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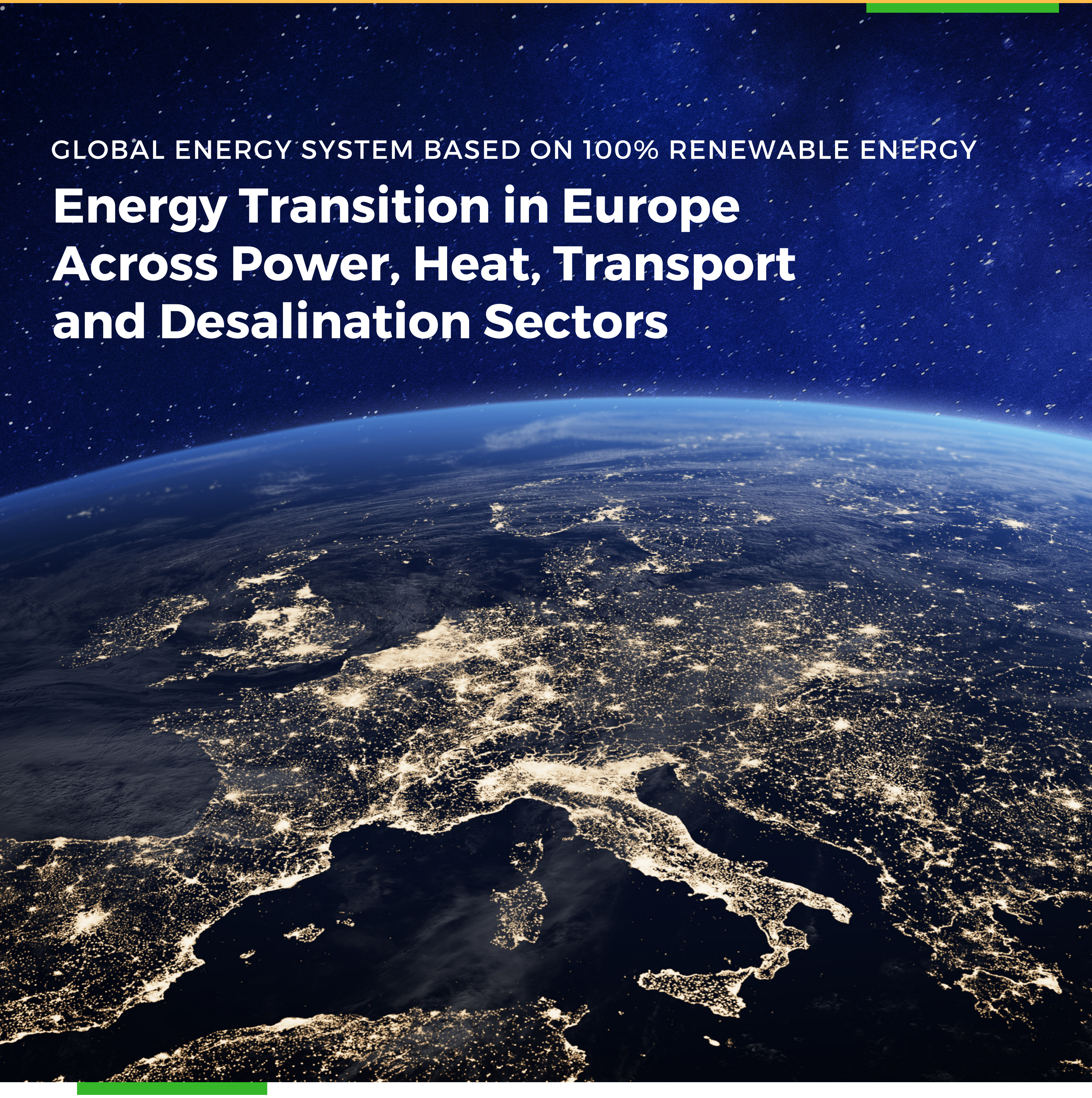
GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY

Energy Transition in Europe Across Power, Heat, Transport and Desalination Sectors



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A Rapid Transition to 100% Renewable Energy Across Europe is Possible

with Zero GHG Emissions from Power, Heat, Transport and Desalination Sectors before 2050

Key Findings

In Europe, a full transition to 100% renewable energy across all sectors – power, heat, transport and desalination is feasible[1]. Existing renewable energy potential and technologies, including storage, can generate sufficient and secure energy supply at every hour throughout the year. The sustainable energy system would be more cost effective than the existing system, which is primarily based on fossil fuels and nuclear energy. The energy transition is not a question of technical feasibility or economic viability, but one of political will.

Electrification across all energy sectors is inevitable, and is more resource efficient than the current system. Electricity generation in 2050 will exceed 4-5 times that in 2015, due to the high electrification rates of the transport and heat sectors. Fuel consumption is reduced by more than 90% from 2015 numbers (see Figure KF-1), as fossil fuels are phased out completely. Electricity will constitute more than 85% of the primary energy demand in 2050.

Electricity generation in the 100% renewable energy system will consist of a mix of power sources, with solar PV generating 62% of electricity followed by wind energy (32%), hydropower (4%), bioenergy (2%) and geothermal energy (<1%). Wind and solar make up 94% of total electricity supply by 2050 and will have a synergetic balancing effect (see Figure KF-1).

Approximately 85% of the renewable energy supply will come from local and regional generation, with much of it being decentralised. Additionally, electric heat pumps, thermal energy storage, and other heating technologies will play a vital role in meeting the heat demand across Europe. In the transport sector, electric vehicles with batteries, plug-in hybrids and fuel cells will cover road transport energy demand, whereas the marine and aviation demand will be covered by a combination of synthetic fuels, such as hydrogen, renewables-based liquefied natural gas and Fischer-Tropsch fuels complemented with low-cost electricity. Also, biofuels, produced in a sustainable way, play a small but important role in the transport sector.

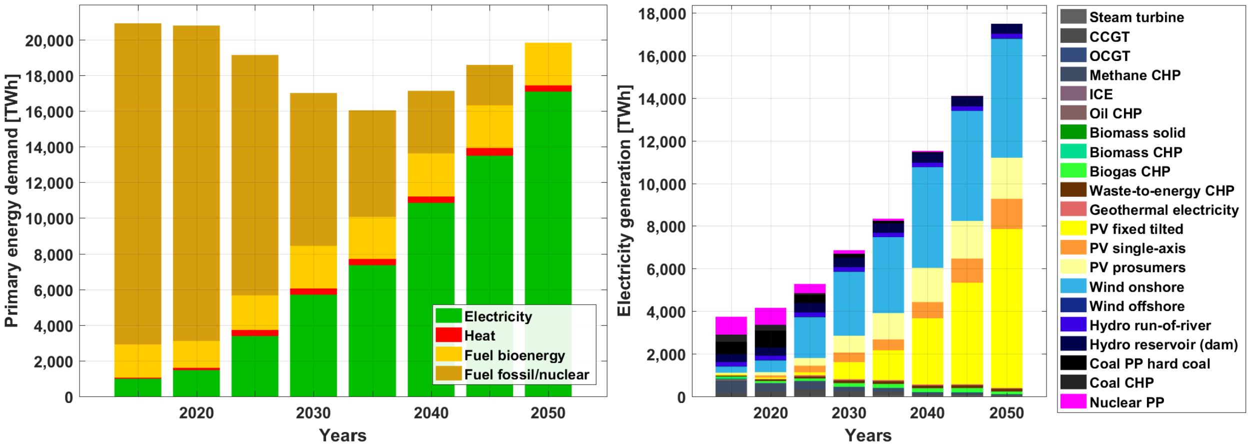

Figure KF-1: Primary energy demand (left) and electricity generation from various power technologies (right) through

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[1] Energy transition simulations in this study are until 2050. Yet, with favourable political frameworks, the transition to 100% renewable energy can be realised much earlier than 2050.

100% renewable energy is not more expensive than the current European energy system.

- The levelised cost of energy for a fully sustainable energy system in Europe remains stable through the transition from 2015 to 2050, ranging from 50-60 €/MWh (see Figure KF-2).
- The levelised cost of electricity decreases substantially from around 80 €/MWh in 2015 to around 57 €/MWh by 2050, while the levelised cost of heat increases marginally from around 41 €/MWh in 2015 to around 47 €/MWh by 2030 and further declines to around 43 €/MWh by 2050.
- Final transport passenger costs decline for road transport and remain stable for aviation through the transition, whereas there is a marginal increase in costs for marine transport. Final transport freight

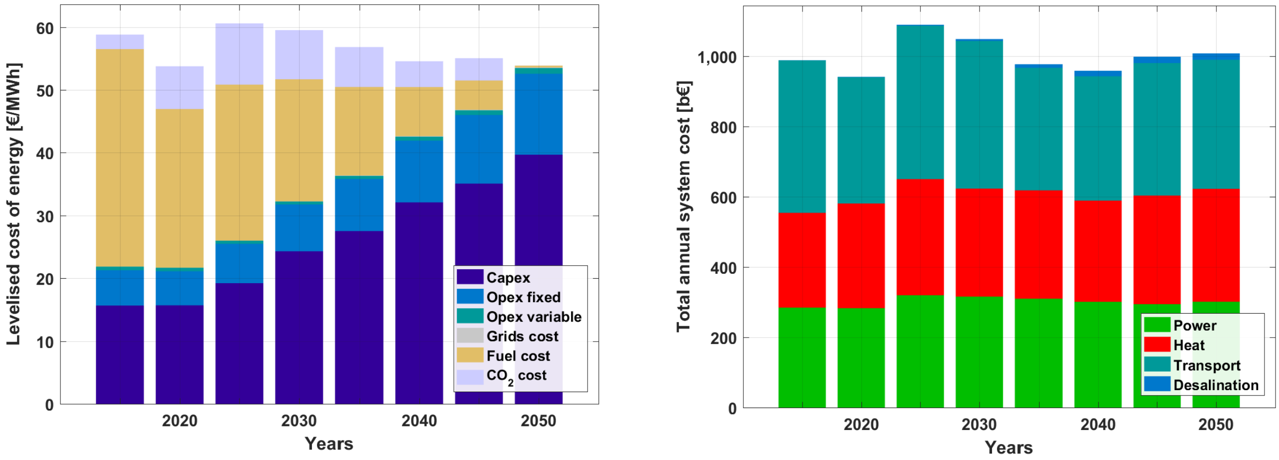

Figure KF-2: Levelised cost of energy (left) and total annual system costs (right) during the energy

Europe can achieve zero greenhouse gas emissions by 2050, or sooner, across all energy sectors

- Europe's annual greenhouse gas emissions decline steadily through the transition from about 4200 $MtCO_{2eq}$ in 2015 to zero by 2050 (see Figure KF-3). The resulting cumulative greenhouse gas emissions are approximately 85 Gt_{CO2eq} from 2016-2050, and would support the EU's goal of limiting temperature increases to 1.5°C above pre-industrial level
- In contrast to popular claims, a deep decarbonisation of the power and heat sectors is possible by 2030 in Europe. The transport sector will lag behind, with a massive decline of greenhouse gas emissions from 2030 to 2050 (see Figure KF-3).

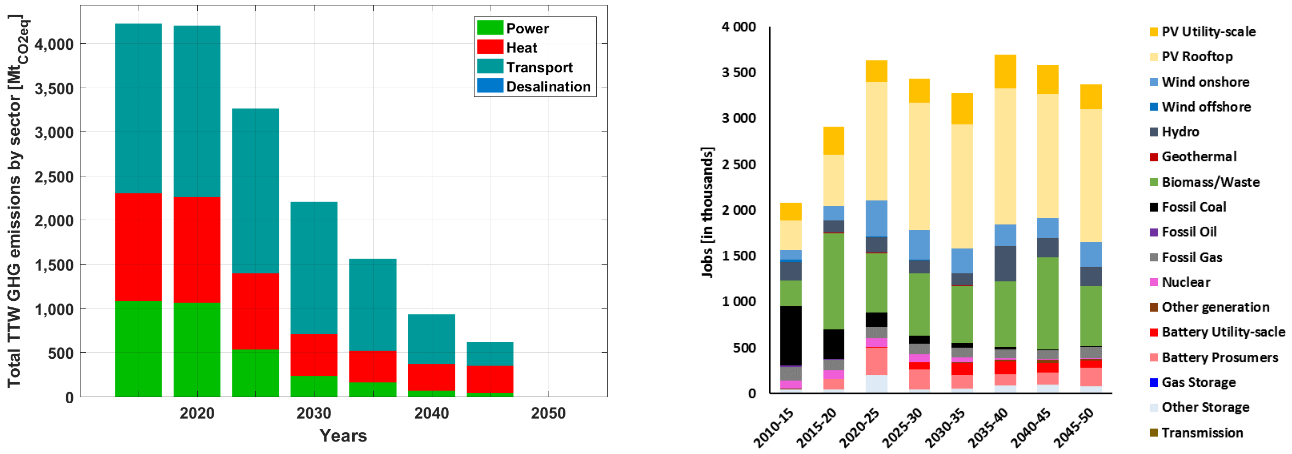

Figure KF-3: Total GHG emissions (left) and jobs in the power sector (right) during the energy transition from 2015-2050

100% renewable energy system in Europe will support millions of local jobs in the power sector

- In 2015, the European power sector employed approximately 2 million people, with approximately half in the fossil fuel sector (see Figure KF-3).
- A 100% renewable power system would employ 3 to 3.5 million people and solar PV emerges as the major job creating industry, employing about 1.7 million in 2050.
- The approximate 800,000 jobs in the European coal industry of 2015 will be decreased to zero by 2050 and will be overcompensated by more than 1.5 million new jobs in the renewable energy sector.

Europe's renewable energy generation and storage capacities will improve efficiencies and create energy independence

- With 94% of renewable electricity generation coming from solar and wind energy by 2050, and a significant amount local generation, the system is more efficient.
- Energy storage will meet nearly 17% of electricity demand and around 20% of heat demand. Batteries will emerge as the most relevant electricity storage technology and thermal energy storage emerges as the most relevant heat storage technology by 2050. Electric heat pumps will also play a significant role, generating more than 30% of heat on district and individual levels by 2050 (see Figure KF-4).
- Through localised renewable energy generation, grid exchange, and storage, Europe is capable of having a highly efficient and self-reliant energy system.

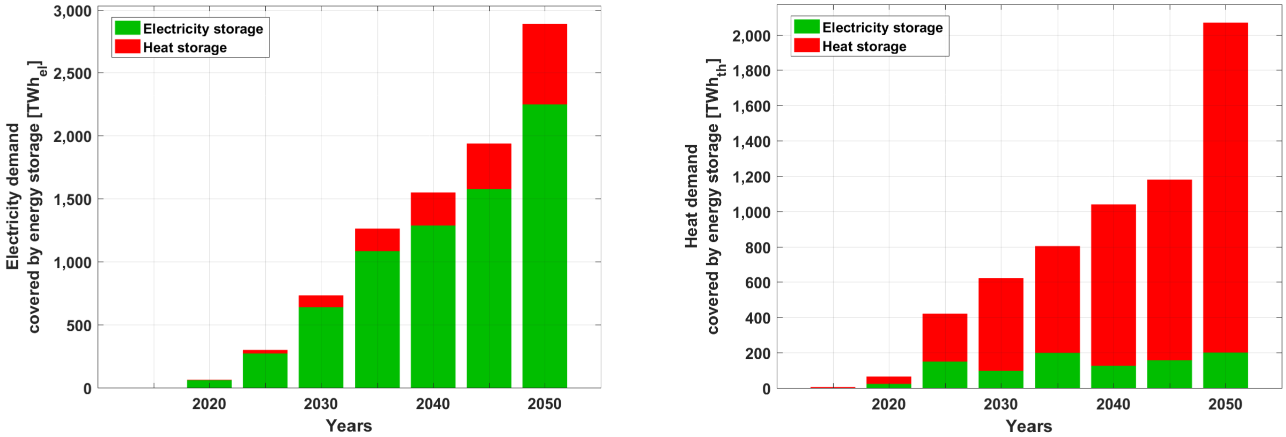

Figure KF-4: Electricity demand covered by energy storage (left) and heat demand covered by energy storage (right) during the transition from 2015-2050 across Europe.

