European Energy System Based on 100% Renewable Energy – Transport Sector

Ram Manish, Bogdanov Dmitrii, Aghahosseini Arman, Khalili Siavash, Child Michael, Fasihi Mahdi, Traber Thure, Breyer Christian

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Title: European Energy System based on 100% Renewable Energy – Transport Sector

Authors: Manish Ram [1], Dmitrii Bogdanov [1], Arman Aghahosseini [1], Siavash Khalili [1], Michael Child [1], Mahdi Fasihi [1], Thure Traber [2], Christian Breyer [1]

Affiliation:

[1] LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland

[2] Energy Watch Group, Albrechtstr. 22, 10117 Berlin, Germany

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Abstract

This chapter presents a technically feasible and economically viable energy pathway for Europe, in which the energy sector (comprised of power, heat, transport, and desalination) reaches 100% renewable energy and zero greenhouse gas emissions by 2050. The research highlights the transition of the transport sector, which is currently dependent on fossil fuels to a great extent, towards being driven by 100% renewables. The transport sector achieves zero greenhouse gas emissions by 2050, mainly through direct and indirect electrification in the form of synthetic fuels, such as hydrogen and Fischer-Tropsch fuels. The methods are comprised of the derivation of the transportation demand, which is converted into final energy demand for direct electrification along with production of hydrogen, methane and Fischer-Tropsch fuels. The power-to-gas (H_2, CH_4) and power-to-liquids (Fischer-Tropsch fuels) value chains are applied for the total energy demand, which is fulfilled entirely by renewables in 2050. The primary energy demand for the transport sector decreases from 21,000 TWh in 2015 to around 20,000 TWh by 2050, driven by massive gains in energy efficiency with a high level of direct and indirect electrification of more than 85% in 2050. While, the final energy demand for transport decreases from 7000 TWh/a in 2015 to 5000 TWh/a, despite the assumed growth of passenger and freight transportation, mainly driven by the massive electrification of road transport. Solar PV and wind energy emerge as the most prominent energy supply sources with around 62% and 32%, respectively, of the total electricity supply by 2050. Batteries emerge as the key storage technology with around 83% of total electricity storage output. Fuel conversion technologies such as water electrolysis, methanation, Fischer-Tropsch synthesis, and others, supply renewable-based fuels along with sustainably produced biofuels and electrification to ensure a 100% renewable energy-based transport sector across Europe. The levelised cost of energy for a fully sustainable energy system across Europe remains stable in the range of €50-60 /MWh through the transition from 2015 to 2050. The final annualised energy costs for transport remain around 300-450 b€ per year through the transition period, with a massive reduction for road transport, while increases for marine and aviation transport by 2050 are projected. Greenhouse gas emissions can be reduced from about 4,200 mega tonnes CO_2 equivalent ($MtCO_{2eq}$) in 2015 in the entire energy system to zero by 2050, with cumulative GHG emissions of around 85 gigatonnes CO_2 equivalent ($GtCO_{2eq}$). While GHG emissions in the transport sector can be reduced from about 1900 $MtCO_{2eq}$ in 2015 to zero by 2050, this could be further accelerated with ambitious policies and targets across Europe. Consequently, a 100% renewable energy system across the transport sector in Europe is far more efficient and cost competitive than a fossil fuel-based option, and most importantly compatible with the Paris Agreement.

1. Introduction

A special report from the Intergovernmental Panel on Climate Change (IPCC) [1] has made it evident that a temperature rise of 2ºC in comparison to pre-industrial levels would be far more harmful and ultimately far more devastating from an economic perspective. Achieving only a 1.5ºC rise means cutting emissions by 45% by 2030 and reaching net zero around 2050. Limiting warming to a rise of 1.5ºC compared with pre-industrial levels will require an unprecedented number of efforts across the world. This fundamental insight is of prime importance since the debate on reacting to the ongoing climate crisis and the necessary transformation of the energy system towards 100% renewable sources demand urgent measures and strong political decisions. The societal tipping point for tackling the climate crisis may have already been passed, but due to the global 'Fridays for Future' movement of youth all around the world with the support of scientists [2,3], there is still hope that rapid and massive measures will be encouraged in the short- to mid-term.

In this context, a transition of the energy sector in Europe is of utmost relevance as the sector is responsible for the majority of greenhouse gas (GHG) emissions [4]. The objective of this research is to generate results for a European energy system transition towards 100% renewables in full hourly resolution for entire years from 2015 until 2050, with an emphasis on the transport sector. Insights for the case of Europe are presented in the following sections.

Energy for the transport sector makes up nearly one-third of global total final energy demand (TFED) [4]. The transport sector is comprised of several modes, namely road, rail, marine and aviation across passenger and freight categories [5]. Despite gains in efficiency, global energy demand in the transport sector increased 39% between 2000 and 2016, a rise attributed to the increased movement of freight globally and to the overall increase in transportation demand in emerging and developing countries, among other factors [4]. Currently, road transport accounts for 79% of global transport energy use, with passenger vehicles representing more than half of this. Additionally, marine transport consumes over 11% of the global energy used in transport, which is mainly from freight and is responsible for approximately 2% of CO_2 emissions. Moreover, aviation accounts for around 9% of the total energy used in transport, while rail accounts for less than 1% of the total energy used in transport and is the most electrified transport mode. The transport sector is Europe's largest contributor to climate change accounting for nearly 27% of its GHG emissions in 2017 [6]. Moreover, pollution from the transport sector is causing the illness and premature death of hundreds of thousands of Europeans [7]. Meanwhile the EU spends over 200 b€ a year importing oil to power its transport fleet [6].

However, there is a movement towards electrification in the transport sector with the evolution of the global electric car stock reaching nearly 2 million within six years from 2010 to 2016 [4]. With more than 1.2 million electric vehicles sold in 2017 (or 1.5% of the global car market), the penetration of this technology in the transport sector could reach the same level as the PV penetration in the power sector in the coming years and possibly evolve even faster [8]. The cumulative global EV stock reached 5.1 million in 2018 and the growth of EV sales is accelerating [9]. Likewise, the marine mode has options with increasing availability of alternative fuels such as biofuels in existing engines, which could be an immediate option, thereafter use of electricity-based synthetic fuels, such as synthetic natural gas, Fischer-Tropsch based fuels or hydrogen [10,11]. Additional fuels are discussed for the marine mode, such as ammonia or methanol, but not considered further here. The production and use of sustainable aviation fuels, specifically bio-based jet fuel or synthetic jet fuel apart from direct electrification for short-distance flights can propel the aviation mode towards being more sustainable [12]. Whereas, the rail mode with a share of electricity at 39% in 2015 is well underway towards maximum electrification [13]. However, just one-fourth of the electricity is estimated to be renewable, constituting 9% of rail energy, which is expected to change along with the power sector. In addition, synthetic fuels, including hydrogen and biofuels, could cover the non-electrified rail transport.

Transport is responsible for more than a quarter of GHG emissions in the EU [6]. All transport modes therefore need to contribute to the defossilisation of the mobility system. This requires a system-based approach. Low and zero emission vehicles with highly efficient alternative powertrains in all modes is the first prong of this approach. Just as for renewable energy in the previous decade, the automotive industry already today heavily invests in the emergence of zero and low emission vehicle technologies, such as electric vehicles. A combination of defossilised, decentralised and digitalised power, more efficient and sustainable batteries, highly efficient electric powertrains, connectivity and autonomous driving offer prospects to defossilise road transport with strong overall benefits including clean air, reduced noise, and possibly reduce accidents, altogether generating major health benefits for citizens and the European economy.

1. Transitioning to a fully renewable-based energy system: Methods and influencing factors across the transport sector

The LUT Energy System Transition model applied for the power sector in Ram et al. [14], Bogdanov et al. [15] and Breyer et al. [16] is further expanded to other energy sectors and its fundamental aspects for application across various energy sectors as is shown in Figure 1. The unique feature of the model enables a global-local energy system transition towards 100% renewables in full hourly resolution for the transition period from 2015 until 2050 across the power, heat, transport, and desalination sectors. In the present set up of the model, the power and heat sectors are completely integrated as shown in Bogdanov et al. [17], while the transport and desalination sectors are modelled separately with identical technical and financial assumptions applied across all the sectors. Furthermore, an aggregation of all the sectors represents the integrated energy sector. The results are visualised and presented in five-year intervals through the transition from 2015 to 2050 for the energy sector and more specifically for the transport sector across Europe in a highly decentralised manner. A rather conservative approach for understanding the limits has been adopted in this research, which suggests that all the 20 regions across Europe will have to fulfil their energy demands on an individual basis, which is a highly decentralised approach. Cooperation between neighbouring countries, within Europe, or internationally could reduce energy costs further. However, the intention of adopting a rather conservative view in this regard is to highlight security of energy supply across the different European countries and regions.

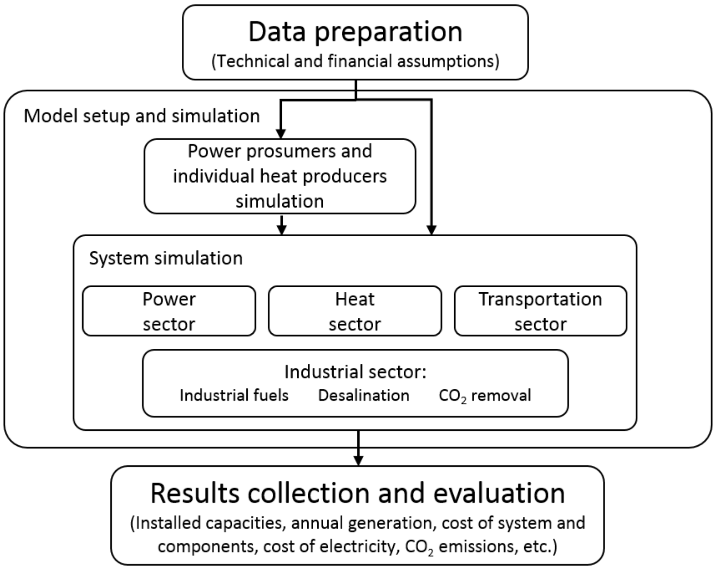

Figure 1: Fundamental structure of the LUT Energy System Transition model.

The model has integrated all crucial aspects of the power, heat, transport, and desalination sectors, which are further described in Ram et al. [18], Bogdanov et al. [15] and Bogdanov et al. [17]. The technologies introduced to the model are:

- electricity generation technologies: renewable energy (RE), fossil, and nuclear technologies;
- heat generation technologies: renewable and fossil;
- energy storage technologies: electricity, heat, gases, and fuel storage technologies;
- fuel conversion technologies: fuels for transport;
- desalination technologies; and
- electricity transmission technologies.

Transportation demand is derived for the modes: road, rail, marine, and aviation for passenger and freight transportation. The road segment is subdivided into passenger LDV (light duty vehicles), passenger 2W/3W (2- and 3-wheel vehicles), passenger buses, freight MDV (medium duty vehicles), and freight HDV (heavy duty vehicles). The other transport modes are comprised of demand for freight and passengers. The demand is estimated in passenger kilometres (p-km) for passenger transportation and in (metric) ton kilometres (t-km) for freight transportation. Further information and data for transportation demand along with fuel shares and specific energy demand are provided in Breyer et al. [5] and Khalili et al. [19].

The transportation demand is converted into energy demand by assuming an energy transition from current fuels to fully sustainable fuels by 2050, whereas the following principal fuel types are taken into account and visualised in Figure 2:

- Road: electricity, hydrogen, liquid fuels
- Rail: electricity, liquid fuels
- Marine: electricity, hydrogen, methane, liquid fuels
- Aviation: electricity, hydrogen, liquid fuels

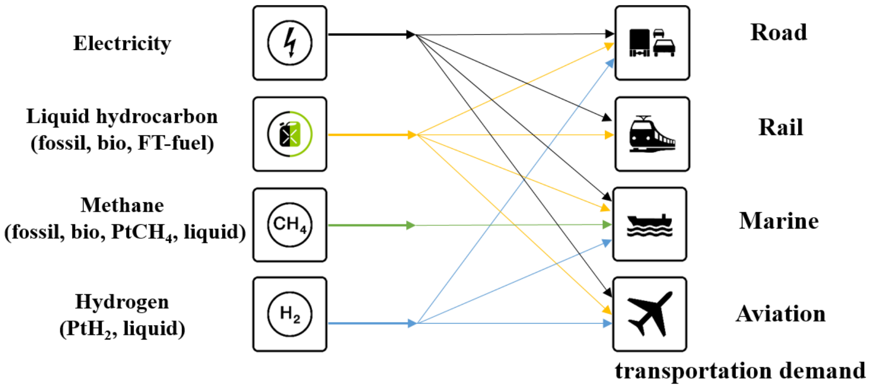

Figure 2: Schematic of the transport modes and corresponding fuels utilised during the energy transition from 2015-2050.

The fuel conversion process adopted to produce sustainable fuels is shown in Figure 3. The recycled heat flows from electrolyser, methanation and FT units and the heat demand of the reverse water-gas shift unit are not shown in the figure but are considered in the simulations.

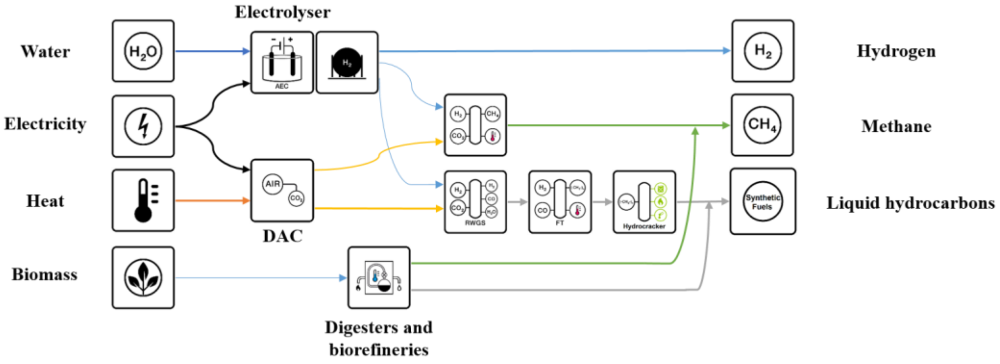

Figure 3: Schematic of the value chain elements in the production of sustainable fuels.

