Annex

A. LUT Energy System Transition Model

The LUT Energy System Transition Model (LUT-ESTM)[1–3] has integrated all crucial aspects of the power, heat, transport and industry sectors into an integrated energy system. Moreover, the model includes prosumers[4], both power and heat, as part of the energy system. The fundamental process to modelling energy system transition pathways from data to results is shown in Figure A1.

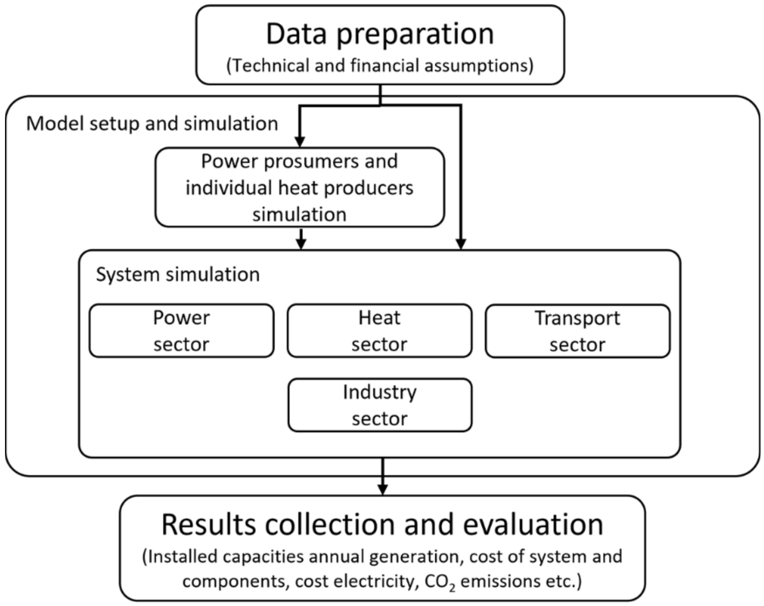

Figure A1: Fundamental structure of the LUT Energy System Transition model[3].

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 renewable energy generation and energy 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 energy generation and total energy 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. 7, 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.[1–3].

Power, heat, transport and industry sectors

The model simulates an integrated energy system development under specific given conditions as shown in Figure A2. For every time step the model defines a cost optimal energy system structure and operation mode for the given set of constraints: power demand, space and domestic water heating, energy demand for transport, energy and feedstock demand for industry, available generation and storage technologies, financial and technical parameters, and limits on installed capacities 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 annualised capital expenditures, operational expenditures (including ramping costs), fuel costs and CO_2 emissions costs for all available technologies. The transition simulation was performed for the period from 2020 to 2050 in five-year time intervals.

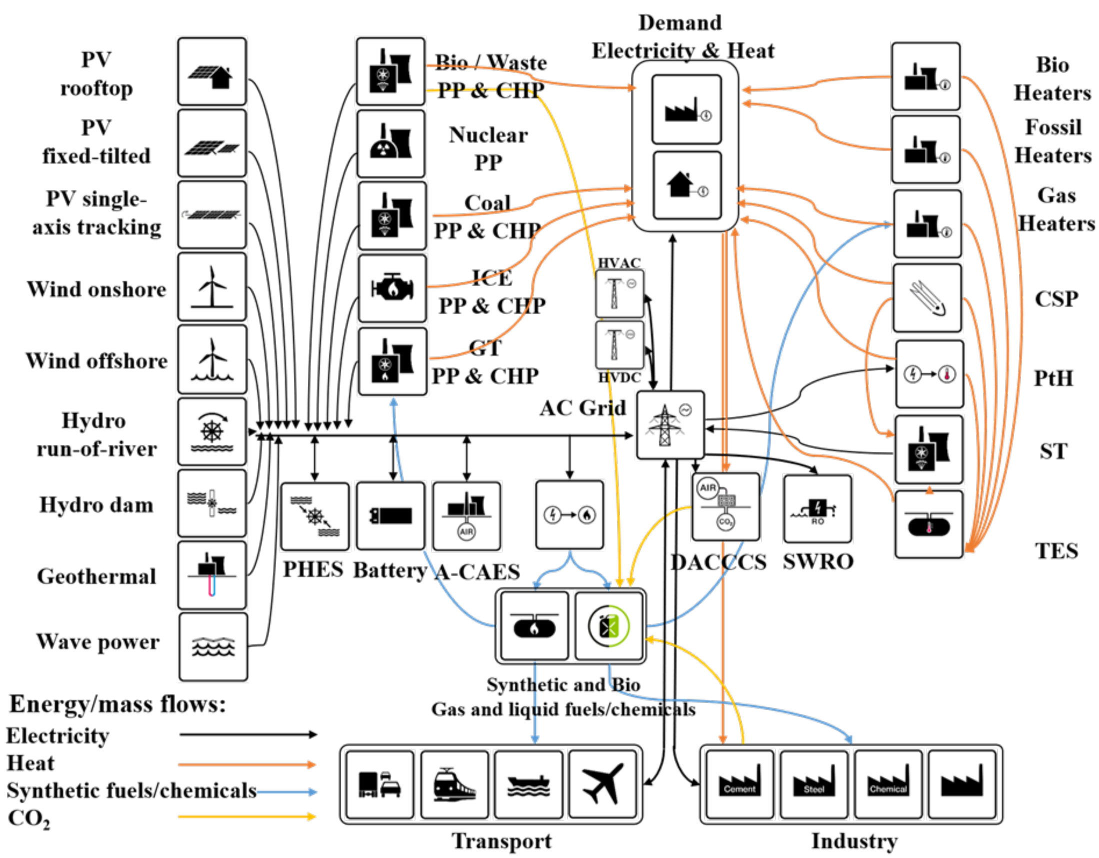

Figure A2: Schematic of the LUT Energy System Transition Model comprised of energy converters for electricity and heat, storage technologies, transmission options, and demand sectors[3].

Prosumers: 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 9% in 2020 to an in-built limit of 20% by 2050. However, the limit of 20% can be reached earlier than 2050 through the transition depending on the scenario settings and retail electricity prices across the different countries and regions.

Energy system: The model has integrated all crucial aspects of an energy system. 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. Renewable electricity generation technologies are solar PV (optimally fixed-tilted, single-axis north-south tracking, and rooftop), wind turbines (onshore and offshore), hydropower (run-of-river and reservoir), geothermal, and bioenergy (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;
- long-term gas storage including power-to-gas (PtG: hydrogen, methane) technology, which allows the production of e-hydrogen and e-methane to be utilised in the system.

Sector coupling technologies are power-to-gas (e-hydrogen, e-methane), steam turbines, electrical heaters, district and individual scale heat pumps, and direct electrical heaters, but also power-to-mobility including smart EV charging and vehicle-to-grid. 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.[1–3].

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) tonne kilometres (t-km) for freight transportation. Further information and data for transportation demand along with fuel shares and specific energy demand are provided in Khalili et al.[5].

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 A3:

- Road: electricity, hydrogen, liquid fuels;
- Rail: electricity, liquid fuels;
- Marine: electricity, hydrogen, methane, liquid fuels, ammonia, methanol;
- Aviation: electricity, hydrogen, liquid fuels.

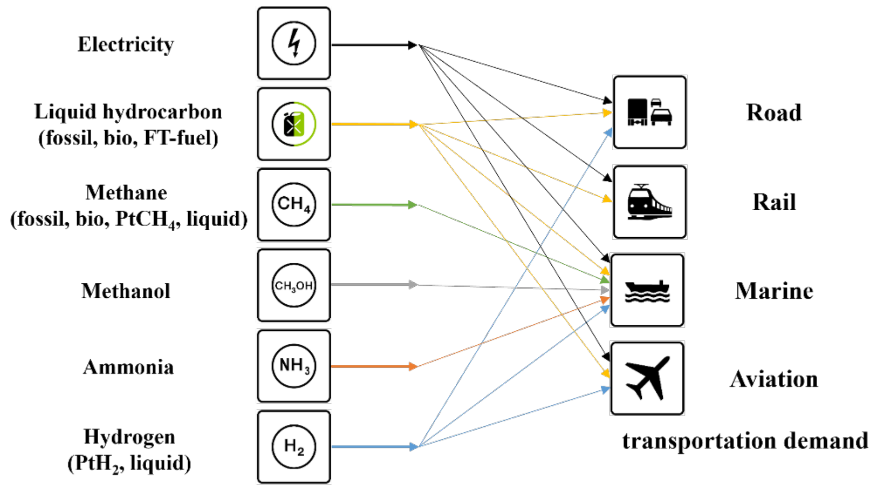

Figure A3: Schematic of the transport modes and corresponding fuels utilised during the energy transition from 2015-2050.

The fuel conversion process adopted to produce sustainable e-fuels is shown in Figure A4.

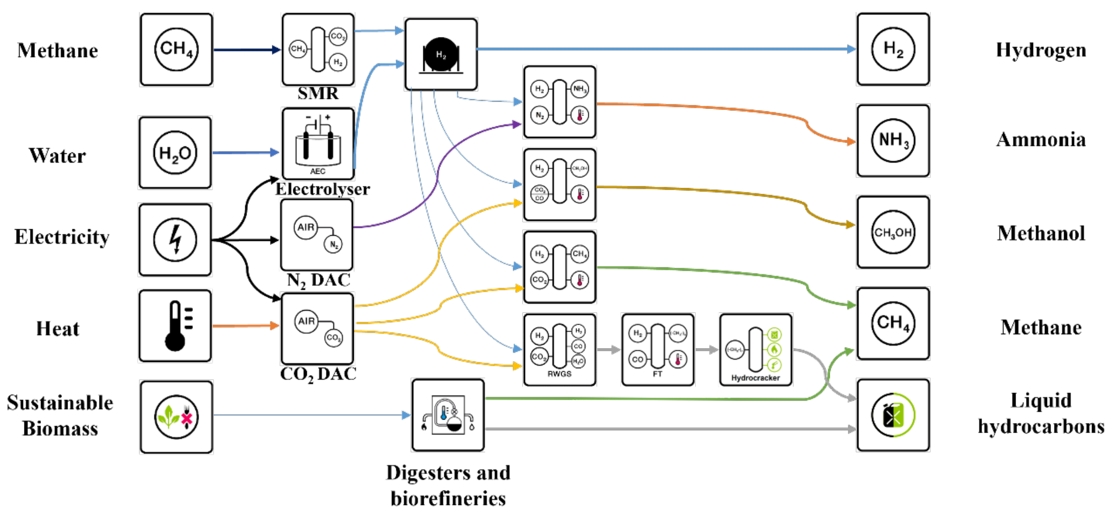

Figure A4: Schematic of the value chain elements in the production of sustainable e-fuels.

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 methods is provided in Khalili et al.[5].

Industrial processes describe the energy and raw materials demand for cement, steel, chemicals, aluminium, pulp and paper and desalination. Considered technologies include conventional and improved technology for cement production; conventional (coal-based blast furnace), hydrogen-based direct reduced iron (H-DRI) with electric arc furnace (EAF) and electrowinning of iron (EWIN), steel scrap recycling using EAF for secondary steel production; ammonia, methanol and naphtha production for the chemical industry; alumina and aluminium production, aluminium recycling for secondary aluminium production; pulp and paper mills for paper production. Other industry is considered to be supplied with industrial process heat, mainly based on conventional fuels in the initial periods of the transition, which shifts towards high shares of direct electric heat supply, some bioenergy, and hydrogen-based heat supply in the later periods. The industry sector and its integration into the energy system is described in Bogdanov et al.[3].

The energy transition simulation considers the existing AC power grid of the region, its development trends and projected overall electricity transmission and distribution losses according to Sadovskaia et al.[6].

Data preparation

This includes determining long-term energy demand across the different sectors of power, heat, transport and industry. In addition, it involves generating hourly demand profiles across all energy sectors, but also creating a database of power plants across the EU. Additionally, assessing the resource potentials of various renewable energy technologies across the different regions of the EU is a vital input. Furthermore, technical and financial details including assumptions, for all technologies are collated. All relevant data are organised across the 20 regions through the transition period from 2020 to 2050, in five-year intervals.

- **Development of energy demand**

The development of the energy demand across the sectors of power, heat, transport and industry are estimated for the different energy transition scenarios across the EU. The increasing demand for electrification of other sectors such as heat, transport and industry has been factored in the energy and feedstock demand. The growth in electricity demand of the power sector in the EU is estimated to represent an average compound annual growth rate of 0.9% in the energy transition period. Moreover, the demand profiles on an hourly basis for the integrated energy sector based on regional variation were computed through the transition from 2020 to 2050, in five-year intervals. The synthetic electricity demand profiles from 2020 until 2050 are generated based on the methodology from Toktarova et al.[7]. Profiles for space and water heating demand are taken from Keiner et al.[8]. Transportation demand for the different transport modes is taken from Khalili et al.[5]. Industrial feedstock and energy demand is calculated based on various sources: cement production[9], steel production[10,11], chemical feedstock demand[12], alumina production[13], aluminium production[13], pulp and paper production[14,15]. Other industries non-energetic feedstock flows are not modelled, while the power and heat demand are estimated based on national and European statistics[16] as a difference between total power and heat demand and the energy demand of industry segments which are traced in detail. Power, heat, transport, and industry demand across the regions and countries of the EU for each step of the transition are provided in the Supplementary Data.

- **Resource potential for renewable energy technologies**

The generation profiles for optimally fixed-tilted PV, solar CSP and wind energy are calculated according to Bogdanov and Breyer[17] and for single-axis tracking PV according to Afanasyeva et al.[18]. The hydropower feed-in profiles are computed based on daily resolved water flow data for the year 2005[19]. The potentials for biomass and waste resources were obtained from Bunzel et al.[20] and further classified into categories of solid wastes, solid residues and biogas. Geothermal energy potential is estimated according to the method described in Aghahosseini and Breyer[21]. The distribution across the EU of full load hours (equivalent to annual generation) of solar PV, for the case of fixed-tilted and single axis, and wind onshore and offshore at 150 m hub height, which are the two most vital sources of electricity in the energy transition, are shown in Figure A5 and A6. It can be observed that regions in southern parts of the EU have a great potential for solar energy all year round (see Figure A5), while regions in the northern and western parts of the EU have exceptional wind energy potential, both onshore and offshore (see Figure A6).

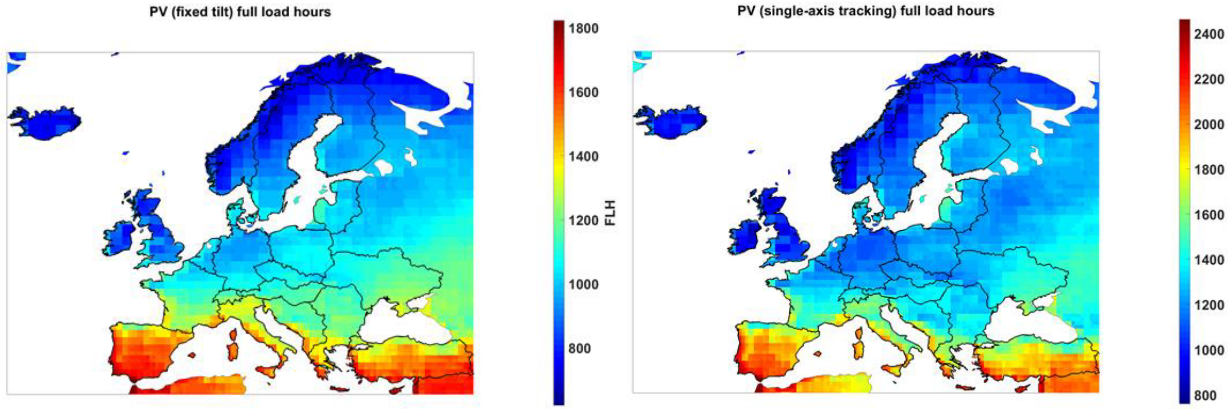

Figure A5: Annual full load hours for solar PV fixed-tilted (left) and single-axis tracking across the EU.

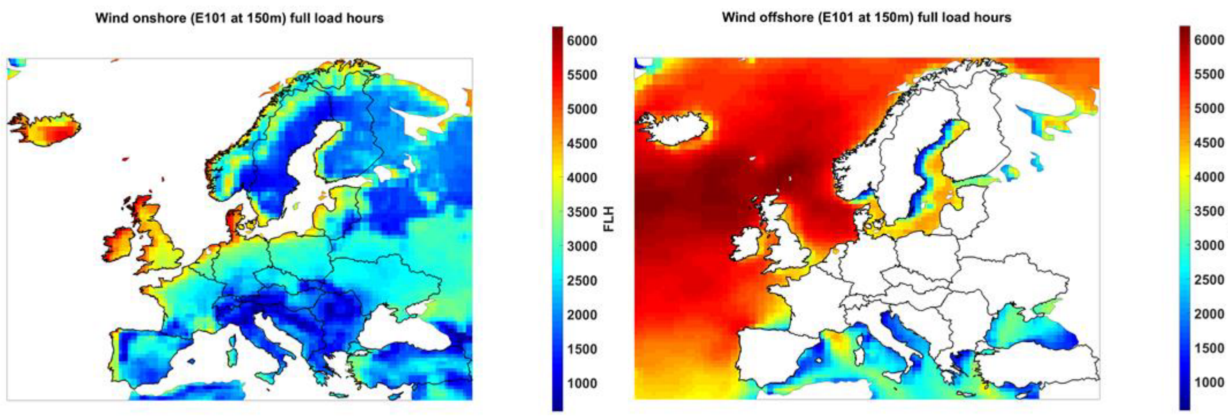

Figure A6: Annual full load hours for onshore (left) and offshore (right) wind power across the EU.

B. Technical and financial assumptions

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

Table B1: *Technical and financial assumptions of energy system technologies used in the energy transition from 2020 to 2050.*

Technologies		Unit	2020	2025	2030	2035	2040	2045	2050	Sources
PV fixed tilted PP	Capex	€/kW$_{el}$	475	370	306	237	207	184	166	[22–25]
	Opex fix	€/(kW$_{el}$ a)	7.76	6.51	5.66	5	4.47	4.04	3.7	
	Opex var	€/kWel	0	0	0	0	0	0	0	
	Lifetime	years	30	35	35	35	40	40	40	
PV rooftop - residential	Capex	€/kW$_{el}$	1150	926	787	622	551	496	453	[22,25]
	Opex fix	€/(kW$_{el}$ a)	9.13	7.66	6.66	5.88	5.26	4.75	4.36	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kW$_{el}$	758	598	502	393	345	308	280	[22,25]
	Opex fix	€/(kW$_{el}$ a)	9.13	7.66	6.66	5.88	5.26	4.75	4.36	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kW$_{el}$	563	437	362	281	245	217	197	[22,25]
	Opex fix	€/(kW$_{el}$ a)	9.13	7.66	6.66	5.88	5.26	4.75	4.36	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	30	35	35	35	40	40	40	
PV single-axis PP	Capex	€/kW$_{el}$	523	407	337	261	228	202	183	[22,26]
	Opex fix	€/(kW$_{el}$ a)	8.54	7.16	6.23	5.5	4.92	4.44	4.07	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	30	35	35	35	40	40	40	
Wind onshore PP	Capex	€/kW$_{el}$	1150	1060	1000	965	940	915	900	[27,28]
	Opex fix	€/(kW$_{el}$ a)	23	21.2	20	19.3	18.8	18.3	18	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	
Wind offshore PP	Capex	€/kW$_{el}$	2973	2561	2287	2216	2168	2145	2130	[28]
	Opex fix	€/(kW$_{el}$ a)	85	73	66	64	62	61	61	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	
Hydro Run-of-River PP	Capex	€/kW$_{el}$	2560	2560	2560	2560	2560	2560	2560	[29]
	Opex fix	€/(kW$_{el}$ a)	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	
	Lifetime	years	50	50	50	50	50	50	50	
Hydro Reservoir/ Dam	Capex	€/kW$_{el}$	1650	1650	1650	1650	1650	1650	1650	[29]
	Opex fix	€/(kW$_{el}$ a)	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	
	Lifetime	years	50	50	50	50	50	50	50	
Geothermal PP	Capex	€/kW$_{el}$	4970	4720	4470	4245	4020	3815	3610	[29,30]
	Opex fix	€/(kW$_{el}$ a)	80	80	80	80	80	80	80	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	40	40	40	40	40	40	40	
Steam turbine (CSP)	Capex	€/kW$_{el}$	968	946	923	902	880	860	840	[31]
	Opex fix	€/(kW$_{el}$ a)	19.4	18.9	18.5	18	17.6	17.2	16.8	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	30	30	30	30	
CCGT PP	Capex	€/kW$_{el}$	775	775	775	775	775	775	775	[32]
	Opex fix	€/(kW$_{el}$ a)	19.375	19.375	19.375	19.375	19.375	19.375	19.375	

Technologies		Unit	2020	2025	2030	2035	2040	2045	2050	Sources
	Opex var	€/kWh$_{el}$	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
	Lifetime	years	35	35	35	35	35	35	35	
OCGT PP	Capex	€/kW$_{el}$	475	475	475	475	475	475	475	[33]
	Opex fix	€/(kW$_{el}$ a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	€/kWh$_{el}$	0.011	0.011	0.011	0.011	0.011	0.011	0.011	
	Lifetime	years	35	35	35	35	35	35	35	
CCGT PP + CCS	Capex	€/kW$_{el}$	2565	2272.5	1980	1845	1710	1640	1570	[34]
	Opex fix	€/(kW$_{el}$ a)	81	72	63	58.5	54	52	50	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	35	35	35	35	35	35	35	
Int Combust Generator	Capex	€/kW$_{el}$	385	385	385	385	385	385	385	[33]
	Opex fix	€/(kW$_{el}$ a)	11.5	11.5	11.5	11.5	11.5	11.5	11.5	
	Opex var	€/kWh$_{el}$	0.0047	0.0047	0.0047	0.0047	0.0047	0.0047	0.0047	
	Lifetime	years	30	30	30	30	30	30	30	
Multifuel Int Combust Generator	Capex	€/kW$_{el}$	569	553	537	522	506	491	475	[29]
	Opex fix	€/(kW$_{el}$ a)	6.2	6.2	6.2	6.2	6.2	6.2	6.2	
	Opex var	€/kWh$_{el}$	0.011	0.011	0.011	0.011	0.011	0.011	0.011	
	Lifetime	years	30	30	30	30	30	30	30	
Coal PP	Capex	€/kW$_{el}$	1600	1600	1600	1600	1600	1600	1600	[32,35]
	Opex fix	€/(kW$_{el}$ a)	20	20	20	20	20	20	20	
	Opex var	€/kWh$_{el}$	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	years	45	45	45	45	45	45	45	
Biomass PP	Capex	€/kW$_{el}$	2620	2475	2330	2195	2060	1945	1830	[31]
	Opex fix	€/(kW$_{el}$ a)	47.2	44.6	41.9	39.5	37.1	35	32.9	
	Opex var	€/kWh$_{el}$	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	
	Lifetime	years	25	25	25	25	25	25	25	
Nuclear PP	Capex	€/kW$_{el}$	6003	6003	5658	5658	5244	5244	5175	[32,36,37]
	Opex fix	€/(kW$_{el}$ a)	113.1	113.1	98.4	98.4	83.6	83.6	78.8	
	Opex var	€/kWh$_{el}$	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	
	Lifetime	years	40	40	40	40	40	40	40	
CHP NG Heating	Capex	€/kW$_{el}$	880	880	880	880	880	880	880	[31]
	Opex fix	€/(kW$_{el}$ a)	74.8	74.8	74.8	74.8	74.8	74.8	74.8	
	Opex var	€/kWh$_{el}$	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	
	Lifetime	years	30	30	30	30	30	30	30	
CHP Oil Heating	Capex	€/kW$_{el}$	880	880	880	880	880	880	880	[31]
	Opex fix	€/(kW$_{el}$ a)	74.8	74.8	74.8	74.8	74.8	74.8	74.8	
	Opex var	€/kWh$_{el}$	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	
	Lifetime	years	30	30	30	30	30	30	30	
CHP Coal Heating	Capex	€/kW$_{el}$	2030	2030	2030	2030	2030	2030	2030	[31]
	Opex fix	€/(kW$_{el}$ a)	46.7	46.7	46.7	46.7	46.7	46.7	46.7	
	Opex var	€/kWh$_{el}$	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	
	Lifetime	years	40	40	40	40	40	40	40	
CHP Biomass Heating	Capex	€/kW$_{el}$	3400	3300	3200	3125	3050	2975	2900	[31]
	Opex fix	€/(kW$_{el}$ a)	97.6	94.95	92.3	90.8	89.3	87.8	86.3	
	Opex var	€/kWh$_{el}$	0.0038	0.0038	0.0037	0.0037	0.0038	0.0038	0.0038	
	Lifetime	years	25	25	25	25	25	25	25	
CHP Biogas	Capex	€/kW$_{el}$	429.2	399.6	370	340.4	325.6	310.8	296	[31]
	Opex fix	€/(kW$_{el}$ a)	17.168	15.984	14.8	13.616	13.024	12.432	11.84	
	Opex var	€/kWh$_{el}$	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	years	30	30	30	30	30	30	30	
MSW incinerator	Capex	€/kW$_{el}$	5630	5440	5240	5030	4870	4690	4540	[31]
	Opex fix	€/(kW$_{el}$ a)	253.35	244.8	235.8	226.35	219.15	211.05	204.3	
	Opex var	€/kWh$_{el}$	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	
	Lifetime	years	30	30	30	30	30	30	30	