Policy recommendations

To ensure a smooth, fast and cost-effective transition to 100% renewable energy across all sectors, governments need to adopt national legislative acts that will ensure the swift uptake and development of renewable energy and storage technologies, sector coupling and smart energy systems. The following key political support measures will accelerate the energy transition:

- Policies and instruments focused on sector coupling and enabling direct private investment in renewable energy and other zero emission technologies (e.g. Feed-in Tariff laws).
- Tax exemptions, direct subsidies and legal privileges for renewable energy technologies.
- A phase-out of all state subsidies to fossil fuel and nuclear energy generation, and introduction of carbon and radioactivity taxes.
- Promotion of cogeneration power.
- Policies and frameworks that promote research and education on renewable energy and zero emission technologies.

Summary

This study presents a technically feasible and economically viable energy pathway for Europe, in which the energy sector (comprising power, heat, transport, and desalination) can reach 100% renewable energy and zero greenhouse gas emissions by 2050. The primary energy demand 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 electrification of more than 85% in 2050. Solar PV and wind energy emerge as the most prominent electricity supply sources with around 62% and 32% respectively of the total electricity supply by 2050. Heat pumps play a significant role in the heat sector with a share of nearly 50% of heat generation by 2050. Batteries emerge as the key storage technology with around 83% of total electricity storage output. Fuel conversion technologies such as Fischer-Tropsch, water electrolysis, methanation, and others supply renewable-based fuels along with 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 at around €50-55/MWh through the transition from 2015-2050. While, the annual energy costs are in the range of €900-1,100 billion through the transition, with cumulative investments of around €9,760 billion up to 2050. Greenhouse gas emissions can be reduced from about 4,300 megatonnes CO_2 equivalent ($MtCO_2$ eq.) in 2015 to zero by 2050, with cumulative greenhouse gas emissions of around 85 gigatonnes CO_2 equivalent ($GtCO_2$ eq.). Additionally, around 3.5 million direct energy jobs are created annually in 2050 across just the power sector in Europe. Consequently, a 100% renewable energy system across the power, heat, transport, and desalination sectors in Europe is more efficient and cost competitive than a fossil fuel-based option, and most importantly compatible with the Paris Agreement.

Brief comment on this report

This report highlights the results for Europe, which forms part of a larger study "Global Energy System based on 100% Renewable Energy – Power, Heat, Transport, and Desalination Sectors" that comprises all major regions across the world. The global study considers 145 regions that are structured into nine major regions of the world. Europe is one amongst the nine major regions and is an aggregation of 20 European regions, which are part of the 145 regions across the world.

Table of Contents

Global Energy System based on 100% Renewable Energy - Energy Transition in Europe Across Power, Heat, Transport and Desalination Sectors.

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 costly 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 amount of effort across the world. In this context, a global transition of the energy sector is of utmost relevance as the sector is responsible for the majority of global greenhouse gas (GHG) emissions. The objective of this research conducted by the LUT University and the Energy Watch Group (EWG) is to generate results for a global energy system transition towards 100% renewables in hourly resolution for entire years from 2015 until 2050 for the power, heat, transport, and desalination sectors. The results for the case of Europe are presented in the following sections.

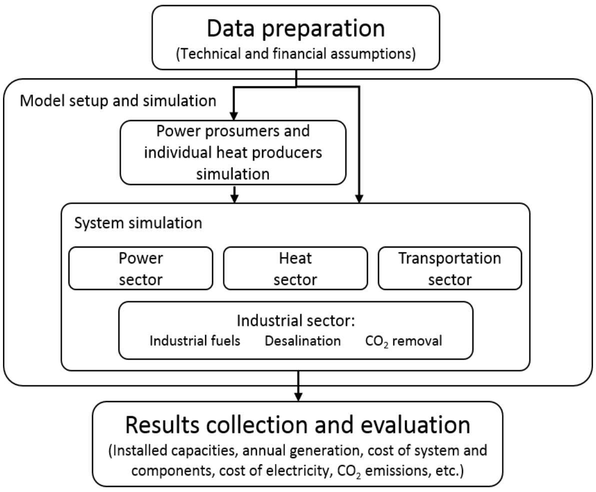

Figure 1: Fundamental structure of the LUT Energy System Transition model

Modelling a Global Transition towards a 100% Renewable Energy System

The LUT Energy System Transition model applied for the power sector in Ram et al., (2017)[2] is further expanded to other energy sectors and its fundamental aspects for application across various energy sectors is shown in Figure 1. The unique feature of the model enables a global-local energy system transition towards 100% renewables in hourly resolution for all years from 2015 until 2050 across the power, heat, transport, and desalination sectors. The results are visualised and presented in 5-year intervals through the transition from 2015-2050 for 145 sub-regions across the world.

The model has integrated all crucial aspects of the power, heat, transport, and desalination sectors, which are further described in the Appendix and shown in Figures A1-A4. Additionally, the technologies introduced to the model are:

- Technologies for electricity generation – renewable energy (RE), fossil, and nuclear technologies;
- Heat generation technologies – renewable and fossil;
- Energy storage technologies – electricity and heat storage technologies;
- Fuel conversion technologies – fuels for transport;
- Fuel storage technologies – fuel storage for transport;
- Desalination technologies; and
- Electricity transmission technologies.

A detailed overview of the methodology along with 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 power sector in Ram et al. (2017)[2].

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 achieve the goals of the Paris Agreement of achieving zero GHG emissions from the energy sector by 2050, in a technically feasible and economically viable manner. 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.

Transition to 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)[3]. 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, as per the estimates of the International Energy Agency (IEA)[4]. 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[5]. 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. The regional composition of Europe considered in this study is shown in Figure 2. 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.

Figure 2: The different countries and regions of Europe considered in the energy transition from 2015 to 2050.

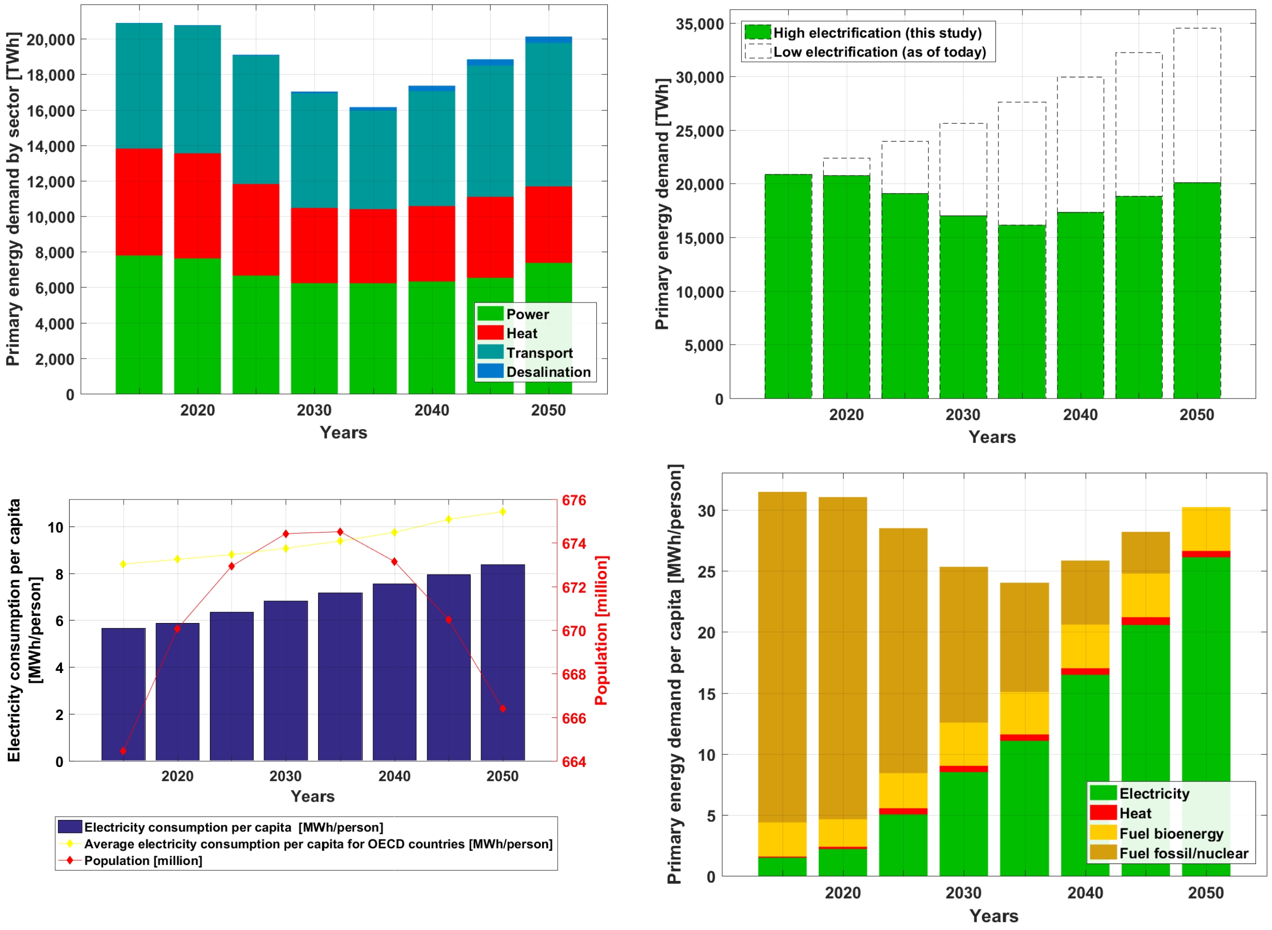

Figure 3: Primary energy demand sector-wise (top left), efficiency gain in primary energy demand (top right), electricity consumption per capita with population (bottom left) and primary energy demand per capita (bottom right) during the energy transition from 2015 to 2050 in Europe.

Penetration of renewables is not just a matter of replacing hydrocarbons with zero-carbon sources of energy supply – it also represents a significant change in resource efficiency. This is illustrated by the overall electrification across the power, heat, transport, and desalination sectors as shown in Figure 3.

The primary energy demand decreases from 21,000 TWh in 2015 to around 16,000 TWh by 2035 and increases up to 20,000 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% by 2050. 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. Additionally, a substantial demand from fuel conversion technologies arises beyond 2040 onwards in producing renewable-based 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 4. 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. 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 4. On the other hand, gas-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).

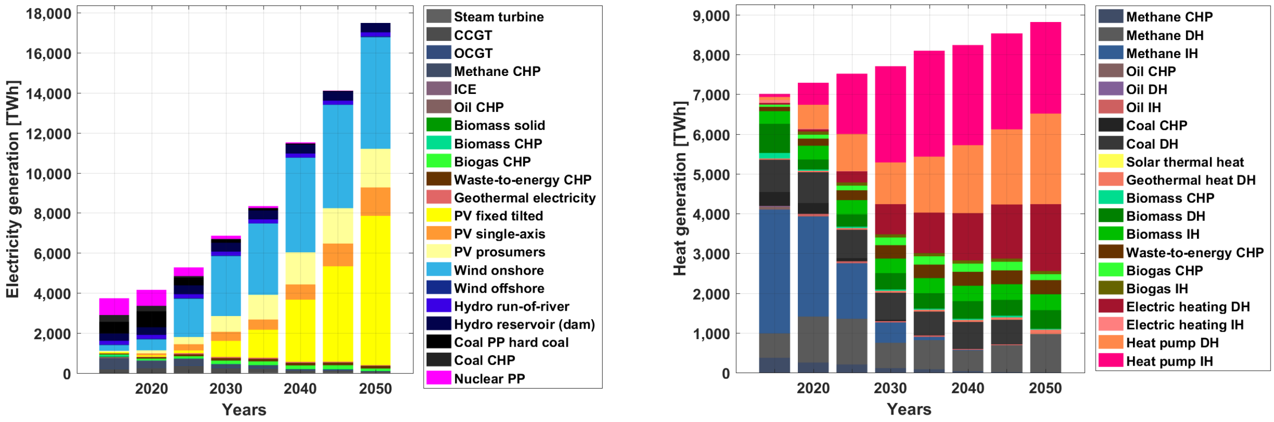

Figure 4: Technology-wise electricity generation (left) and technology-wise heat generation (right) during the energy transition from 2015 to 2050 in Europe

Energy Storage

Energy storage technologies play a critical role in enabling a secure energy supply across Europe, fully based on renewable energy across different sectors. As highlighted in Figure 5, storage output covers 18% of total electricity demand in 2050. The ratio of electricity demand covered by energy storage to electricity generation increases significantly to around 13% by 2030 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.

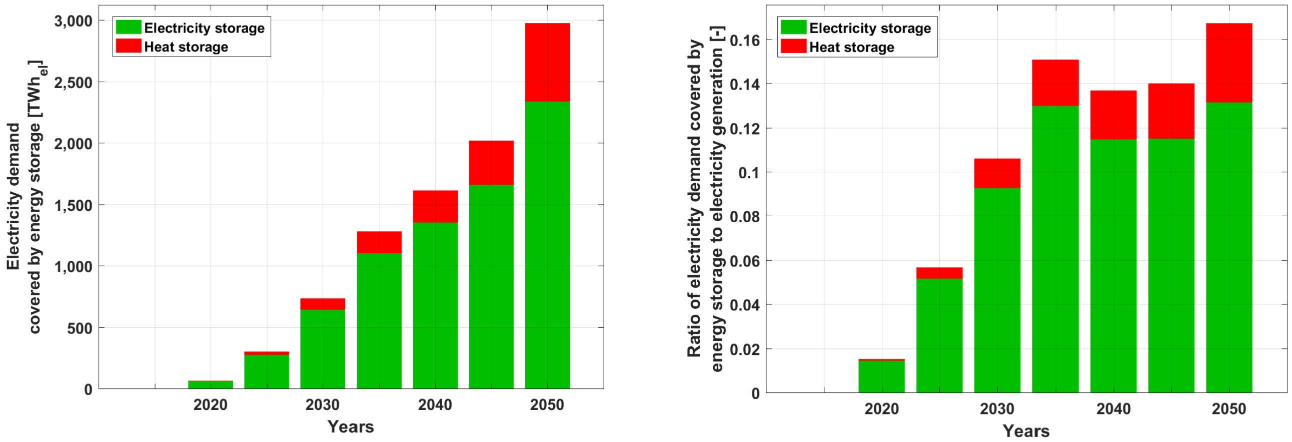

Figure 5: Electricity demand covered by energy storage (left) and ratio of electricity demand covered by different forms of energy storage (right) during the energy transition from 2015 to 2050 in Europe.