The fuel shares of the transportation modes in the road segment are based directly or indirectly on levelised cost of mobility considerations for newly sold vehicles, which change the stock of vehicles according to the lifetime composition of the existing stock. Vehicle stock and overall demand data are then linked to specific energy demand values to calculate demand of fuels and electricity for the transport sector. A more detailed description of the methods is provided in Breyer et al. [5] and Khalili et al. [19]. In addition, all fuel volumes and costs are based on a higher heating value.

A detailed overview of the technical and financial assumptions included in the modelling for the power, heat, transport, and desalination sectors can be found in the Appendix, which is based on the detailed explanation of the model applied to the global energy sector in Ram et al. [18], Bogdanov et al. [15], Breyer et al. [5] and Khalili et al. [19].

Regions of Europe

The regional composition of Europe considered in this study is shown in Figure 4. Some of the smaller countries have been merged with larger countries to form sizeable local regions, as the energy transition is envisioned on a regional basis and interconnections between the regions have not been considered. The regional composition of Europe and further details for the power sector are described in Child et al. [20].

Figure 4: The different countries and regions of Europe considered in the energy transition from 2015 to 2050.

Resource potentials for renewable energy technologies

The generation profiles for optimally fixed-tilted PV, solar CSP and wind energy are calculated according to Bogdanov and Breyer [21] and for single-axis tracking PV according to Afanasyeva et al. [22]. The hydropower feed-in profiles are computed based on daily resolved water flow data for the year 2005 [23]. The potentials for biomass and waste resources were obtained from Bunzel et al. [24] and further classified into the categories of solid wastes, solid residues and biogas. Geothermal energy potential is estimated according to the method described in Gulagi et al. [25] across Europe. More details on renewable resources for Europe can be found in Child et al. [20]. The average profiles of single-axis tracking PV and onshore wind energy across Europe are shown in Figure 5.

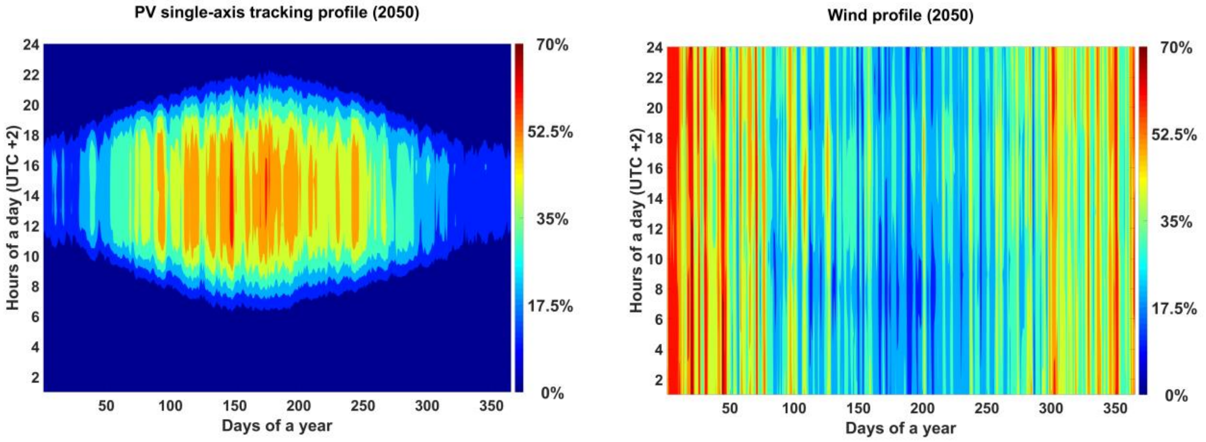

Figure 5: Hourly generation profile on an annual basis for solar PV with single-axis tracking (left) and onshore wind at 150 m hub-height (right) across Europe.

The distribution of full load hours across Europe (equivalent to annual generation) of solar PV, for the case of single-axis tracking, and wind onshore at 150 m hub-height, which are the two most vital sources of electricity in the energy transition, are shown in Figure 6.

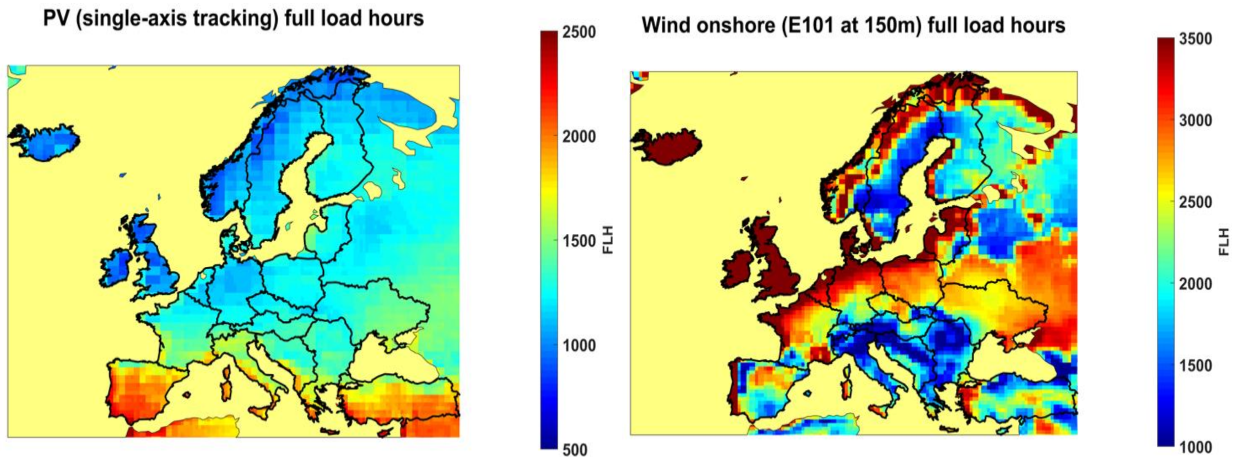

Figure 6: Mapping of annual full load hours for solar PV with single-axis tracking (left) and onshore wind at 150 m hub-height (right) across Europe.

Best Policy Scenario

The LUT Energy System Transition model can be utilised to generate wide-ranging energy scenarios across the different regions of the world on a global-local scale. However, the objective of this study is to highlight an energy scenario that can contribute towards achieving the goals of the Paris Agreement by reaching zero GHG emissions from the energy sector across Europe by 2050, in a technically feasible and economically viable manner and respecting comprehensive sustainability guardrails [26]. Therefore, a Best Policy Scenario is envisioned across the power, heat, transport, and desalination sectors for the case of Europe, from the current system in 2015 towards a cost optimal zero GHG emissions system in 2050. Furthermore, the transport sector is analysed in greater detail in this chapter and presented in the following sections.

2. Results: Transition towards a 100% Renewable Energy System across Europe

Europe is one of the major economic centres of the world with an 18% share of global GDP according to the International Monetary Fund (IMF) [27]. In addition, Europe is amongst the biggest energy consumers across the world, with total electricity consumption of around 4,000 TWh in 2015, which is estimated to rise to around 5,400 TWh by 2050 according to the International Energy Agency (IEA) [28]. Europe has been at the forefront of the global energy transition with about 37% of installed power capacity and nearly 30% of electricity generation from renewables, according to statistics from the European Commission [29]. Moreover, the European Commission has proposed a long-term strategy to confirm Europe's commitment to lead global climate action and present a vision that can lead to achieving net-zero GHG emissions by 2050 through a socially fair transition in a cost-efficient manner [30]. In this context, the study shows that an energy transition to 100% renewable electricity is feasible at every hour throughout the year and is more cost-effective than the existing system, which is largely based on fossil fuels and conventional energy production across Europe. In addition, this study demonstrates that the European transport sector can be defossilised by 2050 or earlier, not only to limit global warming, but also to ensure Europe's competitiveness globally, its energy sovereignty and most importantly the health and well-being of its 665 million citizens.

Energy Sector

The penetration of renewables is not just a matter of replacing hydrocarbons with fossil free sources of energy supply – it also represents a significant change in resource efficiency. This is illustrated by the impact of electrification on energy demand across the power, heat, transport, and desalination sectors as shown in Figure 7. This research assumes a high electrification across the energy system, driven by low-cost renewables, high efficiency of electricity-based solutions and overall sustainability constraints. The resulting primary energy demand with high electrification decreases from 21,000 TWh in 2015 to around 16,000 TWh by 2035 and increases up to 20,000 TWh by 2050. On the contrary, with low electrification (continuation of current practices until 2050) the primary energy demand would reach nearly 35,000 TWh by 2050. The average per capita energy demand decreases from around 33 MWh/person in 2015 to 24 MWh/person by 2035 and increases up to nearly 30 MWh/person by 2050. The massive gain in energy efficiency is primarily due to a high level of electrification of more than 85% resulting in a primary energy demand reduction of around 15,000 TWh by 2050, in comparison to the continuation of current practices (low electrification).

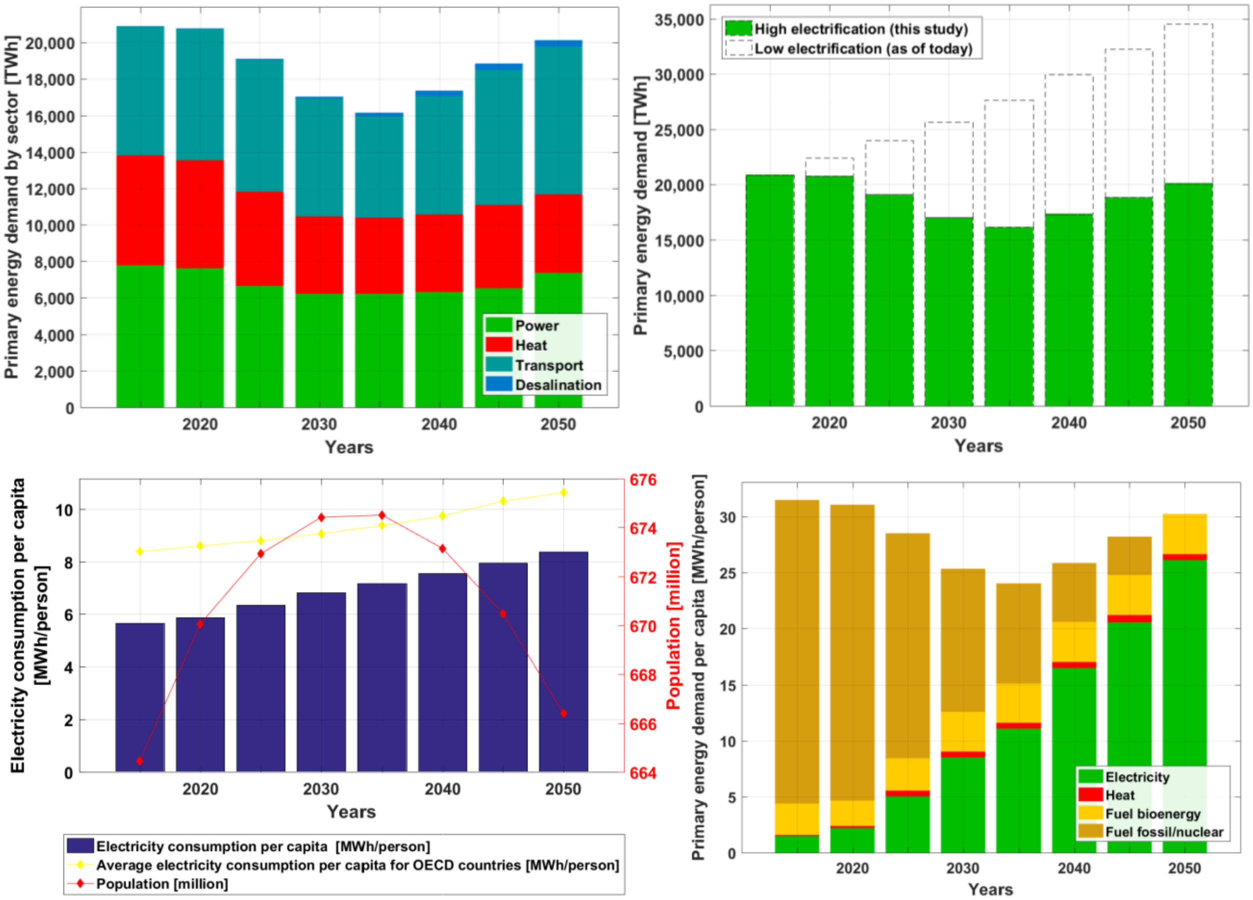

Figure 7: Primary energy demand sector-wise (top left), efficiency gain in primary energy demand (top right), electricity consumption per capita with population (bottom left) and primary energy demand per capita (bottom right) during the energy transition from 2015 to 2050 in Europe.

However, a higher demand for industrial process heat, as well as space heating induced by growing building space per person, reduces the overall gains and contributes to an increase in energy demand in the later years of the transition, from 2035 to 2050. Additionally, a substantial demand from fuel conversion technologies arises beyond 2040, in producing synthetic fuels for the transport sector across Europe.

Energy supply

Electricity generation from the various technologies to cover the demand of power, heat, transport, and desalination sectors is shown in Figure 8. Solar PV supply increases through the transition from 29% in 2030 to about 62% by 2050, becoming the lowest cost energy source. Wind energy increases to 32% by 2030 and contributes a stable share of the mix up to 2050. On the contrary, the share of coal and nuclear power generation decline substantially by 2030 and through the transition, as they are rendered uneconomical. In the heat sector, heat pumps play a significant role through the transition with a share of nearly 50% of heat generation by 2050 on both the district and individual levels, as indicated in Figure 8. On the other hand, fuel-based heating decreases through the transition from over 95% in 2015, to around 30% by 2050. Additionally, fossil fuel-based heating decreases through the transition period, as coal-based combined heat and power (CHP) and district heating (DH) is replaced by waste-to-energy CHP, biomass-based DH, and individual heating (IH).