Technologies		Unit	2020	2025	2030	2035	2040	2045	2050	Sources
Concentrating Solar Heat	Capex	€/kW_{th}	344.5	303.6	274.7	251.1	230.2	211.9	196	[38,39]
	Opex fix	€/(kW_{th} a)	7.9	7	6.3	5.8	5.3	4.9	4.5	
	Opex var	€/kWh_{th}	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	
Residential Solar Heat - Collectors - Space Heating	Capex	€/kW_{th}	1214	1179	1143	1071	1000	929	857	[31]
	Opex fix	€/(kW_{th} a)	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	
	Lifetime	years	25	25	30	30	30	30	30	
DH Electric Heating	Capex	€/kW_{th}	100	100	75	75	75	75	75	[31]
	Opex fix	€/(kW_{th} a)	1.47	1.47	1.47	1.47	1.47	1.47	1.47	
	Opex var	€/kWh_{th}	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	
	Lifetime	years	35	35	35	35	35	35	35	
DH Heat Pump	Capex	€/kW_{th}	660	618	590	568	554	540	530	[31]
	Opex fix	€/(kW_{th} a)	2	2	2	2	2	2	2	
	Opex var	€/kWh_{th}	0.0018	0.0017	0.0017	0.0016	0.0016	0.0016	0.0016	
	Lifetime	years	25	25	25	25	25	25	25	
DH NG Heating	Capex	€/kW_{th}	75	75	100	100	100	100	100	[31]
	Opex fix	€/(kW_{th} a)	2.775	2.775	3.7	3.7	3.7	3.7	3.7	
	Opex var	€/kWh_{th}	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	years	35	35	35	35	35	35	35	
DH Oil Heating	Capex	€/kW_{th}	75	75	100	100	100	100	100	[31]
	Opex fix	€/(kW_{th} a)	2.775	2.775	3.7	3.7	3.7	3.7	3.7	
	Opex var	€/kWh_{th}	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	years	35	35	35	35	35	35	35	
DH Coal Heating	Capex	€/kW_{th}	75	75	100	100	100	100	100	[31]
	Opex fix	€/(kW_{th} a)	2.775	2.775	3.7	3.7	3.7	3.7	3.7	
	Opex var	€/kWh_{th}	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	years	35	35	35	35	35	35	35	
DH Biomass Heating	Capex	€/kW_{th}	75	75	100	100	100	100	100	[31]
	Opex fix	€/(kW_{th} a)	2.8	2.8	3.7	3.7	3.7	3.7	3.7	
	Opex var	€/kWh_{th}	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	years	35	35	35	35	35	35	35	
DH Geothermal Heat	Capex	€/kW_{th}	3642	3384	3200	3180	3160	3150	3146	[31]
	Opex fix	€/(kW_{th} a)	133	124	117	116	115	115	115	
	Opex var	€/kWh_{th}	0	0	0	0	0	0	0	
	Lifetime	years	22	22	22	22	22	22	22	
Local Electric Heating	Capex	€/kW_{th}	100	100	100	100	100	100	100	[31]
	Opex fix	€/(kW_{th} a)	2	2	2	2	2	2	2	
	Opex var	€/kWh_{th}	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	years	30	30	30	30	30	30	30	
Local Heat Pump	Capex	€/kW_{th}	780	750	730	706	690	666	650	[31]
	Opex fix	€/(kW_{th} a)	15.6	15	7.3	7.1	6.9	6.7	6.5	
	Opex var	€/kWh_{th}	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
Local NG Heating	Capex	€/kW_{th}	800	800	800	800	800	800	800	[31]
	Opex fix	€/(kW_{th} a)	27	27	27	27	27	27	27	
	Opex var	€/kWh_{th}	0	0	0	0	0	0	0	
	Lifetime	years	22	22	22	22	22	22	22	
Local Oil Heating	Capex	€/kW_{th}	440	440	440	440	440	440	440	[31]
	Opex fix	€/(kW_{th} a)	18	18	18	18	18	18	18	
	Opex var	€/kWh_{th}	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
Local Biomass Heating	Capex	€/kW_{th}	675	675	750	750	750	750	750	[31]
	Opex fix	€/(kW_{th} a)	2	2	3	3	3	3	3	

Technologies		Unit	2020	2025	2030	2035	2040	2045	2050	Sources
	Opex var	€/kWh$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
Local Biogas Heating	Capex	€/kW$_{th}$	800	800	800	800	800	800	800	[31]
	Opex fix	€/(kW$_{th}$ a)	27	27	27	27	27	27	27	
	Opex var	€/kWh$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	22	22	22	22	22	22	22	
Water Electrolysis	Capex	€/kW$_{H2}$	803	586	446	381	347	313	291	[40]
	Opex fix	€/(kW$_{H2}$ a)	28.1	20.5	15.6	13.3	12.1	11.0	10.2	
	Opex var	€/kWh$_{H2}$	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	
	Lifetime	years	30	30	30	30	30	30	30	
CO_2 direct air capture	Capex	€/(t$_{CO2}$ a)	730	481	338	281	237	217	199	[12]
	Opex fix	€/(t$_{CO2}$ a)	29.2	19.2	13.5	11.2	9.5	8.7	8	
	Opex var	€/t$_{CO2}$	0	0	0	0	0	0	0	
	Lifetime	years	20	30	25	30	30	30	30	
Methanation	Capex	€/kW$_{SNG}$	558	409	309	274	251	227	211	[41,42]
	Opex fix	€/(kW$_{SNG}$ a)	25.7	18.8	14.2	12.6	11.5	10.4	9.7	
	Opex var	€/MWh$_{SNG}$	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	
	Lifetime	years	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW$_{th}$	811	784	755	725	702	676	654	[31]
	Opex fix	€/(kW$_{th}$ a)	32.5	31.4	30.2	29	28.1	27	26.2	
	Opex var	€/kWh$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	25	25	25	25	
Biogas Upgrade	Capex	€/kW$_{th}$	322	300	278	255	244	233	222	[43]
	Opex fix	€/(kW$_{th}$ a)	25.8	24	22.2	20.4	19.5	18.7	17.8	
	Opex var	€/kWh$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
Fischer-Tropsch unit	Capex	€/kW,FT$_{Liq}$	1017	1017	1017	1017	915	915	915	[31]
	Opex fix	€/kW,FT$_{Liq}$	30.5	30.5	30.5	30.5	27.5	27.5	27.5	
	Opex var	€/kWh,FT$_{Liq}$	0	0	0	0	0	0	0	
	Lifetime	years	30	30	30	30	30	30	30	
Gas Liquefaction	Capex	€/kW$_{Liq}$	201	201	201	201	201	201	201	[31]
	Opex fix	€/kW$_{Liq}$	7.0	7.0	7.0	7.0	7.0	7.0	7.0	
	Opex var	€/kWh$_{Liq}$	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	
H_2 Liquefaction	Capex	€/kW$_{Liq}$	420	420	420	206	179	170	162	[44–46]
	Opex fix	€/kW$_{Liq}$	16.8	16.8	16.8	8.2	7.2	6.8	6.5	
	Opex var	€/kWh$_{Liq}$	0	0	0	0	0	0	0	
	Lifetime	years	30	30	30	30	30	30	30	
Steam Methane Reforming	Capex	€/kW$_{H2}$	570	570	570	570	570	570	570	[47]
	Opex fix	€/kW$_{H2}$	25.1	25.1	25.1	25.1	25.1	25.1	25.1	
	Opex var	€/kWh$_{H2}$	0.000208	0.000208	0.000208	0.000208	0.000208	0.000208	0.000208	
	Lifetime	years	30	30	30	30	30	30	30	
Steam Methane Reforming	Capex	€/kW$_{H2}$	1018	1018	1018	925	832	809	785	[47]
	Opex fix	€/kW$_{H2}$	38.7	38.7	38.7	35.2	31.6	30.7	29.8	
	Opex var	€/kWh$_{H2}$	0.000196	0.000196	0.000196	0.000196	0.000196	0.000196	0.000196	
	Lifetime	years	30	30	30	30	30	30	30	
Methanol Synthesis Unit	Capex	€/kW$_{CH3OH}$	835	835	835	835	835	835	835	[48]
	Opex fix	€/kW$_{CH3OH}$	33.4	33.4	33.4	33.4	33.4	33.4	33.4	
	Opex var	€/kWh$_{CH3OH}$	0	0	0	0	0	0	0	
	Lifetime	years	30	30	30	30	30	30	30	
Ammonia Synthesis Unit	Capex	€/kW$_{NH3}$	1285	1285	1285	1285	1285	1285	1285	[48]
	Opex fix	€/kW$_{NH3}$	64.3	64.3	64.3	64.3	64.3	64.3	64.3	

Technologies		Unit	2020	2025	2030	2035	2040	2045	2050	Sources
	Opex var	€/kWh$_{NH3}$	0	0	0	0	0	0	0	
	Lifetime	years	30	30	30	30	30	30	30	
Battery Storage	Capex	€/kWh$_{el}$	234	153	110	89	76	68	61	[24,49]
	Opex fix	€/(kWh$_{el}$ a)	3.28	2.6	2.2	2.05	1.9	1.77	1.71	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Efficiency	%	91%	92%	93%	94%	95%	95%	95%	
	Lifetime	years	20	20	20	20	20	20	20	
Battery Interface	Capex	€/kW$_{el}$	117	76	55	44	37	33	30	[24,49]
	Opex fix	€/(kW$_{el}$ a)	1.64	1.29	1.1	1.01	0.93	0.86	0.84	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
Battery PV pros residential Storage	Capex	€/kWh$_{el}$	462	308	224	182	156	140	127	[31]
	Opex fix	€/(kWh$_{el}$ a)	5.08	4	3.36	3.09	2.81	2.8	2.54	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Efficiency	%	91%	92%	93%	94%	95%	95%	95%	
	Lifetime	years	20	20	20	20	20	20	20	
Battery PV pros residential Interface	Capex	€/kW$_{el}$	231	153	112	90	76	68	62	[31]
	Opex fix	€/(kW$_{el}$ a)	2.54	1.99	1.68	1.53	1.37	1.36	1.24	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
Battery PV pros commercial Storage	Capex	€/kWh$_{el}$	366	240	175	141	121	108	98	[31]
	Opex fix	€/(kWh$_{el}$ a)	4.39	3.6	2.98	2.68	2.54	2.38	2.25	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Efficiency	%	91%	92%	93%	94%	95%	95%	95%	
	Lifetime	years	20	20	20	20	20	20	20	
Battery PV pros commercial Interface	Capex	€/kW$_{el}$	183	119	88	70	59	53	48	[31]
	Opex fix	€/(kW$_{el}$ a)	2.2	1.79	1.5	1.33	1.24	1.17	1.1	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
Battery PV pros industrial Storage	Capex	€/kWh$_{el}$	278	181	131	105	90	80	72	[31]
	Opex fix	€/(kWh$_{el}$ a)	3.89	3.08	2.62	2.42	2.25	2.08	1.94	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Efficiency	%	91%	92%	93%	94%	95%	95%	95%	
	Lifetime	years	20	20	20	20	20	20	20	
Battery PV pros industrial Interface	Capex	€/kW$_{el}$	139	90	66	52	44	39	35	[31]
	Opex fix	€/(kW$_{el}$ a)	1.95	1.53	1.32	1.2	1.1	1.01	0.95	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	20	20	20	20	20	
PHES Storage	Capex	€/kWh$_{el}$	7.7	7.7	7.7	7.7	7.7	7.7	7.7	[29]
	Opex fix	€/(kWh$_{el}$ a)	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	
	Efficiency	%	85%	85%	85%	85%	85%	85%	85%	
	Lifetime	years	50	50	50	50	50	50	50	
PHES Interface	Capex	€/kW$_{el}$	650	650	650	650	650	650	650	[29]
	Opex fix	€/(kW$_{el}$ a)	0	0	0	0	0	0	0	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	
A-CAES Storage	Capex	€/kWh$_{el}$	75	65.3	57.9	53.6	50.8	47	43.8	[29]
	Opex fix	€/(kWh$_{el}$ a)	1.16	0.99	0.87	0.81	0.77	0.71	0.66	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Efficiency	%	59%	65%	70%	70%	70%	70%	70%	
	Lifetime	years	40	40	40	40	40	40	40	
A-CAES Interface	Capex	€/kW$_{el}$	540	540	540	540	540	540	540	[29]
	Opex fix	€/(kW$_{el}$ a)	17.5	17.5	17.5	17.5	17.5	17.5	17.5	

Technologies		Unit	2020	2025	2030	2035	2040	2045	2050	Sources
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	40	40	40	40	40	40	40	
Hot Heat Storage Storage	Capex	€/kWh$_{th}$	41.8	32.7	26.8	23.3	21	19.3	17.5	[31]
	Opex fix	€/(kWh$_{th}$ a)	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	
	Efficiency	%	90%	90%	90%	90%	90%	90%	90%	
	Lifetime	years	25	25	25	30	30	30	30	
Hot Heat Storage Interface	Capex	€/kW$_{th}$	0	0	0	0	0	0	0	[31]
	Opex fix	€/(kW$_{th}$ a)	0	0	0	0	0	0	0	
	Opex var	€/kW$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	30	30	30	30	
Hydrogen Storage	Capex	€/kWh$_{th}$	0.28	0.28	0.28	0.28	0.28	0.28	0.28	[50]
	Opex fix	€/(kWh$_{th}$ a)	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	
	Opex var	€/kWh$_{th}$	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	
	Efficiency	%	100%	100%	100%	100%	100%	100%	100%	
	Lifetime	years	30	30	30	30	30	30	30	
Hydrogen Storage Interface	Capex	€/kW$_{th}$	100	100	100	100	100	100	100	[50]
	Opex fix	€/(kW$_{th}$ a)	4	4	4	4	4	4	4	
	Opex var	€/kW$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	15	15	15	15	15	15	15	
CO_2 Storage	Capex	€/ton	142	142	142	142	142	142	142	[51]
	Opex fix	€/(ton a)	9.94	9.94	9.94	9.94	9.94	9.94	9.94	
	Opex var	€/ton	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	
	Lifetime	years	30	30	30	30	30	30	30	
CO_2 Storage Interface	Capex	€/ton/h	0	0	0	0	0	0	0	[51]
	Opex fix	€/(ton/h a)	0	0	0	0	0	0	0	
	Opex var	€/ton	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	
Gas Storage	Capex	€/kWh$_{th}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	[52]
	Opex fix	€/(kWh$_{th}$ a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/kWh$_{th}$	0	0	0	0	0	0	0	
	Efficiency	%	100%	100%	100%	100%	100%	100%	100%	
	Lifetime	years	50	50	50	50	50	50	50	
Gas Storage Interface	Capex	€/kW$_{th}$	100	100	100	100	100	100	100	[52]
	Opex fix	€/(kW$_{th}$ a)	4	4	4	4	4	4	4	
	Opex var	€/kW$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	15	15	15	15	15	15	15	
District Heat Storage	Capex	€/kWh$_{th}$	40	30	30	25	20	20	20	[31]
	Opex fix	€/(kWh$_{th}$ a)	0.6	0.45	0.45	0.375	0.3	0.3	0.3	
	Opex var	€/kWh$_{th}$	0	0	0	0	0	0	0	
	Efficiency	%	90%	90%	90%	90%	90%	90%	90%	
	Lifetime	years	25	25	25	30	30	30	30	
District Heat Storage Interface	Capex	€/kW$_{th}$	0	0	0	0	0	0	0	[31]
	Opex fix	€/(kW$_{th}$ a)	0	0	0	0	0	0	0	
	Opex var	€/kW$_{th}$	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	30	30	30	30	

Table B2: *Self-discharge rates of storage technologies*[2,3].

Technology	Self-Discharge [%/h]
Battery	0
PHES	0

A-CAES	0.1
TES	0.2
Gas storage	0

Table B3: *Fossil and nuclear fuel prices through the transition.*

Name of component	Unit	2020	2025	2030	2035	2040	2045	2050	References
Coal	€/MWh_{th}	5.4	5.9	6.3	6.2	6.1	6.0	5.9	[53]
Crude oil	€/MWh_{th}	21.7	25.4	29.0	28.3	27.5	26.7	25.9	[53]
Fossil gas	€/MWh_{th}	12.6	17.9	23.1	23.6	24.0	24.5	24.9	[53]
Uranium	€/MWh_{th}	2.6	2.6	2.6	2.6	2.6	2.6	2.6	[36]

Table B4: *Costs of CO_2 emissions.*

Scenario	Unit	2020	2025	2030	2035	2040	2045	2050	References
RES-2035	€/tCO_2	50	107	164	220	220	220	220	[53]
RES-2040	€/tCO_2	50	93	135	178	220	220	220	[53]
REF	€/tCO_2	50	82	114	147	180	200	220	[53]

Table B5: *Efficiencies of HVDC transmission for the reference year – 2030*[6].

Component	Power losses
HVAC line	9.4 % / 1000 km
HVDC line	1.6 % / 1000 km
HVDC converter pair	1.4%

C. Results

The detailed results for each of the three scenarios are presented in the following sections:

C1. REF Scenario

Energy Demand

In the REF scenario, the uptake of renewables is relatively slower as compared to the other two scenarios, which also influences the change in resource efficiency through electrification. Efficiency measures such as improving building renovation rates, modal shift of transport towards electrified rail use and more conscious use of energy enable further gains in final and, consequently, primary energy. This eventually determines the levels of primary energy demand as shown in Figure C1.1.

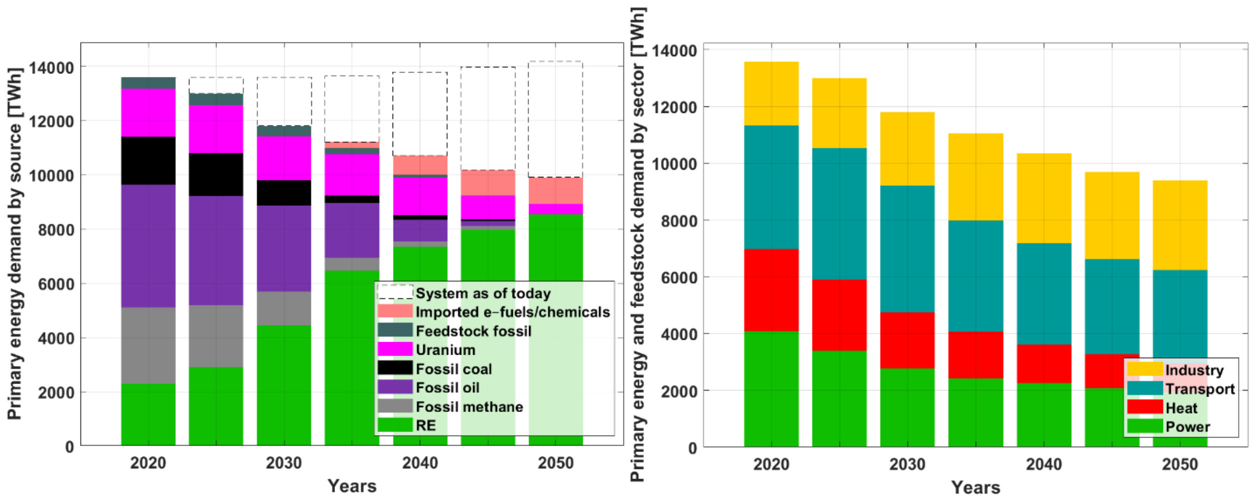

Figure C1.1: Primary energy demand according to sources (left) and on a sectoral basis (right), during the energy transition from 2020 to 2050 across the EU (REF).

The primary energy demand decreases from over 13,500 TWh in 2020 to around 9,500 TWh by 2050 across the EU as shown in Figure C1.1. The gain in efficiencies compared to the 'system as of today' is due to electrification of the heat, transport and industry sectors, while the growth in demand for energy services continues. The final energy declines from about 11,000 TWh in 2020 to around 10,000 TWh in 2050, despite a high level of energy services, as shown in Figure C1.2. The different fuels that constitute the final energy demand[1] transition from mostly fossil fuels in 2020 to renewable electricity, heat, e-fuels and e-chemicals by 2050.

[1] Including the ambient heat for heat pumps

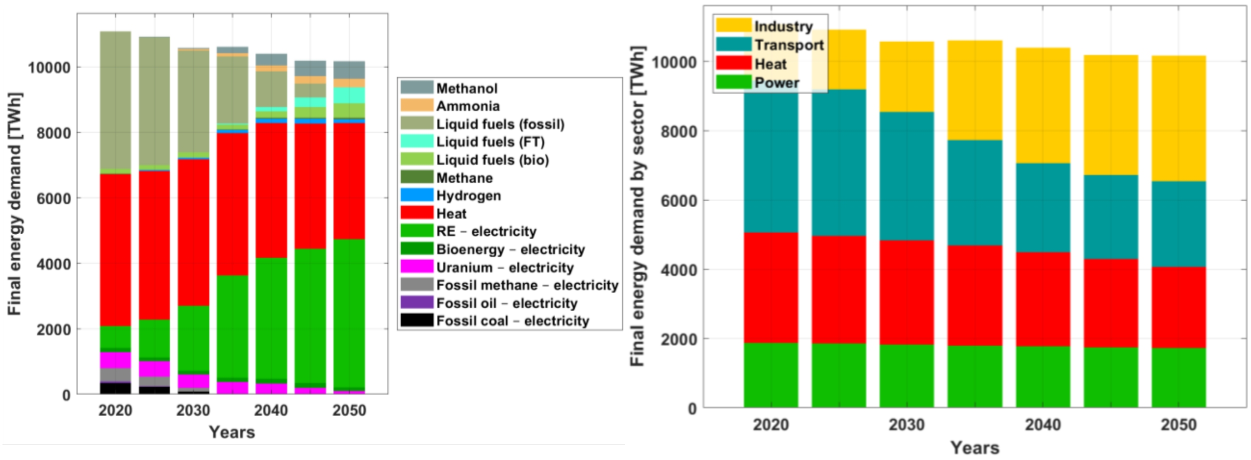

Figure C1.2: Final energy demand[1] according to sources (left) and on a sectoral basis (right), during the energy transition from 2020 to 2050 across the EU (REF).