Similarly, heat storage plays a vital role in ensuring heat demand is covered across all the sectors. As indicated in Figure 6, storage output covers more than 30% of the total heat demand in 2050 and heat storage technologies are crucial to meet this demand. The ratio of heat demand covered by energy storage to heat generation increases substantially to almost 20% by 2050, also shown in Figure 6. 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 5-year period from 2045-2050, there is an increase in heat storage utilisation.

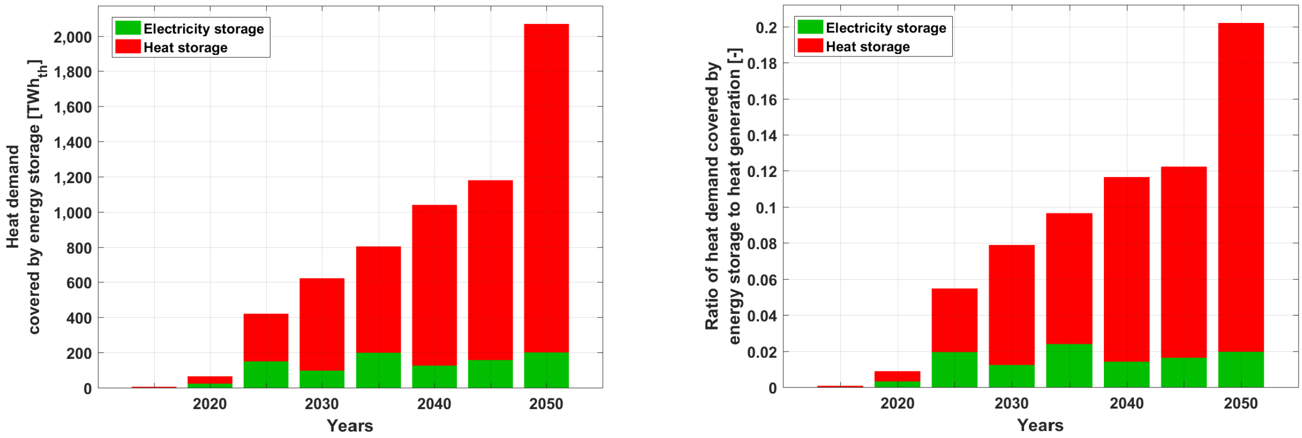

Figure 6: Heat demand covered by energy storage (left) and the ratio of heat demand covered by different forms of energy storage (right) during the energy transition from 2015 to 2050 in Europe.

Cost and Investments

The total annual costs are in the range of €950-1,100 billion 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 7, power, heat, and transport costs are in the range of around €300-350 billion through the transition. In addition, as indicated in Figure 7 capital expenditure (CAPEX) increases 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.

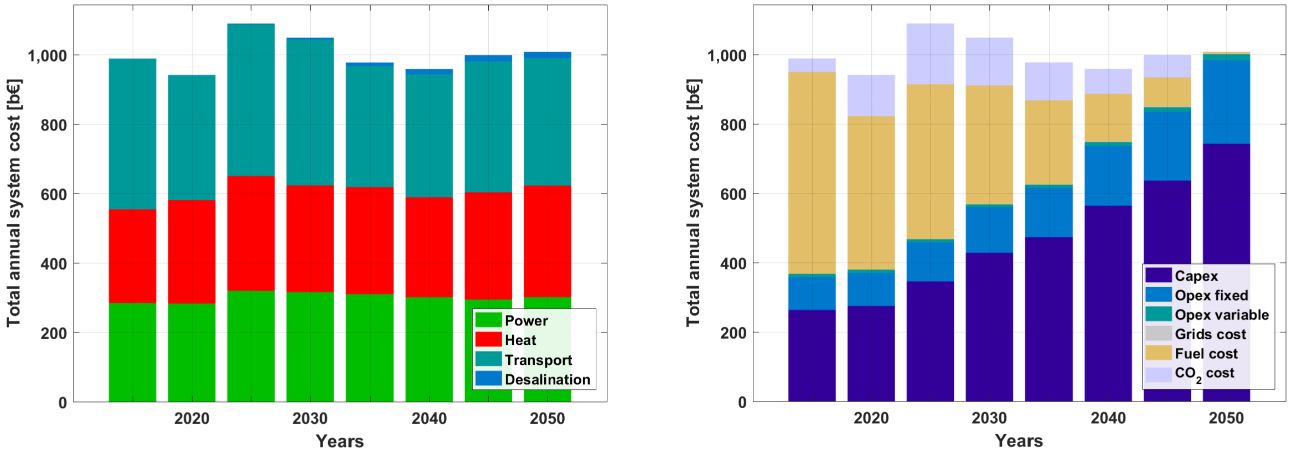

Figure 7: Annual system costs, sector-wise (left) and functionality-wise (right) during the energy transition from 2015 to 2050 in Europe.

As increasing shares of power generation capacities are added globally, renewable energy sources on a levelised cost of energy (LCOE) basis become the lowest cost power generation source[7]. As indicated in Figure 8, LCOE 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 8. The cumulative investments are about €9,910 billion through the transition from 2016-2050.

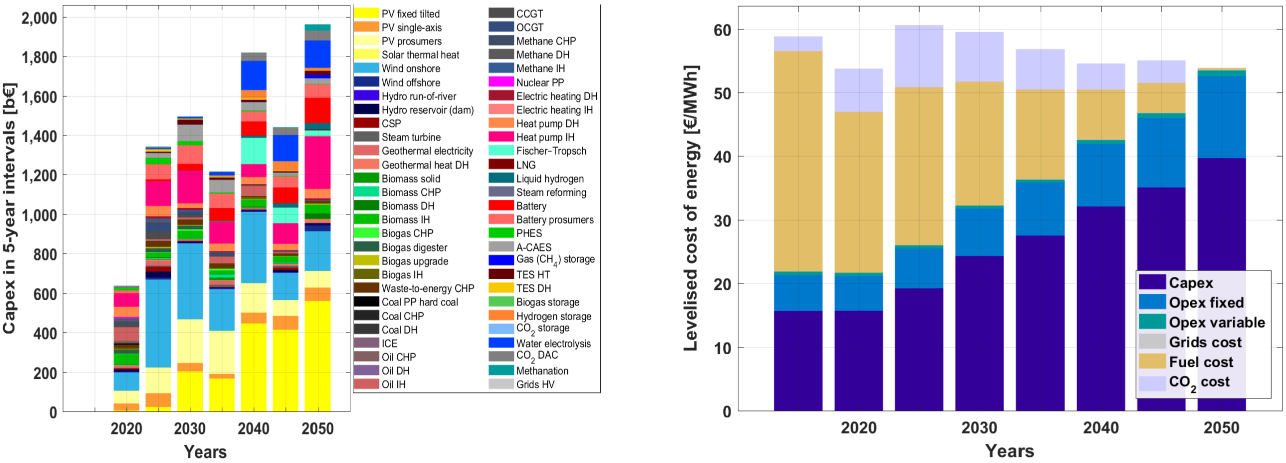

Figure 8: Capital costs for 5-year intervals (left) and levelised cost of energy (right) during the energy transition from 2015 to 2050 in Europe.

Outlook across Sectors

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 individual sectors provides vital insights into the energy transition across Europe towards 100% renewable energy.

Power and Heat

The total installed power generation capacity increases from nearly 1,100 GW in 2015 to around 6,000 GW by 2050, as shown in Figure 9.

Across the power sector, solar PV with 4,400 GW and wind with 960 GW constitute the majority of installed capacities by 2050. In the heat sector, heat pumps, electric heating, and biomass-based heating constitute the majority of installed capacity by 2050, also shown in Figure 9. A significant increase in installed capacity of heat pumps and biomass-based heating occurs in the final 5-year period leading up to 2050, as fossil fuels are completely eliminated from the energy system.

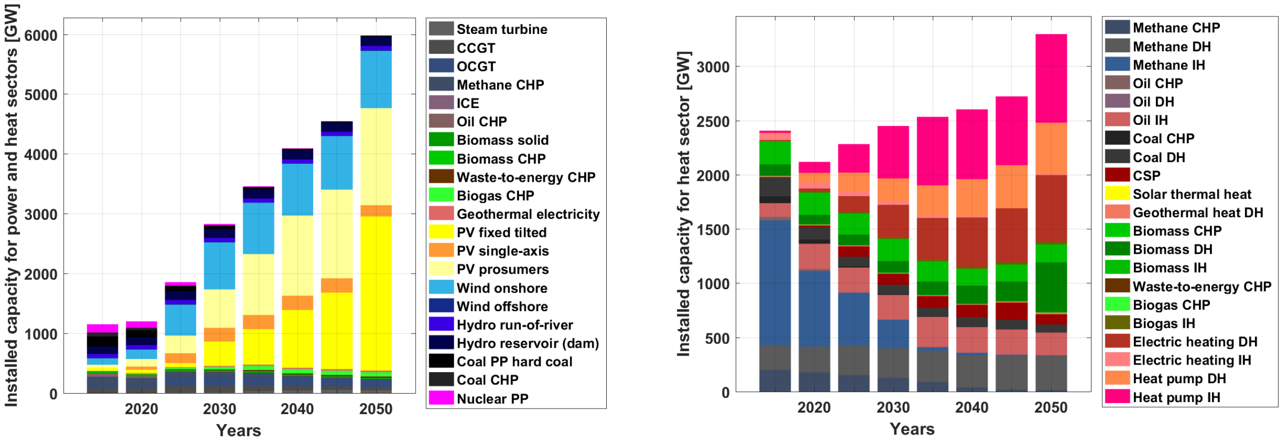

Figure 9: Technology-wise installed capacities for power (left) and heat (right) during the energy transition from 2015 to 2050 in Europe.

A transition across Europe results in a power and heat sector dominated by fossil fuel and nuclear in 2015 moving towards a solar PV and wind energy dominated sector by 2050, with some hydropower and bioenergy as shown in Figure 10. The primary electricity generation increases from around 3,750 TWh in 2015 to around 9,500 TWh by 2050, which is primarily from PV and wind. Heat generation increases from around 7,000 TWh in 2015 to around 9,000 TWh by 2050, which is predominantly from heat pumps and electric heating with some biomass-based heating, also shown in Figure 10.

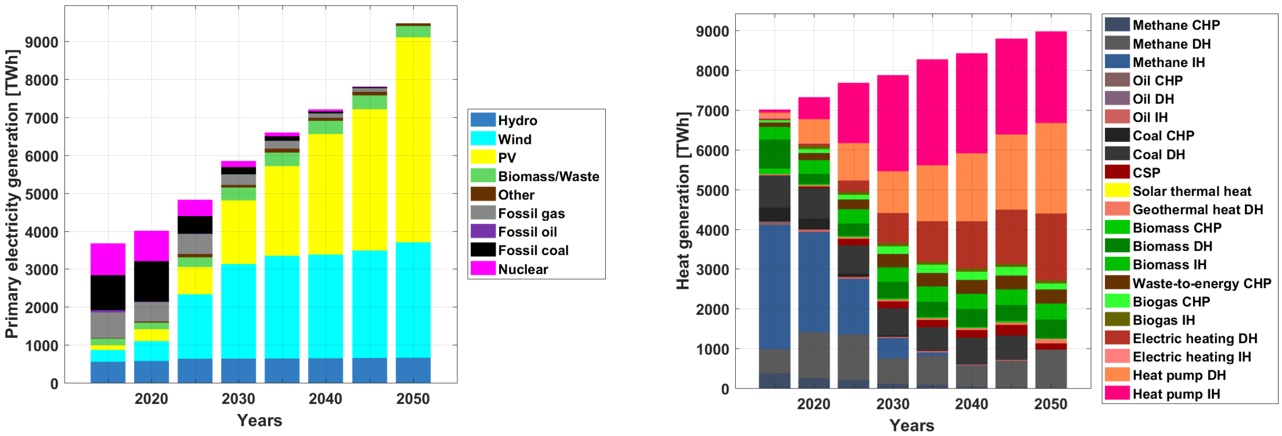

Figure 10: Primary electricity generation (left) and technology-wise heat generation (right) during the energy transition from 2015 to 2050 in Europe.

The installed electricity storage capacity increases from just 0.3 TWh in 2015 to around 7.4 TWh by 2050, as shown in Figure 11. Utility-scale and prosumer batteries with some shares of PHES and A-CAES are installed through the transition. The installed capacities of A-CAES are also a consequence of the modelling approach, which prioritises full domestic energy supply for all European regions. Other research indicates that interconnected European regions would require less electricity storage, and in particular A-CAES storage, which would mainly be substituted by the flexibility offered with interconnected power transmission grids. The installed heat storage increases gradually until 2045 to around 25 TWh, but in the final 5-year period up to 2050, a massive capacity of gas storage of nearly 225 TWh is added, as shown in Figure 11. This substantial capacity addition is mainly to provide seasonal storage across Europe covering the heat demand in the absence of fossil fuels. The present gas storage capacity across Europe is around 1,000 TWh, hence an even lesser amount of gas storage would be needed in the future.

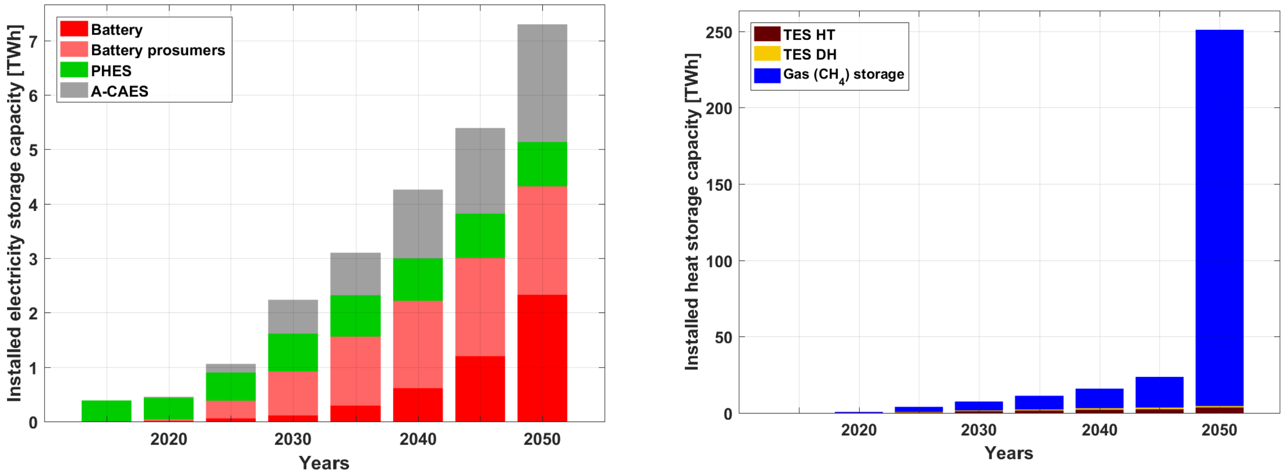

Figure 11: Installed electricity storage capacities (left) and heat storage capacities (right) during the energy transition from 2015 to 2050 in Europe.

Utility-scale and prosumer batteries contribute a major share of electricity storage output with nearly 83% by 2050, as highlighted by Figure 12. In addition, PHES and A-CAES contribute through the transition. TES emerges as the most relevant heat storage technology with around 40-60% of heat storage output from 2030 until 2050, also seen in Figure 12. Gas storage contributes around 40% of the heat storage output in 2050 covering predominantly seasonal demand, which is covered by fossil gas before 2050.