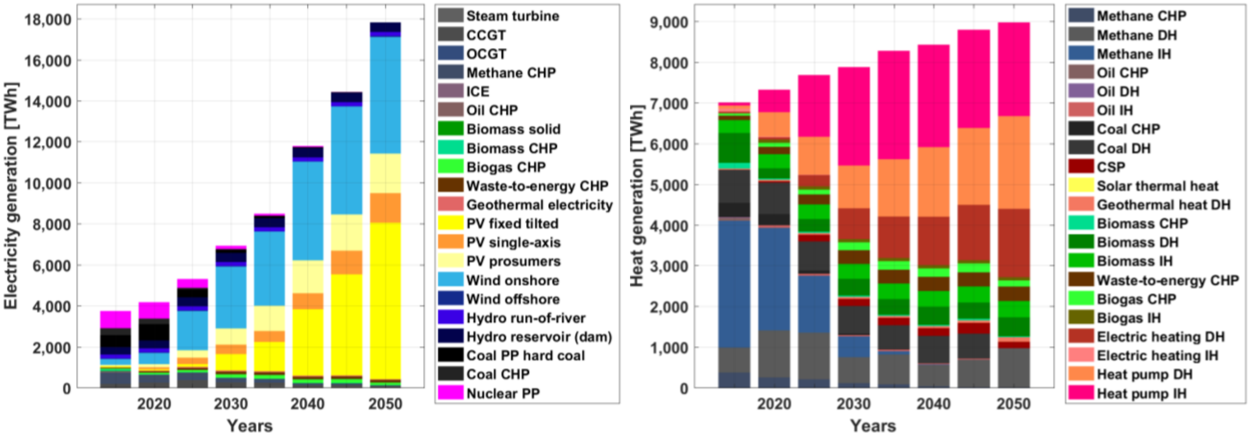

Figure 8: Technology-wise electricity generation (left) and technology-wise heat generation (right) during the energy transition from 2015 to 2050 in Europe.

Energy storage

Energy storage technologies play critical roles in enabling a secure energy supply across Europe, fully based on renewable energy across different sectors. As highlighted in Figure 9, storage output covers 17% of total electricity demand in 2050. The ratio of electricity demand covered by electrical energy storage output increases significantly to around 13% by 2035 and remains around 11-13%. An additional 4% is covered by heat storage conversion to electricity by 2050. Batteries emerge as the most relevant electricity storage technology contributing about 83% of the total electricity storage output by 2050. Additionally, a significant share of gas storage is installed to provide seasonal storage primarily during the cold winter season across Europe.

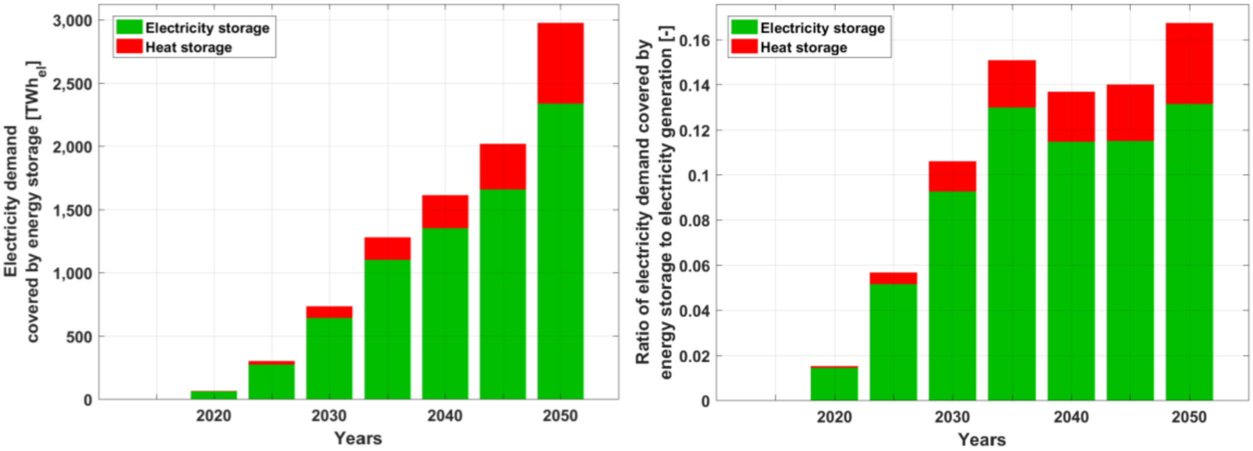

Figure 9: Electricity demand covered by energy storage (left) and ratio of electricity demand covered by different forms of energy storage (right) during the energy transition from 2015 to 2050 in Europe.

Similarly, heat storage plays a vital role in ensuring heat demand is covered across all the sectors. As indicated in Figure 10, the ratio of heat demand covered by energy storage to heat generation increases substantially to almost 20% by 2050. Thermal energy storage (TES) emerges as the most relevant heat storage technology with around 40-60% of heat storage output from 2030 until 2050. Furthermore, power-to-gas (PtG) contributes around 40% of heat storage output in 2050. As fossil fuel usage for heat generation is completely eliminated in the final five-year period from 2045-2050, there is an increase in heat storage utilisation.

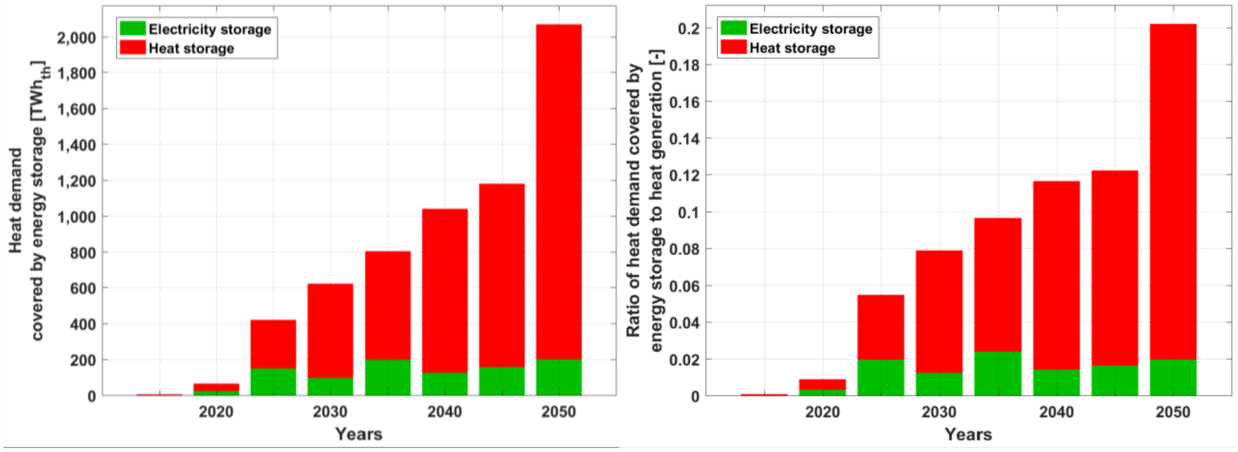

Figure 10: Heat demand covered by energy storage (left) and the ratio of heat demand covered by different forms of energy storage (right) during the energy transition from 2015 to 2050 in Europe.

Costs and investments

The total annual costs are in the range of 950-1,100 b€ through the transition period and are well distributed across the major sectors of power, heat, and transport, as desalination demand in Europe is relatively smaller compared to other regions of the world. As indicated by Figure 11, power, heat, and transport costs are in the range of around 300-350 b€ each through the transition. In addition, as indicated in Figure 11 capital expenditures (CAPEX) increase through the transition, as fuel costs decline. The steady increase in CAPEX-related energy system costs indicate that fuel imports and the respective negative impacts on trade balances will fade out through the transition. In addition, a low fuel import dependency will lead to a higher level of energy security across Europe.

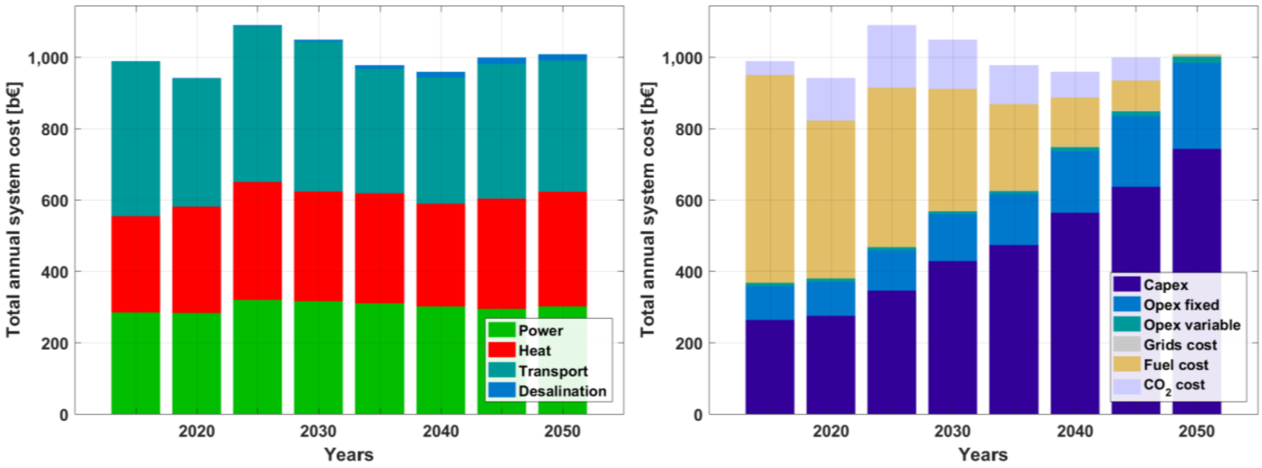

Figure 11: Annual system costs, sector-wise (left) and functionality-wise (right) during the energy transition from 2015 to 2050 in Europe.

As increasing shares of power generation capacities are added globally, renewable energy sources on a levelised cost of energy basis become the lowest cost power generation sources [31]. As indicated in Figure 12, levelised cost of energy remains around 50-60 €/MWh and is increasingly dominated by capital costs as fuel costs continue to decline through the transition period, which could mean increased self-reliance in terms of energy for Europe by 2050 as mentioned earlier. Capital costs are well spread across a range of technologies with major investments for PV, wind energy, batteries, heat pumps, and synthetic fuel conversion up to 2050, as shown in Figure 12. The cumulative investments are about 9,910 b€ through the transition from 2016 to 2050.

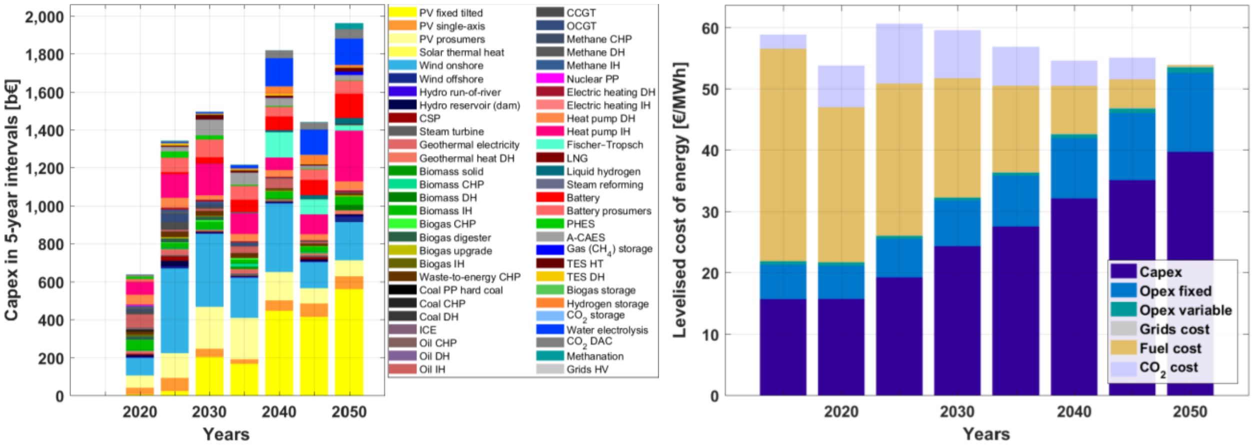

Figure 12: Capital costs for five-year intervals (left) and levelised cost of energy (right) during the energy transition from 2015 to 2050 in Europe.

Different trends in the power, heat, transport, and desalination sectors across Europe emerge through the transition. As the sectors transition towards having higher shares of renewable energy, different technologies have vital roles in ensuring the stability of the energy system. A closer look at the transport sector provides vital insights into the energy transition across Europe towards 100% renewable energy based transport.

Transport Sector

The final passenger demand and freight demand in Europe through the transition from 2015 to 2050 is shown in Figure 13. Also included are international marine and aviation transportation demands, which are often ignored on the regional level by other studies due to statistical reasons. More details on that aspect can be found in Khalili et al. [19]. For transportation passenger demand, the largest increase is projected for aviation by about 370% from 2015 to 2050, followed by about 160% increase in road transportation passenger demand. For transportation freight demand, the marine mode shows the highest increase by about 230%, followed by about 150% for the road mode.

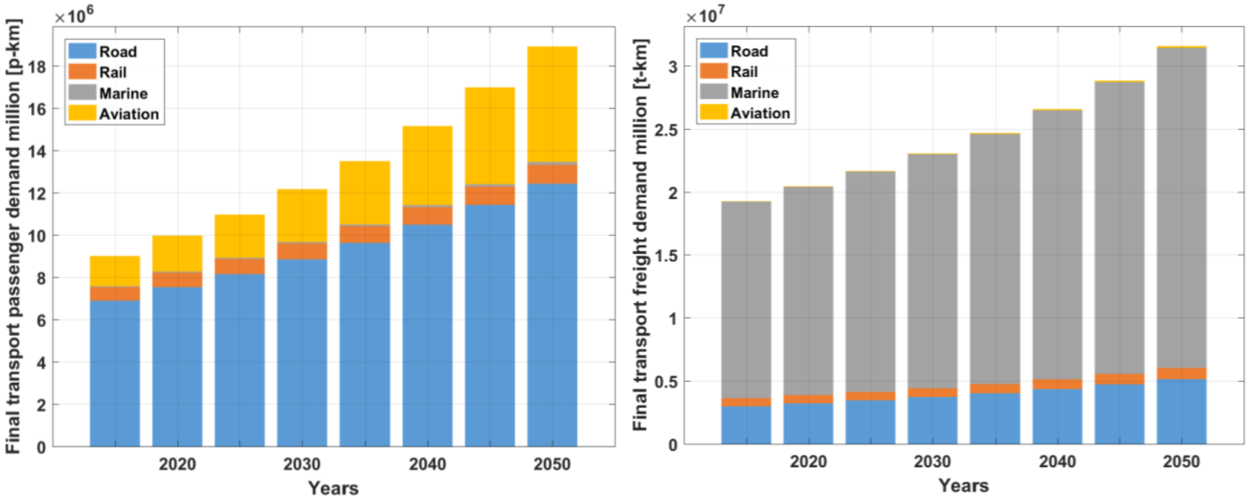

Figure 13: Final transport passenger demand (left) and freight demand (right) during the energy transition from 2015 to 2050 in Europe.