Sectoral Outlook

Energy supply is mainly through electricity and heat, as high levels of electrification are achieved through the transition. An increasing amount of electricity generation is needed along with heat, storage and supply of fuels and chemicals to cover the future energy demand.

Electricity

The electricity generation capacity across the EU satisfies demand form all energy sectors including power, heat, transport and industry. The total installed capacity grows massively from about 750 GW in 2020 to nearly 4000 GW by 2050 as shown in Figure C1.3. In the initial period of the transition, a larger share of wind power capacities is installed up to 2030, but in the later part of the transition solar PV dominates the shares of installed capacities reaching almost 3000 GW by 2050. On the other hand, the shares of fossil fuels and nuclear power decline through the transition, with some shares in 2050, while the absolute contribution of nuclear energy remain only due to operational status of nuclear power plants until end of technical lifetimes.

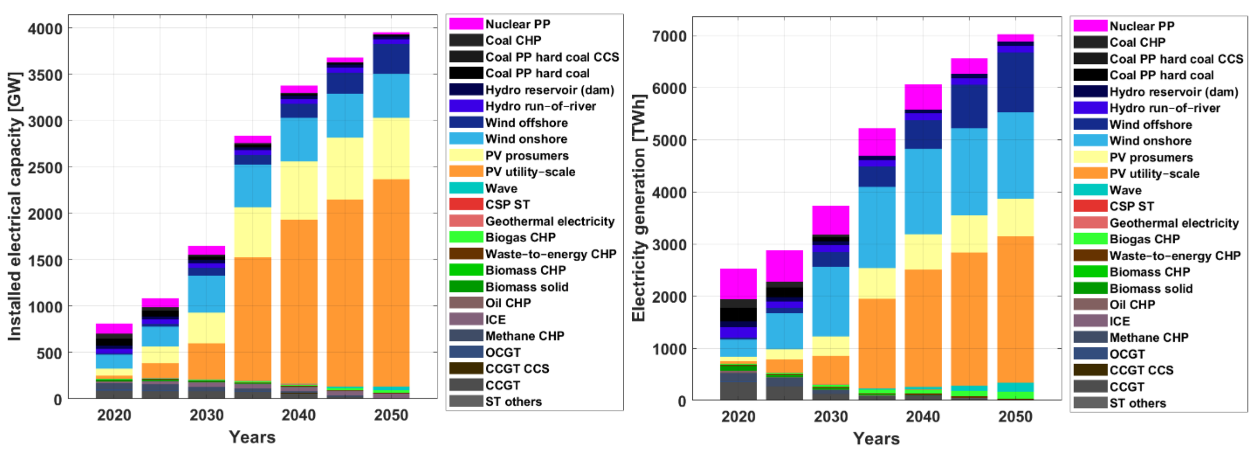

Figure C1.3: Technology-wise installed capacities (left) and technology-wise electricity generation (right) during the energy transition from 2020 to 2050 across the EU (REF).

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[1] Including the ambient heat for heat pumps

Electricity generation from the various technologies to cover the demand of power, heat, transport and industry sectors is shown in Figure C1.3. Solar PV supply increases through the transition along with wind power, wave power and electricity from waste and residual biomass up to 2050. Nuclear power has some minor shares, as plants remain in the system until end of technical lifetimes.

Heat

In the heat sector, heat pumps, electric heating, and biomass-based heating constitute the majority of installed capacity by 2050, also shown in Figure C1.4. A decrease in total installed capacity of heating technologies occurs mainly due to efficiency gains with heat pumps and electric heating, as fossil fuels recede from the energy system. The key driver is the doubling of building renovation rates and linear increase of industrial heat efficiency to 1.5% per annum until 2030. Heat pumps play a significant role through the transition with a share of over 50% of heat generation by 2050 on both the district and individual levels, as indicated in Figure C1.4. On the other hand, fossil gas-based heating decreases through the transition from over 75% in 2020, to almost zero by 2050. Moreover, fossil fuels based heat generation declines through the transition period as coal-based combined heat and power (CHP) and district heating (DH) are replaced by heat generation from heat pumps, waste-to-energy CHP, biomass-based DH, and individual heating (IH).

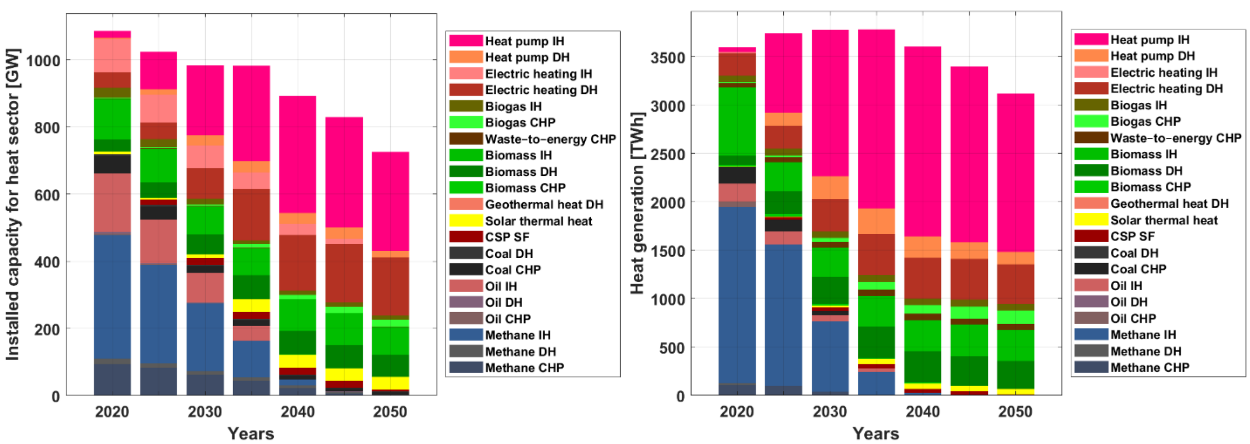

Figure C1.4: Technology-wise heat generation capacities (left) and technology-wise heat generation (right) during the energy transition from 2025 to 2050 across the EU (REF).

Electricity, Heat and Gas Storage

Energy storage technologies play a critical role in enabling a secure energy supply across the EU, fully based on renewable energy across different sectors. The installed electricity storage capacity increases from just 0.4 TWh in 2020 to around 5.5 TWh by 2050, as shown in Figure C1.5. Utility-scale and prosumer batteries with major shares of vehicle-to-grid dominate, some PHES remains through the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with hydrogen and methane based output contributing beyond 2035, as highlighted by Figure C1.5. In addition, vehicle-to-grid, PHES contributes some shares through the transition.

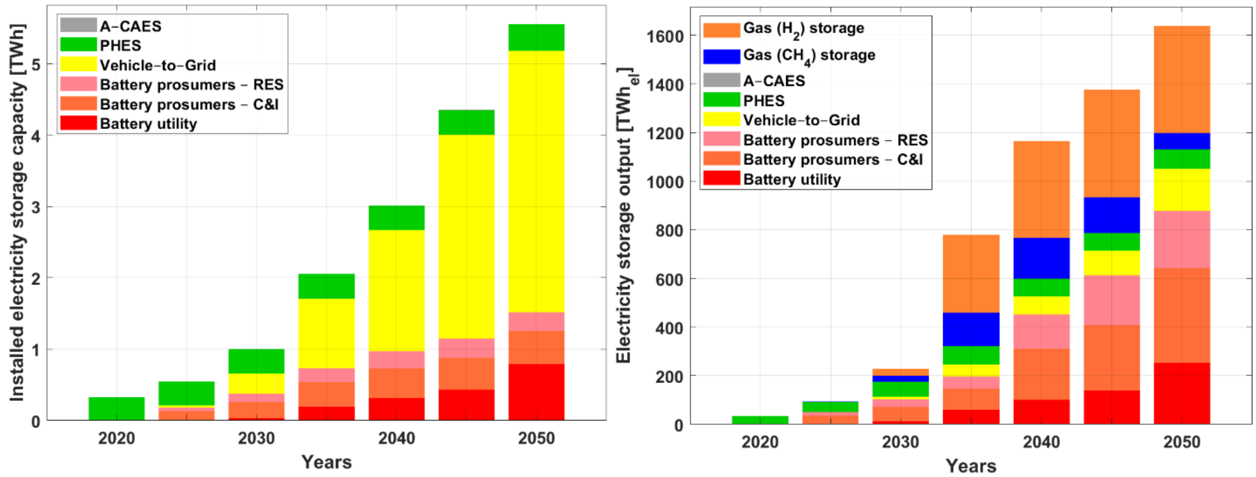

Figure C1.5: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2020 to 2050 across the EU (REF).

Heat storage plays a vital role in ensuring that the heat demand is covered in all sectors. The installed heat storage grows substantially from 2030 onwards, installed capacities are dominated by gas storage (hydrogen and methane), as shown in Figure C1.6. This substantial capacity addition is mainly to provide seasonal storage across the EU covering the heat demand in the absence of fossil fuels. The present fossil gas storage capacity across the EU is around 1000 TWh[54], hence an even lesser amount of gas storage would be needed for an integrated energy system in the future. Thermal energy storage emerges with heat storage output from 2030 until 2050, as shown in Figure C1.6. Hydrogen gas storage contributes a majority of the heat storage output from 2035 to 2050 with some shares of biomethane, covering predominantly the seasonal demand, which is covered by fossil gas before 2030.

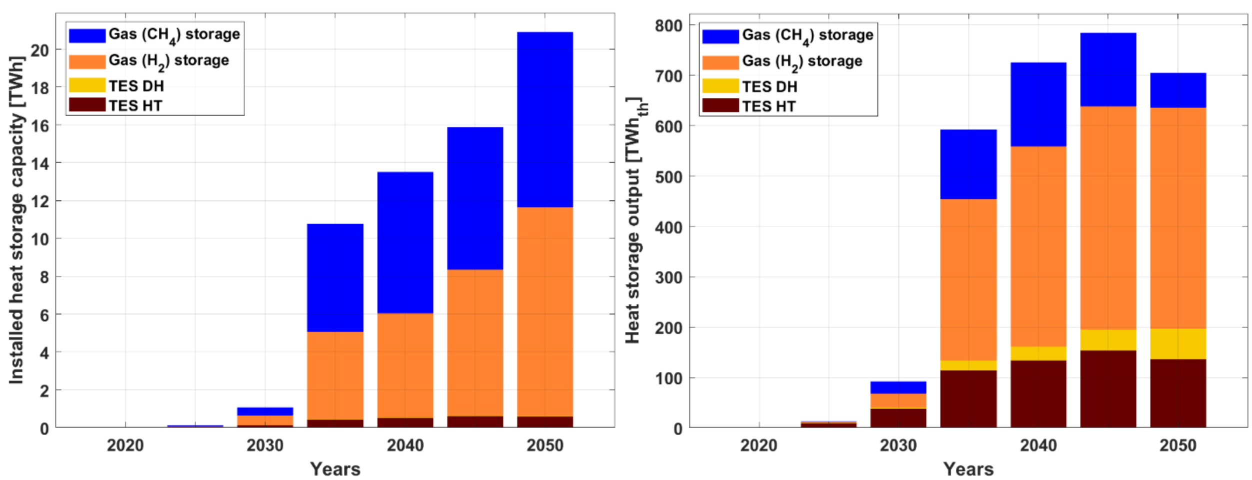

Figure C1.6: Heat storage installed capacities (left) and heat storage output (right) during the energy transition from 2020 to 2050 across the EU (REF).

Transport and Industry

The final energy demand of the transport sector across the EU is almost twice the energy demand from the power sector at around 4400 TWh in 2020. However, this demand declines through the transition to around 2000 TWh by 2050, as shown in Figure C1.7. This is achieved mainly due to efficiency gains brought about by electrification of the sector, mainly road transport. On the other hand, the energy and feedstock demand for the industry sector grows through the transition driven by production of sustainable chemicals and fuels, as shown in Figure C1.7.

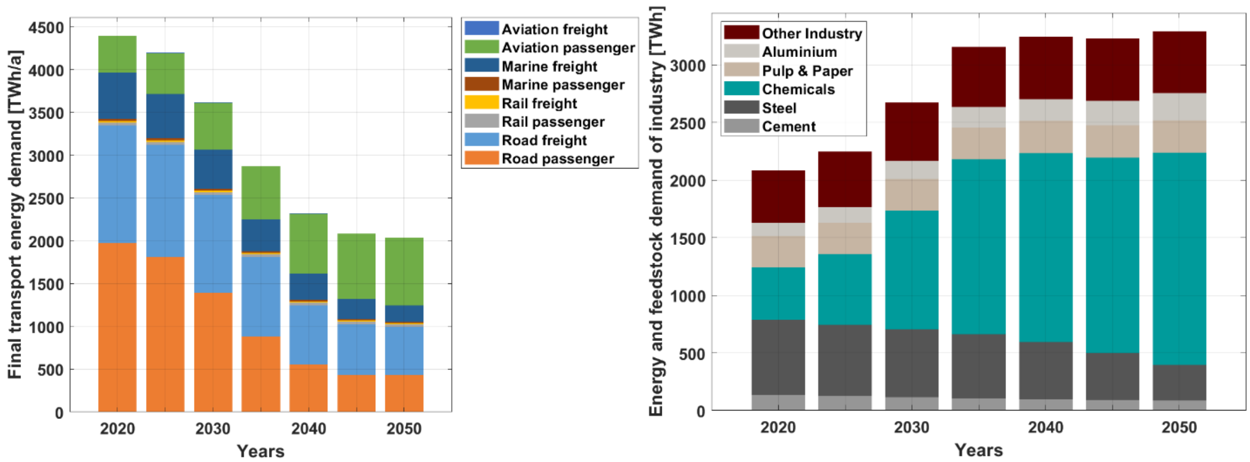

Figure C1.7: Final energy demand for transport (left) and energy and feedstock demand for various industries[1] (right) during the energy transition from 2020 to 2050 across the EU (REF).

The road transport energy demand declines through the transition with massive gains from high levels of direct electrification, whereas the final energy demand increases for aviation in the last few years, not only due to a continuous transportation demand, but also driven by increasing specific energy demand due to production of synthetic e-fuels. Energy demand for the rail mode remains fairly stable through the transition, as it already at a high level of electrification across the EU. The development of the final energy demand for the different transport modes through the transition is shown in Figure C1.7. The low efficiency of the present transport sector is highlighted by the projection of an about 80% increase in transportation demand, but stabilised final energy demand for the transport sector.

Electrification of Heat, Transport and Industry Sectors

The heat, transport and industry sectors undergo a significant transformation in the course of the energy transition, as high levels of electrification (direct and indirect) lead to higher demand for electricity and a rapid decline in demand for fossil fuels.

The share of electricity in the final energy demand[2] for heat increases substantially with about 2300 TWh by 2050, while the share of fossil fuels in the final energy demand declines to zero from nearly 2400 TWh in 2020, as shown in Figure C1.8.

[1] Including the ambient heat for heat pumps
[2] Including the ambient heat for heat pumps

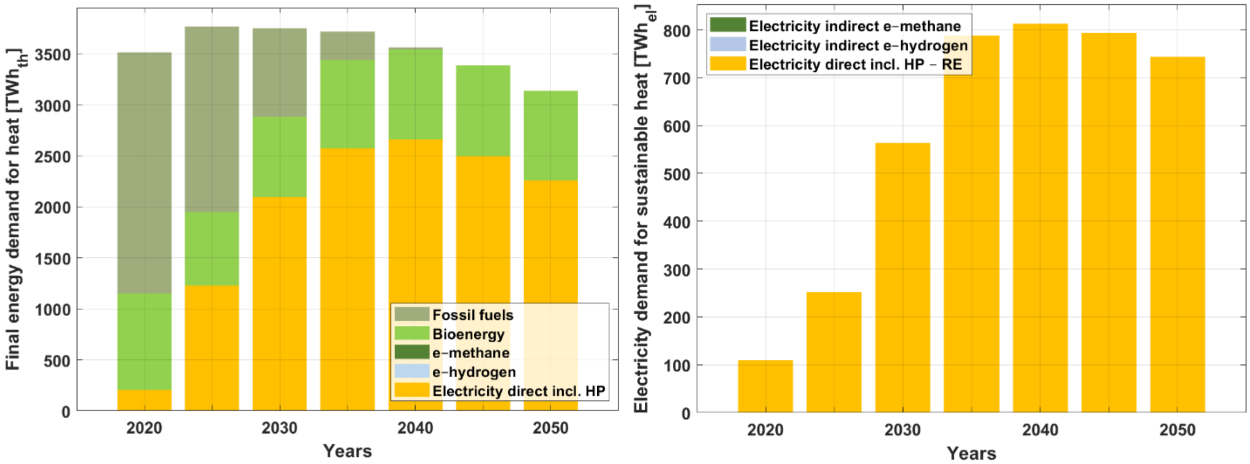

Figure C1.8: Final energy demand for heat[1] *(left) and electricity demand for sustainable heat (right) during the energy transition from 2020 to 2050 across the EU (REF).*

Electricity demand to provide sustainable heat increases through the transition to around 720 TWh_{el} by 2050.

Fossil fuels consumption in the transport sector across the EU is seen to decline through the transition from about 95% in 2020 to zero by 2050. On the other hand, liquid fuels produced by renewable electricity contribute around 30% of final energy demand in 2050. In addition, hydrogen constitutes around 10% of final energy demand along with some shares of e-methanol and e-ammonia in 2050, as shown in Figure C1.9. Sustainable biofuels from waste and residual biomass contribute some shares as part of renewable liquid fuels. Electrification of the transport sector creates an electricity demand of about 2200 TWh_{el} by 2050. In the initial periods demand is driven by direct electrification of road transport, while indirect electrification of marine and aviation drives the demand from 2035 onwards. The massive production of e-fuels, most importantly FT-fuels, e-methanol, e-ammonia, and e-hydrogen, kicks in from 2035 onwards up until 2050, as indicated in Figure C1.9.

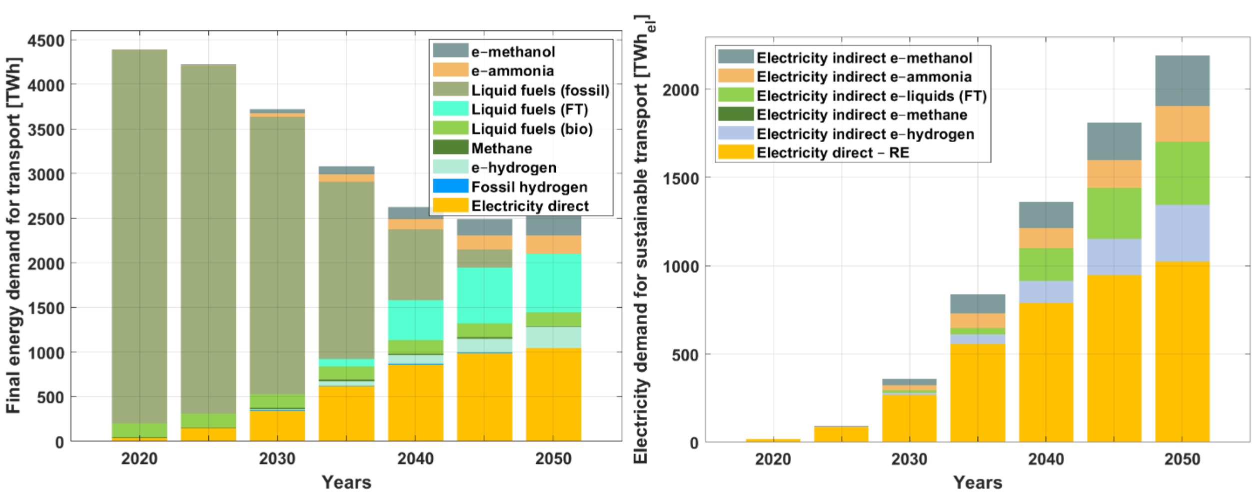

Figure C1.9: Final energy demand for transport (left) and electricity demand for sustainable transport (right) during the energy transition from 2020 to 2050 across the EU (REF).

[1] Including the ambient heat for heat pumps

As renewable electricity use in the industry sector grows, fossil fuels are replaced by green e-hydrogen and other e-fuels and e-chemicals until 2050, as shown in Figure C1.10. Electrification of the industry sector creates an electricity demand of about 2000 TWh_{el} by 2050. The massive demand for green e-hydrogen kicks in from 2030 onwards up until 2050, mainly for the production of sustainable e-chemicals, as indicated in Figure C1.10.

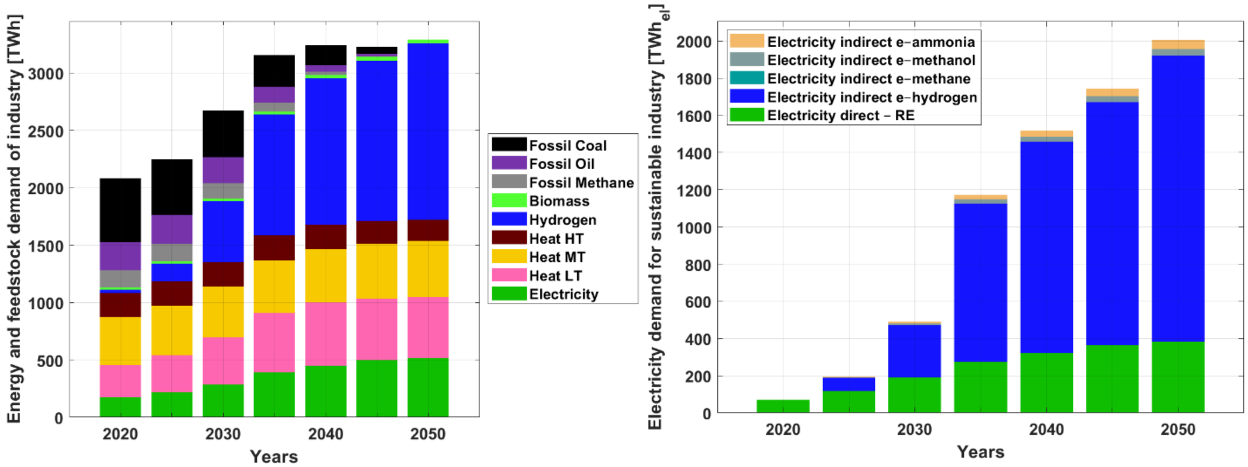

Figure C1.10: Energy and feedstock demand for industry[1] (left) and electricity demand for sustainable industry (right) during the energy transition from 2020 to 2050 across the EU (REF).