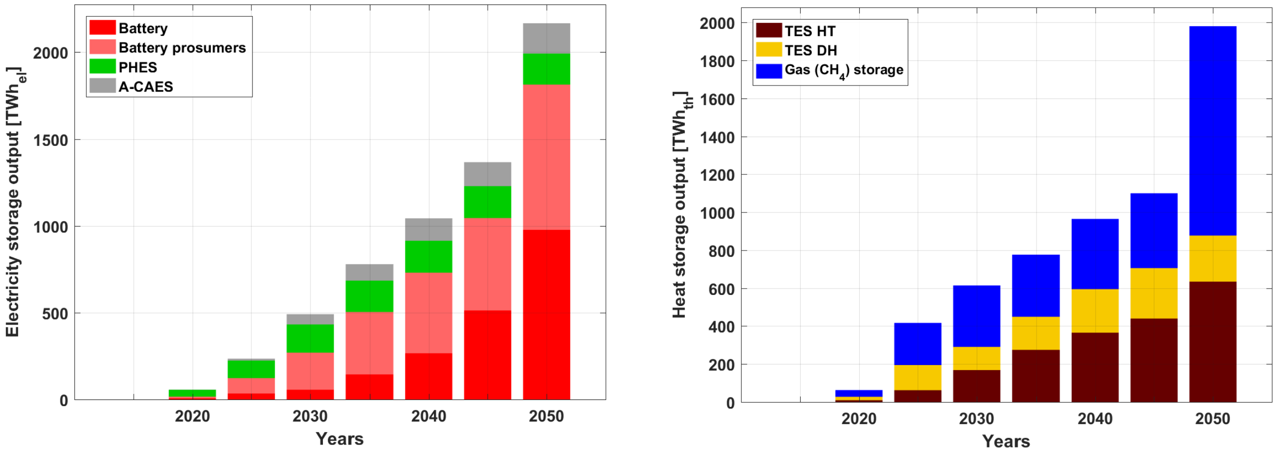

Figure 12: Electricity storage output (left) and heat storage output (right) during the energy transition from 2015 to 2050 in Europe.

The LCOE of the power sector decreases substantially from around €80/MWh in 2015 to around €56/MWh by 2050, as shown in Figure 13. LCOE is predominantly comprised of CAPEX as fuel costs decline through the transition. The LCOH of the heat sector increases marginally from around €41/MWh in 2015 to around €47/MWh by 2030 and further declines to around €42/MWh by 2050, as shown in Figure 13. LCOH is predominantly comprised of CAPEX as fuel costs decline through the transition. Despite a substantial increase in heat demand across Europe, mainly driven by industrial process heat and increased space heating, the LCOH remains quite stable up to 2050.

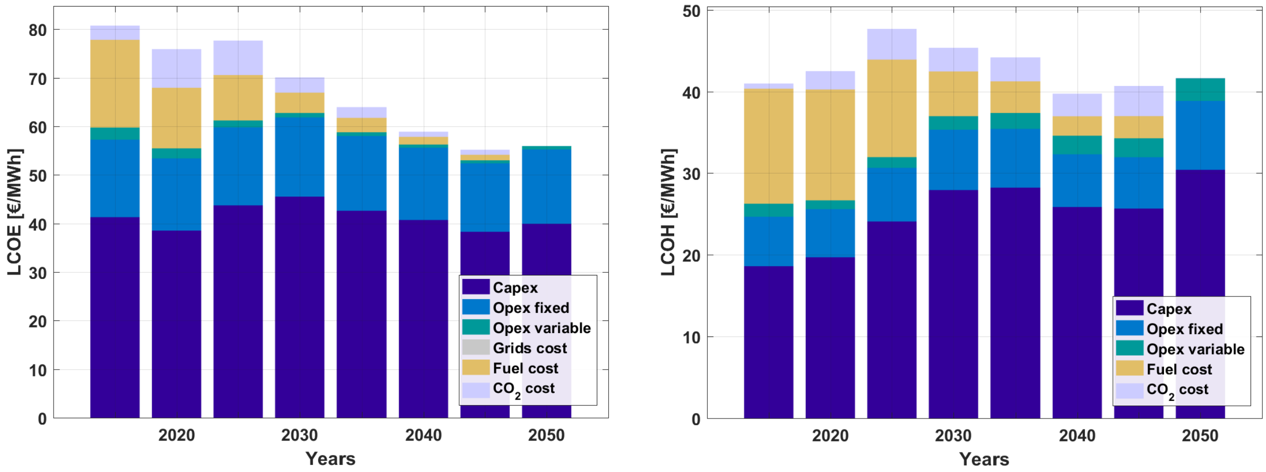

Figure 13: Levelised cost of electricity (left) and levelised cost of heat (right) during the energy transition from 2015 to 2050 in Europe.

Investments are well spread across a range of power generation technologies with the majority share in wind energy up to 2030, beyond which solar PV dominates investments up to 2050, as shown in Figure 14. Investments in the heat sector are mainly in heat pumps and some shares in biomass heating up to 2050, also shown in Figure 14. The steep increase in heat pump investments in the final five-year period until 2050 is mainly to cover the heat demand in the absence of fossil fuels as well as the lower costs of heat pumps by 2050.

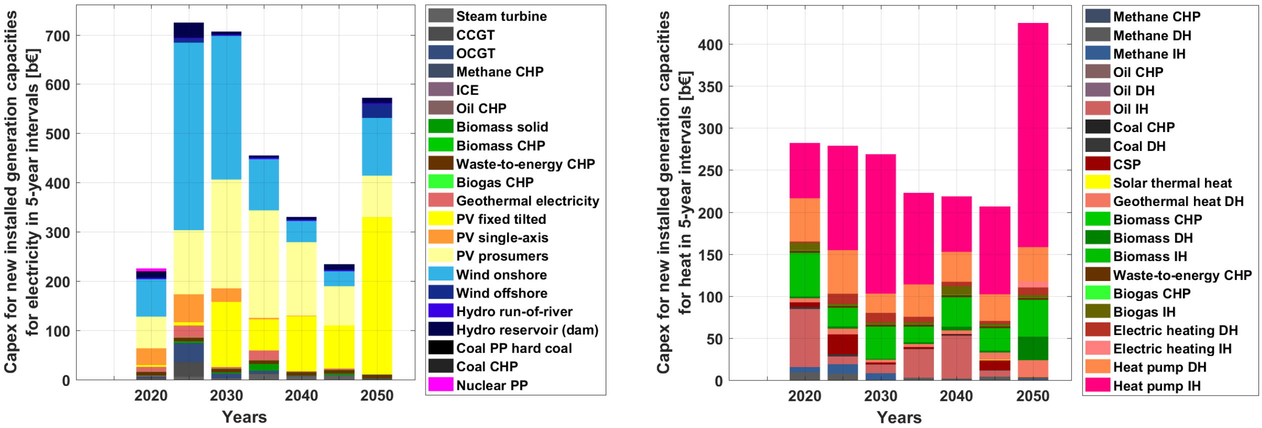

Figure 14: Capital costs of installed generation capacities in five-year intervals for electricity (left) and heat (right) during the energy transition from 2015 to 2050 in Europe.

Transport

The primary 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 electrification of the sector as shown in Figure 15. 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. Sustainably produced biofuels contribute a minor share to enable a complete elimination of fossil fuel usage in the transport sector. Sustainable biofuels produced from energy crops such as Jatropha could play a vital role in ensuring 100% renewable energy systems[8]. 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 until 2050, indicated in Figure 15.

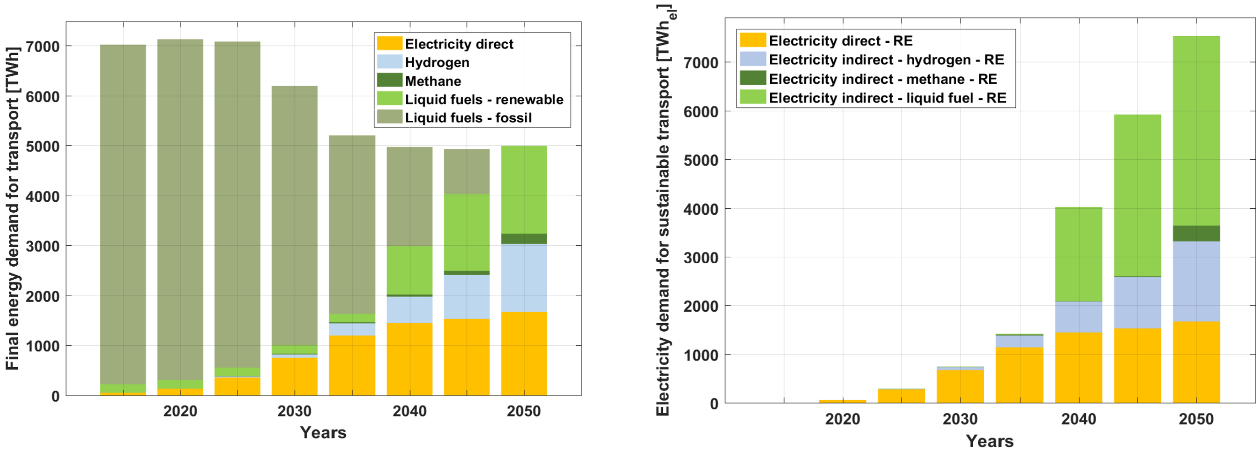

Figure 16: Transport sector installed power generation capacity (left) and electricity generation (right) during the energy transition

A critical aspect to complement the electrification of the transport sector is the installation of storage technologies. As seen in Figure 17, the installed capacities of electricity storage increase through the transition to around 3.3 TWh by 2050. The majority of installed capacities are utility-scale batteries and A-CAES. Similarly, electricity storage output increases through the transition to over 700 TWh_{el} by 2050 as shown in Figure 17. 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.

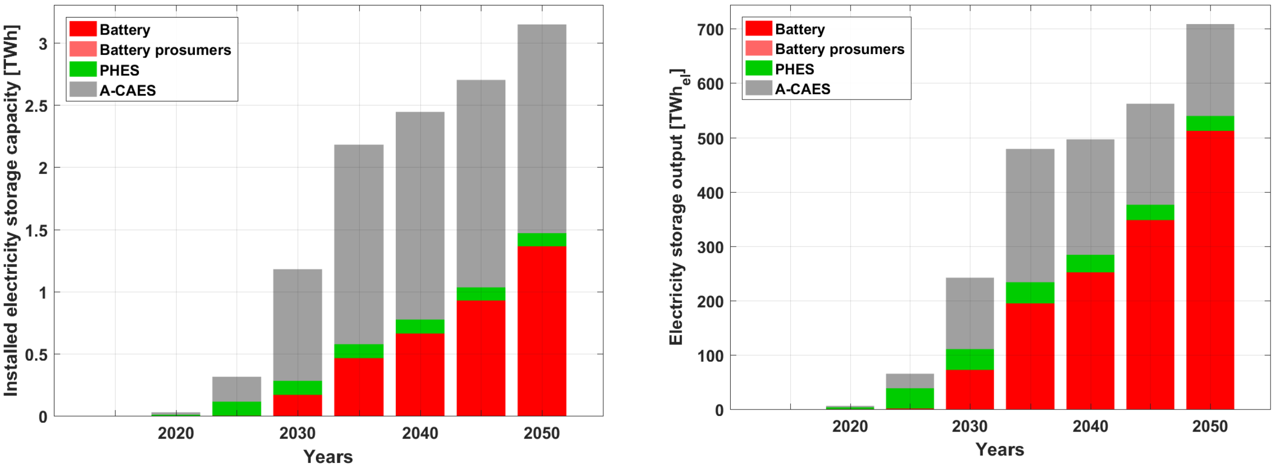

Figure 17: Transport sector installed electricity storage capacity (left) and electricity storage output (right) during the energy transition from 2015 to 2050 in Europe.

An 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 18, 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 needed during the production of synthetic fuels, mainly for energy-efficient CO_2 direct air capture, and this is enabled by managing process heat, which is otherwise not useable. Heat utilisation is in the range of 1,100 TWh_{th} by 2050, which is comprised of excess heat and recovered heat, as shown in Figure 18.

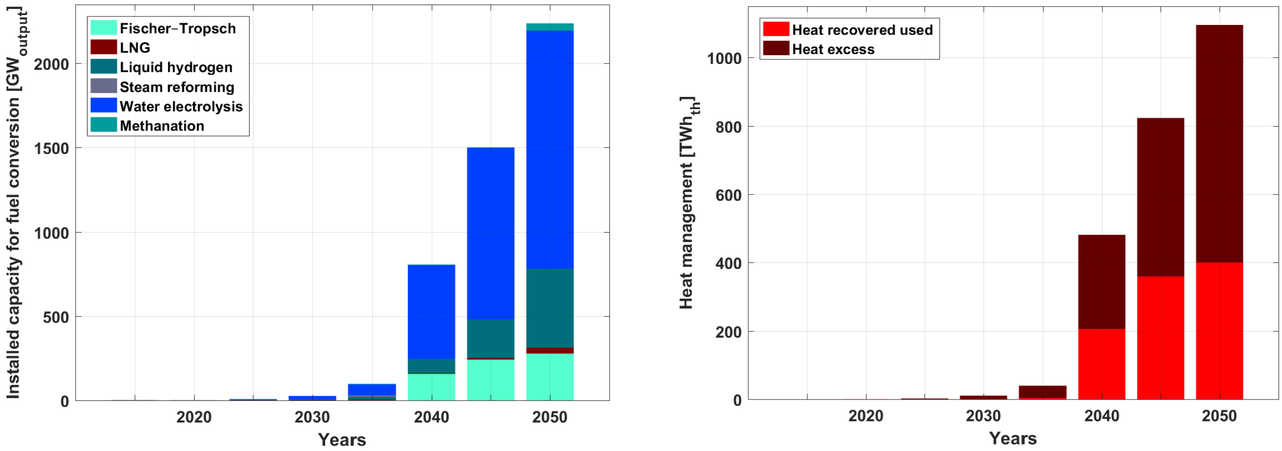

Figure 18: Transport sector installed capacity for fuel conversion (left) and heat management (right) during the energy transition from 2015 to 2050 in Europe.

Similarly, gas storage is necessary in the production of synthetic fuels. As shown in Figure 19, 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 fuels, are installed from 2040 onwards. The installed capacity for CO_2 storage and CO_2 direct air capture increases up to around 390 $MtCO_2$ by 2050, as shown in Figure 19. The major share of installed storage capacity is CO_2 direct air capture, which is on an annual basis as compared to CO_2 storage. Despite having a lower storage capacity, CO_2 storage has a substantial utilisation and correspondingly higher throughput.