The corresponding final energy demand in the transport sector undergoes an increase from around 7,000 TWh in 2015 and thereafter a decline to below 5,000 TWh in 2050, as subsequent overall transport technological efficiencies increase during the transition, during which shifts to more efficient power trains are projected. This is shown in Figure 14.

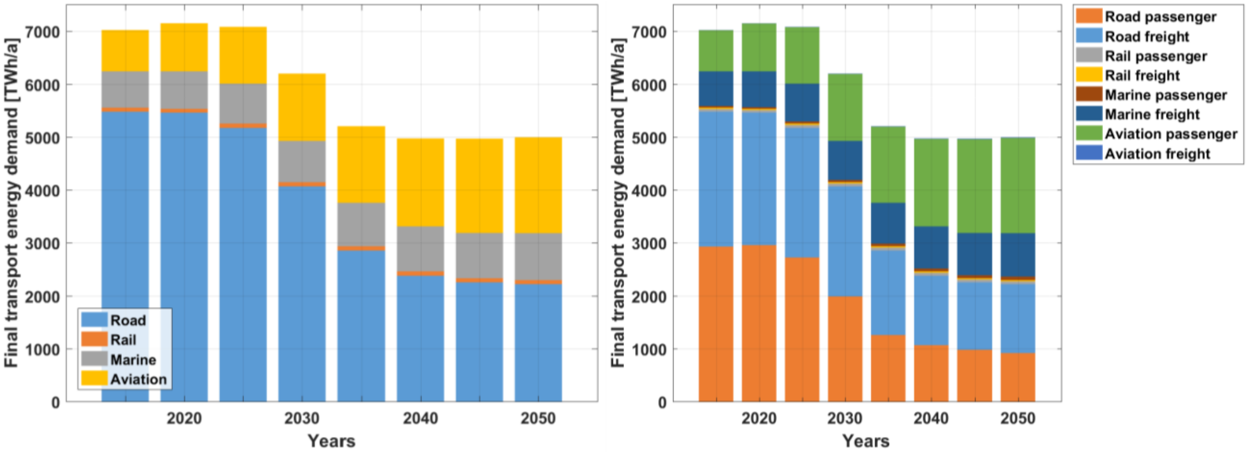

Figure 14: Final energy demand for different transport modes (left) and different transport categories (right) during the energy transition from 2015 to 2050 in Europe.

The road transport energy demand declines through the transition with massive gains from a high level of direct electrification, whereas the final energy demand increases continuously for marine and aviation modes due to continued transportation demand increase, limited options for fuel shifts and further increase in efficiencies of existing power trains. Energy demand for the rail mode remains fairly stable through the transition, as steady rail transportation demand growth is well compensated by efficiency gains due to electrification. The development of final energy demand for the different transport modes through the transition is shown in Figures 14-16.

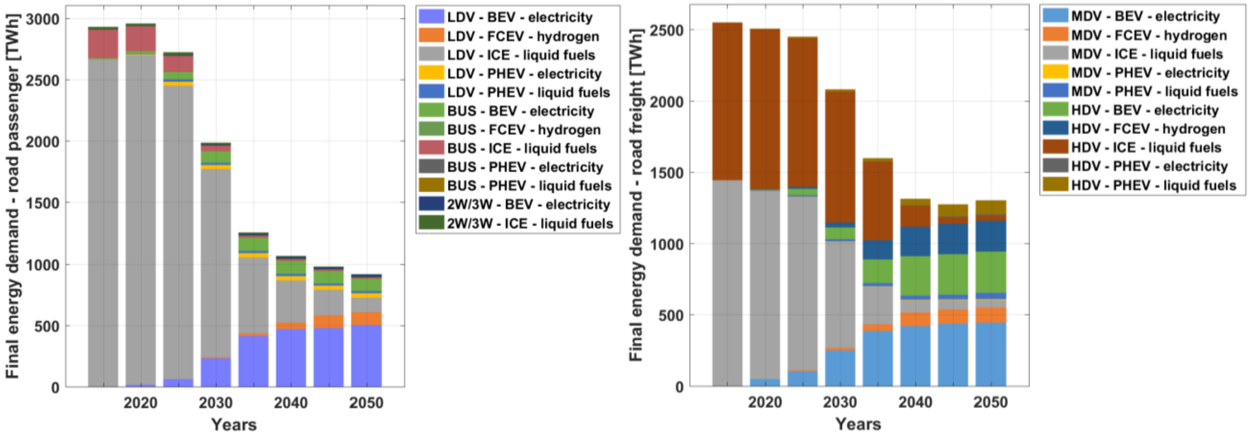

Figure 15: Final energy demand for road passenger transport (left) and road freight transport (right) during the energy transition from 2015 to 2050 in Europe.

The low efficiency of the present transport sector is illustrated by the projection of a threefold increase in transportation demand, but stabilised final energy demand for the transport sector.

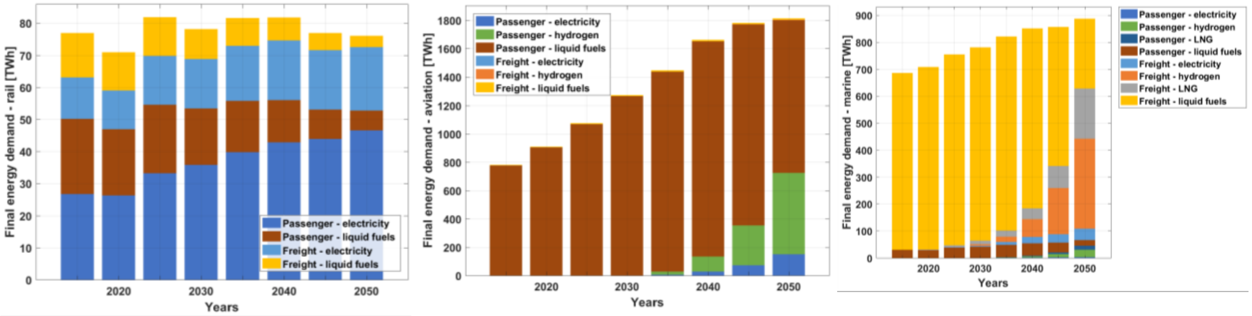

Figure 16: Final energy demand for rail (left), aviation (centre) and marine (right) during the energy transition from 2015 to 2050 in Europe.

The final energy demand of the transport sector across Europe is almost the same as the energy demand from the power sector at around 7,000 TWh in 2015. However, this demand declines through the transition to around 5,000 TWh, mainly due to the efficiency gains brought about by direct electrification of the sector as shown in Figure 17. Fossil fuel consumption in the transport sector across Europe is seen to decline through the transition from about 97% in 2015 to zero by 2050. On the other hand, liquid fuels produced by renewable electricity contribute around 35% of final energy demand in 2050. In addition, hydrogen constitutes more than 25% of final energy demand in 2050. Sustainable biofuels, produced from forest industry residues, contribute a minor share to enable a complete elimination of fossil fuel usage in the transport sector. Additionally, sustainable biofuels produced from energy crops such as Jatropha could contribute towards enabling 100% renewable energy systems [32]. Electrification of the transport sector creates an electricity demand of around 7,500 TWh_{el} by 2050. The massive demand for liquid fuels kicks in from 2040 onwards up until 2050, as indicated in Figure 17.

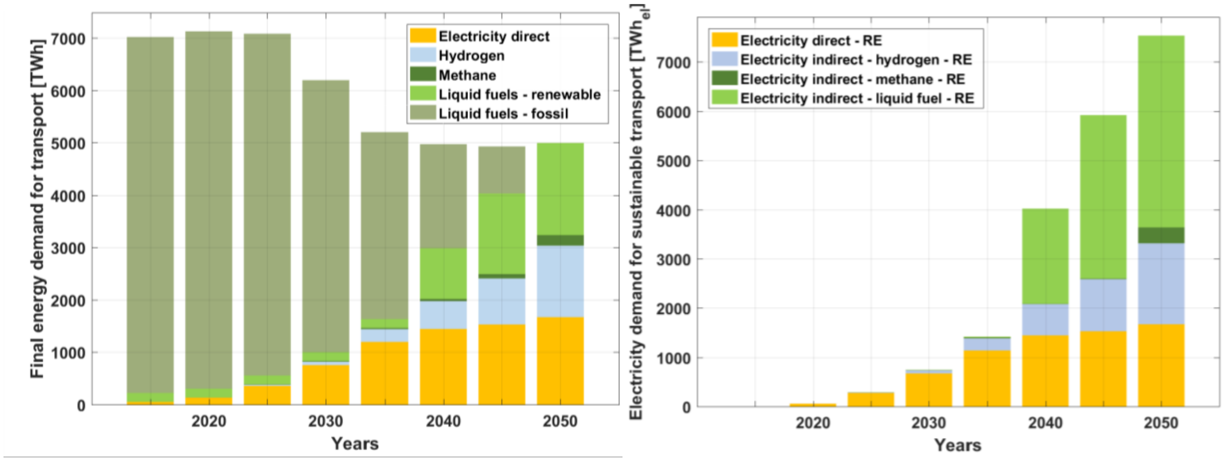

Figure 17: Final energy demand for transport (left) and electricity demand for sustainable transport (right) during the energy transition from 2015 to 2050 in Europe.

Installed power generation capacity for the transport sector increases substantially through the transition to around 5,250 GW by 2050, as shown in Figure 18. Solar PV and wind form the majority share of the power generation capacity for the transport sector, as they are the lowest cost energy sources by 2050. Similarly, electricity generation increases substantially up to almost 8,000 TWh by 2050 as also seen in Figure 18. Solar PV and wind energy can generate all the electricity required to meet the demand of the transport sector in 2050, as only a small biofuel share is assumed comparable to the present. The electricity requirement of 8,000 TWh$_{el}$ is higher than the final energy demand of 5,000 TWh, which is caused by the conversion of electricity to synthetic fuels and respective conversion efficiencies.

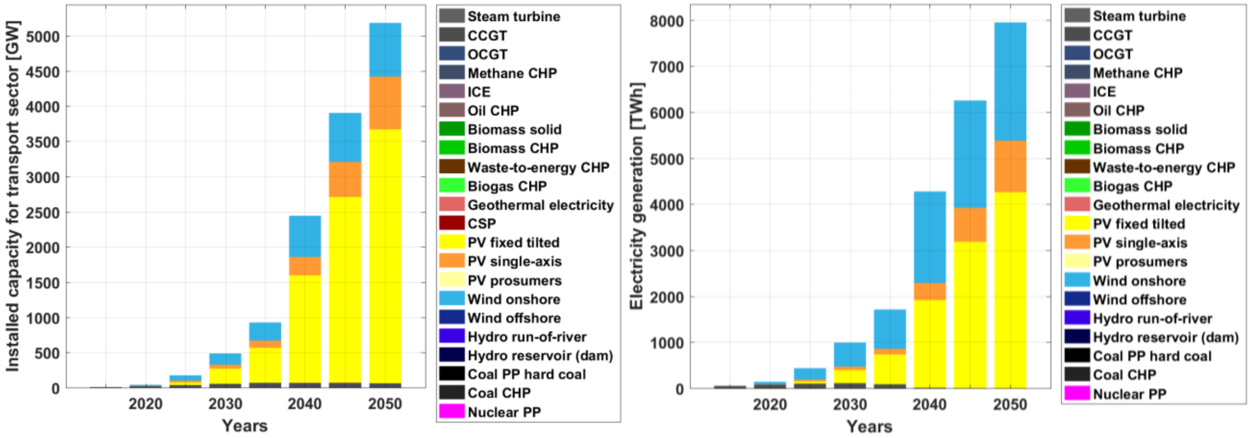

Figure 18: Transport sector installed power generation capacity (left) and electricity generation (right) during the energy transition from 2015 to 2050 in Europe.

A critical aspect to complement the electrification of the transport sector is the installation of storage technologies. As seen in Figure 19, the installed capacities of electricity storage increase through the transition to around 3.3 TWh$_{cap}$ by 2050. The majority of installed capacities are utility-scale batteries and compressed air energy storage (A-CAES). Similarly, electricity storage output increases through the transition to over 700 TWh$_{el}$ by 2050 as shown in Figure 19. Utility-scale batteries play a vital role as they contribute a major portion of the output through the transition, with over 500 TWh$_{el}$ by 2050. The relatively low electricity storage of less than 10% of generated electricity for the transport sector is enabled by the flexible operation of batteries, water electrolyser units, and hydrogen buffer storage for synthetic fuel production.

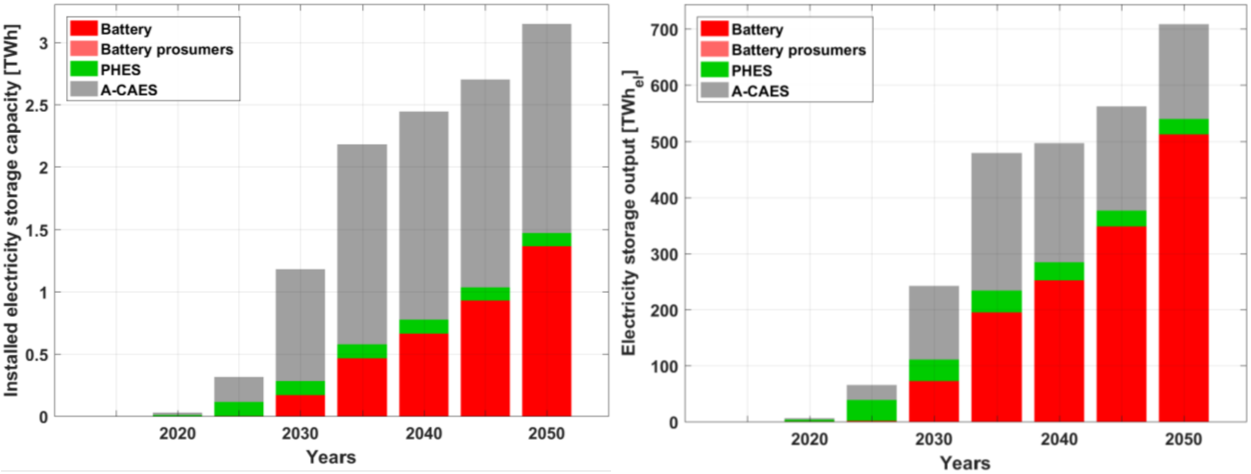

Figure 19: Transport sector installed electricity storage capacity (left) and electricity storage output (right) during the energy transition from 2015 to 2050 in Europe.