Fuels, Chemicals and Carbon Supply

An essential aspect in the transition of the transport sector towards higher electrification completely based on high shares of renewable energy is the production of synthetic fuels and chemicals: e-hydrogen, e-methane, Fischer-Tropsch fuels, e-methanol and e-ammonia. As indicated in Figure C1.11, fossil fuels are completely replaced by a combination of sustainable fuels and chemicals by 2050. Additionally, CO_2 direct air capture, which is vital in the production of synthetic e-fuels, supplies up to nearly 290 $MtCO_2$ by 2050, as shown in Figure C1.12. Some CO_2 buffer storage, which stores CO_2 from DAC systems to be utilised in the production of e-fuels and e-chemicals, complements CO_2 supply in the energy system.

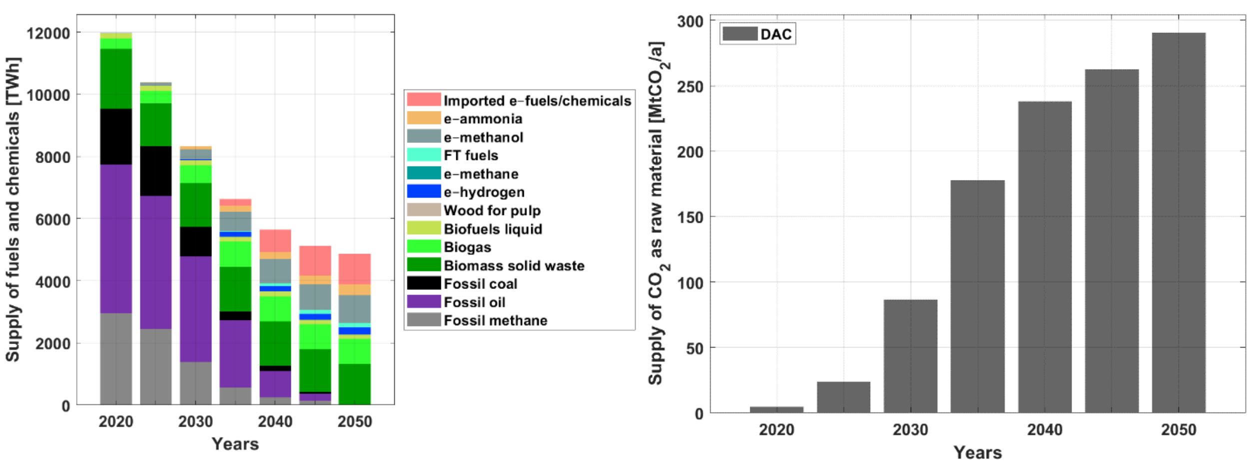

Figure C1.11: Supply of fuels and chemicals (left) and CO_2 as raw material (right) during the energy transition from 2020 to 2050 across the EU (REF).

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[1] Including the ambient heat for heat pumps

Costs and Investments

The total annual costs decline from about 610 b€ in 2025 to about 450 b€ in 2050 through the transition period and are well distributed across the major sectors of power, heat, transport and industry across the EU. As indicated in Figure C1.12, 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 the EU.

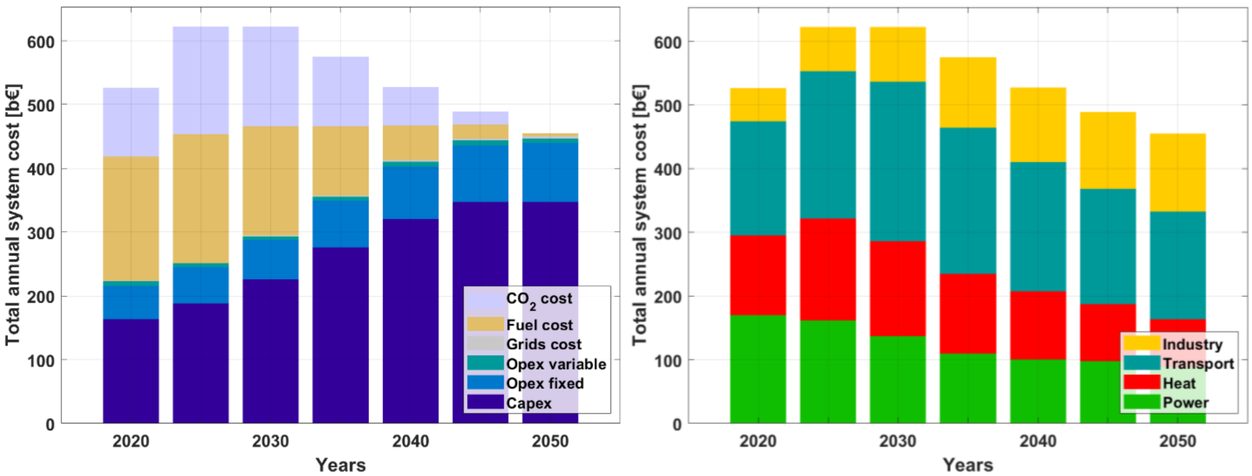


Figure C1.12: Annual energy system costs composed of different parameters (left) and of different sectors (right) during the energy transition from 2020 to 2050 across the EU (REF).

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 source[55]. As indicated in Figure C1.13, levelised cost of energy remains stable at around 50 €/MWh by 2050 and is increasingly dominated by capital costs as fuel costs continue to phase out through the transition period, which could mean increased self-reliance in terms of energy for the EU by 2050. Capital costs are well spread across a range of technologies with major investments for solar PV, wind power, batteries, heat pumps, and synthetic e-fuel and e-chemicals conversion technologies up to 2050, as shown in Figure C1.13.

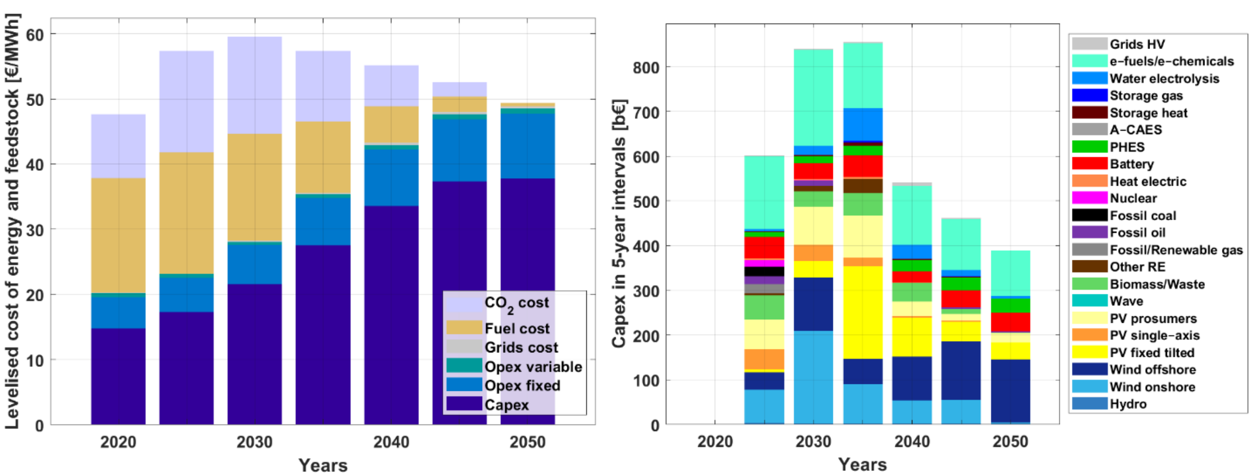


Figure C1.13: Levelised cost of energy (left) and capital expenditures in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (REF).

Capital expenditures are well spread across a range of power generation technologies with the majority share in wind power up to 2030, beyond which solar PV dominates investments up to 2050, as shown in Figure C1.14. The LCOE of the power sector decreases substantially from around 84 €/MWh in 2020 to around 42 €/MWh by 2050, as shown in Figure C1.14. LCOE is predominantly comprised of Capex as fuel costs decline through the transition.

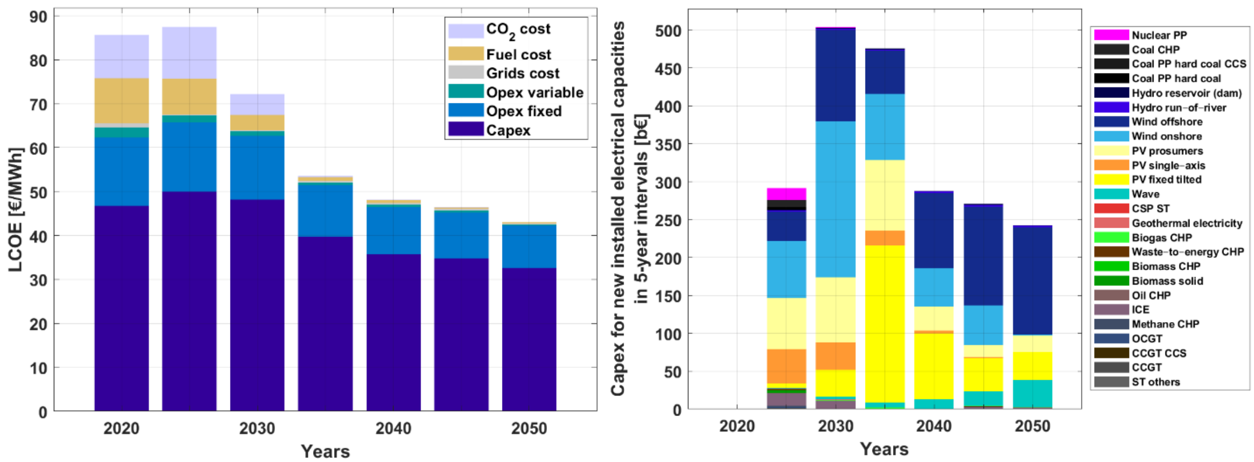


Figure C1.14: Levelised cost of electricity (left) and capital expenditures for electricity generation in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (REF).

Investments in the heat sector are mainly in heat pumps and some shares in biomass heating up to 2050, also shown in Figure C1.15. 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. The LCOH of the heat sector, after an initial increase, declines from around 46 €/MWh in 2020 to around 24 €/MWh by 2050, as shown in Figure C1.15. The LCOH is predominantly comprised of Capex as fuel costs decline through the transition. Growing electrification and improvements in building renovation rates with efficiency gains enable the LCOH to decline in a stable manner up to 2050.

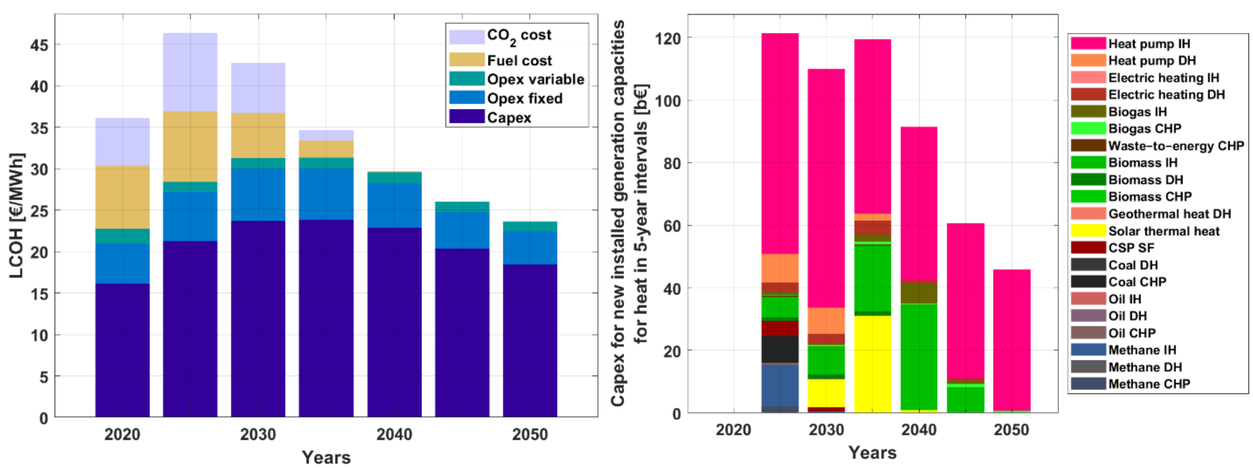


Figure C1.15: Levelised cost of heat (left) and capital expenditures for heat generation in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (REF).

The total annual energy costs for transport decline to about 120 b€ by 2050, as shown in Figure C1.16. During the same period, passenger transportation services increase by more than 50% and freight services by 25%, while energy demand decreases. This is primarily due to efficiency gains through electrification of the sector resulting in lower annual system costs. Furthermore, annual system costs transit from being heavily dominated by fuel costs in 2020 to a very diverse share of costs across various technologies for electricity, synthetic e-fuels and sustainable biofuel production by 2050. Similarly, the final energy cost of energy and feedstock for the industry sector declines to about 65 b€ by 2050, driven by process changes as shown in Figure C1.16.

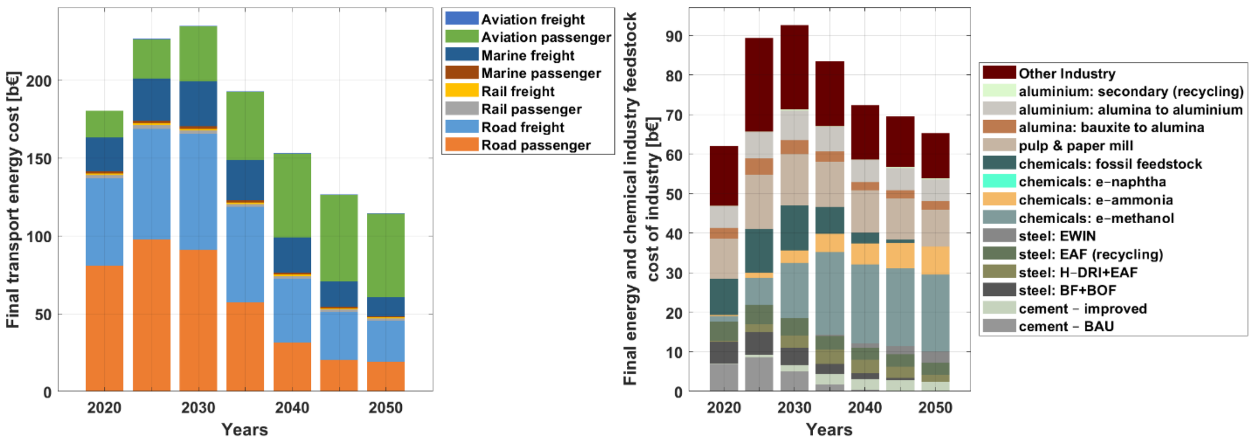


Figure C1.16: Final transport energy costs for different modes (left) and final energy and chemicals feedstock costs of different industries and processes (right) during the energy transition from 2020 to 2050 across the EU (REF).

CO_2 Emissions

The results of the energy transition towards high shares of renewable energy indicate a sharp decline in CO_2 emissions, reaching almost zero by 2050, across the power, heat, transport and industry sectors across the EU as shown in Figure C1.17. The power and heat sectors undergo a rapid transition towards renewables, whereas in the transport sector the transition is rather slow. In the industry sector, CO_2 emissions reduction are gradual with some residual emissions from limestone use in the cement industry in 2050. However, this emission is mitigated through natural climate or capture and storage solutions.

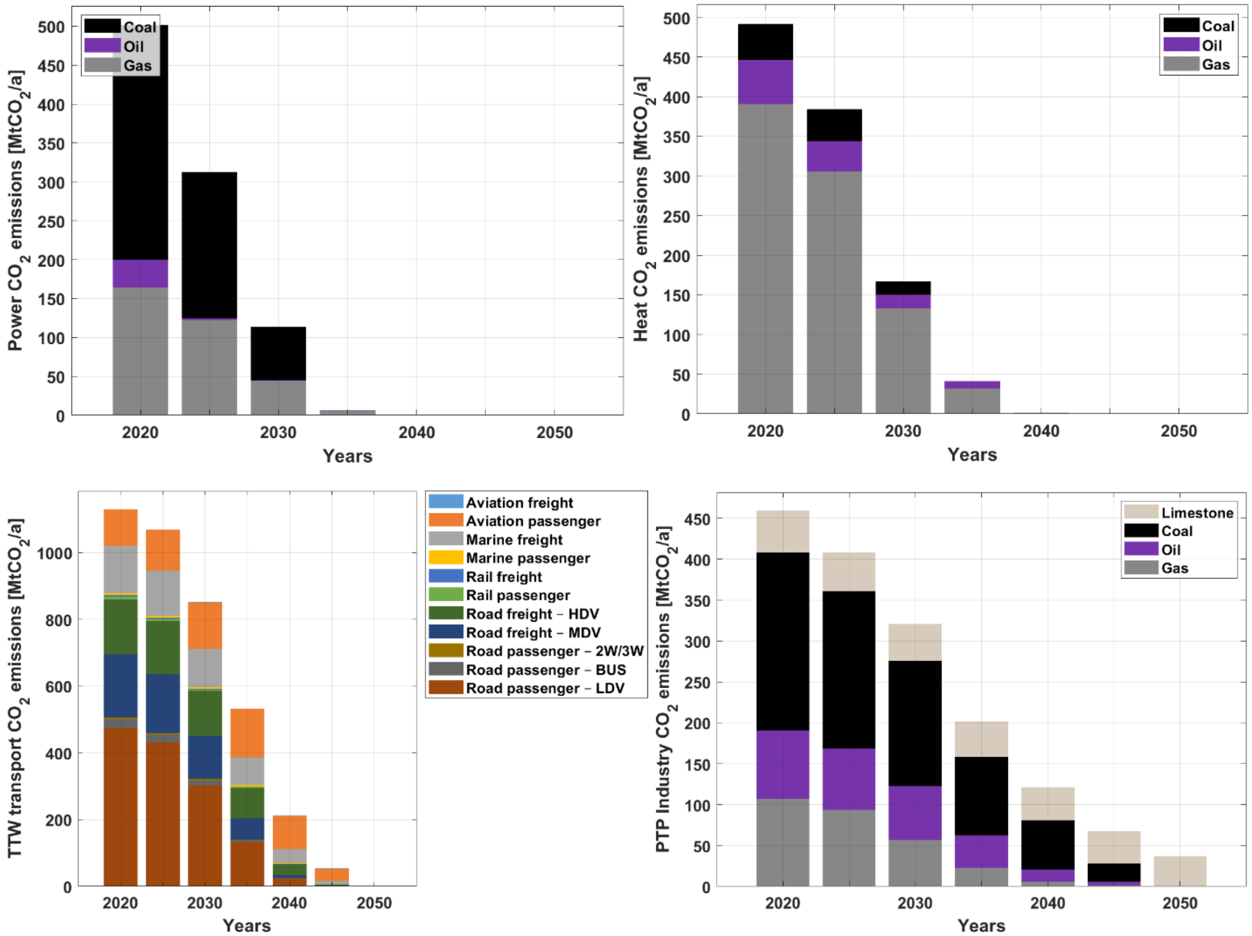


Figure C1.17: CO_2 emissions in the power sector from different fuels (top left), CO_2 emissions in the heat sector from different fuels (top right), CO_2 emissions in the transport sector from different modes (bottom left) and CO_2 emissions in the industry sector from different fuels (bottom right), during the energy transition from 2020 to 2050 across the EU. Tank to Wheel (TTW) and Plant to Product (PTP) considers CO_2 emissions from readily available fuels and does not consider CO_2 emissions from the upstream production and delivery of fuels (REF).

CO_2 emissions from the power sector decline through the transition from around 500 $MtCO_2$/a in 2020 to zero by 2050 as shown in Figure C1.17. Similarly, CO_2 emissions from the heat sector decline through the transition from over 480 $MtCO_2$/a in 2020 to zero by 2050 as shown in Figure C1.17. CO_2 emissions from the transport sector decline through the transition from around 1100 $MtCO_2$/a in 2020 to zero by 2050 and CO_2 emissions from the industry sector decline through the transition from over 450 $MtCO_2$/a in 2020 to nearly zero by 2050, with some residual emissions from limestone, as shown in Figure C1.17.

Regional Outlook

The regional distribution of electricity generation capacities, electricity generation, heat generation capacities, heat generation, electricity storage output, heat storage output, supply of fuels and chemicals across the EU, and electricity exchange across the European network are illustrated in the Figures C1.18 to C1.25. Further information during the different years of the transition for the 27 EU member states is provided in a supplementary data file.

Power generation capacities are distributed throughout the EU, with major shares of solar PV in the Southern member states, while wind power has major shares in the northern and western members states of the EU in 2050 (see Figure C1.18). PV prosumers are a relevant energy system feature in all member states. The total power generation capacity installed across the EU in the REF scenario in 2050 is 3952 GW.

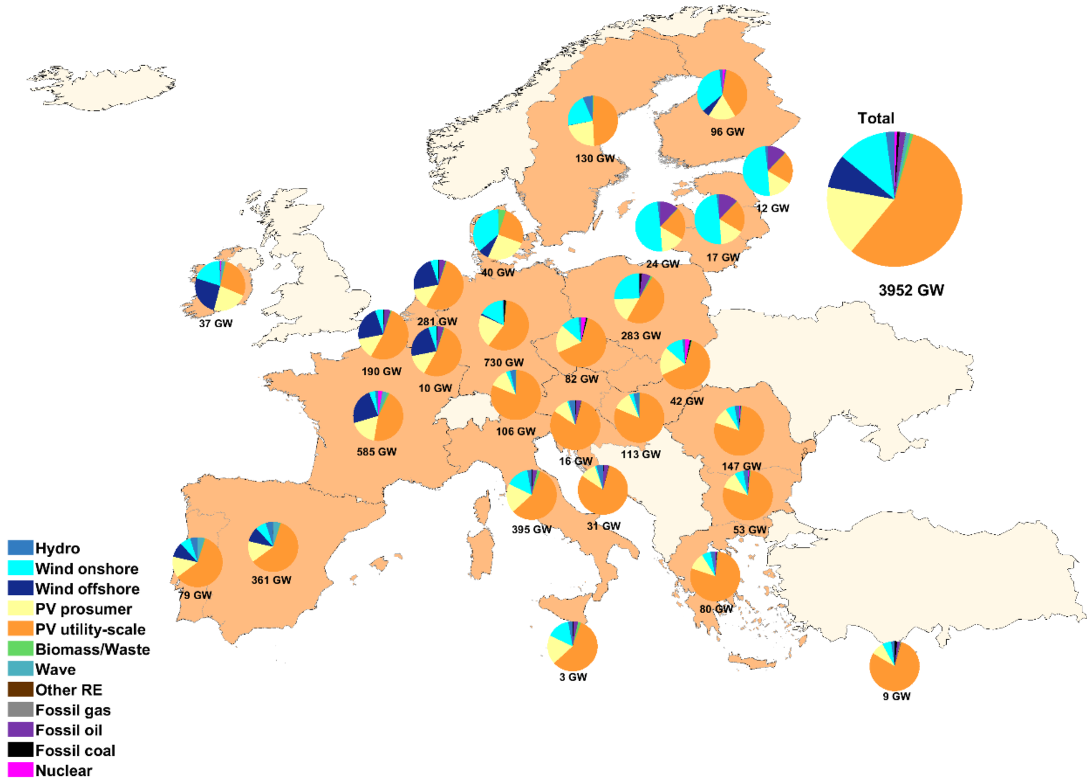


Figure C1.18: Regional electricity generation capacities in 2050 across the EU (REF).