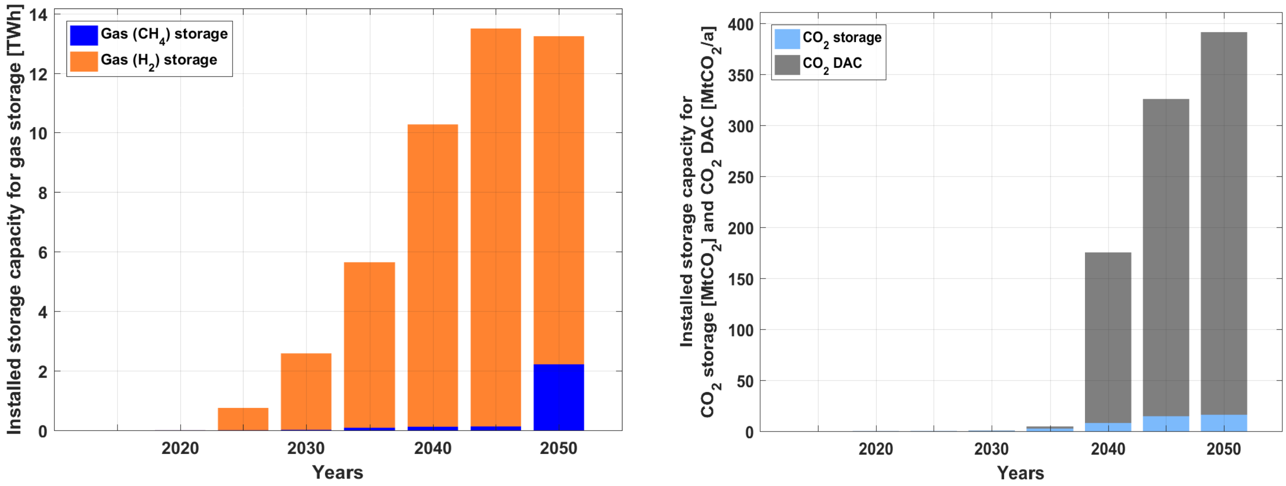

Figure 19: Transport sector installed capacity for gas (methane and hydrogen) storage (left) and CO_2 storage and CO_2 direct air capture (right) during the energy transition from 2015 to 2050 in Europe.

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 20. Fischer-Tropsch (FT) and Synthetic Natural Gas (SNG) fuel 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, SNG is more cost effective than LNG in 2050. Electricity emerges as the most cost effective option with LCOE primary around 25 €/MWh and along with complementary costs of storage and other system components, total LCOE 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. CO_2 from DAC is a critical component for synthetic fuels at around 33 €/MWh in 2050, using waste heat, as shown in Figure 20.

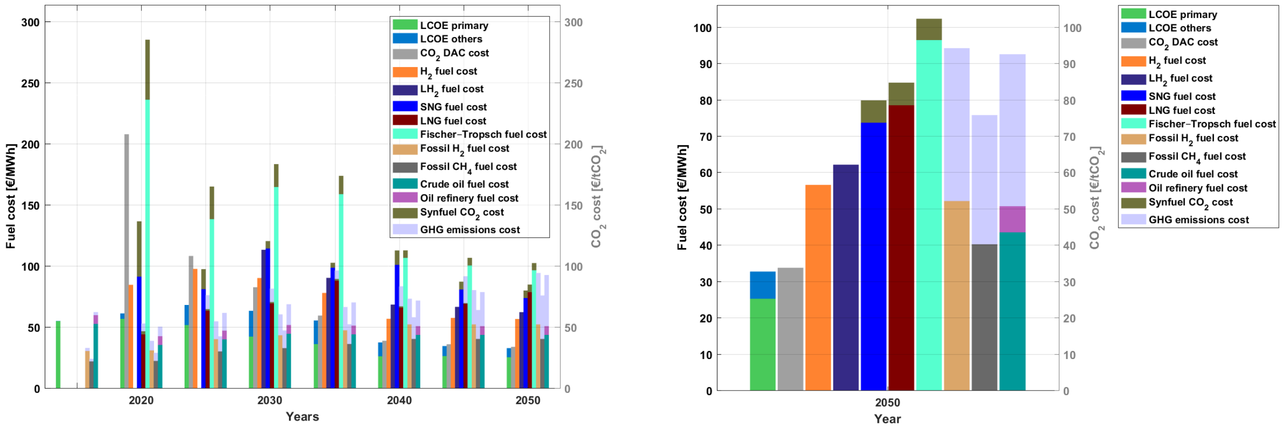

Figure 20: Fuel costs for the transport sector during the energy transition from 2015 to 2050 (left) and fuel costs in 2050 (right) in Europe.

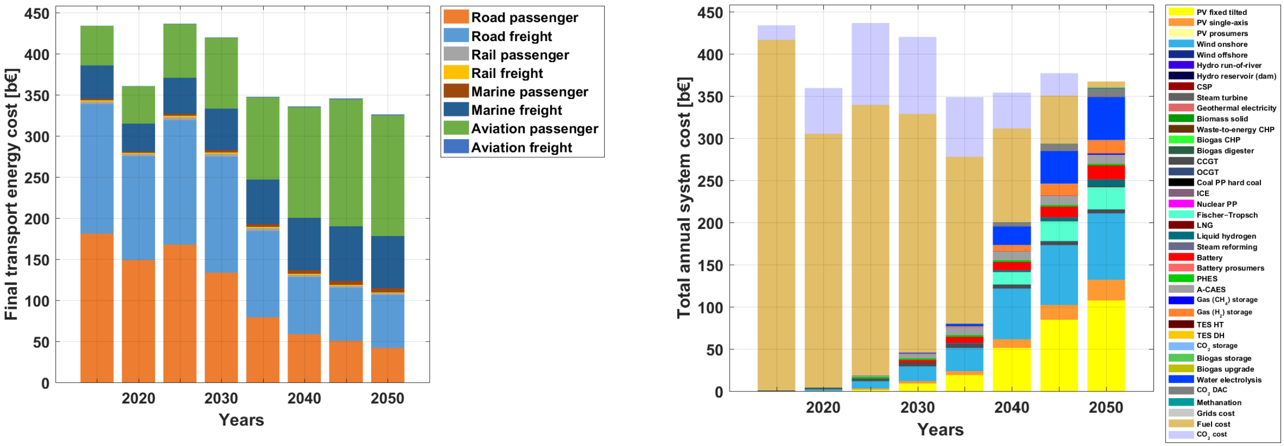

Figure 21: Final transport energy costs based on mode of transport (left) and source of energy (right) during the energy transition from 2015 to 2050 in Europe.

The total annual energy costs for transport are in the range of €300-450 billion through the transition period with a decline from around €430 billion in 2015 to about €330 billion by 2050, as shown in Figure 21. 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, as highlighted in Figure 21. 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.

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 22. 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 22. The final freight costs in the case of road declines through the transition, whereas it increases slightly for aviation and remains stable for rail and marine.

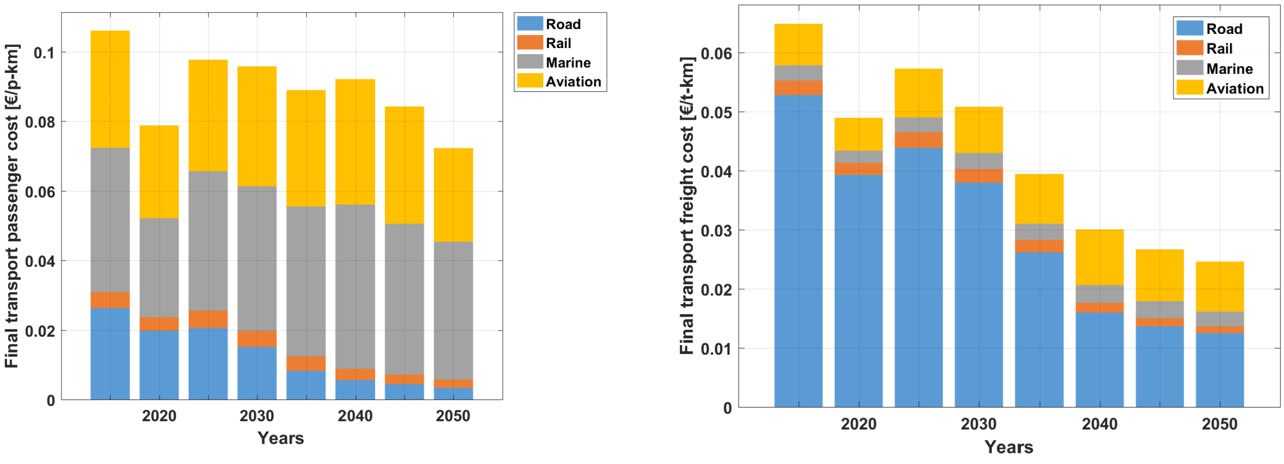

Figure 22: Final transport passenger cost (left) and final transport freight cost (right) during the energy transition from 2015 to 2050 in Europe.

Desalination

The desalination demand in Europe is relatively small compared to other regions of the world. Therefore, the installed capacity of power generation for the desalination sector increases from around 1 GW in 2050 to around 250 GW by 2050 as shown in Figure 23. Solar PV and wind comprise the majority of installed capacities from 2030 until 2050. Primary electricity generation to meet the desalination demand in the initial period of the transition is from fossil gas up to 2030, beyond which PV and wind dominate as highlighted in Figure 23.

The installed storage capacity for desalination occurs mainly from 2035 onwards, with most of the capacity added in the final 5-year period until 2050 as shown in Figure 24. Gas comprises more than 95% of the 23 TWh installed storage capacity in 2050, whereas batteries contribute the majority of the storage output, which reaches more than 110 TWh_{el} by 2050 shown in Figure 24.

Investments in power generation for the desalination sector occur mainly during 2025 to 2040, as shown in Figure 25. A majority of the investment is in wind, PV, and batteries, which reaches a high of around €60 billion in 2040. The levelised cost of water declines through the transition from around €1.2/m^3 in 2015 to around €0.6/m^3 by 2050, as shown in Figure 25.

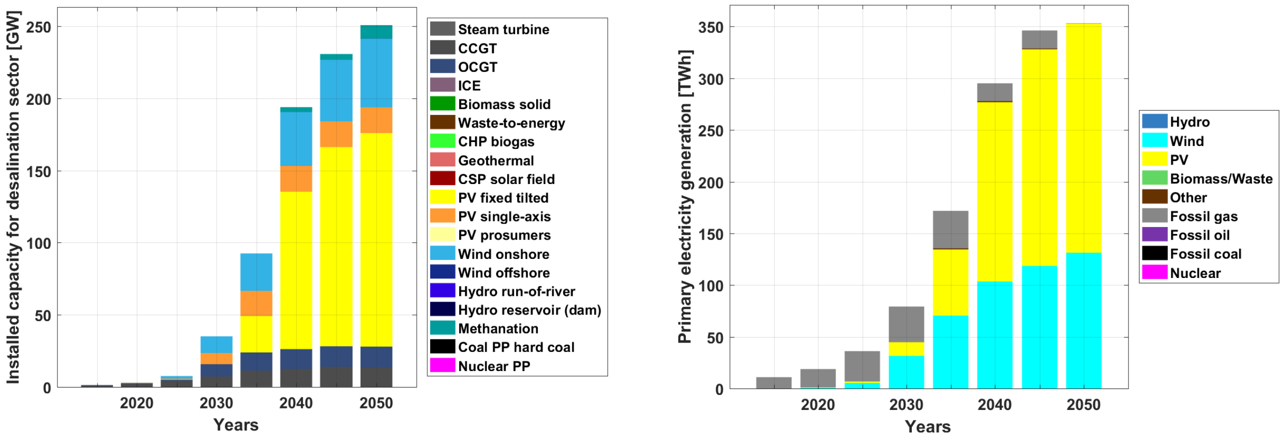

Figure 23: Technology-wise installed capacities for the desalination sector (left) and primary electricity generation for the desalination sector (right) during the energy transition from 2015 to 2050 in Europe.

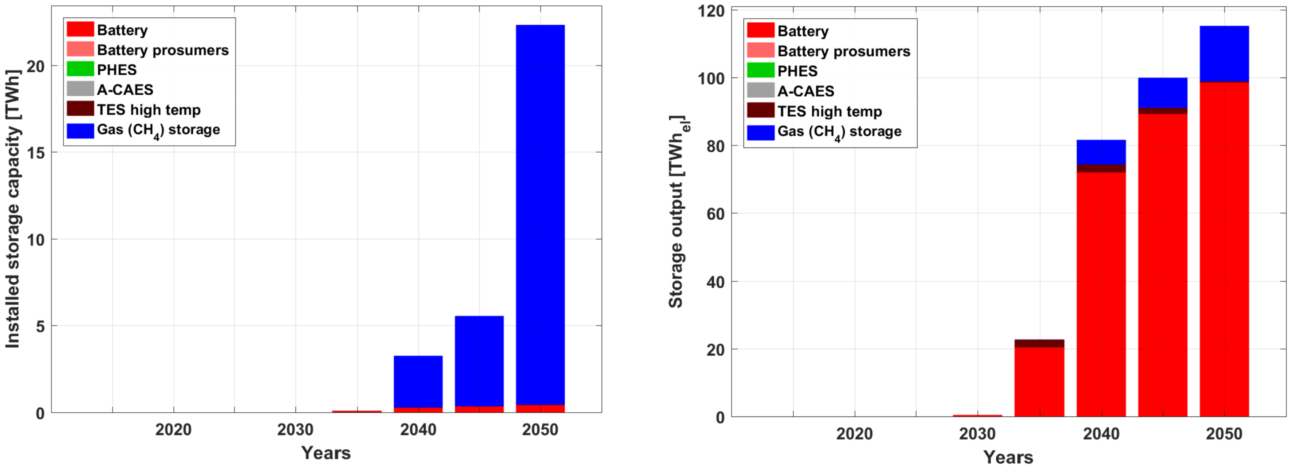

Figure 24: Installed storage capacity (left) and storage output (right) during the energy transition from 2015 to 2050 in Europe.

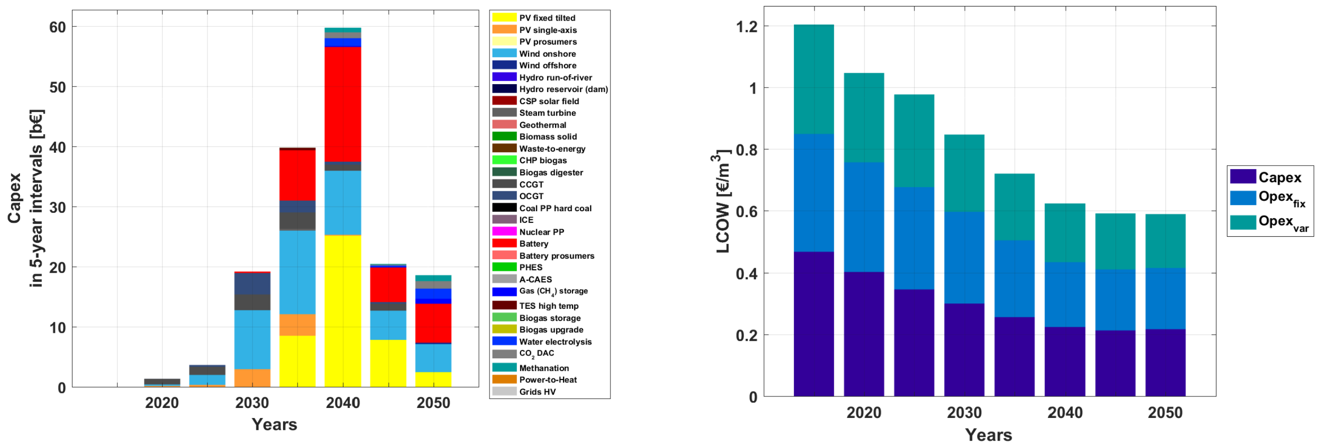

Figure 25: Capital costs for five-year intervals (left) and levelised cost of water (right) during the energy transition from 2015 to 2050 in Europe.