Another essential aspect in the transition of the transport sector towards higher electrification completely based on renewable energy is the production of synthetic fuels, hydrogen and sustainable biofuels. As indicated in Figure 20, the installed capacities of fuel conversion technologies increase substantially from 2040 onwards to over 2,300 GW by 2050. Water electrolysis forms the majority share of fuel conversion capacities through the transition. Additionally, heat is generated during the production of synthetic fuels, which leads to higher overall energy system efficiency if recovered heat is used for CO_2 direct air capture (DAC) [33] . Heat availability is in the range of 1,100 TWh$_{th}$ by 2050, which partly is recovered, and the rest is excess heat, as shown in Figure 20. In a model with coupled heat and transport sectors, such excess heat from the transport sector could be used by the heat sector, which would further lower the overall cost of the energy system, due to improved overall energy system efficiency.

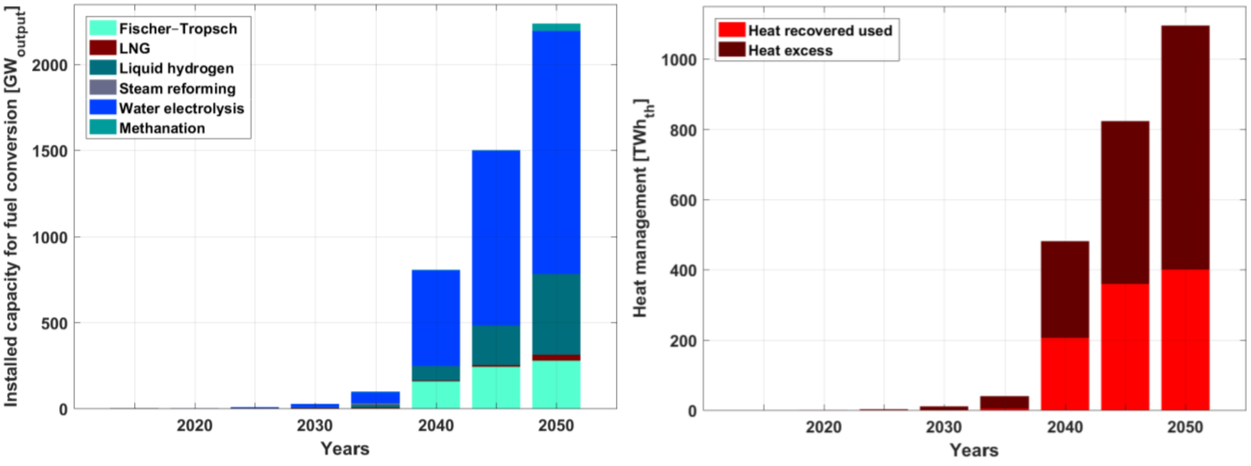

Figure 20: Transport sector installed capacity for fuel conversion (left) and heat management (right) during the energy transition from 2015 to 2050 in Europe.

Similarly, gas storage is necessary in the production of synthetic fuels. As shown in Figure 21, the installed storage capacity for gas increases through the transition to around 13 TWh by 2050. Hydrogen storage is the major gas stored through the transition, with a minor share for methane gas in 2050. CO_2 storage and

CO_2 direct air capture, which are vital in the production of synthetic liquid fuels and methane, are installed from 2040 onwards. The installed capacity for CO_2 direct air capture increases up to around 375 $MtCO_2$/a by 2050 while CO_2 storage reaches 16 $MtCO_2$, as shown in Figure 21. Despite having a lower storage capacity, CO_2 storage has a substantial utilisation and correspondingly higher throughput, comparable to the CO_2 direct air capture capacity.

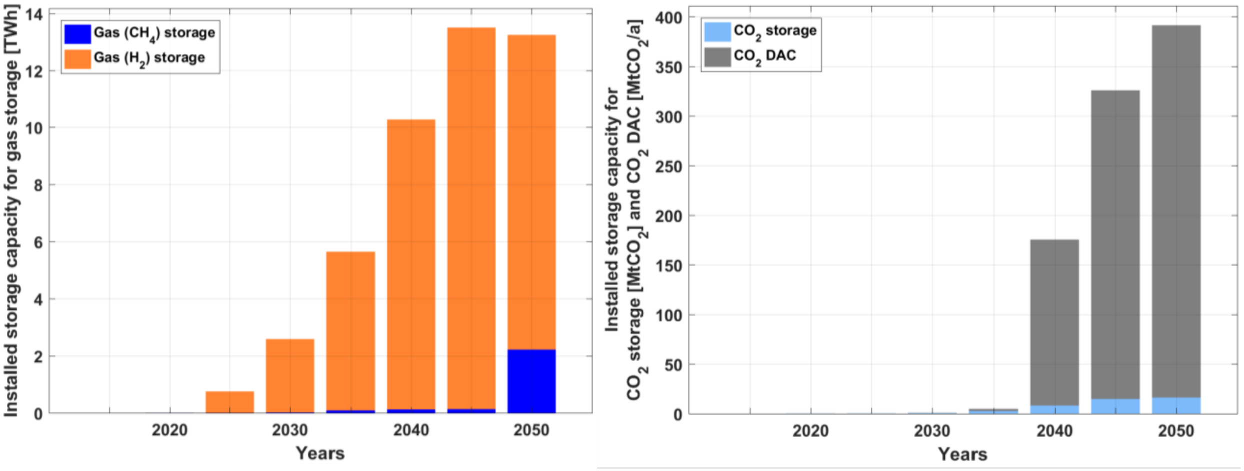

Figure 21: Transport sector installed capacity for gas (methane and hydrogen) storage (left) and CO_2 storage and CO_2 direct air capture (right) during the energy transition from 2015 to 2050 in Europe.

Fuel costs are a deciding factor in the overall energy mix for the transport sector across Europe and their developing trends are highlighted in Figure 22. Fischer-Tropsch fuel and synthetic natural gas (SNG) costs decline through the transition up to 2050. FT-fuels are in the range of costs of fossil liquid fuels including GHG emissions costs, in the range of 90-100 €/MWh in 2050. Figure 22 also shows that SNG and liquefied synthetic natural gas (LNG) are more cost effective than FT-fuels. Electricity emerges as the most cost-effective option with primary levelised cost of electricity around 25 €/MWh and along with complementary costs of storage and other system components, total levelised cost of electricity is around 32 €/MWh in 2050. Hydrogen (H_2) fuel costs decline to be more cost competitive that fossil fuels, in the range of 55 €/MWh in 2050, while liquid H_2 is in the range of 60 €/MWh. The cost of CO_2 from DAC, which is a critical component for synthetic fuels, is at around 33 €/t_{CO2} in 2050, as shown in Figure 22. A methodological upgrade has resulted in higher costs of FT-fuels of around 3-4 €/MWh by 2050, which builds a slightly less favourable case for renewable powered synthetic fuels. However, this has little impact on the overall structural results, as presented in this chapter, but will enable more accurate estimations in future research.

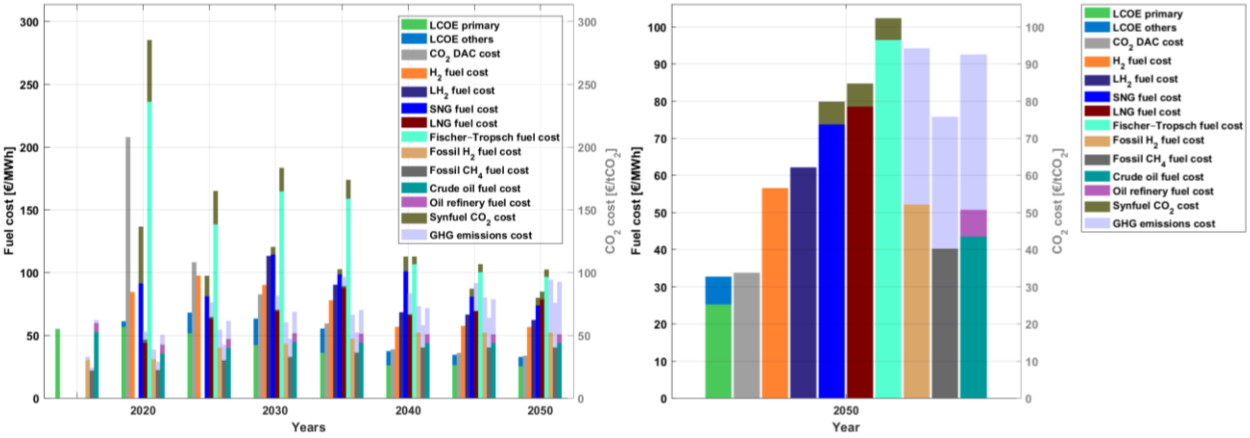

Figure 22: Fuel costs for the transport sector during the energy transition from 2015 to 2050 (left) and fuel costs in 2050 (right) in Europe.

The total annual energy costs for the energy supply of the transport sector are in the range of 300-450 b€ through the transition period with a decline from around 430 b€ in 2015 to about 330 b€ by 2050, as shown in Figure 23. Furthermore, annual system costs transit from being heavily dominated by fuel costs in 2015 to a very diverse share of costs across various technologies for electricity, synthetic fuels and sustainable biofuel production by 2050. The difference in annual final transport energy and system costs is predominantly due to additional aspects of the system beyond 2040, as FT units produce naphtha as a by-product, that adds to the overall system costs. The cost for naphtha is allocated to the industry sector as input for the chemical industry, since it is a valuable feedstock there.

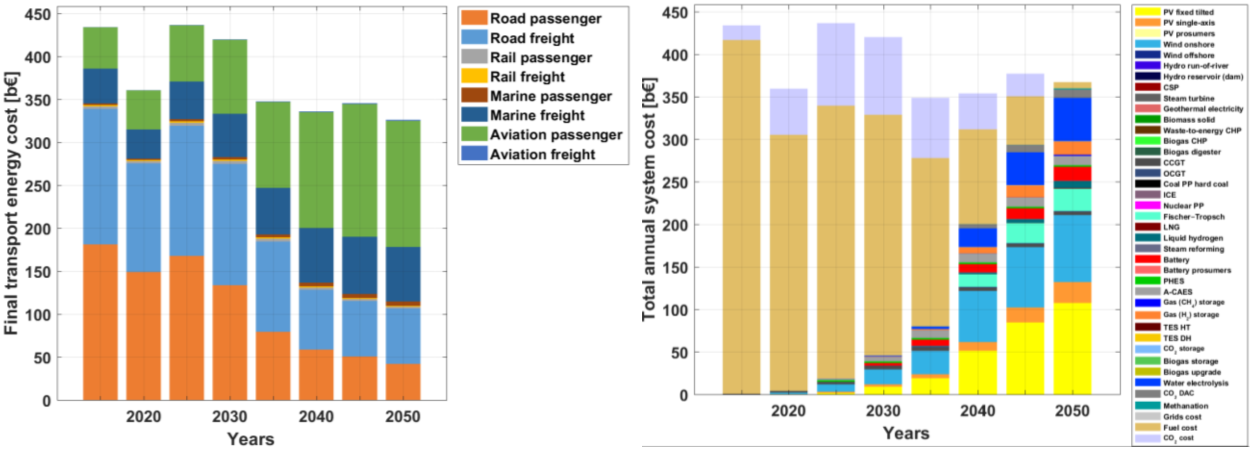

Figure 23: Final energy cost of transport based on mode of transport (left) and source of energy (right) during the energy transition from 2015 to 2050 in Europe.

The final transport passenger cost declines from around 0.011 €/p-km in 2015 to 0.07 €/p-km by 2050, as shown in Figure 24. Final transport passenger costs decline for road transport through the transition, whereas for marine and aviation there is a marginal increase. Similarly, final transport freight costs decline from around 0.065 €/t-km in 2015 to 0.025 €/t-km by 2050, as shown in Figure 24. The final freight cost in the case of road declines through the transition, whereas it increases slightly for aviation and remains stable for rail and marine.

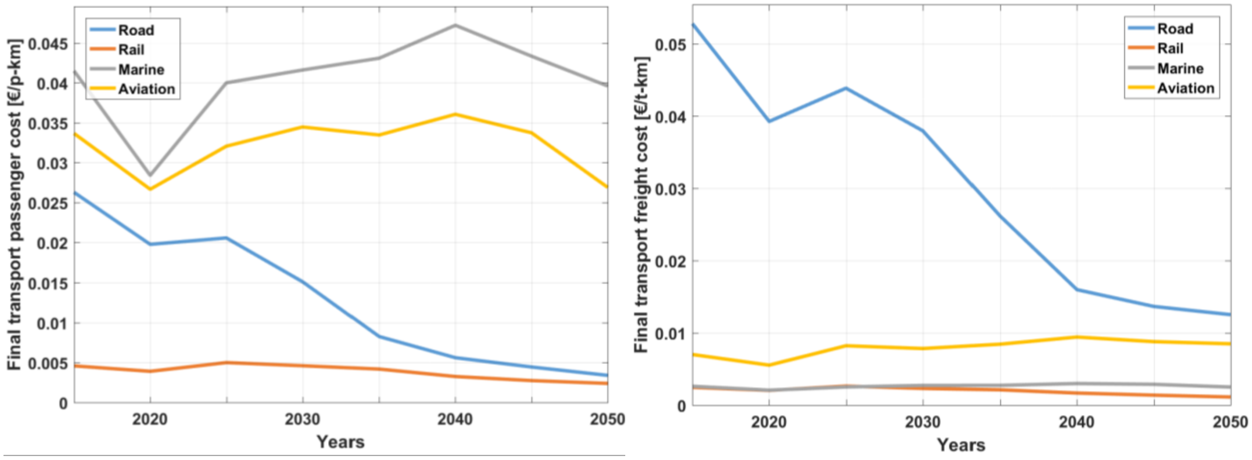

Figure 24: Final energy cost of transport passenger (left) and transport freight (right) during the energy transition from 2015 to 2050 in Europe.

Greenhouse gas emissions

The results of the global transition towards a 100% renewable energy system indicate a sharp decline in GHG emissions until 2050, reaching zero GHG emissions by 2050. Moreover, the GHG emissions from the transport sector decline through the transition from around 1,900 $MtCO_2$ eq./a in 2015 to zero by 2050, as shown in Figure 25. In addition, the GHG emissions from the road transport mode, which are the majority, reduce from around 1500 $MtCO_2$ eq./a in 2015 to zero by 2050 as indicated in Figure 25. These results clearly indicate that at the latest from 2030 onwards pressure on ship operators and airlines would dramatically increase, since the relative contribution of these two transport modes will start to dominate the total GHG emissions of the transport sector in Europe.