Similarly, electricity generation shares vary across the EU, with total generation of 7042 TWh in the REF scenario in 2050. Solar PV generation shares dominate in the southern and western member states, while wind power has the major shares in the northern and Baltic member states (see Figure C1.19). PV prosumers are a relevant energy system feature in all member states. From an EU energy system point of view, the southern and northern member states have great complementarity in terms of resources.

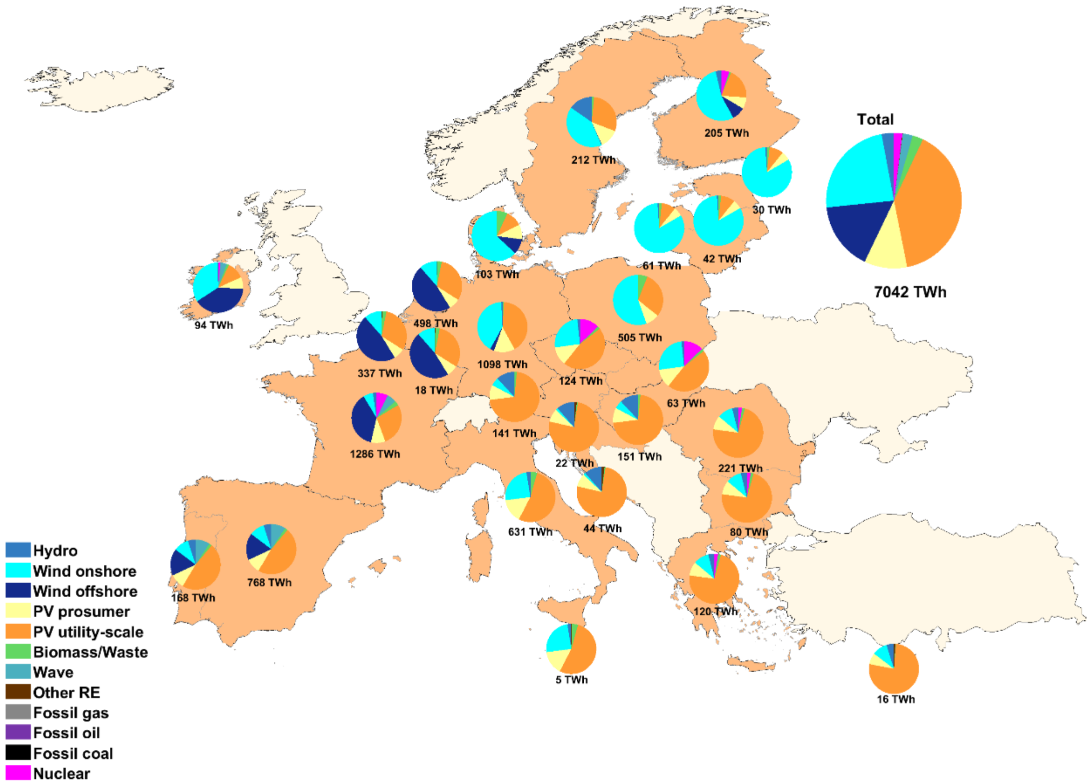


Figure C1.19: Regional electricity supply in 2050 across the EU (REF).

Heat generation capacities are about 695 GW across the EU in the REF scenario in 2050 and well distributed across the member states. Heat pumps[1] and electric heating are the major heat sources in 2050 and are predominant in the southern and western member states. While higher shares of bioenergy provide heat in the northern and Baltic states along with minor shares across the rest of the EU (see Figure C1.20).

[1] Heat pumps can be either air sourced or ground sourced depending on local conditions, but not deeper than 150 meters, thus ambient heat is utilised and not geothermal heat that is mostly available at greater depths.

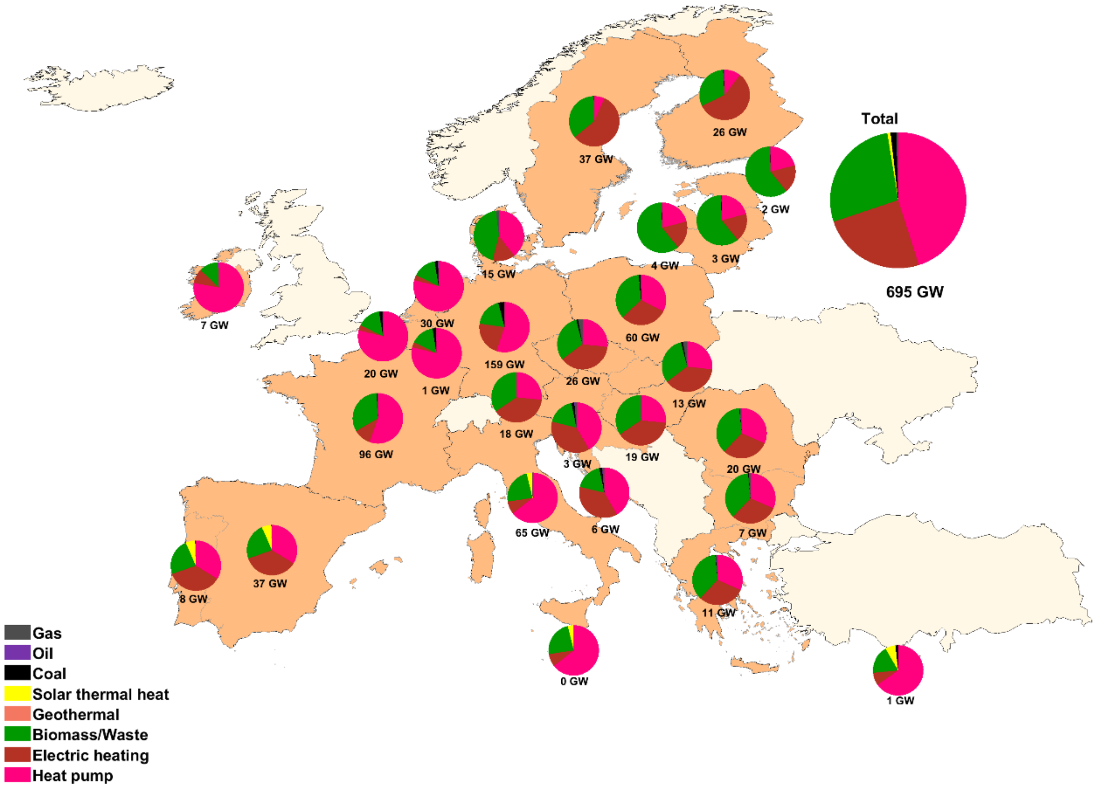


Figure C1.20: Regional heat generation capacities in 2050 across the EU (REF).

Total heat generation across the EU is 3064 TWh in the REF scenario in 2050. Major share is from heat pumps and electric heating across most states, while bioenergy contributes most of the heating in the eastern and Baltic states of the EU (see Figure C1.21).

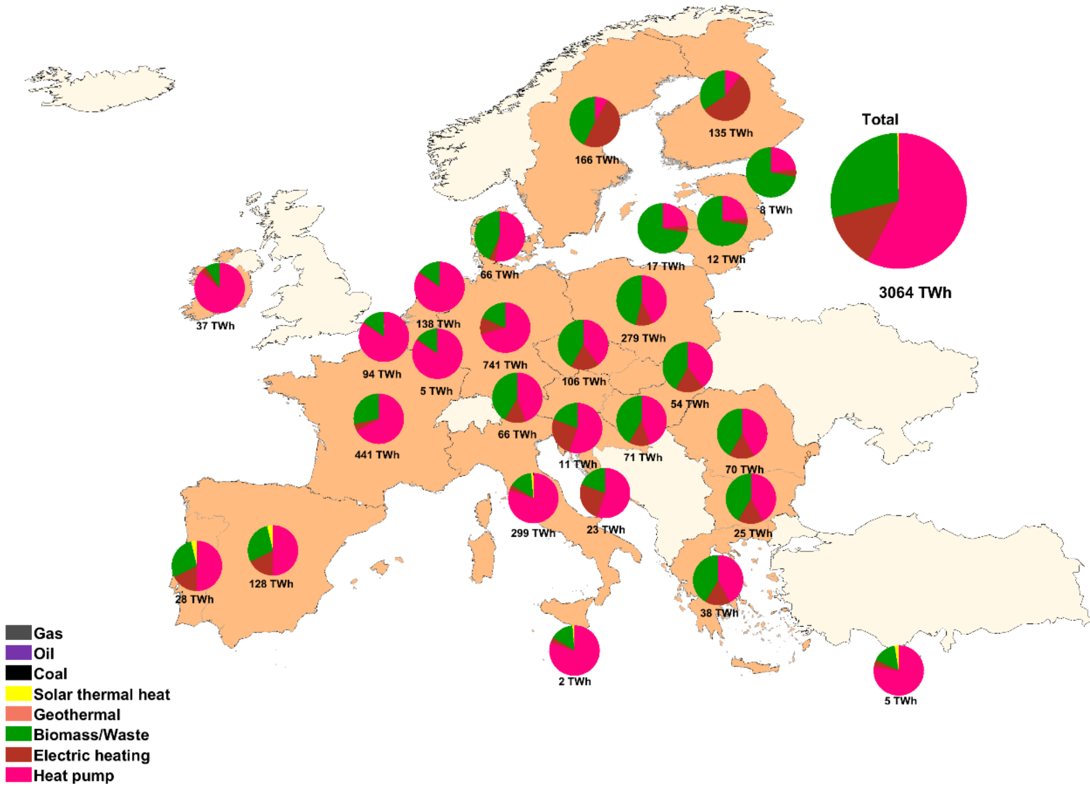


Figure C1.21: Regional heat supply in 2050 across the EU (REF).

Batteries (prosumers and utility-scale) along with vehicle-to-grid emerge as the dominant electricity storage sources across the EU in 2050, with 1147 TWh of storage output in the REF scenario. Prosumer batteries dominate across the EU, with some shares of utility scale batteries, vehicle-to grid and pumped hydro energy storage across the EU (see Figure C1.22).

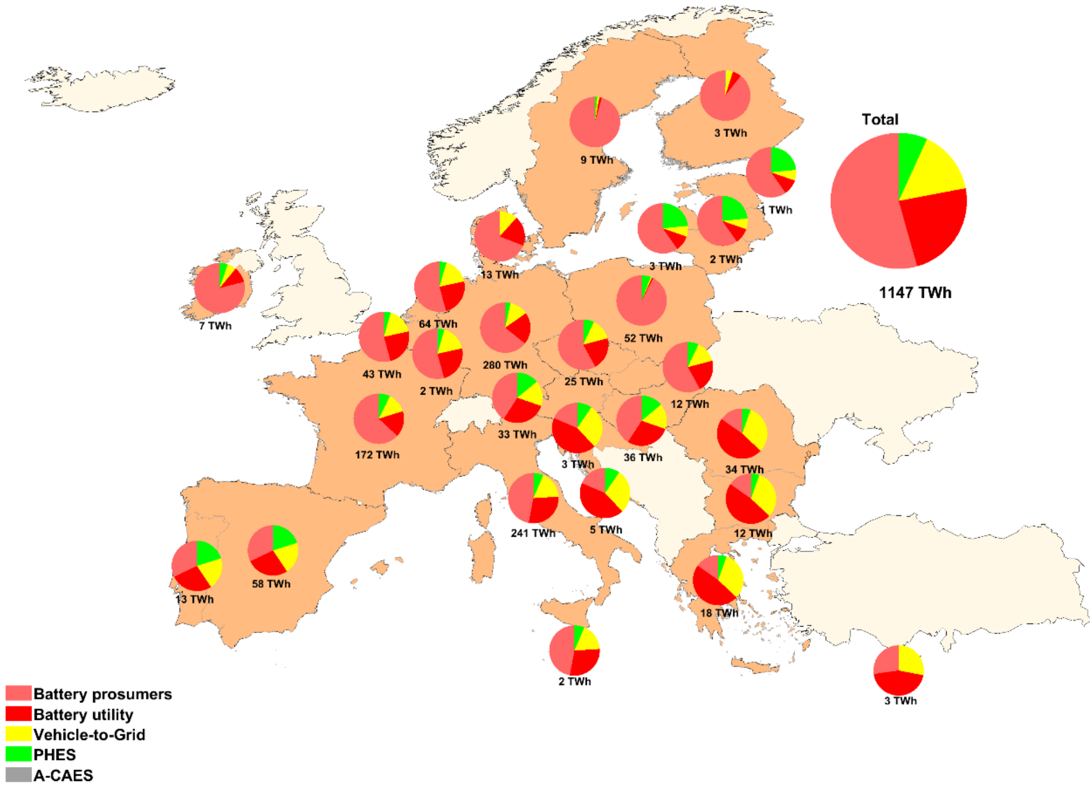


Figure C1.22: Regional electricity storage output in 2050 across the EU (REF).

Heat storage output is 704 TWh in 2050 across the EU in the REF scenario. It is well distributed across the member states and hydrogen storage provides the bulk of the heat across members states in 2050. While thermal energy storage provides major shares of the heat in some member states with high temperature heat. Some shares of biomethane storage output contribute across the EU for seasonal heat (see Figure C1.23).

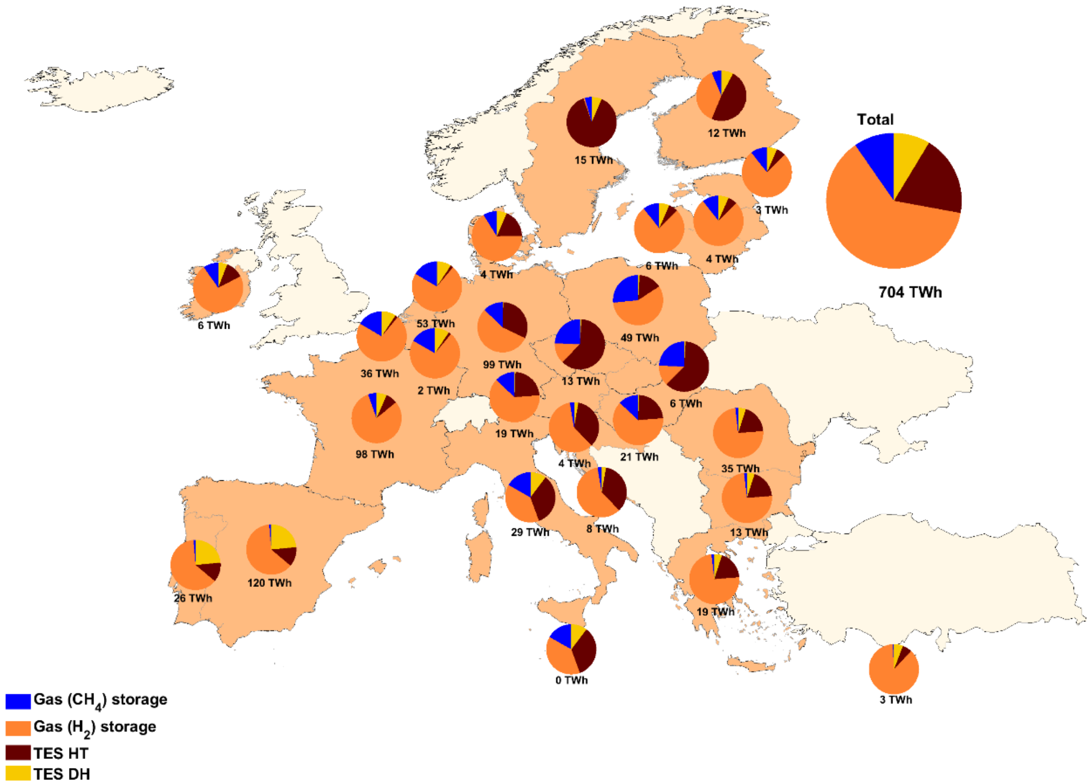


Figure C1.23: Regional heat storage output in 2050 across the EU (REF).

Supply of fuels and chemicals is well distributed across the EU with 4881 TWh in the REF scenario in 2050. Waste and residual biomass contribute the major share of fuels, while e-fuels and e-chemicals are well distributed across the EU (see Figure C1.24). Imports of e-fuels and e-chemicals contribute about 20% of the cost optimal supply in the REF scenario in 2050 and are dominant in the states with major ports in the EU.

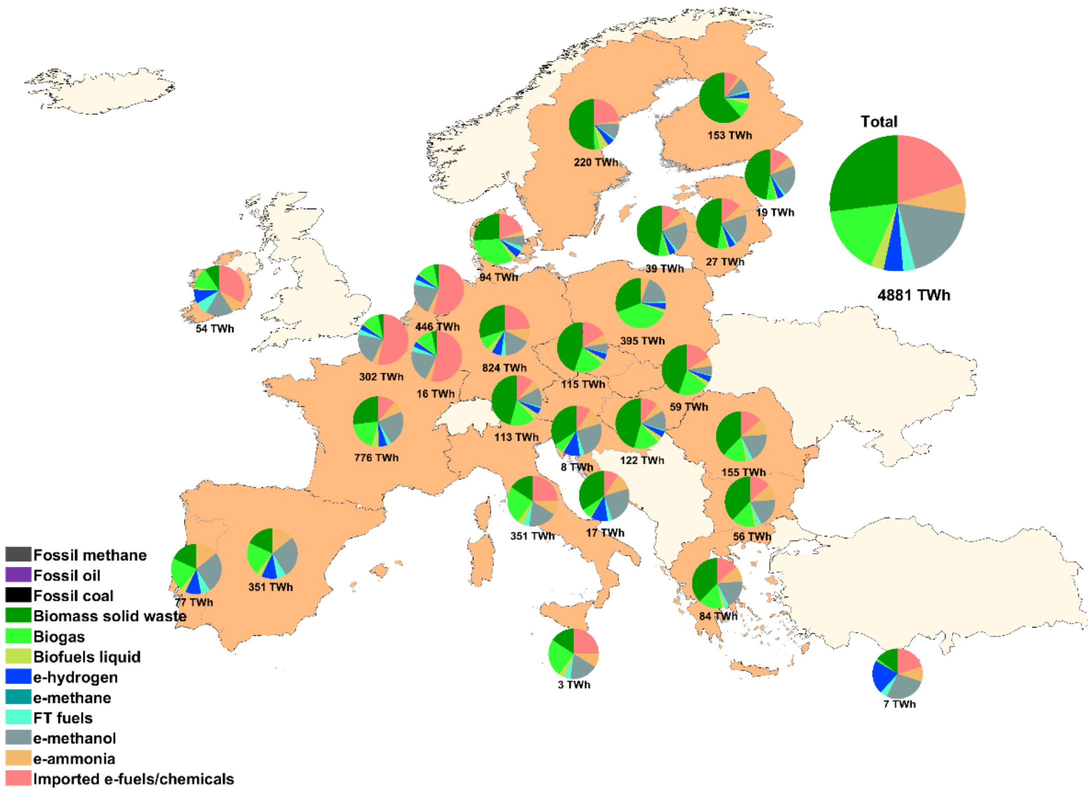


Figure C1.24: Regional fuels and chemicals supply in 2050 across the EU (REF).

The electricity network is robust and rapidly developing across the EU and beyond covering Europe. With energy resources distributed across the region, electricity trade is 830 TWh in 2050 across Europe in the REF scenario (see Figure C1.25), representing less than 12% of total electricity generation in EU. Net exporters and importers emerge across Europe to enable a cost optimal energy mix for the whole region.

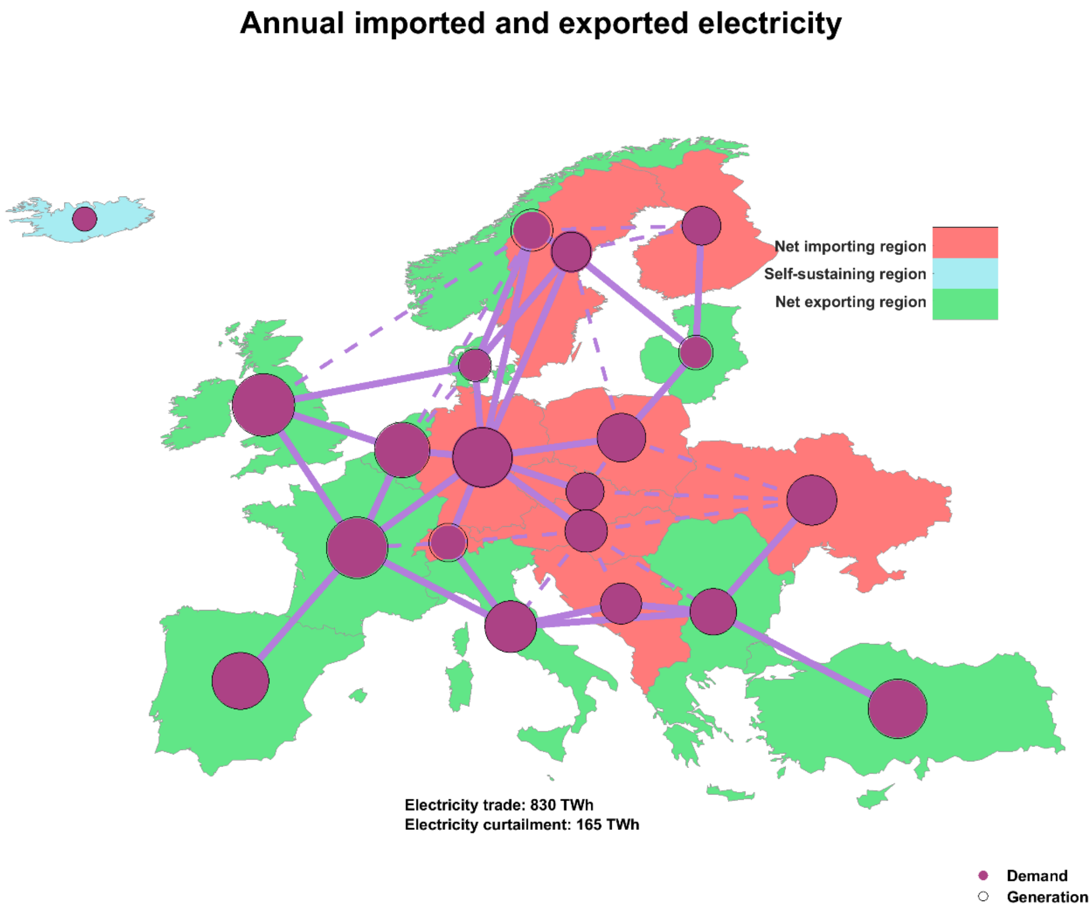


Figure C1.25: Regional electricity trade with net-importers and net-exporters in 2050 across Europe. Solid and dashed lines indicate used and not used interconnections, respectively (REF).

In the REF scenario, the energy system is highly sector coupled with flexible storage options, as shown in Figure C1.26. However, it still has some shares of nuclear power and imports (e-fuels and e-chemicals). The high level of diversification of energy sources is evident across the power, heat, transport and industry sectors, as shown by the increasing complexity in energy flows in Figure C1.26.