Regional Outlook

Electricity generation capacities are installed across Europe to satisfy the demand for power, heat, transport, and desalination up to 2050. Solar PV capacities are predominantly in the southern regions of Europe that have better solar resources through the year, while wind energy capacities are mainly in the northern regions of Europe that have much better wind conditions, as shown in Figure 26. Overall, solar PV and wind capacities along with some hydropower capacities constitute the majority of installed capacity in 2050 across Europe. Similarly, higher shares of solar PV generation are in the southern regions and higher shares of wind energy are in the northern regions as highlighted in Figure 26. This could enhance the complementarity of solar PV and wind in an interconnected European energy system.

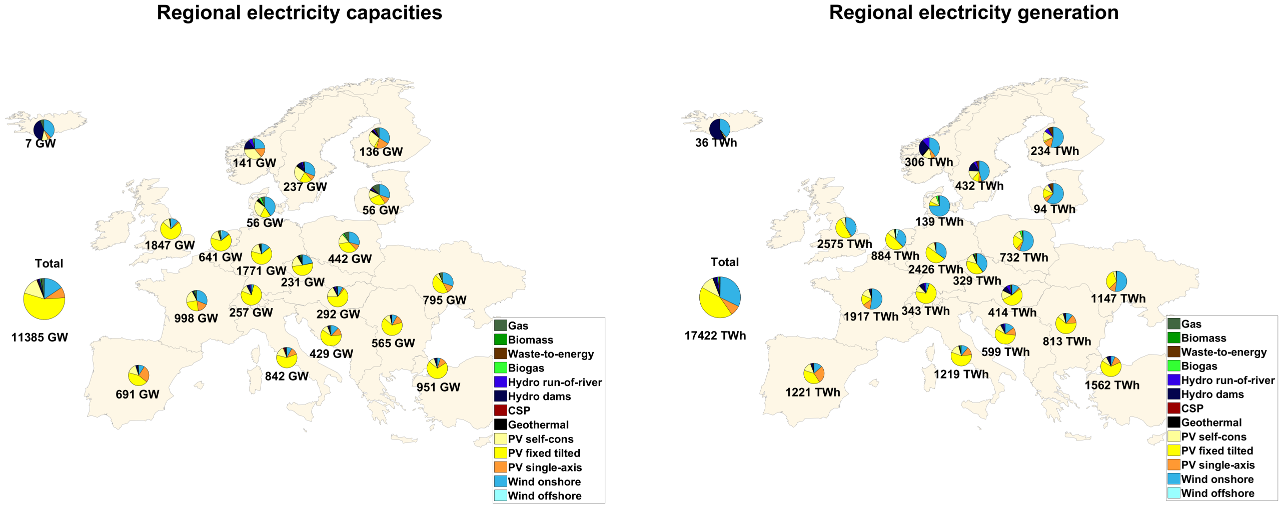

Figure 26: Regional electricity generation capacities (left) and electricity generation (right) in 2050 across Europe.

The electricity generation across the power, heat, transport, and desalination sectors of Europe are predominantly from PV and wind in 2050, as shown in Figure 27. Solar PV, which supplies an average of 61.9% of electricity generation across Europe, is more common in the southern regions of Europe. While wind energy, which contributes an average of 32.3% of electricity generation across Europe, is mainly found in the northern regions of Europe. Overall, solar PV and wind generate most of the electricity needed across Europe by 2050, which is around 94.2% of total electricity generation. Utility-scale and prosumer batteries contribute a major share of electricity storage capacities, with some shares of PHES and A-CAES by 2050, as shown in Figure 28. Storage capacities are much higher in the southern parts of Europe, to complement higher shares of installed solar PV capacities, compared to the northern regions. Batteries, both prosumers and utility-scale, deliver the largest shares of output by 2050, as shown in Figure 28. PHES and A-CAES contribute complementary shares of electricity storage output through the transition, across the different regions of Europe.

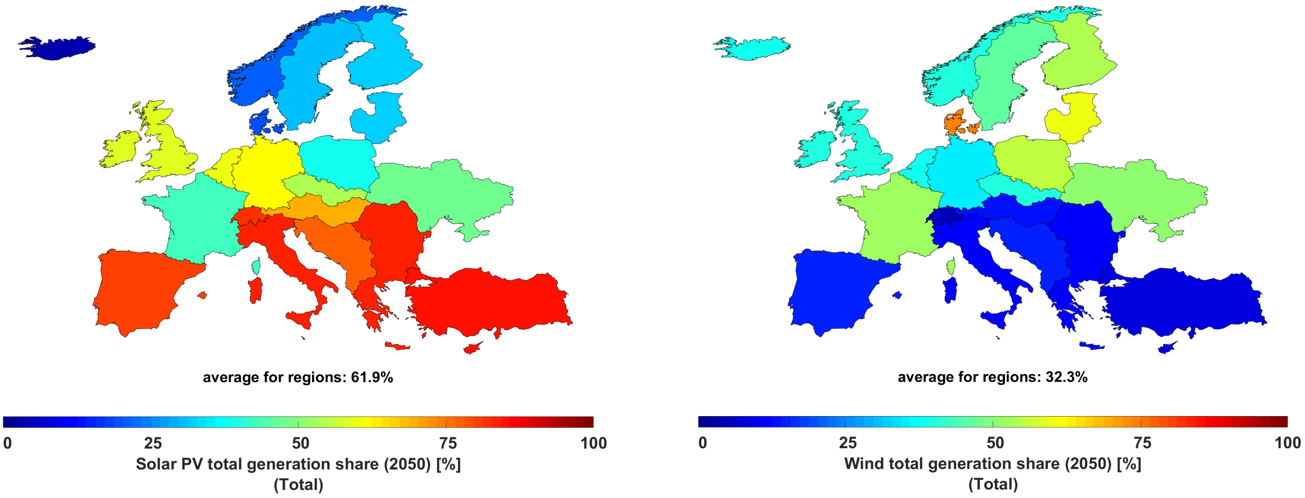

Figure 27: Regional variation of electricity generation shares of solar PV (left) and wind energy (right) in 2050 across Europe.

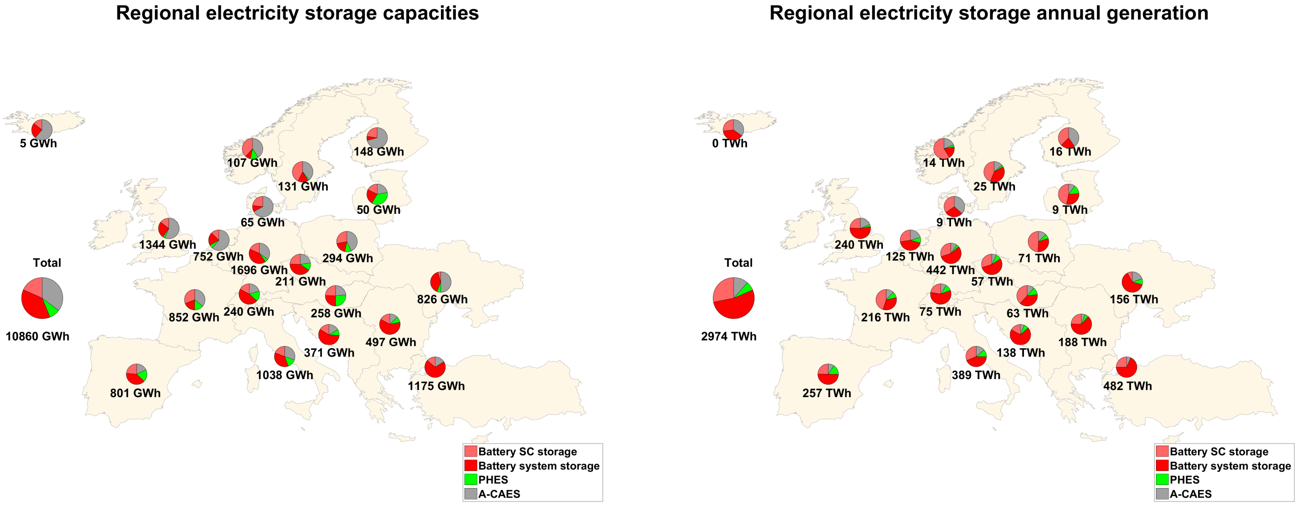

Figure 28: Regional electricity storage capacities (left) and electricity storage annual throughput (right) in 2050 across Europe.

The storage output across the power, heat, transport, and desalination sectors of Europe is predominantly from batteries (both utility-scale and prosumers) and some synthetic natural gas supply in 2050, as shown in Figure 29. Batteries, which supply an average of 15.5% of the storage output across Europe, are more common in the southern regions of Europe. Synthetic natural gas, which supplies an average of 0.3% of the storage output across Europe, is predominant in the eastern regions of Europe. This is complemented with a supply share of storage from biomethane of around 0.2% in 2050 across Europe.

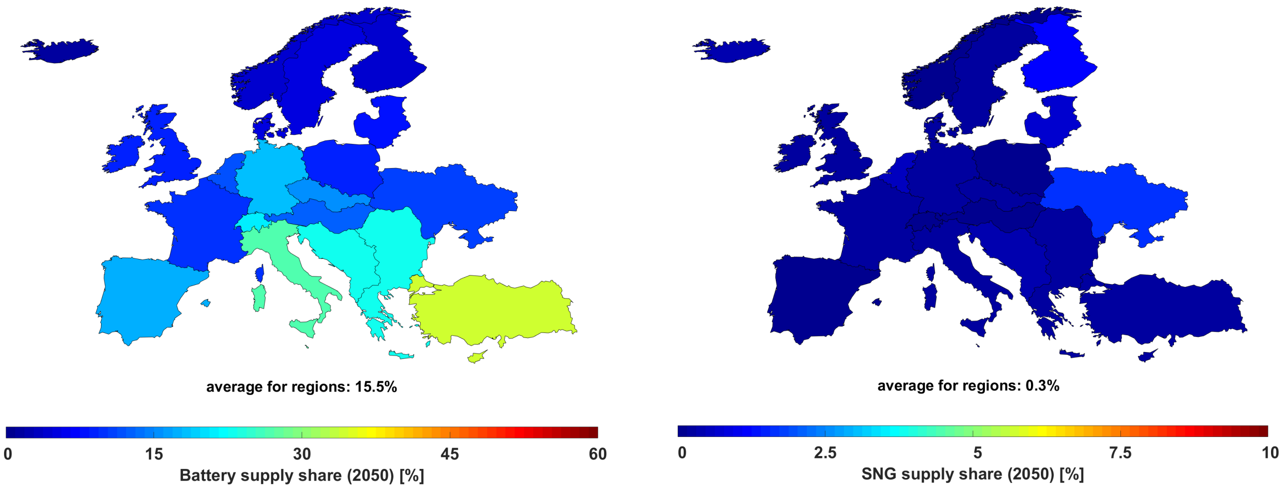

Figure 29: Regional variation of storage supply shares of batteries (left) and synthetic natural gas (right) in 2050 across Europe.

Socio-economic Benefits

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 to reduce resource conflicts in water-stressed regions of the world.

Greenhouse Gas Emissions

The results of the global transition towards a 100% renewable energy system indicate a sharp decline in greenhouse gas (GHG) emissions until 2050, reaching zero GHG emissions by 2050 across the power, heat, transport, and desalination sectors in Europe as shown in Figure 30. The power sector undergoes a deep decarbonisation by 2030, whereas for the heat and transport sectors this occurs mostly between 2030 and 2050.

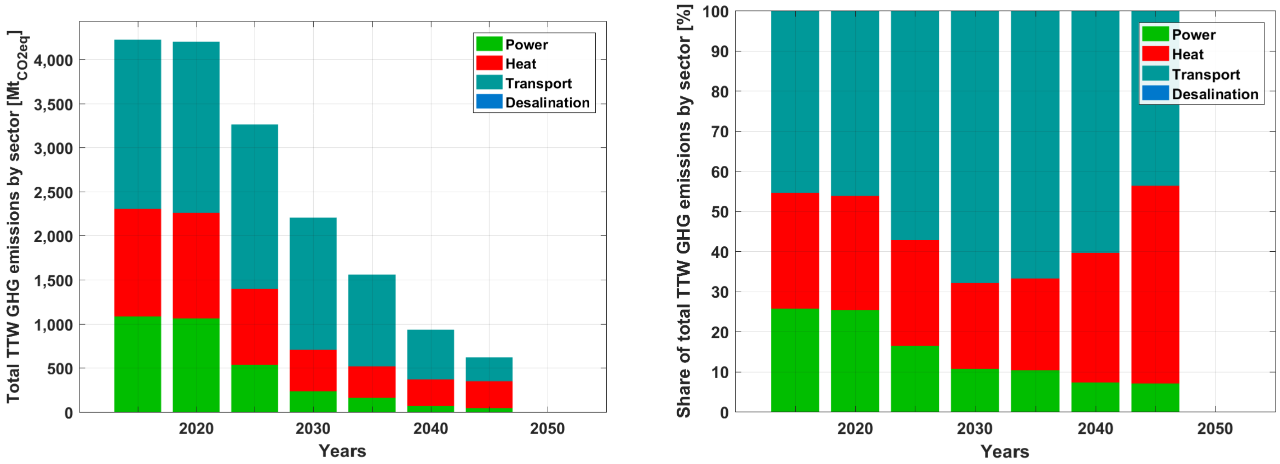

Figure 30: Sector-wise GHG emissions (left) and the share of GHG emissions of different sectors (right) during the energy transition from 2015 to 2050 in Europe.

The GHG emissions from the power sector decline through the transition from around 1,100 $MtCO_2$ eq./a in 2015 to zero by 2050 (shown in Figure 31). Similarly, The GHG emissions from the heat sector decline through the transition from over 1200 $MtCO_2$ eq./a in 2015 to zero by 2050 (shown in Figure 31).

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 32. Similarly, The GHG emissions from the desalination sector, which are much lower than those of other sectors, decline through the transition from around 4.5 $MtCO_2$ eq./a in 2015 to zero by 2050, also visible in Figure 32.

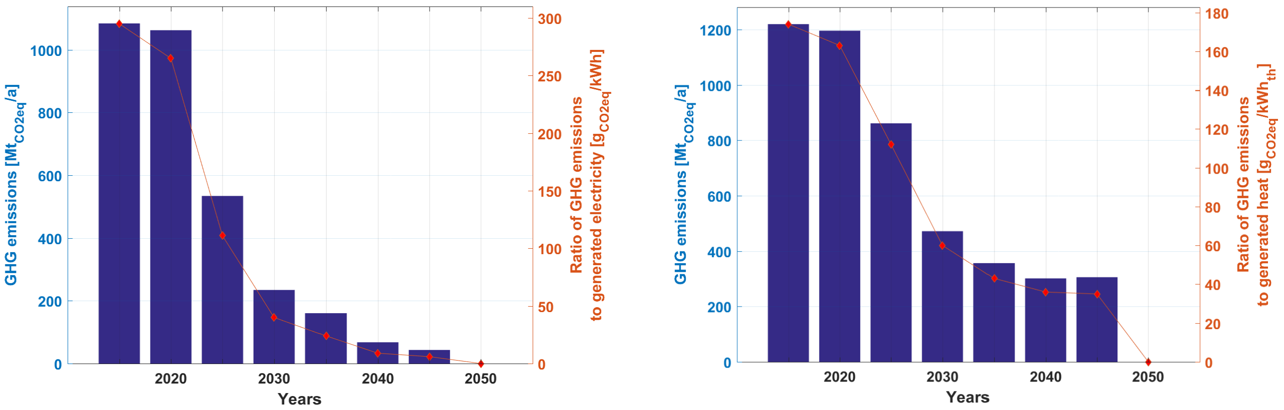

Figure 31: GHG emissions in the power sector (left) and GHG emissions in the heat sector (right) during the energy transition from 2015 to 2050 in Europe.