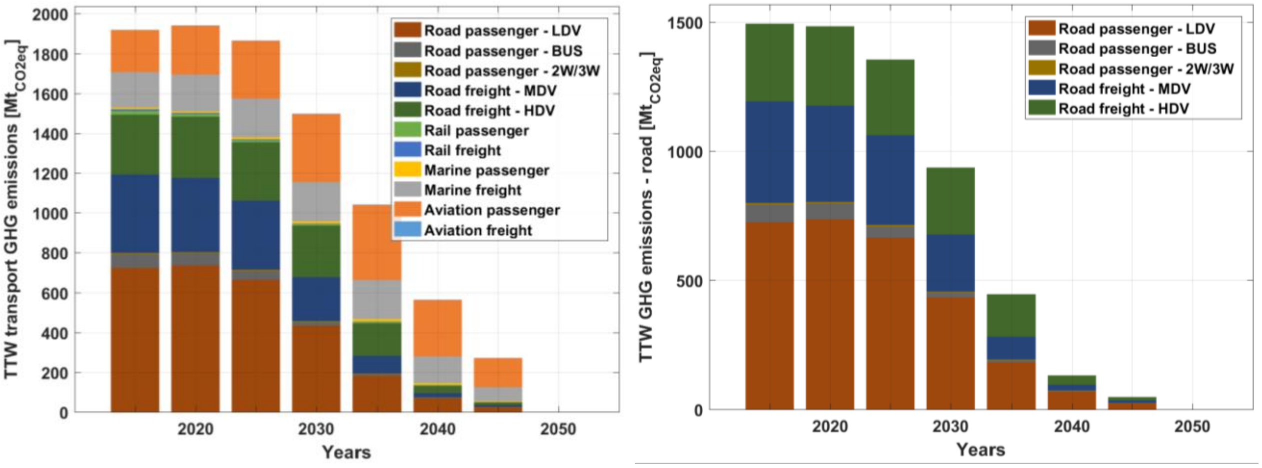

Figure 25: GHG emissions in the transport sector (left) and GHG emissions in the road transport mode (right) during the energy transition from 2015 to 2050 in Europe. Tank to Wheel (TTW) considers GHG emissions from readily available fuels and does not consider GHG emissions from the upstream production and delivery of fuels.

3. Discussion

A paradigm shift is observed, wherein electricity emerges as the energy carrier of the future, replacing fossil fuels within the transport sector by 2050. In a highly digitalised future with strong global climate policies, electrification of energy services will be pervasive [34]. Primarily, fossil and nuclear fuels used in the energy sector are substituted by technologies directly extracting electricity from the environment, in particular solar PV and wind energy. As highlighted by the results, electric vehicles will largely replace fossil-fuelled 2-wheelers, 3-wheelers, cars and trucks. While heat pumps and electric heating substitute oil and gas furnaces in buildings and industries. Electricity from renewables will cover the growing electricity demand and will be used to produce hydrogen and other synthetic fuels for applications where direct electrification is challenging. The advantages of widespread electrification are clear and compelling. Substantial efficiency gains are observed throughout the European transport sector with final energy demand in transport declining by nearly 30%. The high generation contribution of solar PV of about two-thirds of all generated electricity for the transport sector can be explained by four main drivers: Firstly, a further decline in costs of solar PV and batteries, most likely at even lower costs than as assumed in this research, as recently discussed by Vartiainen et al. [35]. Secondly, the anticipated cost decline of electrolyser units allows a cost optimised operation in the range of 3000 to 4000 full load hours, so that the low cost electricity of solar PV can be utilised to a very high extent. Thirdly, low cost storage of hydrogen, methane and CO_2 allows a more pronounced decoupling of the electricity supply from solar PV plants and synthesis plants for refining the fuels for final energy demand in the transport sector. Lastly, the partial flexibility of several components further helps in integrating higher shares of low cost solar PV while still keeping curtailment at a low level, so that overall optimum costs can be achieved. Several of these aspects are detailed in the following section.

From the research, it can be derived that the electrification of the transport sector will proceed in three major phases. Firstly, direct electrification across the different modes mainly led by road transport occurs till about 2030- Thereafter, a broader indirect electrification through the production of FT-fuels occurs across the different transport modes. Finally, more usage of liquefied gases (CH_4, H_2) in the 2040s is observed across the transport sector mainly for long-distance, heavy-duty transport modes, such as marine and aviation. This projection leads to zero GHG emissions in the transport sector by 2050 across Europe.

Full hourly operation is visualised for several of the major components needed for the transport sector, in particular for the production of synthetic fuels. The highly flexible operation of electrolysers, as shown in Figure 26 is a key reason for achieving competitive cost structures for synthetic fuels in the transport sector. This reveals that wind energy is mainly used for direct electricity supply, whereas solar PV is the dominant source for the production of synthetic fuels (see also Fig. 5 for the solar resource availability).

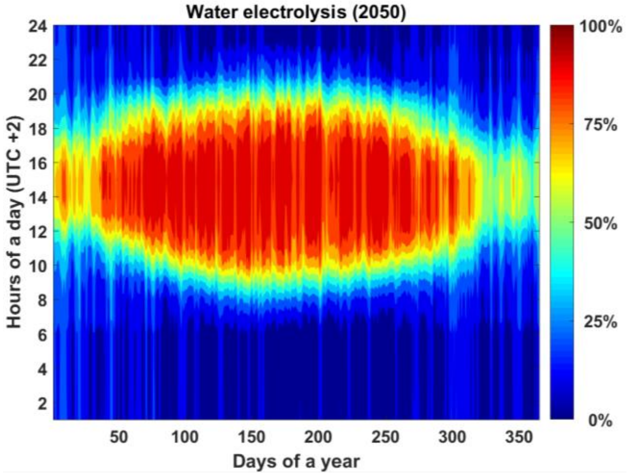

Figure 26: Hourly production profiles of electrolysers in 2050 across Europe.

The operation patterns of aggregated FT and methanation facilities are illustrated in Figure 27. By 2050, it can be observed that FT-fuels are produced throughout the year and methane production is predominantly during the summer periods with good solar conditions. Methanation follows the solar PV generation profile, but in a more diversified way so that higher full load hours can be achieved, and phases of excellent wind conditions can be used.

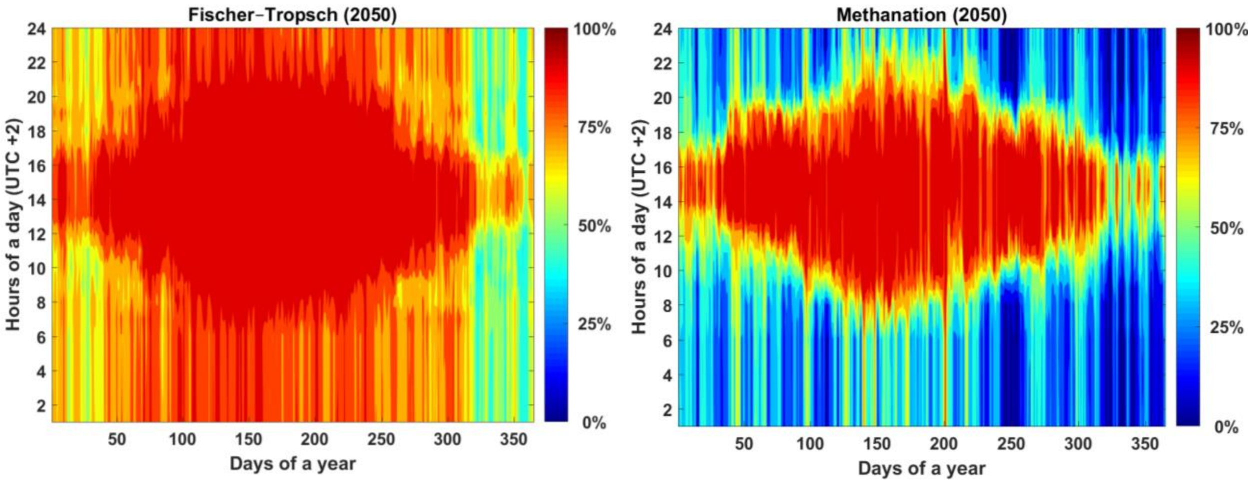

Figure 27: Hourly production profiles of Fischer-Tropsch fuels (left) and Methanation (right) in 2050 aggregated for Europe.

There is no place for fossil fuels in a fully sustainable energy system, if the goals of the Paris Agreement are to be realised. As highlighted by the results for 2050, a zero GHG emissions global energy system can be achieved across the power, heat, transport and desalination sectors. Additionally, it is evident that a complete substitution of hydrocarbons by renewable electricity is not possible with currently available technologies, as electricity cannot be directly used in some sectors such as aviation (for long distance flights) or marine in many cases. Thus, renewable electricity based synthetic fuels are essential to fulfil this demand. FT-fuels, hydrogen and liquefied gases (methane and hydrogen) are a viable alternative to fossil fuels by 2040 and have a vital role through the transition.

Furthermore, as highlighted earlier, regional variation of production costs of these fuels has been factored into the cost optimal energy transition pathway. Production costs for FT-fuels vary significantly across the different regions of Europe with an average cost of nearly 95 €/MWh in 2050. FT-fuel costs in Europe are higher due to a decentralised and localised approach to the production of FT-fuels, whereas an integrated European production of FT-fuels will most likely reduce the costs, due to production in the regions with the most beneficial RE conditions. Additionally, considering global production and trade of FT-fuels could potentially lower the costs, as fuels could be shipped from least-cost production sites from around the world. The operation modes in Figure 27 are not for individual plants, but for the aggregated capacity of all respective plants across Europe. The entire required FT capacity in 2050 is slightly less than 240 GW of liquids output for Europe. Depending on the modular size of the FT units it is rather likely that several hundreds of FT units can be in operation in Europe if the modular size would be for a few hundreds of MW output capacity. The aggregated fleet of FT units would be able to follow the resource availability and the buffered hydrogen in a cost-optimised way. The operational flexibility of methanation units is higher than that of FT units. Some flexibility of FT units will help to better follow the resource availability of solar PV electricity. This is currently demonstrated by smaller and decentralised FT units which are offered to the market [36][37]. Scientific literature also confirms that identical geometric designs of FT reactors can follow different syngas volume streams and adjust respective process parameters accordingly [38]. Such characteristics are required for large scale roll-out of FT units for the transport sector. The flexibility aspect of LNG liquefaction facilities has to be further investigated, in particular for large scale units. Smaller scale LNG liquefaction units, currently offered to the market show enhanced flexibility characteristics [39], which may be required more and also for large-scale units in the future to better follow renewable resource availability. Both, liquefied hydrogen and methane, can be in principle operated at baseload and buffered by gas storage on the input side and liquefied hydrogen along with LNG at the output, if this would lead to better economics for the overall process chain.

DAC technology is increasingly being seen as a viable technology option for zero GHG emission fuels [33], but also as negative CO_2 emission technology option [40,41]. DAC units can be used for both major emerging applications, whereas CO_2 supply for fully defossilised fuels and chemicals may be the first major application, followed by CO_2 direct removal [33,42]. The challenge of fast ramp up of DAC technology is comparable to the fast ramp up of solar PV in the past 20 years and requires respective policies [42]. As further highlighted by the results, DAC plays a key role in the production process of synthetic fuels. Moreover, DAC has several key features, in particular a very good area footprint for large-scale deployment, no major conflicts with land use, and an excellent match to the renewables based energy systems of the future [33,41,42], which are mainly based on solar PV and wind energy as highlighted by the results. Figure 29 highlights the hourly utilisation of the DAC process, which is almost through the year, as a consequence of the relatively high CAPEX for DAC units. The DAC technology can be further pursued to enable higher levels of carbon capture and utilisation and also in processes where carbon can be utilised as an input product, which will boost mitigation efforts in achieving the goals of the Paris Agreement. The air captured CO_2 is stored in a seasonal characteristic as visualised in Figure 28. The main demand for captured CO_2 is for FT-fuels and methanation to finally obtain the liquefied methane for the marine mode. The aggregated FT units have higher full load hours and run throughout the year, however with a production peak during the summertime as shown for the aggregated FT capacity in Figure 27. Whereas methanation has a more pronounced production peak during the summertime as presented in Figure 27. Since DAC units require very high utilisation for economic reasons, more captured CO_2 has to be stored during the winter period, so that CO_2 is available as input for the flexible synthesis processes during the production peak in summer, as shown in Figure 28.

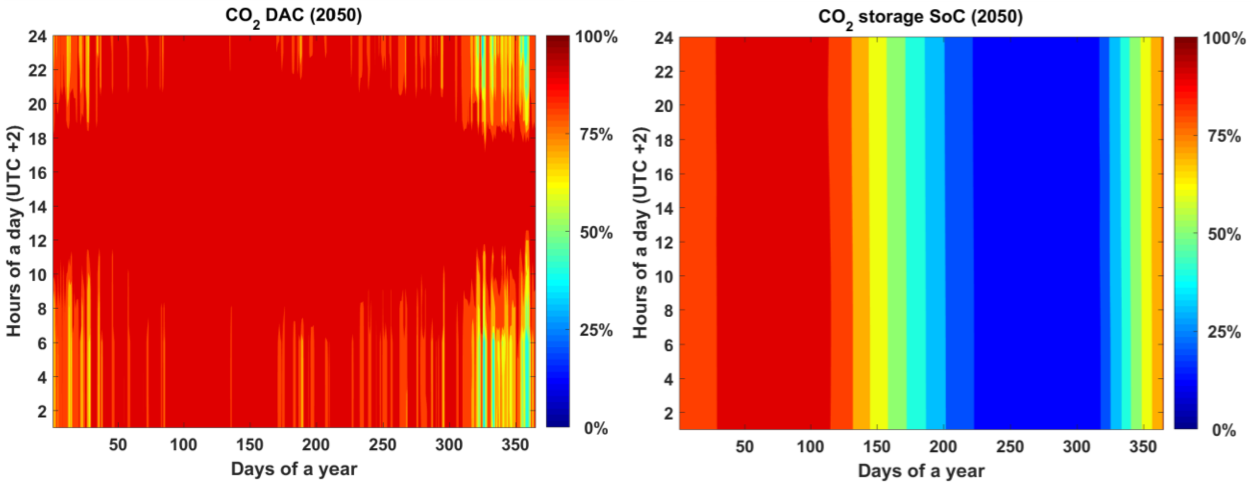

Figure 28: Hourly production profiles of CO_2 DAC units (left) and storage of CO_2 (right) in 2050 across Europe.