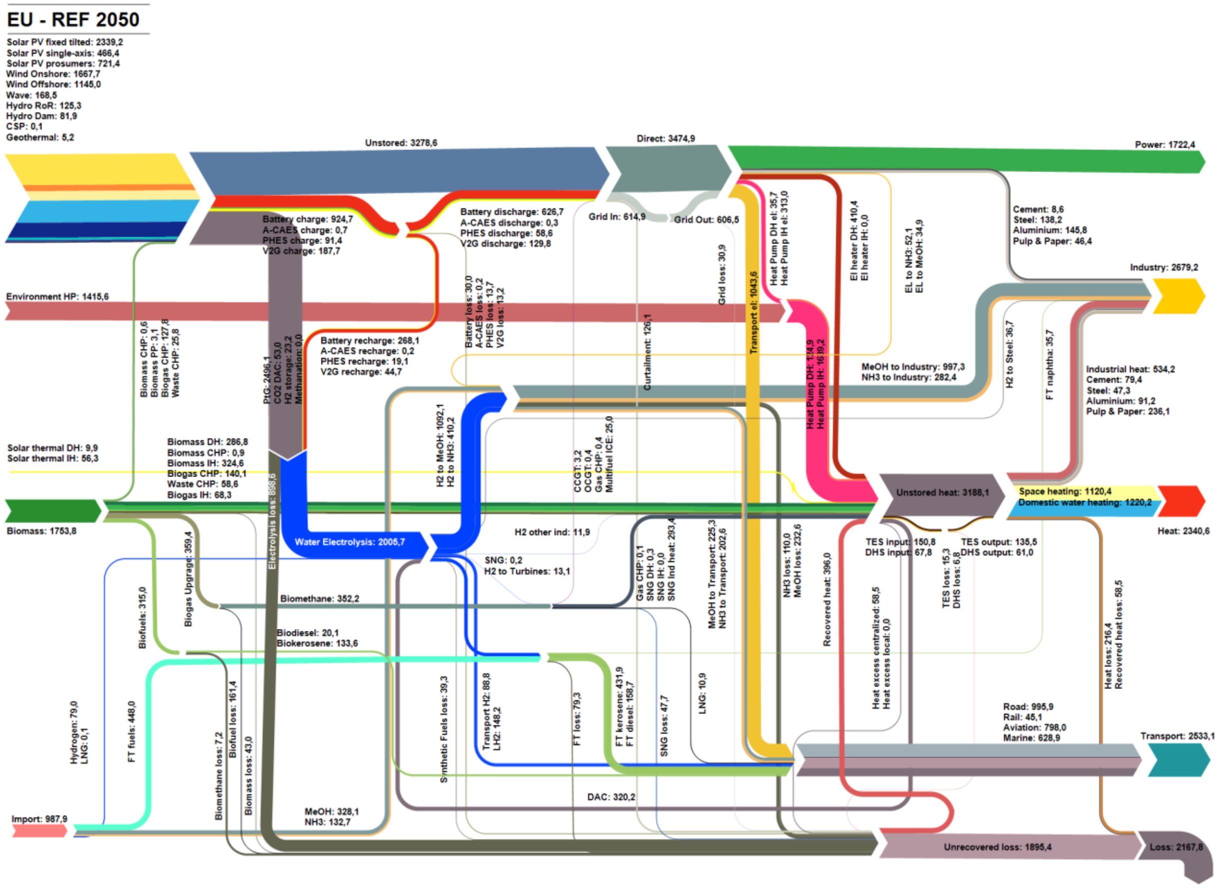


Figure C1.26: Energy flows of the EU energy system in 2050 (REF).

C2. RES-2040 Scenario

Energy Demand

In the RES-2040 scenario, the uptake of renewables is relatively faster as compared to the REF scenario, which also influences the change in resource efficiency through accelerated electrification. Efficiency measures such as improving building renovation rates, modal shift of transport towards electrified rail use and more conscious use of energy enable further gains in final and, consequently, primary energy. This eventually determines the levels of primary energy demand as shown in Figure C2.1.

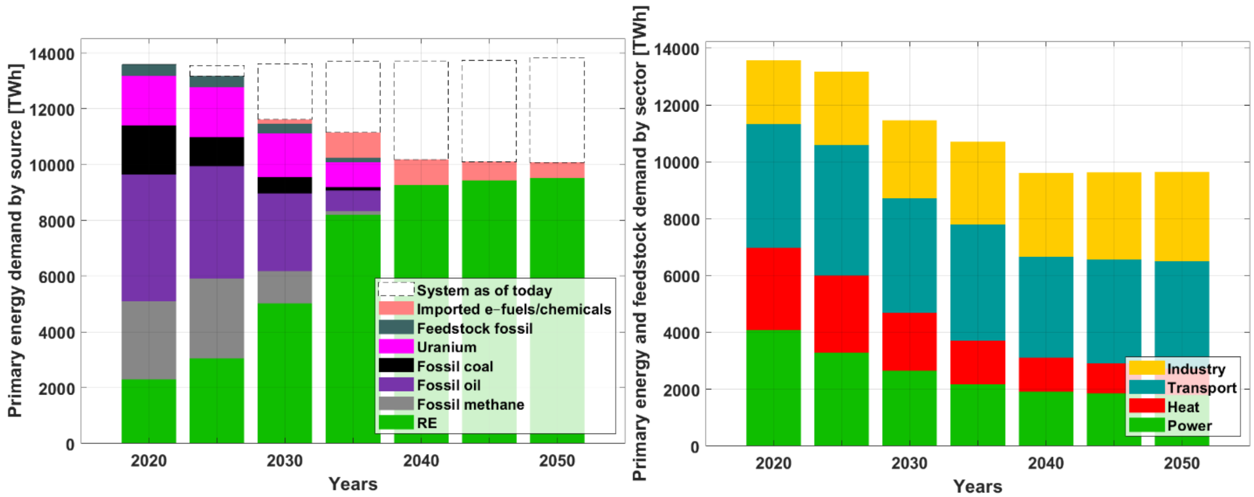
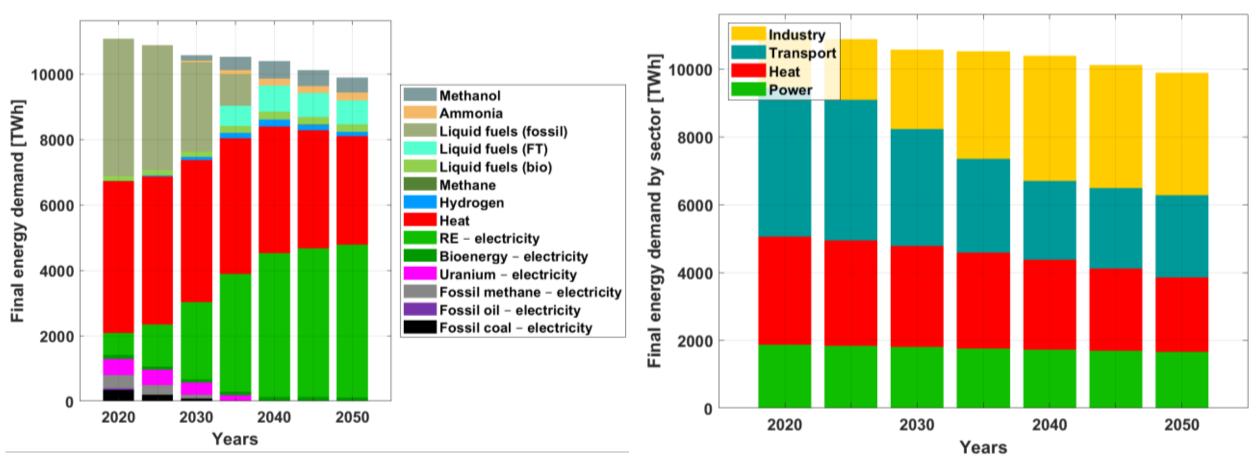


Figure C2.1: Primary energy demand according to sources (left) and on a sectoral basis (right), during the energy transition from 2020 to 2050 across the EU (RES-2040).

The primary energy demand decreases from over 13,500 TWh in 2020 to around 10,000 TWh by 2050 across the EU as shown in Figure C2.1. The gain in efficiencies compared to the 'system as of today' is due to electrification of the heat, transport and industry sectors, while the growth in demand for energy services continues. The final energy declines from about 11,000 TWh in 2020 to nearly 10,000 TWh in 2050, despite a high level of energy services, as shown in Figure C2.2. The different fuels that constitute the final energy demand[1] transition from mostly fossil fuels in 2020 to renewable electricity, heat, e-fuels and e-chemicals by 2050.



[1] Including the ambient heat for heat pumps

Figure C2.2: Final energy demand[1] according to sources (left) and on a sectoral basis (right), during the energy transition from 2020 to 2050 across the EU (RES-2040).

Sectoral Outlook

Energy supply is mainly through electricity and heat, as accelerated levels of electrification are achieved through the transition. An increasing amount of electricity generation is needed along with heat, storage and supply of fuels and chemicals to cover the future energy demand.

Electricity

The electricity generation capacity across the EU satisfies demand form all energy sectors including power, heat, transport and industry. The total installed capacity grows massively from about 750 GW in 2020 to over 4500 GW by 2050 as shown in Figure C2.3. In the initial period of the transition, a larger share of wind power capacities is installed up to 2030, but in the later part of the transition solar PV dominates the shares of installed capacities reaching almost 3500 GW by 2050. On the other hand, the shares of fossil fuels and nuclear power decline through the transition, with complete phaseout by 2040.

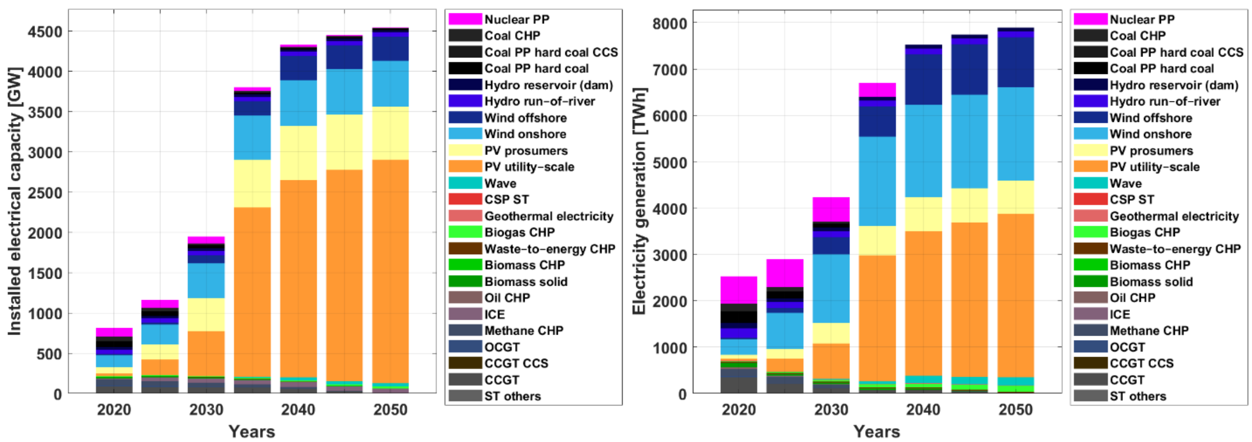


Figure C2.3: Technology-wise installed capacities (left) and technology-wise electricity generation (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Electricity generation from the various technologies to cover the demand of power, heat, transport and industry sectors is shown in Figure C2.3. Solar PV supply increases through the transition along with wind power, wave power and electricity from waste and residual biomass up to 2050.

Heat

In the heat sector, heat pumps, electric heating, and biomass-based heating constitute the majority of installed capacity by 2050, also shown in Figure C2.4. A decrease in total installed capacity of heating technologies occurs mainly due to efficiency gains with heat pumps and electric heating, as fossil fuels recede from the energy system. The key driver is the tripling of building renovation rates and linear increase of industrial heat efficiency to 2.2% per annum until 2030. Heat pumps play a significant role through the transition with a share of over 50% of heat generation by 2050 on both the district and individual levels, as indicated in Figure C2.4. On the other hand, fossil gas-based heating decreases through the transition from over 75% in 2020, to zero by 2040. Moreover, fossil fuels based heat generation declines through the

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[1] Including the ambient heat for heat pumps

transition period as coal-based combined heat and power (CHP) and district heating (DH) are replaced by heat generation from heat pumps, waste-to-energy CHP, biomass-based DH, and individual heating (IH).

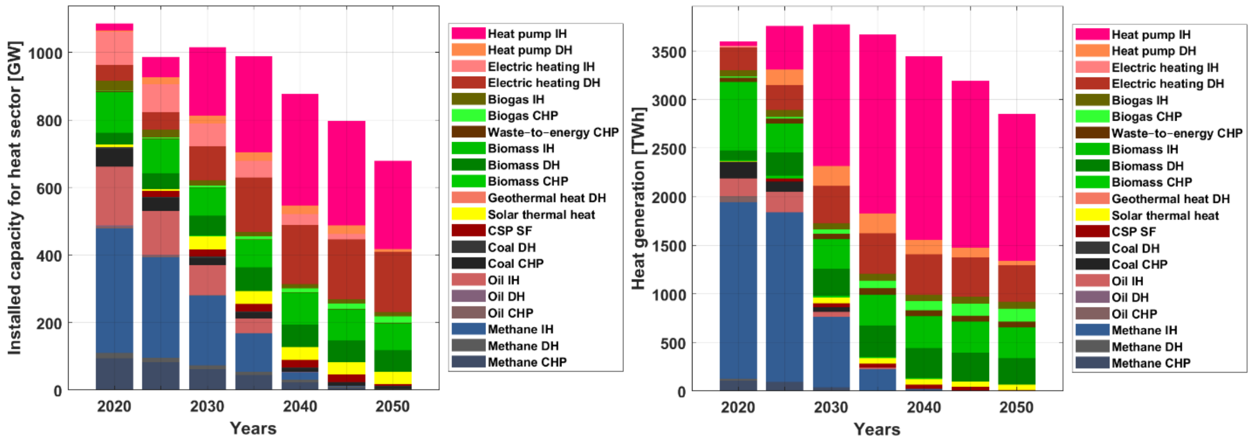

Figure C2.4: Technology-wise heat generation capacities (left) and technology-wise heat generation (right) during the energy transition from 2025 to 2050 across the EU (RES-2040).

Electricity, Heat and Gas Storage

Energy storage technologies play a critical role in enabling a secure energy supply across the EU, fully based on renewable energy across different sectors. The installed electricity storage capacity increases from just 0.4 TWh in 2020 to around 5.5 TWh by 2050, as shown in Figure C2.5. Utility-scale and prosumer batteries with major shares of vehicle-to-grid dominate, some PHES remains through the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with hydrogen and methane based output contributing beyond 2035, as highlighted by Figure C2.5. In addition, vehicle-to-grid, PHES contributes some shares through the transition.

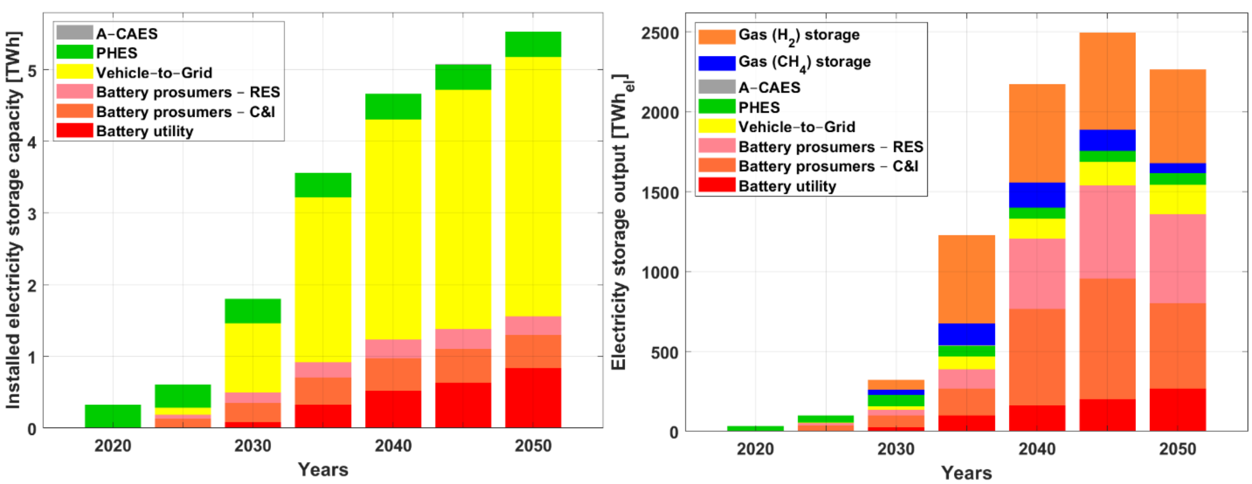

Figure C2.5: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Heat storage plays a vital role in ensuring that the heat demand is covered in all sectors. The installed heat storage grows substantially from 2030 onwards, installed capacities are dominated by gas storage (hydrogen and methane), as shown in Figure C2.6. This substantial capacity addition is mainly to provide seasonal storage across the EU covering the heat demand in the absence of fossil fuels. The present fossil gas storage capacity across the EU is around 1000 TWh[54], hence an even lesser amount of gas storage would be needed for an integrated energy system in the future. Thermal energy storage emerges with heat storage output from 2030 until 2050, as shown in Figure C2.6. Hydrogen gas storage contributes a majority of the heat storage output from 2035 to 2050 along with some shares of biomethane, covering predominantly the seasonal demand, which is covered by fossil gas before 2030.

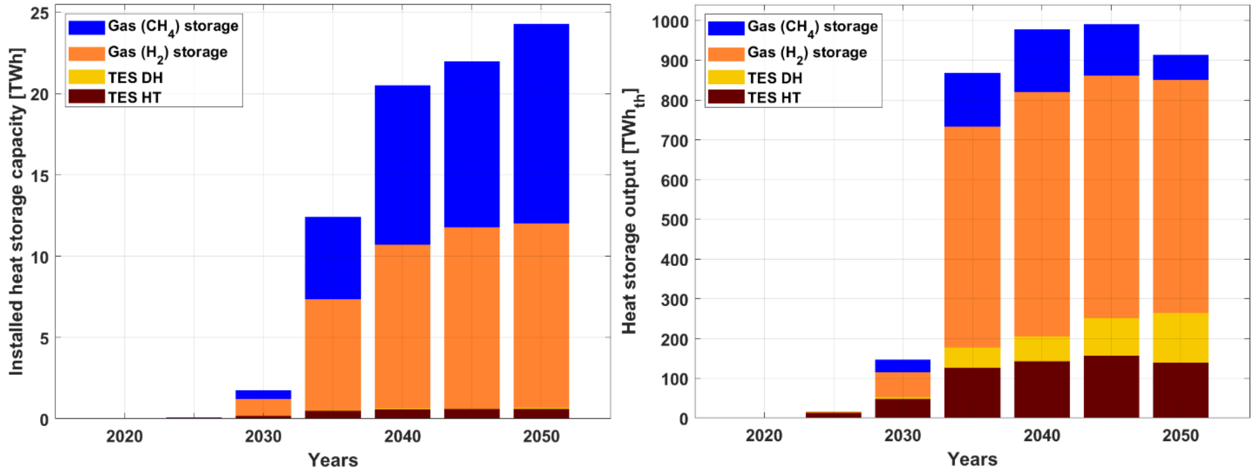

Figure C2.6: Heat storage installed capacities (left) and heat storage output (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Transport and Industry

The final energy demand of the transport sector across the EU is almost twice the energy demand from the power sector at around 4400 TWh in 2020. However, this demand declines through the transition to around 2000 TWh by 2050, as shown in Figure C2.7. This is achieved mainly due to efficiency gains brought about by electrification of the sector, mainly road transport. On the other hand, the energy and feedstock demand for the industry sector grows through the transition driven by production of sustainable chemicals and fuels, as shown in Figure C2.7.

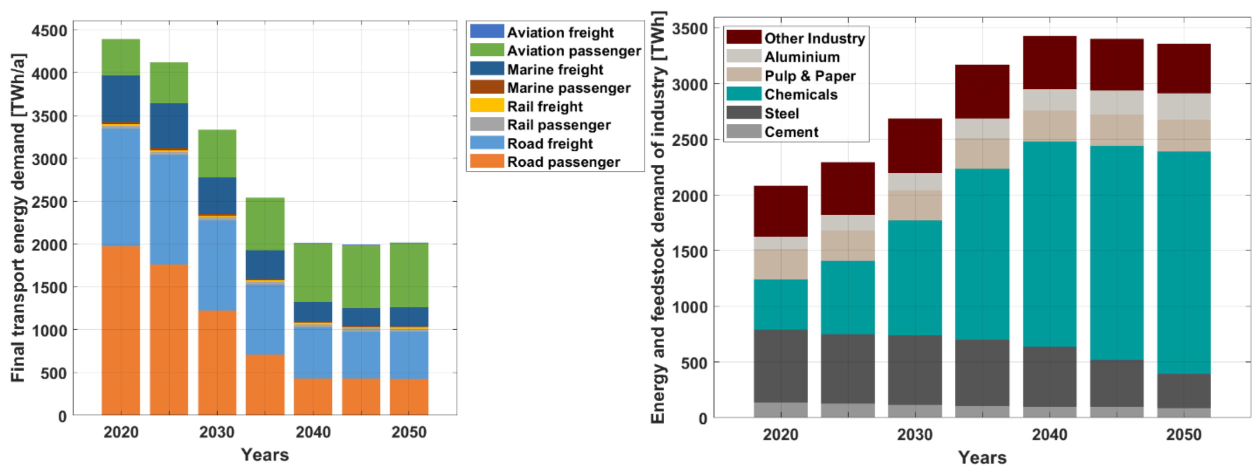

Figure C2.7: Final energy demand for transport (left) and energy and feedstock demand[1] for various industries (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

The road transport energy demand declines through the transition with massive gains from high levels of direct electrification, whereas the final energy demand increases for aviation in the last few years, not only

[1] Including the ambient heat for heat pumps

due to a continuous transportation demand, but also driven by increasing specific energy demand due to production of synthetic e-fuels. Energy demand for the rail mode remains fairly stable through the transition, as it already at a high level of electrification across the EU. The development of the final energy demand for the different transport modes through the transition is shown in Figure C2.7. The low efficiency of the present transport sector is highlighted by the projection of an about 80% increase in transportation demand, but declining final energy demand for the transport sector.

Electrification of Heat, Transport and Industry Sectors

The heat, transport and industry sectors undergo a significant transformation in the course of the energy transition, as high levels of electrification (direct and indirect) lead to higher demand for electricity and a rapid decline in demand for fossil fuels.

The share of electricity in the final energy demand for heat increases substantially with about 2100 TWh by 2050, while the share of fossil fuels in the final energy demand declines to zero by 2040 from nearly 2400 TWh in 2020, as shown in Figure C2.8.

