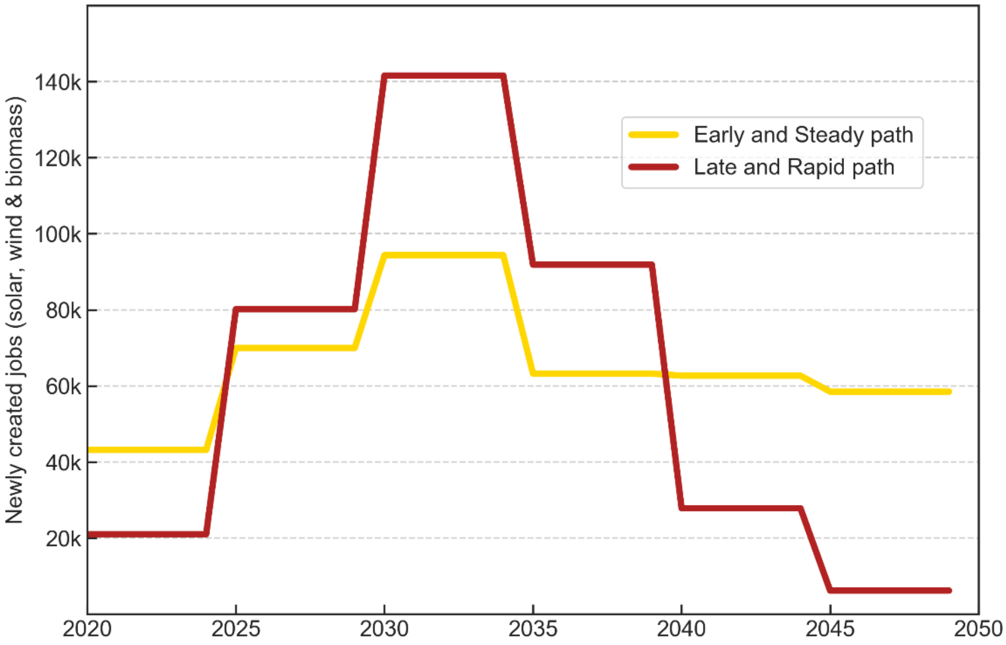

Figure 6.2: Estimated employment creation in wind, solar PV, and biomass throughout transition paths showing early and Steady, and late and rapid transition paths. [31]

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