Figure 29 highlights the role of storage for hydrogen and methane with their hourly profiles in 2050. They show a structural difference as the hydrogen storage has a daily profile with low stored volumes in the morning hours. This can be explained by the operation mode of the electrolysers as shown in Figure 26, since they are mainly in operation during daytime hours, which leads to accumulated hydrogen stored in the evening and already depleting hydrogen volumes during the night hours due to continued need for FT units and some methanation. The methane storage shows a weekly to monthly storage profile, since it buffers the methane production from methanation units before the gaseous methane is converted to liquefied methane (LNG).

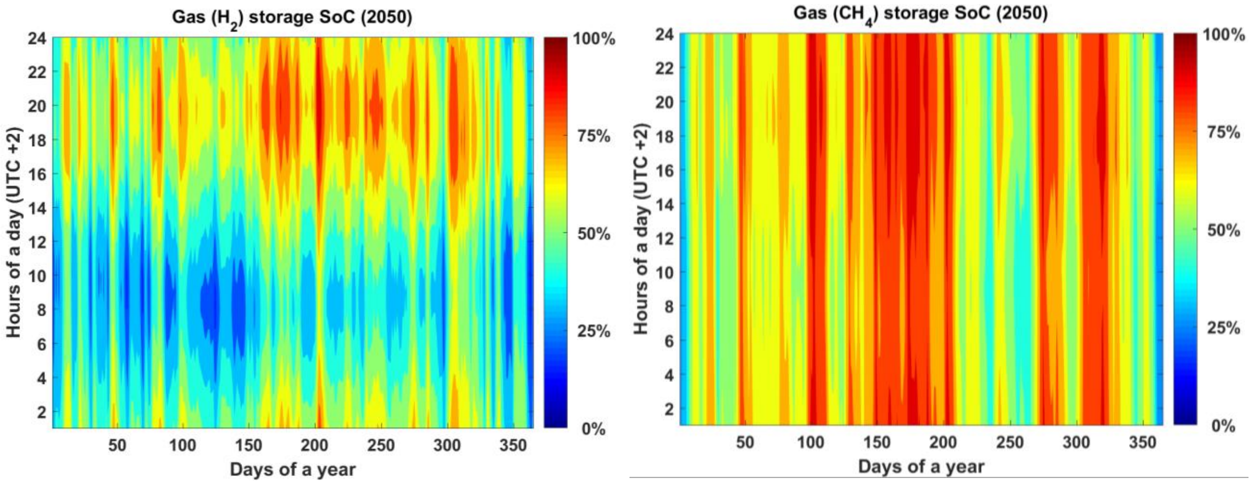

Figure 29: Hourly operation profiles of hydrogen storage (left) and methane storage (right) in 2050 across Europe.

A critical integration of the production process of synthetic fuels with renewable energy generation along with heat management increases the overall flexibility of the transport sector and reduces the need for curtailment and storage technologies. As highlighted in Figure 30, the excess heat is generated during the water electrolysis, methanation process and in FT units, which is utilised in the DAC units. The highly flexible operation of electrolyser units allows to reduce the curtailment to a low level of 3.6% of the total generated electricity from all solar PV and wind energy plants. Effectively, no wind electricity has to be curtailed and at moderate sunny days, during the European summer no further curtailment is needed. The partly flexible operation of a series of FT units and the higher level of flexibility of methanation units lower the buffered hydrogen demand, which further support the low level of curtailment in an indirect way.

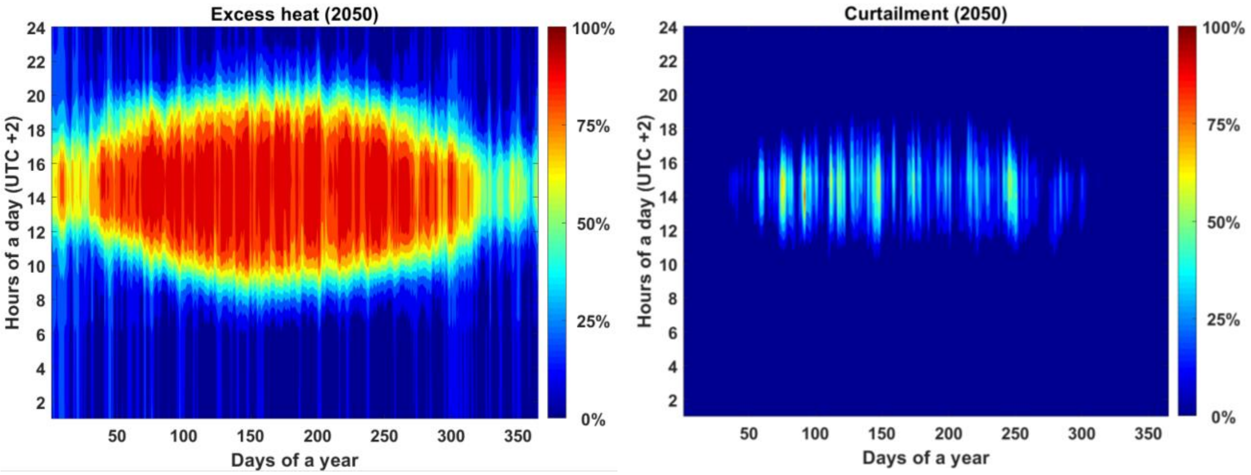

Figure 30: Hourly profile of excess heat (left) and curtailment (right) in 2050 across Europe.

Development of renewable energy has emerged as a true multi-beneficial phenomenon, which enables climate change mitigation, drives economic growth, creates local value based on technology development, production, installation, and maintenance, helps to increase energy access in a timely manner, and reduced resource conflicts in water-stressed regions of the world. Moreover, as indicated by the results of this study renewable energy can drive a predominantly electricity driven transport sector across Europe and globally [18].

4. Conclusions

The shift in fuel types from the conventional fossil based transport system to a fully sustainable renewable energy based transport system through the transition will affect the entire energy industry – generation and supply of energy, system operations across the different energy sectors, as well as transmission and distribution of energy. Solar PV and wind energy will become the leading sources of electricity generation complemented by battery storage. This trend is already seen, driven by increasing demand and rapidly declining costs across Europe. The cost declines for solar PV and batteries are expected to continue at a high pace, followed by further important components for a fully sustainable energy system, in particular electrolysers and CO_2 direct air capture units. The chapter presents a radical transformation of the entire energy sector across Europe in evolutionary steps, which encompasses power generation through various renewable electricity generation technologies; heat generation through various renewable heat generation technologies including heat management systems; enhanced system operations through storage technologies for electricity, heat and sustainable fuels; as well as enhanced sector coupling and flexibility through integration of power and heat technologies. Most importantly, transformation of the transport sector through increased utilisation of renewable electricity, renewable energy based fuels and sustainable biofuels ensures sustainable energy supply with renewable electricity and storage technologies. Furthermore, achieving zero GHG emissions from harder-to-abate sectors such as heavy-duty transport is shown to be neither a technical nor an economical challenge [12]. This chapter has presented a technically feasible and economically viable pathway for a rapid transition of the entire energy system across Europe, aligned with the goals of the Paris Agreement and the United Nations Sustainable Development Goals. Moreover, a shift in spending from imported oil to domestically produced technology and energy would not only have major economic benefits but would also help eliminate transport pollution and GHG emissions across Europe. A further integration of the transport sector with the power and heat sectors is most likely to result in greater flexibility and reduce overall system costs, also due to lower curtailment and storage demand, making an integrated 100% renewable energy system even more cost effective. However, this crucial and prudent energy transition will not be achieved unless policymakers, businesses and civil society jointly take immediate and forceful actions to transform the energy-transport-economic systems across Europe, as well as globally.

A consistent policy orientation towards the expansion of the required renewable energies is urgently needed in order to enable sustainable change in the transport sector. This includes first of all the abolition of all subsidies and privileges for fossil and nuclear energies, the promotion of the markets for renewable energies and sector coupling through administratively fixed rules. Additional support for renewable energies through tax exemptions may help to overcome any remaining economic barriers.

The successful conversion of transport modes requires the development of a transport infrastructure that enables the rapid penetration of electric drives. This includes not only completing the electrification of railways, but also promoting charging infrastructures. In addition, tax incentives for the purchase of electric vehicles are also appropriate. The necessary additional taxation of all GHG and other pollutants and risks in line with the polluter-pays principle must create the basis for the overall conversion of all sectors and modes of transport.

Acknowledgements

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Appendix

Abbreviations

A-CAES	Adiabatic compressed air energy storage
BEV	Battery electric vehicle
CAES	Compressed air energy storage
CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CSP	Concentrated solar thermal power
DAC	CO_2 Direct air capture
DACCS	Direct air carbon capture and storage
DH	District heating
FLH	Full load hours
FT	Fischer-Tropsch
GHG	Greenhouse gas
GT	Gas turbine
GW	Gigawatt
HDV	Heavy duty vehicle
HHB	Hot heat burner
HT	High temperature
HVAC	High voltage alternating current
HVDC	High voltage direct current
ICE	Internal combustion engine
IEA	International Energy Agency
IH	Individual heating
LDV	Light duty vehicle
LNG	Liquefied natural gas
LT	Low temperature
MDV	Medium duty vehicle
MT	Medium temperature
MW	Megawatt
OCGT	Open cycle gas turbine
OPEX	Operational expenditures
PHEV	Plug-in hybrid electric vehicle
PHES	Pumped hydro energy storage
PP	Power plant
PtG	Power-to-gas
PtH	Power-to-heat
PtL	Power-to-liquids
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable energy
SNG	Synthetic natural gas
ST	Steam turbine
TES	Thermal energy storage
TPED	Total primary energy demand
TW	Terawatt
TTW	Tank-to-wheels

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Technical and financial assumptions

The following tables show the various technical and financial assumptions that were factored into the modelling of the global energy transition.

Table A1: *Electricity growth rates across the nine major regions assumed for the energy transition from 2015 to 2050.*

	Electricity Growth Rates [%]						
Regions	**2015-20**	**2020-25**	**2025-30**	**2030-35**	**2035-40**	**2040-45**	**2045-50**
Europe	0.7	0.6	0.8	0.8	1	1	0.7

Table A2: *Technical and financial assumptions of energy system technologies used in the energy transition from 2015 to 2050.*

Technologies		Units	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV rooftop - residential	Capex	€/kW,$_{el}$	1360	1169	966	826	725	650	589	537
	Opex fix	€/(kW,$_{el}$ a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	35	35	35	40	40	40
PV rooftop - commercial	Capex	€/kW,$_{el}$	1360	907	737	623	542	484	437	397
	Opex fix	€/(kW,$_{el}$ a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	35	35	35	40	40	40
PV rooftop - industrial	Capex	€/kW,$_{el}$	1360	682	548	459	397	353	318	289
	Opex fix	€/(kW,$_{el}$ a)	20	17,6	15,7	14,2	12,8	11,7	10.7	9.8
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	35	35	35	40	40	40
PV optimally tilted	Capex	€/kW,$_{el}$	1000	580	466	390	337	300	270	246
	Opex fix	€/(kW,$_{el}$ a)	15	13.2	11.8	10.6	9.6	8.8	8	7.4
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	35	35	35	40	40	40
	Capex	€/kW,$_{el}$	1150	638	513	429	371	330	297	271

PV single-axis tracking	Opex fix	€/(kW,$_{el}$ a)	17.25	15	13	12	11	10	9	8
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	35	35	35	40	40	40
Wind onshore	Capex	€/kW,$_{el}$	1250	1150	1060	1000	965	940	915	900
	Opex fix	€/(kW,$_{el}$ a)	25	23	21	20	19	19	18	18
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	25	25	25	25	25	25	25	25
Wind offshore	Capex	€/kW,$_{el}$	3220	2880	2700	2580	2460	2380	2320	2280
	Opex fix	€/(kW,$_{el}$ a)	112.7	92.16	83.7	77.4	71.34	66.64	58	52.44
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifeteime	years	20	25	25	25	25	25	25	25
Hydro Reservoir/ Dam	Capex	€/kW,$_{el}$	1650	1650	1650	1650	1650	1650	1650	1650
	Opex fix	€/(kW,$_{el}$ a)	49.5	49.5	49.5	49.5	49.5	49.5	49.5	49.5
	Opex var	€/(kWh,$_{el}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
	Lifeteime	years	50	50	50	50	50	50	50	50
Hydro Run-of-River	Capex	€/kW,$_{el}$	2560	2560	2560	2560	2560	2560	2560	2560
	Opex fix	€/(kW,$_{el}$ a)	76.8	76.8	76.8	76.8	76.8	76.8	76.8	76.8
	Opex var	€/(kWh,$_{el}$)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Lifeteime	years	50	50	50	50	50	50	50	50
Geothermal power	Capex	€/kW,$_{el}$	5250	4970	4720	4470	4245	4020	3815	3610
	Opex fix	€/(kW,$_{el}$ a)	80	80	80	80	80	80	80	80
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	40	40	40	40	40	40	40	40
Coal PP	Capex	€/(kW,$_{el}$)	1500	1500	1500	1500	1500	1500	1500	1500
	Opex fix	€/(kW$_{el}$ a)	20	20	20	20	20	20	20	20
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Lifetime	years	40	40	40	40	40	40	40	40
Nuclear PP	Capex	€/(kW$_{el}$)	6210	6003	6003	5658	5658	5244	5244	5175
	Opex fix	€/(kW$_{el}$ a)	162	157	157	137	137	116	116	109
	Opex var	€/(kWh,$_{el}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
	Lifetime	years	40	40	40	40	40	40	40	40
CCGT	Capex	€/(kW$_{el}$)	775	775	775	775	775	775	775	775
	Opex fix	€/(kW$_{el}$ a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	35	35	35	35	35	35	35	35
OCGT	Capex	€/(kW$_{el}$)	475	475	475	475	475	475	475	475
	Opex fix	€/(kW$_{el}$ a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	35	35	35	35	35	35	35	35
Steam turbine (CSP)	Capex	€/(kW$_{el}$)	760	740	720	700	670	640	615	600
	Opex fix	€/(kW$_{el}$ a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	25	25	25	25	30	30	30	30
CHP NG Heating	Capex	€/kW,$_{el}$	880	880	880	880	880	880	880	880
	Opex fix	€/(kW,$_{el}$ a)	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8
	Opex var	€/(kWh,$_{el}$)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	Lifetime	years	30	30	30	30	30	30	30	30
CHP Oil Heating	Capex	€/kW,$_{el}$	880	880	880	880	880	880	880	880
	Opex fix	€/(kW,$_{el}$ a)	74.8	74.8	74.8	74.8	74.8	74.8	74.8	74.8
	Opex var	€/(kWh,$_{el}$)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	Lifetime	years	30	30	30	30	30	30	30	30
CHP Coal Heating	Capex	€/kW,$_{el}$	2030	2030	2030	2030	2030	2030	2030	2030
	Opex fix	€/(kW,$_{el}$ a)	46.7	46.7	46.7	46.7	46.7	46.7	46.7	46.7
	Opex var	€/(kWh,$_{el}$)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Lifetime	years	40	40	40	40	40	40	40	40
CHP Biomass Heating	Capex	€/kW,$_{el}$	3560	3300	3145	2990	2870	2750	2645	2540
	Opex fix	€/(kW,$_{el}$ a)	81.9	75.9	72.3	68.8	66	63.3	60.8	58.4
	Opex var	€/(kWh,$_{el}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
	Lifetime	years	25	25	25	25	25	25	25	25
CHP Biogas	Capex	€/kW,$_{el}$	503	429	400	370	340	326	311	296
	Opex fix	€/(kW,$_{el}$ a)	20.1	17.2	16	14.8	13.6	13	12.4	11.8
	Opex var	€/(kWh,$_{el}$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