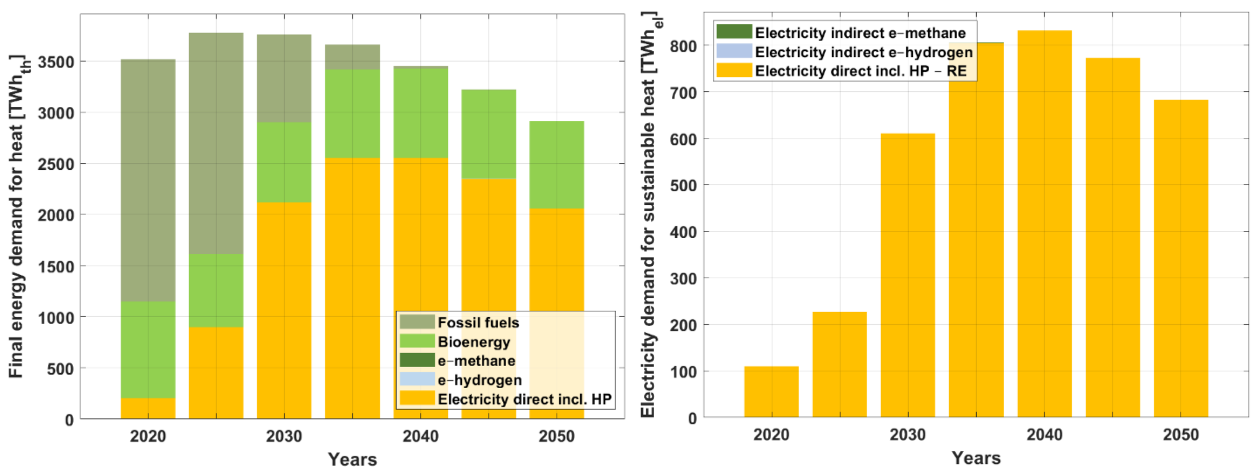

Figure C2.8: Final energy demand for heat[1] (left) and electricity demand for sustainable heat (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Electricity demand to provide sustainable heat increases through the transition to around 680 TWh$_{el}$ by 2050.

Fossil fuels consumption in the transport sector across the EU is seen to decline through the transition from about 95% in 2020 to zero by 2040. On the other hand, liquid fuels produced by renewable electricity contribute around 25% of final energy demand in 2050. In addition, hydrogen constitutes around 15% of final energy demand in 2050 along with some shares of e-methanol and e-ammonia, as shown in Figure C2.9. Sustainable biofuels from waste and residual biomass contribute some shares as part of renewable liquid fuels. Electrification of the transport sector creates an electricity demand of nearly 3100 TWh$_{el}$ by 2050. The massive demand for synthetic e-chemicals and liquid e-fuels kicks in from 2035 onwards up until 2050, as indicated in Figure C2.9. This demand for e-fuels and e-chemicals is predominantly induced by aviation and marine modes in the transport sector.

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[1] Including the ambient heat for heat pumps

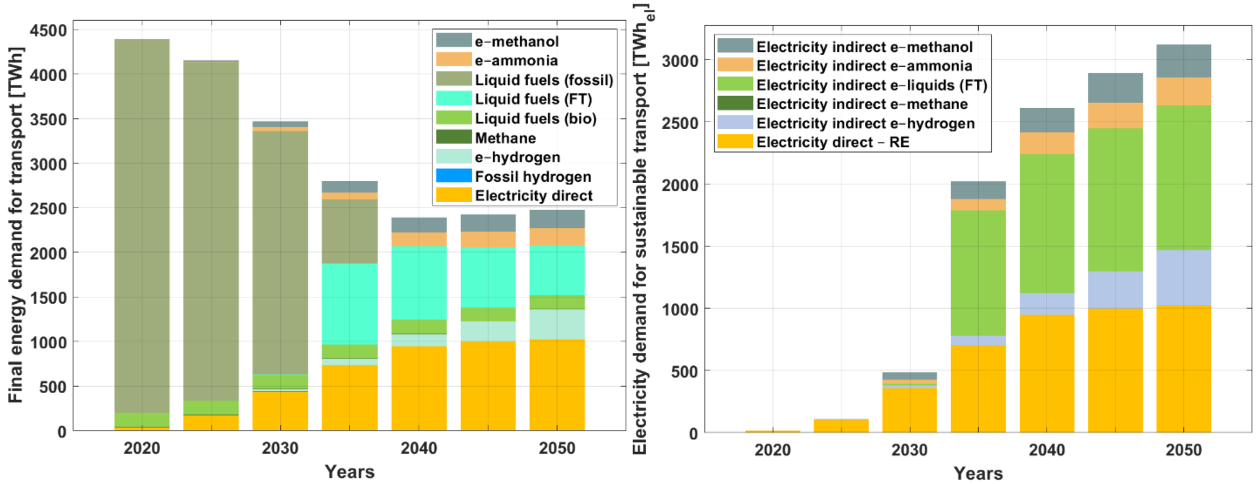


Figure C2.9: Final energy demand for transport (left) and electricity demand for sustainable transport (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

As renewable electricity use in the industry sector grows, fossil fuels are replaced by green e-hydrogen and other e-fuels and e-chemicals in 2040, as shown in Figure C2.10. Electrification of the industry sector creates an electricity demand of about 2200 TWh$_{el}$ by 2050. The massive demand for green e-hydrogen kicks in from 2030 onwards up until 2050, mainly for the production of sustainable e-chemicals, as indicated in Figure C2.10.

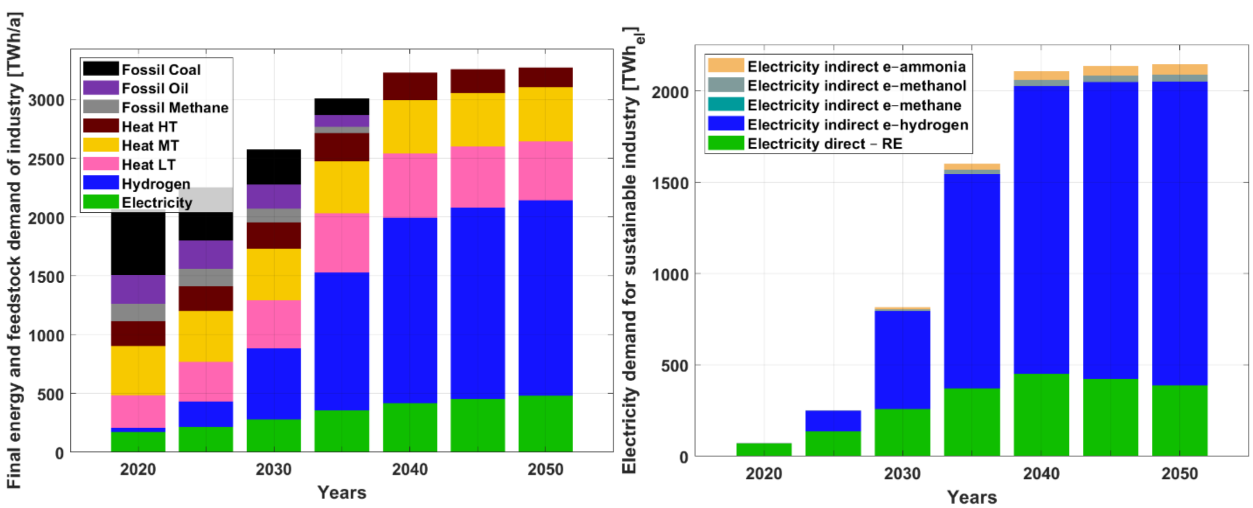


Figure C2.10: Energy and feedstock demand for industry[1] (left) and electricity demand for sustainable industry (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Fuels, Chemicals and Carbon Supply

An essential aspect in the transition of the transport sector towards higher electrification completely based on high shares of renewable energy is the production of synthetic fuels and chemicals: e-hydrogen, e-methane, Fischer-Tropsch fuels, e-methanol and e-ammonia. As indicated in Figure C2.11, fossil fuels are completely replaced by a combination of sustainable fuels and chemicals by 2040. Additionally, CO_2 direct air capture, which is vital in the production of synthetic e-fuels, supplies up to nearly 430 $MtCO_2$ by 2050,

[1] Including the ambient heat for heat pumps

as shown in Figure C2.12. Some CO_2 buffer storage, which stores CO_2 from DAC systems to be utilised in the production of e-fuels and e-chemicals, complements CO_2 supply in the energy system.

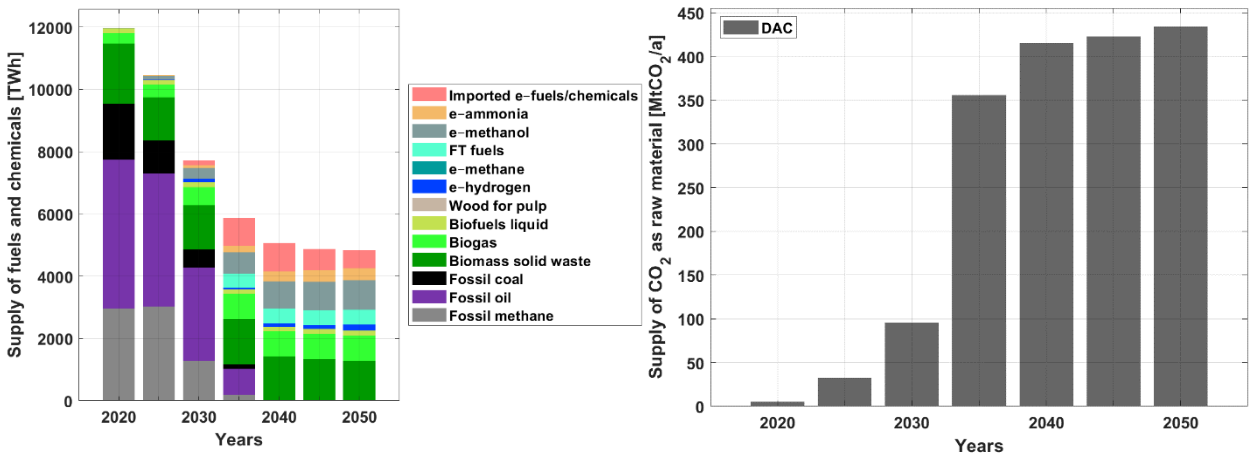


Figure C2.11: Supply of fuels and chemicals (left) and CO_2 as raw material (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Costs and Investments

The total annual costs decline from about 620 b€ in 2025 to about 480 b€ in 2050 through the transition period and are well distributed across the major sectors of power, heat, transport and industry across the EU. As indicated in Figure C2.12, 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 the EU much faster.

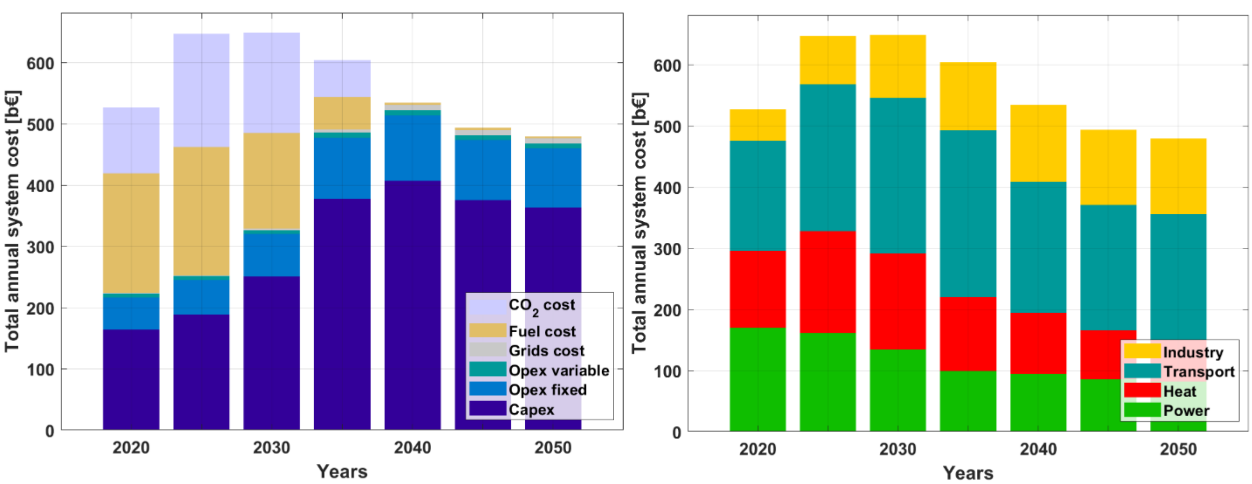


Figure C2.12: Annual energy system costs composed of different parameters (left) and of different sectors (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

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 source[55]. As indicated in Figure C2.13, levelised cost of energy remains stable at around 52 €/MWh by 2050 and is increasingly dominated by capital costs as fuel costs continue to phase out through the transition period, which could mean increased self-reliance in terms of energy for the EU by 2040. Capital costs are well spread across a range of technologies with major investments for solar PV, wind power, batteries, heat pumps, and synthetic e-fuel and e-chemicals conversion technologies up to 2050, as shown in Figure C2.13.

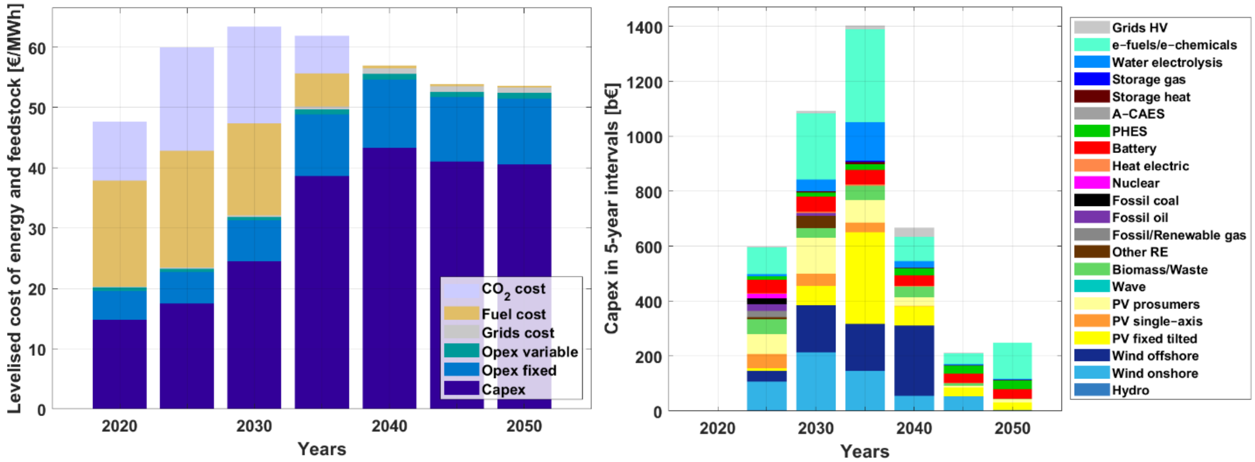


Figure C2.13: Levelised cost of energy (left) and capital expenditures in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Capital expenditures are well spread across a range of power generation technologies with the majority share in wind power up to 2030, beyond which solar PV dominates investments up to 2050, as shown in Figure C2.14. The LCOE of the power sector decreases substantially from around 84 €/MWh in 2020 to around 41 €/MWh by 2050, as shown in Figure C2.14. LCOE is predominantly comprised of Capex as fuel costs decline through the transition.

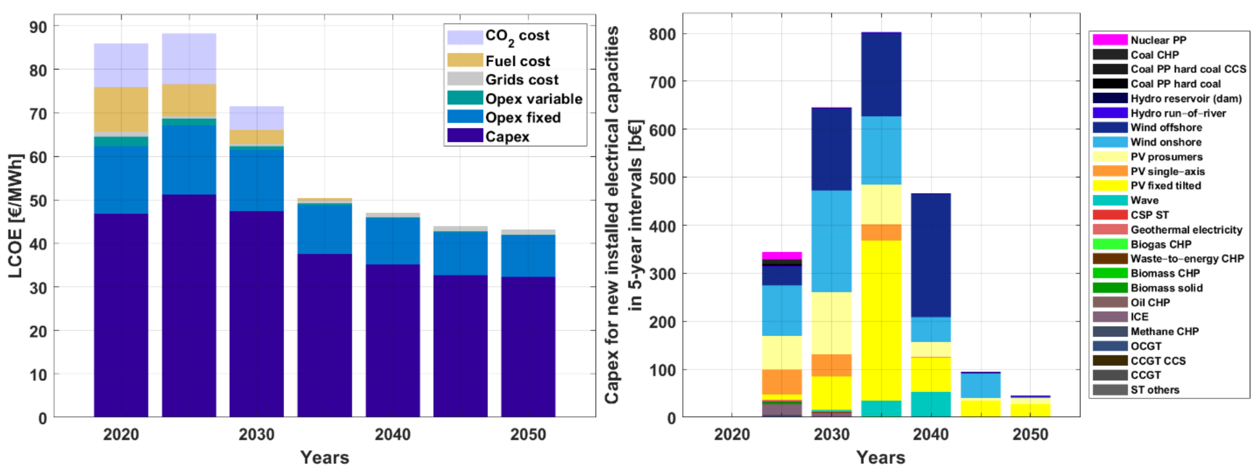


Figure C2.14: Levelised cost of electricity (left) and capital expenditures for electricity generation in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

Investments in the heat sector are mainly in heat pumps and some shares in biomass heating up to 2050, also shown in Figure C2.15. 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. The LCOH of the heat sector, after an initial increase, declines from over 48 €/MWh in 2025 to around 23 €/MWh by 2050, as shown in Figure C2.15. The LCOH is predominantly comprised of Capex as fuel costs decline through the transition. Rapid electrification and improvements in building renovation rates with efficiency gains enable the LCOH to decline in a stable manner up to 2050.

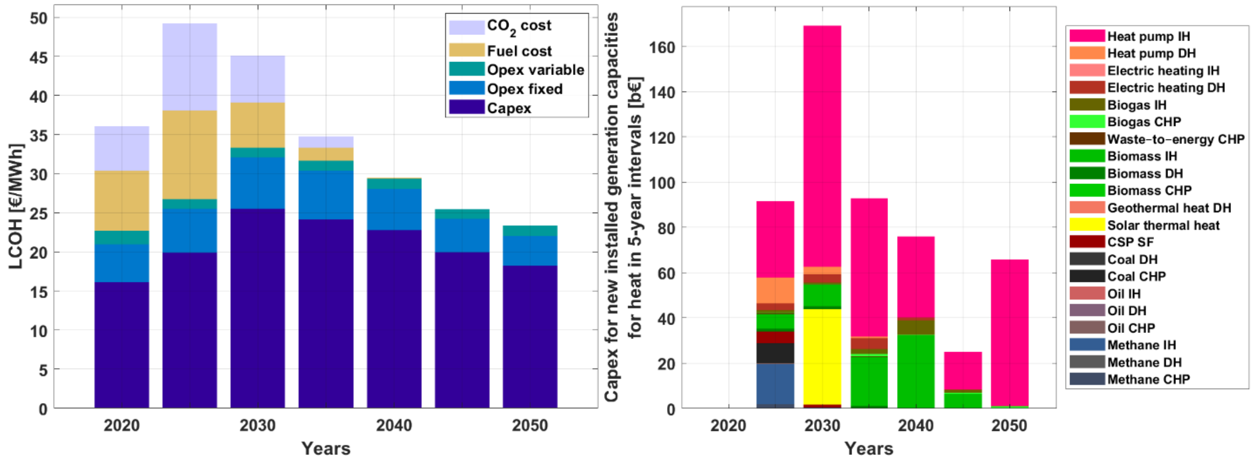


Figure C2.15: Levelised cost of heat (left) and capital expenditures for heat generation in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

The total annual energy costs for transport decline to about 140 b€ by 2050, as shown in Figure C2.16. During the same period, passenger transportation services increase by more than 50% and freight services by 25%, while energy demand decreases. This is primarily due to efficiency gains through electrification of the sector resulting in lower annual system costs. Furthermore, annual system costs transit from being heavily dominated by fuel costs in 2020 to a very diverse share of costs across various technologies for electricity, synthetic e-fuels and sustainable biofuel production by 2050. Similarly, the final energy cost of energy and feedstock for the industry sector declines to about 65 b€ by 2050, driven by process changes as shown in Figure C2.16.

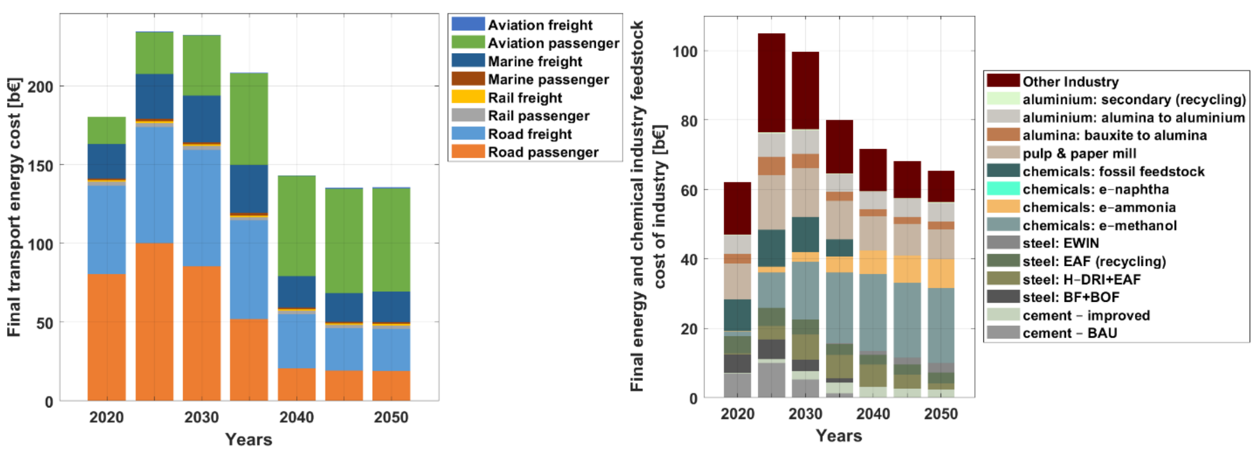


Figure C2.16: Final transport energy costs for different modes (left) and final energy and chemicals feedstock costs of different industries and processes (right) during the energy transition from 2020 to 2050 across the EU (RES-2040).

CO_2 Emissions

The results of the energy transition towards high shares of renewable energy indicate a sharp decline in CO_2 emissions, reaching almost zero by 2040, across the power, heat, transport and industry sectors across the EU as shown in Figure C2.18. The power and heat sectors undergo a deep defossilisation, whereas for the transport sector it is rather slow. In the industry sector, CO_2 emissions reduction are rather slow with some residual emissions from limestone use in the cement industry from 2040. However, this emission is mitigated through natural climate or capture and storage solutions.