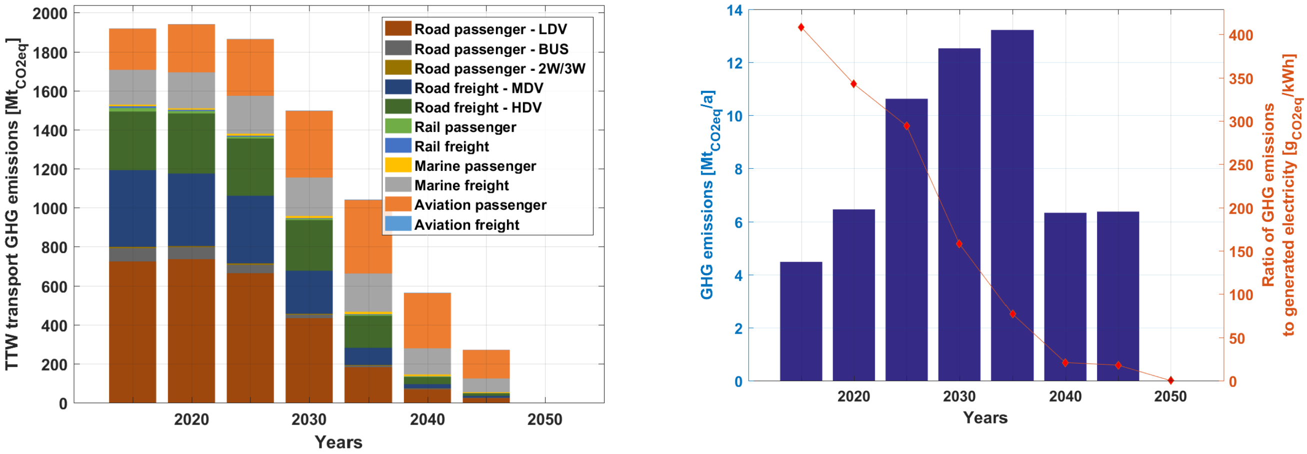

Figure 32: GHG emissions in the transport sector (left) and GHG emissions in the desalination sector (right) during the energy transition from 2015 to 2050 in Europe.

Jobs in the European Power Sector

Job creation across Europe to meet only the electricity demand arising from the transition in the power sector (thus excluding electricity demand from the heat, transport, and desalination sectors) is estimated utilising the methodology presented in Ram et al., (2018)[9]. There were just over 2 million direct jobs in the energy sector across Europe in 2015, with more than 50% of these in the renewable energy sector. With the rapid increase in renewable energy installations up to 2025, jobs in the energy sector are seen to rise to around 3.7 million, and stabilise between 3.3 million by 2035 and 3.4 million by 2050 as shown in Figure 33. Solar PV emerges as the major job creating sector with 1.73 million jobs by 2050. Storage technologies led by batteries are observed to start creating jobs from 2025 onwards, with a stable share until 2050 (277,000 jobs in the battery sector). Conversely, jobs in the fossil fuel and nuclear sectors decline through the transition period and by 2050 are almost non-existent apart from a few thousand jobs associated with the decommissioning of conventional power plants.

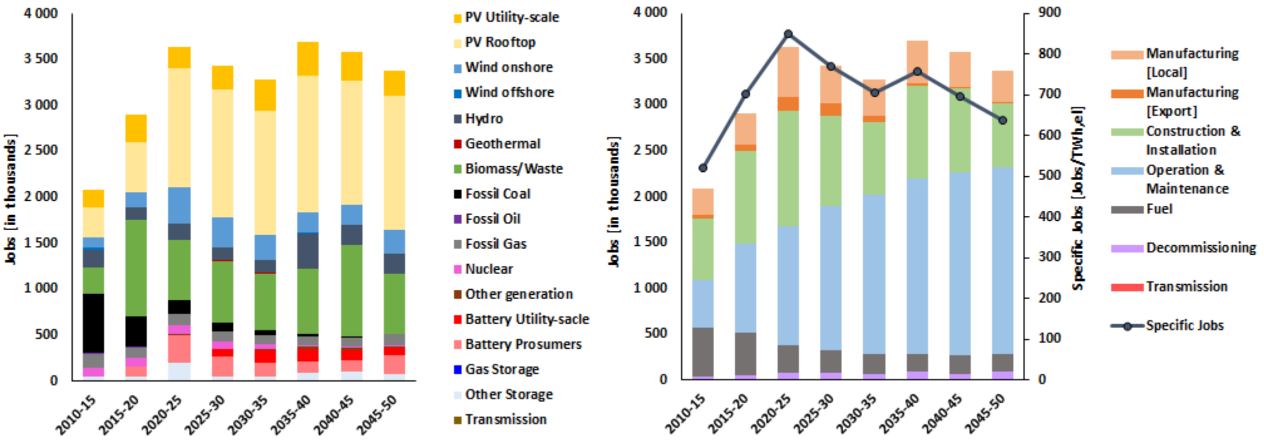

Figure 33: Jobs created by various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Europe.

Manufacturing, construction, and installation of renewable energy technologies create a significant share of jobs enabling the rapid ramp-up of capacity until 2025. Beyond this period there are a stable number of jobs created in these sectors up to 2050 with over a million jobs. Furthermore, manufacturing includes goods both for local use as well as for exporting to other regions. The share of exports initially increases up until 2030 with over 4% of total jobs, beyond which it declines and manufacturing predominantly caters to the local power market across Europe. Fuel jobs continue to decline through the transition period reaching just 6% of total jobs by 2050, as capacities of conventional power plants continue to decline. In contrast, operations and maintenance jobs continue to grow through the transition period and become the major job segment by 2050 with 61% of total jobs. As operations and maintenance jobs last through the lifetime of power plants, they offer relatively stable long-term job prospects. The electricity demand specific jobs indicates the total number of jobs created annually for every TWh$_{el}$ of annual electricity generation during the energy transition. As indicated in Figure 32, the specific jobs were at 516 jobs/TWh$_{el}$ in 2015, increasing to 859 jobs/TWh$_{el}$ in 2025 with the rapid ramp-up in renewable energy installations. Beyond 2025, it declines steadily to 638 jobs/TWh$_{el}$ by 2050.

Conclusions

Solar PV and wind energy are the leading sources of electricity generation complemented by battery storage, which are driven by increasing demand and rapidly declining costs across Europe. The shift in generation types from the conventional (fossil and nuclear) energy system to more sustainable renewable energy system through the transition will affect the entire energy industry – generation and production of energy, system operations across the different energy sectors, transmission and distribution of energy. This report 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; enhanced sector coupling and flexibility through integration of power and heat technologies; transformation of the transport sector through increased utilisation of renewable electricity, renewable energy based fuels and sustainable biofuels; ensuring sustainable water supply with renewable electricity and storage technologies. Furthermore, achieving zero GHG emissions from harder-to-abate sectors such as heavy industry and heavy-duty transport is neither a technical nor an economical challenge anymore[10]. This report 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. 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-economic systems across Europe as well as globally.

Policy Recommendations

The global movement for 100% renewable energy has been growing rapidly in recent years. On a global scale, thousands of cities, and even entire nations, such as Sweden, Denmark, New Zealand, Costa Rica and Iceland have all set the ambitious goal to achieve 100% renewable energy.

Under the Paris Agreement, European countries and the global community committed to taking action to limit global warming to well below 2°C above pre-industrial levels, aiming to limit it to 1.5°C. A full defossilisation can best be achieved by a rapid transition toward 100% renewable sources.

The first crucial prerequisite for a transition to renewable energy is public and government support. The second prerequisite is a clear legislative framework that promotes rapid and exponential growth of renewables while simultaneously phasing out all subsidies and policies that support fossil fuels and nuclear power generation.

To ensure a smooth, fast and cost-effective transition to 100% renewable energy across all sectors, governments need to adopt national legislative acts. Policies must ensure sufficient flow of private investment in renewable energy, storage technologies, sector coupling, and smart energy systems. Public financing is indispensable and can leverage private funding. However, private investment is instrumental to enable competition and a rapid scaling-up of renewable energy.

The following political and financial measures and instruments are key

1. Policies and instruments focusing on sector coupling

During the transition to 100% renewable energy, heat and transport sectors will be significantly electrified. Additionally, sustainable biofuels and production of synthetic fuels based on renewable energy, such as green hydrogen, will require integration across sectors, and will play a significant role in emission-free heat and transport sectors.

Therefore, policies for 100% renewable energy in all sectors must focus on sector coupling.

2. Instruments enabling direct private investments in renewable energy and other zero-emission technologies.

The German Renewable Energy Sources Act (EEG) 2000, with a fixed feed-in tariff and privileged grid access, is one of the most well-known and proven successful policy frameworks for renewable energy. The policy played a major role in reducing costs for initially cost-intensive wind, solar PV and other renewable technologies. It is imperative that an EEG law includes a privileged guaranteed feed-in-tariff for renewable energy generation. Feed-in tariff laws are also necessary for renewable heat in district heating and for renewable gas in gas pipelines.

In recent years, a range of countries have introduced tenders instead of feed-in tariffs. An analysis[2] conducted by the Energy Watch Group has shown that tenders are limiting the deployment of renewable energy sources. Furthermore, tenders limit investment to large companies and exclude investment from decentralised actors, such as cooperatives. Tendering procedures should therefore only apply for capacities above 40 MW. In cases below 40 MW, the EEG framework with feed-in tariffs should apply.

Political regulations should encourage investment across the whole population, with focus on decentralised actors, such as individuals, homeowners, prosumers, small and medium enterprises, farmers, cooperatives, local utilities, as well as utility-scaled investment like offshore wind farms.

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[2] Fell, H.J. (2017): The shift from feed-in-tariffs to tenders is hindering the transformation of the global energy supply to renewable energies, IRENA Policy Paper.

We also need new, innovative political measures encouraging investment in renewable energy, storage and grid integration simultaneously. The implementation of feed-in tariffs for compatible and dispatchable renewable energy systems is a key incentive scheme for sector coupling.

A reformed version of the EEG – a hybrid renewable power plant remuneration (Incentive Scheme for 100% Renewable Combined Power Solutions), granting feed-in tariffs for electricity, generated solely by a mix of renewable energy sources, providing hourly, year-round demand coverage – enables just that.

3. Tax exemptions, direct subsidies and legal privileges for renewable energy technologies

Renewable energy technology needs to be supported by tax exemptions on property, trade, purchase and more. In new markets, exemptions are crucial to ensure renewable energy market growth and an overall attractive return on investment.

For example, VAT exemptions for solar thermal modules purchases have proven to be effective in encouraging private investment. In the transport sector, mineral oil tax exemptions for biofuels, power-to-gas and CO_2 neutral synthetic fuels have already been successfully demonstrated and tested. Additionally, zero-emission vehicles could be exempted from the motor vehicle tax. Tax exemptions and/or tax incentives for new and existing building energy projects will stimulate efficient zero emission properties.

In Germany, direct tax subsidies have proven to be effective, for example the market incentive programme for renewable heat and storage, as well as a buyer's premium for electric cars. Such incentive programmes could be implemented on the European level.

4. Phase-out all state subsidies to fossil fuel and nuclear power generation

To accelerate the growth of renewable energy sources, all subsidies and tax exemptions for conventional fossil energy plants, foremost coal power plants, need to be phased out. This would save public money, which could instead be spent on education and research.

5. Energy consumption must be efficient and demand must be supplied solely by renewable energy

Implementing energy efficiency measures to support a fossil fuel based system does not lead to the level of defossilisation that is necessary to address climate change. To accelerate the energy transition to 100% renewables, strong attention must be placed on ensuring a clean energy supply, while simultaneously focusing on energy efficiency for end-use consumption. High efficiency buildings, lighting, electric appliances, electronic devices, and other energy loads need to be supported by responsible policies, regulation, mandates, and infrastructure planning. Efficient transport systems that are powered by renewables will reduce energy demand.

6. Promoting co-generation power and heat

Support for co-generation (especially bioenergy and power-to-gas) with full heat recovery is also a key element to Europe's energy transition. This requires for good space and construction planning in local and district heating networks, combined with seasonal heat storage (e.g. ice storage) and integrated solar thermal energy.

Additional support to boost renewable heat supply can be provided by feed-in tariff and renewable heat supply laws. Construction obligations for buildings to use solar for heat and electricity generation, as in the case of Barcelona and California, have proven to be efficient.

7. Introducing carbon and radioactivity tax

Carbon, methane, and radioactivity taxes will sanction energy companies that are producing greenhouse gas emissions through fossil fuels and nuclear power generation. A carbon tax can be effective under the condition that it exceeds the average renewable energy price. While it does not directly promote renewable energy supply as the EEG does, it will reflect real costs of fossil fuel and nuclear power generation (including hidden environmental, social and economic costs), and would make it economically unviable over time. A continuously rising carbon and radioactivity tax should replace the emission trading system, which has proven to be an ineffective climate change policy.

8. Promoting research and education in the sphere of renewable energy and zero-emission technologies

Research, education and training on renewable energy and zero-emission technologies at all levels, including schools, universities, and vocational training for professionals in economics, politics, engineering and social sciences, needs be strengthened. Furthermore, it is important to promote research in engineering and technology assessments, while simultaneously enabling an exchange of know-how across the world. Within the industrial sector, research and development also needs to be strengthened, with a particular emphasis on pilot projects and small-scale applications.

Appendix

Abbreviations

A-CAES	Adiabatic compressed air energy storage
BECCS	Bioenergy carbon capture and storage
BEV	Battery electric vehicle
CAES	Compressed air energy storage
CAPEX	Capital expenditures
CCS	Carbon capture and storage
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
DME	Dimethyl ether
FCEV	Fuel cell electric vehicle
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
LCOC	Levelised cost of curtailment
LCOE	Levelised cost of electricity
LCOH	Levelised cost of heat
LCOS	Levelised cost of storage
LCOT	Levelised cost of transmission
LCOW	Levelised cost of water
LDV	Light duty vehicle
LNG	Liquefied natural gas
LT	Low temperature
MDV	Medium duty vehicle
MED	Multiple-effect distillation
MSF	Multi-stage flash
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
R/O	Reverse osmosis (seawater)
SNG	Synthetic natural gas
ST	Steam turbine
TES	Thermal energy storage
TPED	Total primary energy demand
TW	Terawatt
TTW	Tank-to-wheels

References

1. United Nations Framework Convention on Climate Change (UNFCCC). *IPCC - Special Report on 1.5 Degrees*. Geneva; 2018. http://www.ipcc.ch/report/sr15/.
2. Ram M, Bogdanov D, Aghahosseini A, Oyewo AS, Gulagi A, Child M, Fell H-J, Breyer C. *Global Energy System Based on 100% Renewable Energy - Power Sector. Study by Lappeenranta University of Technology and Energy Watch Group*. Lappeenranta, Berlin; 2017. https://goo.gl/NjDbck.
3. [IMF] - International Monetary Fund. *World Economic Outlook (April 2017) - Real GDP Growth*. Washington, D.C; 2017. http://www.imf.org/external/datamapper/NGDP_RPCH@WEO/OEMDC/ADVEC/WEOWORLD.
4. [IEA] - International Energy Agency. *World Energy Outlook 2016*. Paris; 2016. doi:http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf.
5. Agora Energiewende, Sandbag. *The European Power Sector in 2017. State of Affairs and Review of Current Developments*. Berlin; 2018.
6. [EC] - European Commission. *A Clean Planet for All A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*. Brussels; 2018. doi:COM (2018) 773.
7. Ram M, Child M, Aghahosseini A, Bogdanov D, Poleva A, Breyer C. *Comparing Electricity Production Costs of Renewables to Fossil and Nuclear Power Plants in G20 Countries. Prepared by Lappeenranta University of Technology (LUT) for Greenpeace*. Hamburg; 2017. http://bit.ly/2u28u0L.
8. Gruber G, Dalheimer B. *Sustainable Jatropha Oil as Liquid Energy Storage Option for a World 100 % Renewable Energy Supply Study : Resources , Financial and Technical Aspects. Study by Vereinigte Werkstatten Fur Pflanzenoltechnologie (VWP) and University of Goettingen*. Allersberg and Gottingen; 2017.
9. Ram M, Aghahosseini A, Breyer C. Job creation during the global energy transition towards 100% renewable power system by 2050. *Technol Forecast Soc Change*. 2018;Submitted.
10. [ETC] - Energy Transitions Comission. *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century*. London; 2018. http://www.energy-transitions.org/mission-possible.
11. Bogdanov D, Farfan J, Sadovskaia K, Aghahosseini A, Child M, Gulagi A, Oyewo AS, Barbosa LSNS, Breyer C. Pathway towards sustainable electricity: Radical transformation via evolutionary steps. *Submitt Publ*. 2018.
12. Breyer C, Khalili S, Rantanen E, Bogdanov D. Solar Photovoltaic Capacity Demand for a fully sustainable Transport Sector - How to fulfil the Paris Agreement by 2050. In: *7th World Conference on Photovoltaic Energy Conversion (WCPEC-7), Waikoloa*. Waikoloa; 2018. https://bit.ly/2KY948W.
13. Caldera U, Breyer C. Potential for the use of 100% renewable energy powered desalination for crop irrigation in the decades to come. In: *Water Science for Impact Conference, Wageningen, Netherlands*. Wageningen; 2018.