	Lifetime	years	30	30	30	30	30	30	30	30
Waste incinerator	Capex	€/kW,$_{el}$	5940	5630	5440	5240	5030	4870	4690	4540
	Opex fix	€/(kW,$_{el}$ a)	267.3	253.4	244.8	235.8	226.4	219.2	211.1	204.3
	Opex var	€/(kWh,$_{el}$)	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
	Lifetime	years	30	30	30	30	30	30	30	30
Biogas digester	Capex	€/kW,$_{th}$	771	731	706	680	653	632	609	589
	Opex fix	€/(kW,$_{th}$ a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	20	20	20	20	25	25	25	25
Biogas upgrade	Capex	€/kW,$_{th}$	340	290	270	250	230	220	210	200
	Opex fix	€/(kW,$_{th}$ a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	20	20	20	20	25	25	25	25
CSP (solar field, parabolic trough)	Capex	€/kW,$_{th}$	438.3	344.5	303.6	274.7	251.1	230.2	211.9	196
	Opex fix	€/(kW,$_{th}$ a)	10.1	7.9	7	6.3	5.8	5.3	4.9	4.5
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	25	25	25	25	25	25	25	25
Residential Solar Heat Collectors - space heating	Capex	€/kW,$_{th}$	1286	1214	1179	1143	1071	1000	929	857
	Opex fix	€/(kW,$_{th}$ a)	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifeteime	years	20	25	25	30	30	30	30	30
Residential Solar Heat Collectors - hot water	Capex	€/kW,$_{th}$	485	485	485	485	485	485	485	485
	Opex fix	€/(kW,$_{th}$ a)	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifeteime	years	15	15	15	15	15	15	15	15
DH Rod Heating	Capex	€/kW,$_{th}$	100	100	100	75	75	75	75	75
	Opex fix	€/(kW,$_{th}$ a)	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47
	Opex var	€/(kWh,$_{th}$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Lifetime	years	35	35	35	35	35	35	35	35
DH Heat Pump	Capex	€/kW,$_{th}$	700	660	618	590	568	554	540	530
	Opex fix	€/(kW,$_{th}$ a)	2	2	2	2	2	2	2	2
	Opex var	€/(kWh,$_{th}$)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	Lifetime	years	25	25	25	25	25	25	25	25
Local Rod Heating	Capex	€/kW,$_{th}$	800	800	800	800	800	800	800	800
	Opex fix	€/(kW,$_{th}$ a)	10	10	10	10	10	10	10	10
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	30	30	30	30	30	30
Local Heat Pump	Capex	€/kW,$_{th}$	800	780	750	730	706	690	666	650
	Opex fix	€/(kW,$_{th}$ a)	16	15.6	15	7.3	7.1	6.9	6.7	6.5
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	20	20	20	20	20	20	20	20
Water electrolysis	Capex	€/kW,$_{H_2}$	800	685	500	363	325	296	267	248
	Opex fix	€/(kW,$_{H_2}$ a)	32	27	20	12.7	11.4	10.4	9.4	8.7
	Opex var	€/(kWh,$_{H_2}$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Lifetime	years	30	30	30	30	30	30	30	30
Methanation	Capex	€/kW,$_{CH_4}$	547	502	368	278	247	226	204	190
	Opex fix	€/(kW,$_{CH_4}$ a)	25.16	23.09	16.93	12.79	11.36	10.4	9.38	8.74
	Opex var	€/(kWh,$_{CH_4}$)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	Lifetime	years	30	30	30	30	30	30	30	30
CO_2 direct air capture	Capex	€/t$_{CO_2}$ a	1000	730	493	335	274.4	234	210.6	195
	Opex fix	€/t$_{CO_2}$ a	40	29.2	19.7	13.4	11	9.4	8.4	7.8
	Opex var	€/t$_{CO_2}$	0	0	0	0	0	0	0	0
	Lifetime	years	20	20	25	25	30	30	30	30
Fischer-Tropsch unit	Capex	€/kW,FT$_{Liq,output}$	947	947	947	947	947	852.3	852.3	852.3
	Opex fix	€/kW,FT$_{Liq,output}$	28.41	28.41	28.41	28.41	28.41	25.57	25.57	25.57
	Opex var	€/kW,FT$_{Liq,output}$	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	30	30	30	30	30	30
Battery storage	Capex	€/kWh,$_{el}$	400	270	182	134	108	92	78	70
	Opex fix	€/(kWh,$_{el}$ a)	24	9	5	3.75	3	2.5	2.125	1.875

	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
Battery interface	Capex	€/kW,$_{el}$	200	135	91	67	54	46	39	35
	Opex fix	€/(kW,$_{el}$ a)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
Battery PV prosumer - residential storage	Capex	€/kWh,$_{el}$	603	407	280	209	170	146	124	111
	Opex fix	€/(kWh,$_{el}$ a)	36.2	13.6	7.7	5.8	4.7	4	3.4	3
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
Battery PV prosumer - residential interface	Capex	€/kW,$_{el}$	302	204	140	104	85	73	62	56
	Opex fix	€/(kW,$_{el}$ a)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
Battery PV prosumer - commercial storage	Capex	€/kWh,$_{el}$	513	346	235	174	141	120	102	91
	Opex fix	€/(kWh,$_{el}$ a)	30.8	11.5	6.5	4.9	3.9	3.3	2.8	2.5
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
Battery PV prosumer - commercial interface	Capex	€/kW,$_{el}$	256	173	117	87	70	60	51	46
	Opex fix	€/(kW,$_{el}$ a)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
Battery PV prosumer - industrial storage	Capex	€/kWh,$_{el}$	435	294	198	146	118	100	85	76
	Opex fix	€/(kWh,$_{el}$ a)	26.1	9.8	5.4	4.1	3.3	2.7	2.3	2
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
Battery PV prosumer - industrial interface	Capex	€/kW,$_{el}$	218	147	99	73	59	50	42	38
	Opex fix	€/(kW,$_{el}$ a)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	20	20	20	20	20	20	20
PHES	Capex	€/kWh,$_{el}$	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
	Opex fix	€/(kWh,$_{el}$ a)	1.335	1.335	1.335	1.335	1.335	1.335	1.335	1.335
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	50	50	50	50	50	50	50	50
PHES interface	Capex	€/kW,$_{el}$	650	650	650	650	650	650	650	650
	Opex fix	€/(kW,$_{el}$ a)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	50	50	50	50	50	50	50	50
A-CAES	Capex	€/kWh,$_{el}$	35	35	32.6	31.1	30.3	29.8	27.7	26.3
	Opex fix	€/(kWh,$_{el}$ a)	0.53	0.53	0.50	0.47	0.46	0.45	0.42	0.40
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	40	55	55	55	55	55	55	55
A-CAES interface	Capex	€/kW,$_{el}$	600	600	558	530	518	510	474	450
	Opex fix	€/(kW,$_{el}$ a)	0	0	0	0	0	0	0	0
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	40	55	55	55	55	55	55	55
Gas Storage	Capex	€/kWh,$_{el}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Opex fix	€/(kWh,$_{el}$ a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Opex var	€/(kWh,$_{el}$)	0	0	0	0	0	0	0	0
	Lifetime	years	50	50	50	50	50	50	50	50
Gas Storage interface	Capex	€/kW,$_{th}$	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8
	Opex fix	€/(kW,$_{th}$ a)	31	31	31	31	31	31	31	31
	Opex var	€/(kWh,$_{th}$)	36.2	36.2	36.2	36.2	36.2	36.2	36.2	36.2
	Lifetime	years	41.4	41.4	41.4	41.4	41.4	41.4	41.4	41.4
Hot Heat Storage	Capex	€/kWh,$_{th}$	50.8	41.8	32.7	26.8	23.3	21	19.3	17.5
	Opex fix	€/(kWh,$_{th}$ a)	0.76	0.63	0.49	0.4	0.35	0.32	0.29	0.26
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	25	25	25	25	30	30	30	30
District Heat Storage	Capex	€/kWh,$_{th}$	50	40	30	30	25	20	20	20
	Opex fix	€/(kWh,$_{th}$ a)	0.8	0.6	0.5	0.5	0.4	0.3	0.3	0.3
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	25	25	25	25	30	30	30	30

Hydrogen Storage	Capex	€/kWh,$_{th}$	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
	Opex fix	€/(kWh,$_{th}$ a)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	30	30	30	30	30	30
Hydrogen Storage interface	Capex	€/kW,$_{th}$	255.85	255.85	255.85	255.85	255.85	255.85	255.85	255.85
	Opex fix	€/(kW,$_{th}$ a)	10.23	10.23	10.23	10.23	10.23	10.23	10.23	10.23
	Opex var	€/(kWh,$_{th}$)	0	0	0	0	0	0	0	0
	Lifetime	years	15	15	15	15	15	15	15	15
CO_2 Storage	Capex	€/ton	142	142	142	142	142	142	142	142
	Opex fix	€/(ton a)	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94
	Opex var	€/ton	0	0	0	0	0	0	0	0
	Lifetime	years	30	30	30	30	30	30	30	30
Reverse Osmosis Seawater Desalination	Capex	€/(m^3/day)	1150	960	835	725	630	550	480	415
	Opex fix	€/(m^3/day a)	46	38.4	33.4	29	25.2	22	19.2	16.6
	Consumption	kWh$_{th}$/m^3	0	0	0	0	0	0	0	0
	Lifetime	years	25	25	30	30	30	30	30	30
	Consumption	kWh$_{el}$/m^3	4.1	3.6	3.35	3.15	3	2.85	2.7	2.6
Multistage Flash Standalone	Capex	€/(m^3/day)	2000	2000	2000	2000	2000	2000	2000	2000
	Opex fix	€/(m^3/day a)	100	100	100	100	100	100	100	100
	Consumption	kWh$_{th}$/m^3	85	85	85	85	85	85	85	85
	Lifetime	years	25	25	25	25	25	25	25	25
	Consumption	kWh$_{el}$/m^3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Multi Stage Flash Cogeneration	Capex	€/(m^3/day)	3069	3069	3069	3069	3069	3069	3069	3069
	Opex fix	€/(m^3/day a)	121.4	121.4	121.4	121.4	121.4	121.4	121.4	121.4
	Consumption	kWh$_{th}$/m^3	202.5	202.5	202.5	202.5	202.5	202.5	202.5	202.5
	Lifetime	years	25	25	25	25	25	25	25	25
	Consumption	kWh$_{el}$/m^3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Multi Effect Distillation Standalone	Capex	€/(m^3/day)	1438	1200	1044	906.3	787.5	687.5	600	518.8
	Opex fix	€/(m^3/day a)	47.44	39.60	34.44	29.91	25.99	22.69	19.80	17.12
	Consumption	kWh$_{th}$/m^3	68	51	44	38	32	28	28	28
	Lifetime	years	25	25	25	25	25	25	25	25
	Consumption	kWh$_{el}$/m^3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Multi Effect Distillation Cogeneration	Capex	€/(m^3/day)	2150	2150	2150	2150	2150	2150	2150	2150
	Opex fix	€/(m^3/day a)	61.69	61.69	61.69	61.69	61.69	61.69	61.69	68.81
	Consumption	kWh$_{th}$/m^3	168	168	168	168	168	168	168	168
	Lifetime	years	25	25	25	25	25	25	25	25
	Consumption	kWh$_{el}$/m^3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Water Storage	Capex	€/m^3	64.59	64.59	64.59	64.59	64.59	64.59	64.59	64.59
	Opex fix	€/(m^3 a)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	Opex var	€/m^3	0	0	0	0	0	0	0	0
	Lifetime	years	50	50	50	50	50	50	50	50

Table A3: *Energy to power ratio as found for 2050 in the transport sector and self-discharge rates of storage technologies.*

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-Discharge [%/h]
Battery	95	4.3	0
PHS	85	8.0	0
A-CAES	70	9.7	0.1
TES	90	1.3	0.2
Gas storage	100	49	0

Table A4: *Financial assumptions for the fossil-nuclear fuel prices and GHG emission cost. The referenced values are all till 2040 and are kept stable for later periods (fuels) or are assumed to further increase for matching the Paris Agreement (GHG emissions).*

Name of component	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Coal	€/MWh$_{th}$	7.7	7.7	8.4	9.2	10.2	11.1	11.1	11.1
Fuel oil	€/MWh$_{th}$	52.5	35.2	39.8	44.4	43.9	43.5	43.5	43.5
Fossil gas	€/MWh$_{th}$	21.8	22.2	30.0	32.7	36.1	40.2	40.2	40.2
Uranium	€/MWh$_{th}$	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
GHG emissions	€/tCO$_{2eq}$	9	28	52	61	68	75	100	150