Methodology

The optimisation model of the energy system is based on a linear optimisation of the system parameters under a set of applied constraints with the assumption of a perfect foresight of RE power generation and power demand. A multi-node approach enables the description of any desired configuration of sub-regions and power transmission interconnections. The main constraint for the optimisation is the matching of total power generation and total power demand values for every hour of the applied year and the optimisation criterion is the minimum of the total annual cost of the system. The hourly resolution of the model significantly increases the computation time. However, it guarantees that for every hour of the year the total supply within a sub-region covers the local demand and enables a more precise system description including synergy effects of different system components.

The optimisation is performed in a third-party solver. Currently, the main option is MOSEK ver. 8, but other solvers (Gurobi, CPLEX, etc.) can also be used. The model is compiled in the Matlab environment in the LP file format, so that the model can be read by most of the available solvers. After the simulation, results are parsed back to the Matlab data structure and post-processed. A detailed description is provided in Bogdanov et al., (2018)[11].

Power and Heat Sectors

The LUT model simulates an energy system development under specific given conditions as shown in Figure A1. For every time step the model defines a cost optimal energy system structure and operation mode for the given set of constraints: power demand, heat demand for industry, space and domestic water heating, available generation and storage technologies, financial and technical parameters, and limits on installed capacity for all available technologies. The target of the optimisation is the minimisation of total system cost. Costs of the system are calculated as a sum of the annual capital and operational expenditures (including ramping costs) for all available technologies. The transition simulation was performed for the period from 2015 to 2050 in 5-year time intervals.

The distributed generation and self-consumption of residential, commercial, and industrial prosumers are included in the energy system analysis and defined with a special model describing the development of the individual power and heat generation capacities. Prosumers can install their own rooftop PV systems, lithium-ion batteries, buy power from the grid, or sell surplus electricity in order to fulfil their demand. At the same time prosumers can install individual heaters for space and water heating. The target function for prosumers is minimisation of the cost of consumed electricity and heat, calculated as a sum of self-generation equipment annual costs, costs of fuels, and costs of electricity consumed from the grid. The share of consumers that is expected to be interested in self-generation gradually increases from 3% in 2015 to an in-built limit of 20% by 2050.

The model has integrated all crucial aspects of an energy system. Technologies introduced to the model can be classified into five main categories:

- Electricity generation: fossil, nuclear, and RE technologies
- Heat generation: fossil and RE technologies
- Energy storage
- Energy sector bridging
- Electricity transmission

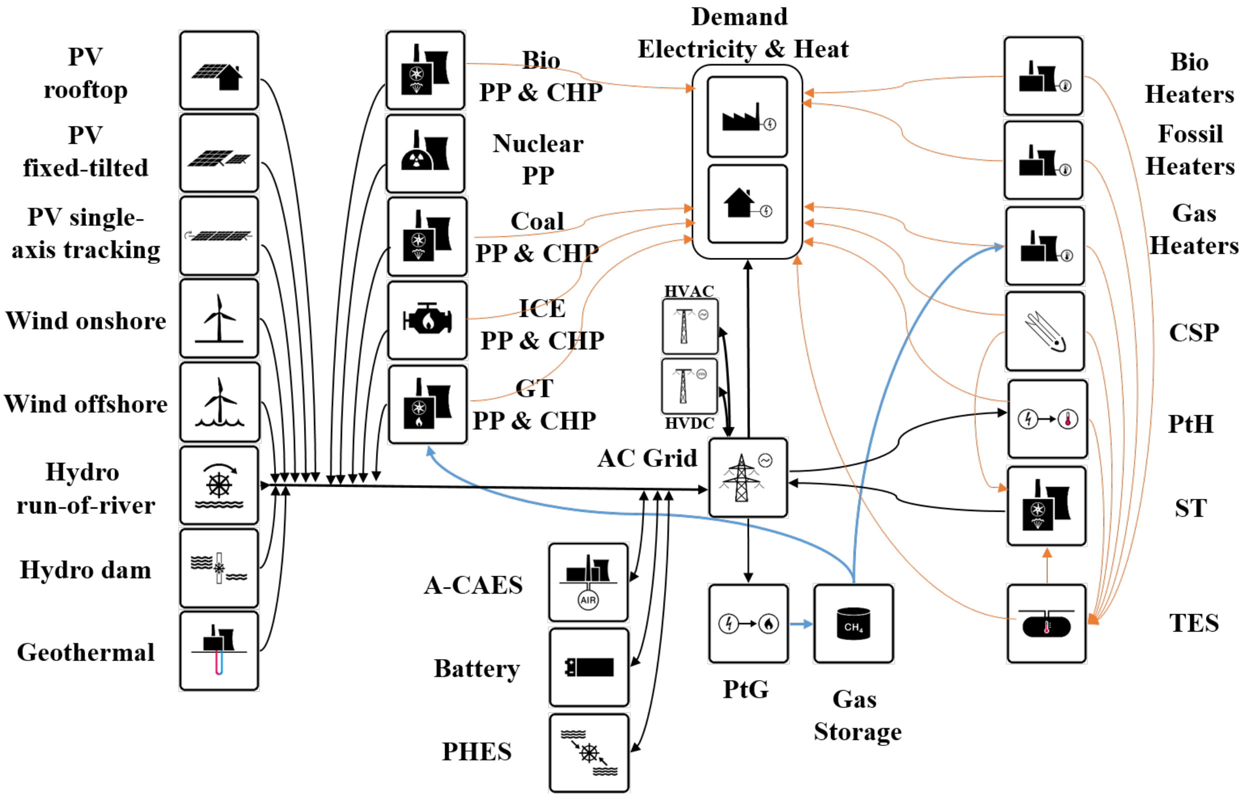

Figure A1: Schematic of the LUT Energy System Transition model comprised of energy converters for power and heat, storage technologies, transmission options, and demand sectors

Fossil electricity generation technologies are coal power plants, combined heat and power (CHP), oil-based internal combustion engine (ICE) and CHP, open cycle (OCGT) and combined cycle gas turbines (CCGT), and gas-based CHP. RE electricity generation technologies are solar PV (optimally fixed-tilted, single-axis north-south tracking, and rooftop), wind turbines, hydropower (run-of-river and reservoir), geothermal, and bio energy (solid biomass, biogas, waste-to-energy power plants, and CHP). Fossil heat generation technologies are coal-based district heating, oil-based district and individual scale boilers, and gas-based district and individual scale boilers. RE-based heat generation technologies are concentrated solar thermal power (CSP) parabolic fields, individual solar thermal water heaters, geothermal district heaters, and bioenergy (solid biomass, biogas district heat, and individual boilers).

Storage technologies can be divided into three main categories: short-term storage – lithium-ion batteries and pumped hydro energy storage (PHES); medium-term storage – adiabatic compressed air energy storage (A-CAES), and high and medium temperature thermal energy storage (TES) technologies; and long-term gas storage including power-to-gas (PtG) technology, which allows the production of synthetic methane to be utilised in the system.

Bridging technologies are power-to-gas, steam turbines, electrical heaters, district and individual scale heat pumps, and direct electrical heaters. These technologies convert energy from one sector into valuable products for another sector in order to increase total system flexibility, efficiency, and decrease overall costs. A detailed overview can be found in Bogdanov et al., (2018)[11].

Transport Sector

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, passenger 2W/3W, passenger bus, freight MDV, and freight HDV. The other transportation 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., (2018)[12].

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 A2:

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

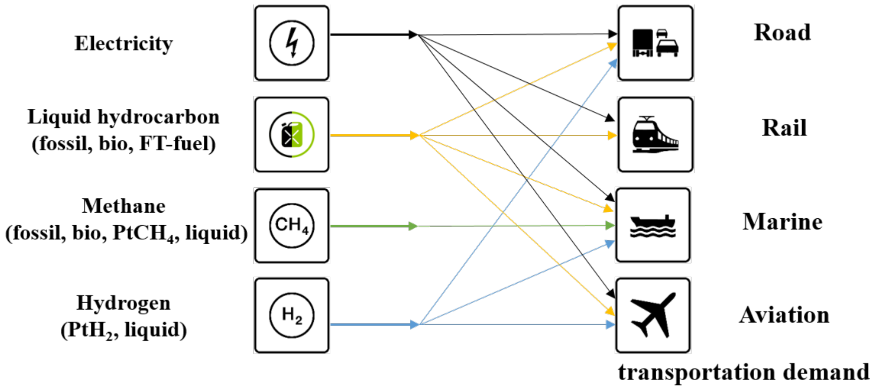

Figure A2: Schematic of the transport modes and corresponding fuels utilised during the energy transition from 2015-2050.

The fuel conversion process adopted to produce sustainable fuels is shown in Figure A3. The fuel shares of the transportation modes in the road segment are based directly or indirectly on levelised cost of mobility (LCOM) 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 methodology is provided in Breyer et al., (2018)[12].

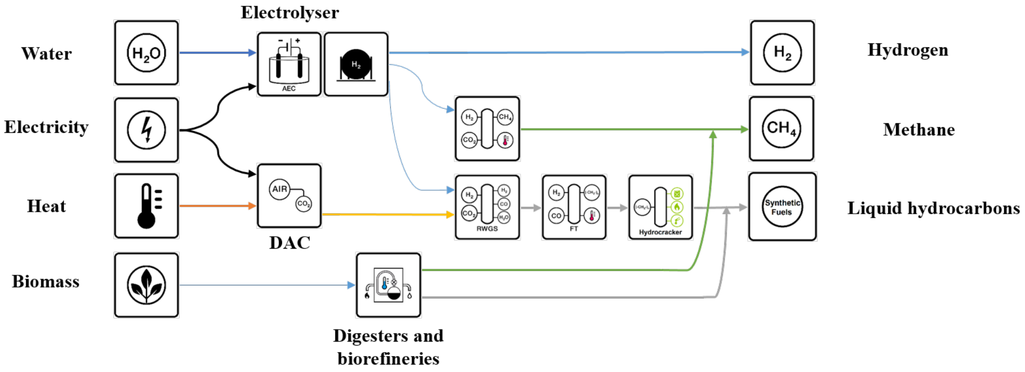

Figure A3: Schematic of the value chain elements in the production of sustainable

Desalination Sector

The LUT Energy System Transition model is used to identify the lowest cost configuration of 100% RE hybrid power plants to enable a low water production cost. The levelised cost of water includes the water production cost as well as the pumping of water from the coastline to the irrigation site. An hourly simulation is performed with a modified version of the LUT Energy System Transition model as indicated in Figure A4. A more detailed description of the methodology, data, and assumptions can be found in Caldera and Breyer (2018)[13].

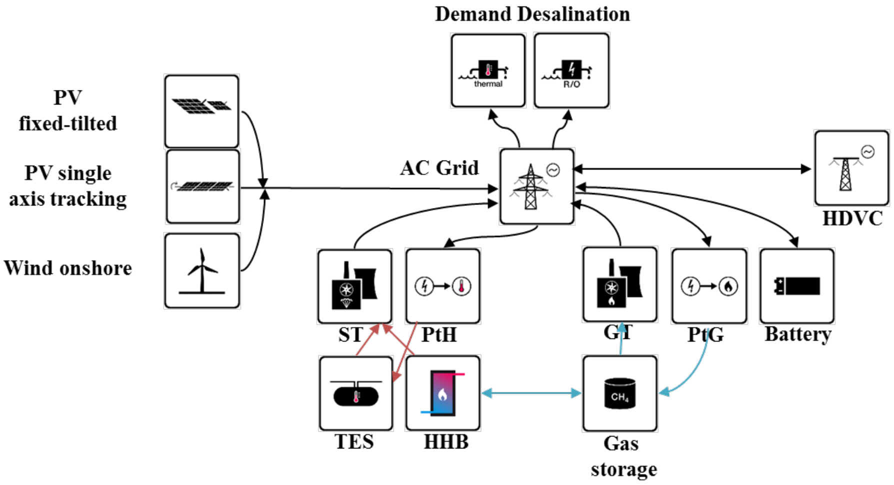

Figure A4: Schematic of the LUT Energy System Transition model to determine the optimal combination of components that meet the hourly electricity demand of SWRO desalination capacities

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
PV single-axis tracking	Capex	€/kW$_{,el}$	1150	638	513	429	371	330	297	271
	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$_{,H2}$	800	685	500	363	325	296	267	248
	Opex fix	€/(kW$_{,H2}$·a)	32	27	20	12.7	11.4	10.4	9.4	8.7
	Opex var	€/(kWh$_{,H2}$)	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$_{,CH4}$	547	502	368	278	247	226	204	190
	Opex fix	€/(kW$_{,CH4}$·a)	25.16	23.09	16.93	12.79	11.36	10.4	9.38	8.74
	Opex var	€/(kWh$_{,CH4}$)	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$_{CO2}$·a	1000	730	493	335	274.4	234	210.6	195
	Opex fix	€/t$_{CO2}$·a	40	29.2	19.7	13.4	11	9.4	8.4	7.8
	Opex var	€/t$_{CO2}$	0	0	0	0	0	0	0	0
	Lifetime	years	20	20	30	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	15	15	15	15	15	15	15	15
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
Multi Stage 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 and self-discharge rates of storage technologies

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-Discharge [%/h]
Battery	90	6	0
PHS	85	8	0
A-CAES	70	100	0.1
TES	90	8	0.2
Gas storage	100	80 24	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

Table A5: Efficiency assumptions for HVDC transmission for the 2030 reference year.

Component	Power losses
HVDC line	1.6 % / 1000 km
HVDC converter pair	1.4%