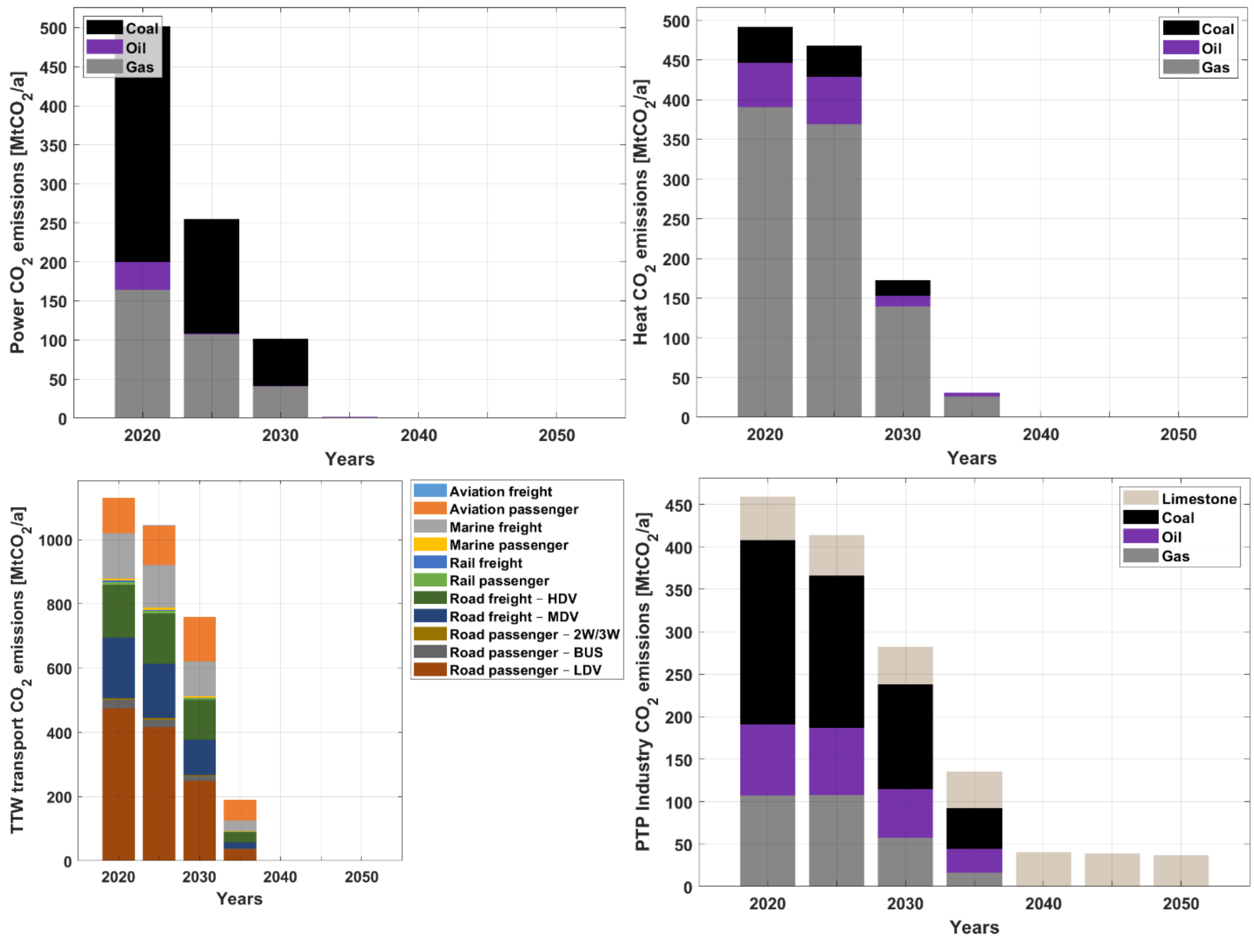


Figure C2.17: CO_2 emissions in the power sector from different fuels (top left), CO_2 emissions in the heat sector from different fuels (top right), CO_2 emissions in the transport sector from different modes (bottom left) and CO_2 emissions in the industry sector from different fuels (bottom right), during the energy transition from 2020 to 2050 across the EU. Tank to Wheel (TTW) and Plant to Product (PTP) considers CO_2 emissions from readily available fuels and does not consider CO_2 emissions from the upstream production and delivery of fuels (RES-2040).

CO_2 emissions from the power sector decline through the transition from around 500 $MtCO_2$/a in 2020 to zero by 2035 as shown in Figure C2.17. Similarly, CO_2 emissions from the heat sector decline through the transition from over 480 $MtCO_2$/a in 2020 to zero by 2040 as shown in Figure C2.17. CO_2 emissions from the transport sector decline through the transition from around 1100 $MtCO_2$/a in 2020 to zero by 2040 and CO_2 emissions from the industry sector decline through the transition from over 450 $MtCO_2$/a in 2020 to nearly zero by 2040, with some residual emissions from limestone, as shown in Figure C2.17.

Regional Outlook

The regional distribution of electricity generation capacities, electricity generation, heat generation capacities, heat generation, electricity storage output, heat storage output, supply of fuels and chemicals across the EU, and electricity exchange across the European network are illustrated in the Figures C2.18 to C2.25. Further information during the different years of the transition for the 27 EU member states is provided in a supplementary data file.

Power generation capacities are distributed throughout the EU, with major shares of solar PV in the Southern member states, while wind power has major shares in the northern and western members states of the EU in 2050 (see Figure C2.18). PV prosumers are a relevant energy system feature in all member states. The total power generation capacity installed across the EU in the RES-2040 scenario in 2050 is 4543 GW.

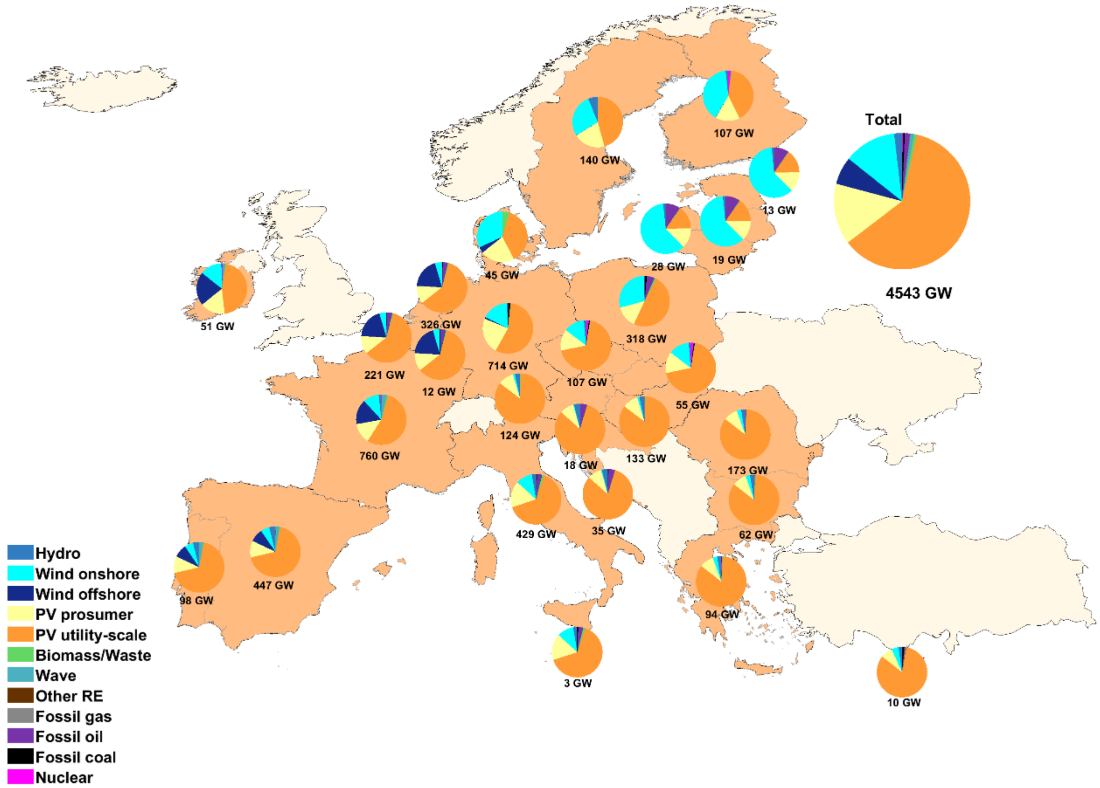


Figure C2.18: Regional electricity generation capacities in 2050 across the EU (RES-2040).

Similarly, electricity generation shares vary across the EU, with total generation of 7911 TWh in the RES-2040 scenario in 2050. Solar PV generation shares dominate in the southern and western member states, while wind power has the major shares in the northern and Baltic member states (see Figure C2.19). PV prosumers are a relevant energy system feature in all member states. From an EU energy system point of view, the southern and northern member states have great complementarity in terms of resources.

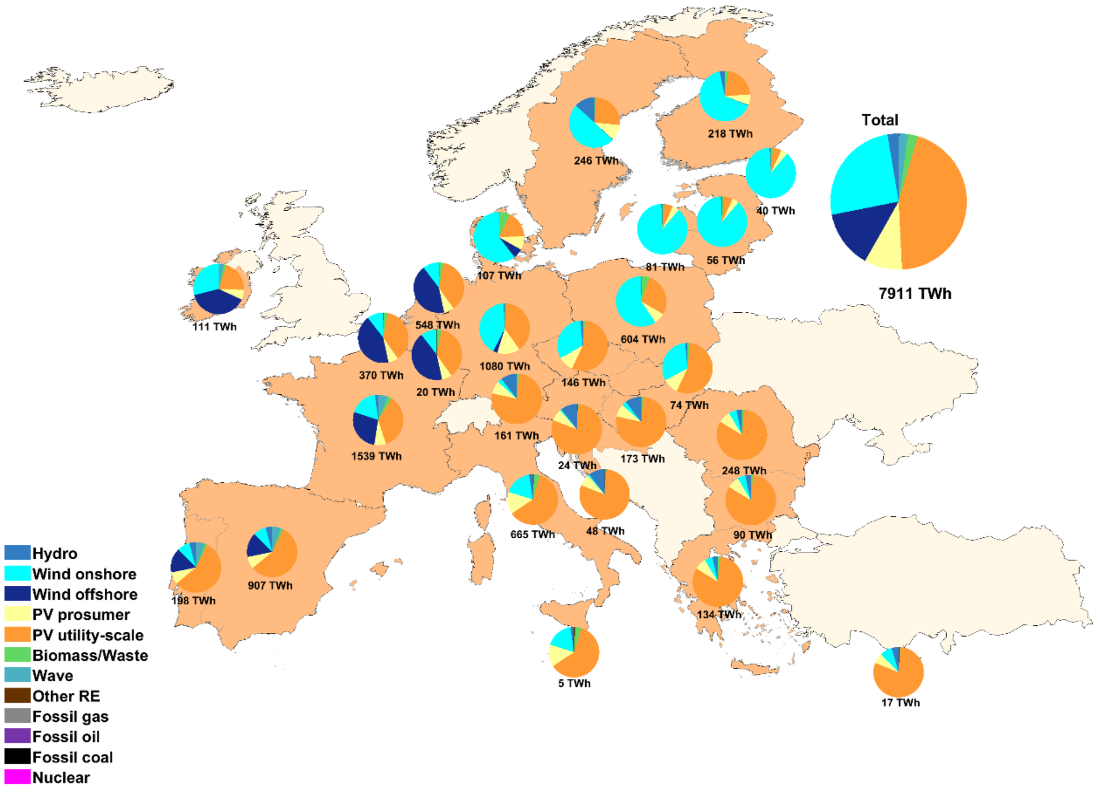


Figure C2.19: Regional electricity supply in 2050 across the EU (RES-2040).

Heat generation capacities are about 650 GW across the EU in the RES-2040 scenario in 2050 and well distributed across the member states. Heat pumps and electric heating are the major heat sources in 2050 and are predominant in the southern and western member states. While higher shares of bioenergy provide heat in the northern and Baltic states along with minor shares across the rest of the EU (see Figure C2.20).

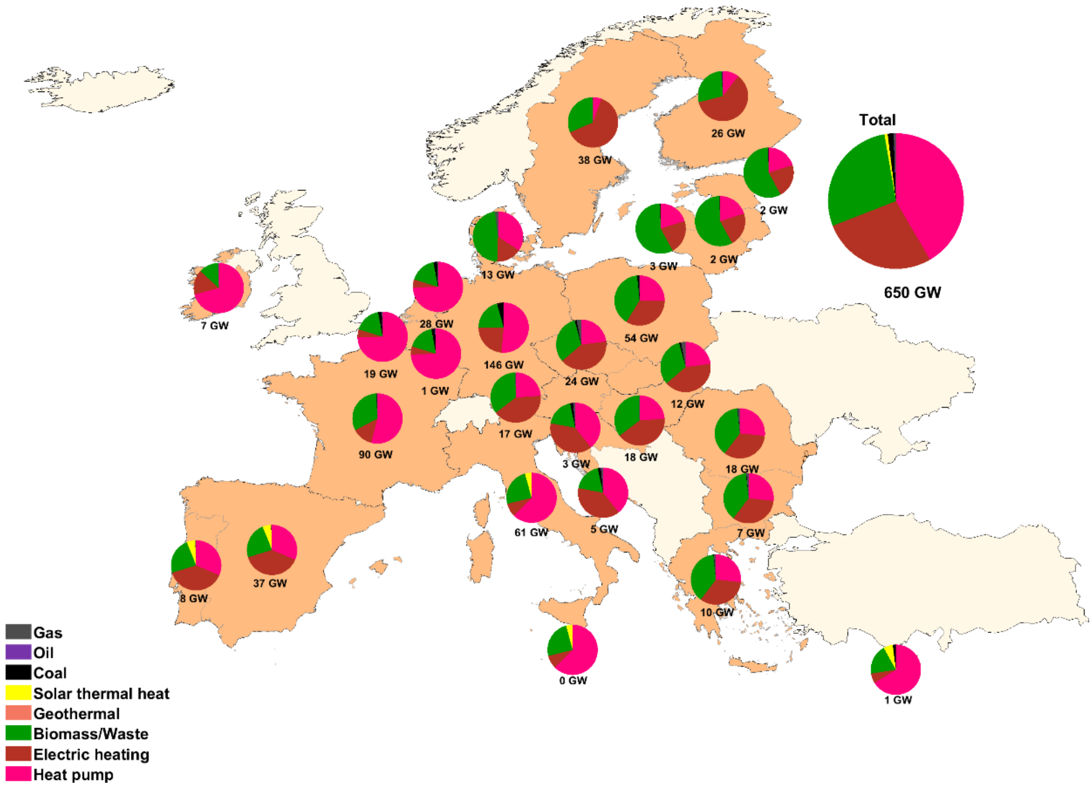


Figure C2.20: Regional heat generation capacities in 2050 across the EU (RES-2040).

Total heat generation across the EU is 2802 TWh in the RES-2040 scenario in 2050. Major share is from heat pumps and electric heating across most states, while bioenergy contributes most of the heating in the eastern and Baltic states of the EU (see Figure C2.21).

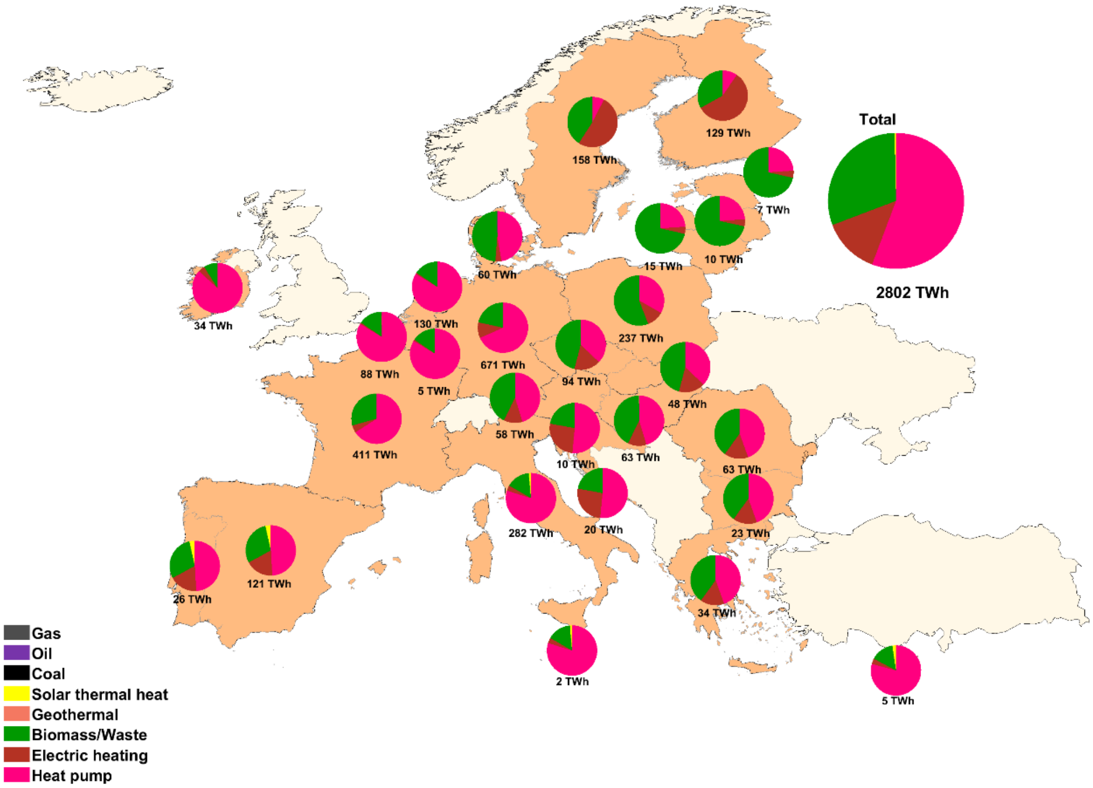


Figure C2.21: Regional heat supply in 2050 across the EU (RES-2040).

Batteries (prosumers and utility-scale) along with vehicle-to-grid emerge as the dominant electricity storage sources across the EU in 2050, with 1634 TWh of storage output in the RES-2040 scenario. Prosumer batteries dominate across the EU, with some shares of utility scale batteries, vehicle-to grid and pumped hydro energy storage across the EU (see Figure C2.22).

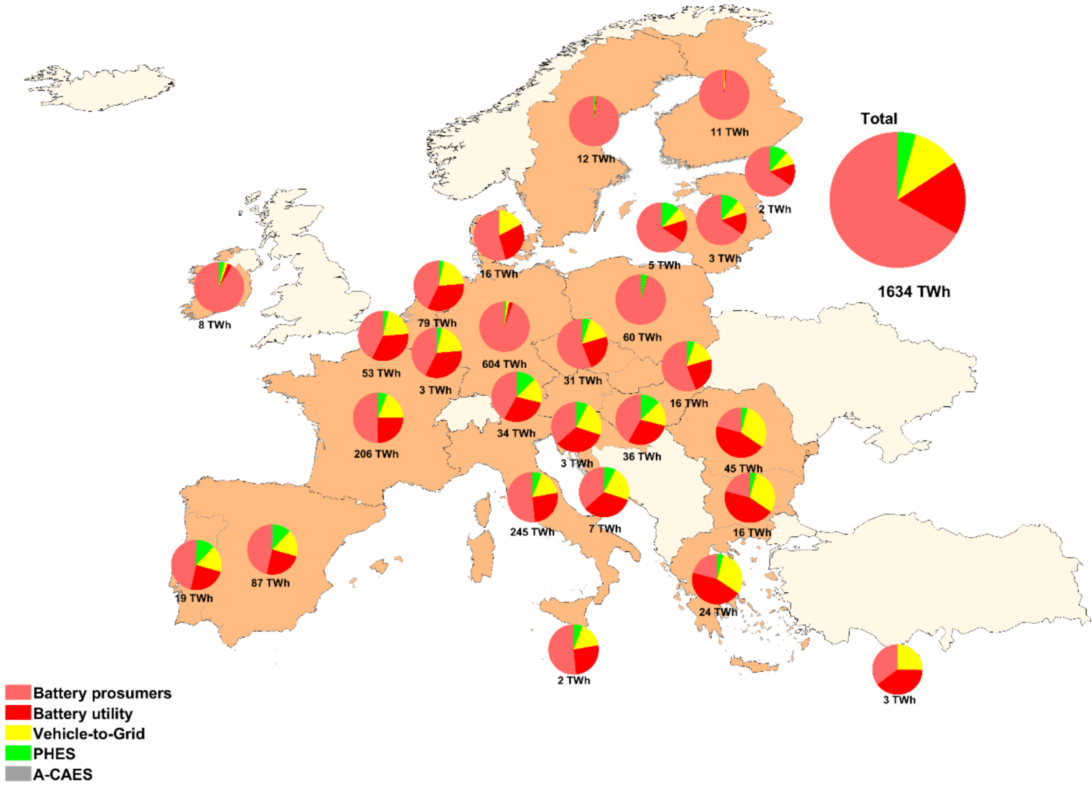


Figure C2.22: Regional electricity storage output in 2050 across the EU (RES-2040).

Heat storage output is 914 TWh in 2050 across the EU in the RES-2040 scenario. It is well distributed across the member states and hydrogen storage provides the bulk of the heat across members states in 2050. While thermal energy storage provides major shares of the heat in some member states with high temperature heat. Some shares of biomethane storage output contribute across the EU for seasonal heat (see Figure C2.23).

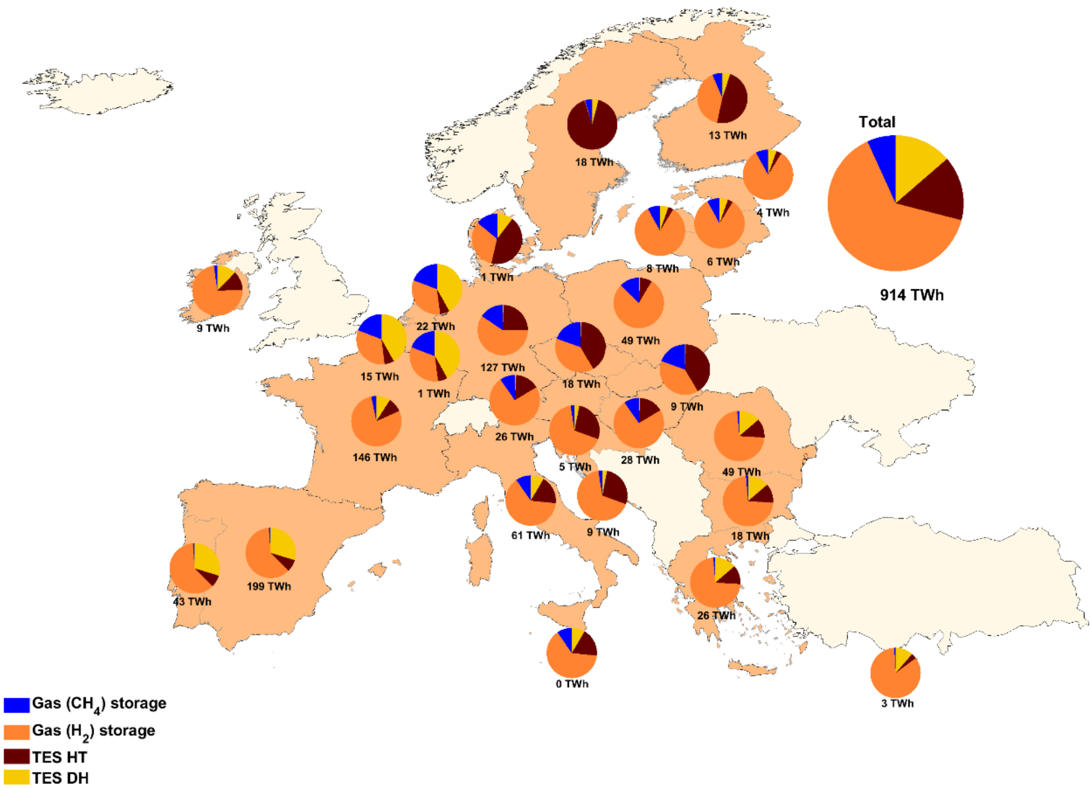


Figure C2.23: Regional heat storage output in 2050 across the EU (RES-2040).

Supply of fuels and chemicals is well distributed across the EU with 4938 TWh in the RES-2040 scenario in 2050. Waste and residual biomass contribute the major share of fuels, while e-fuels and e-chemicals are well distributed across the EU (see Figure C2.24). Imports of e-fuels and e-chemicals contribute over 10% of the cost optimal supply in the RES-2040 scenario in 2050 and are dominant in the states with major ports in the western states of the EU.

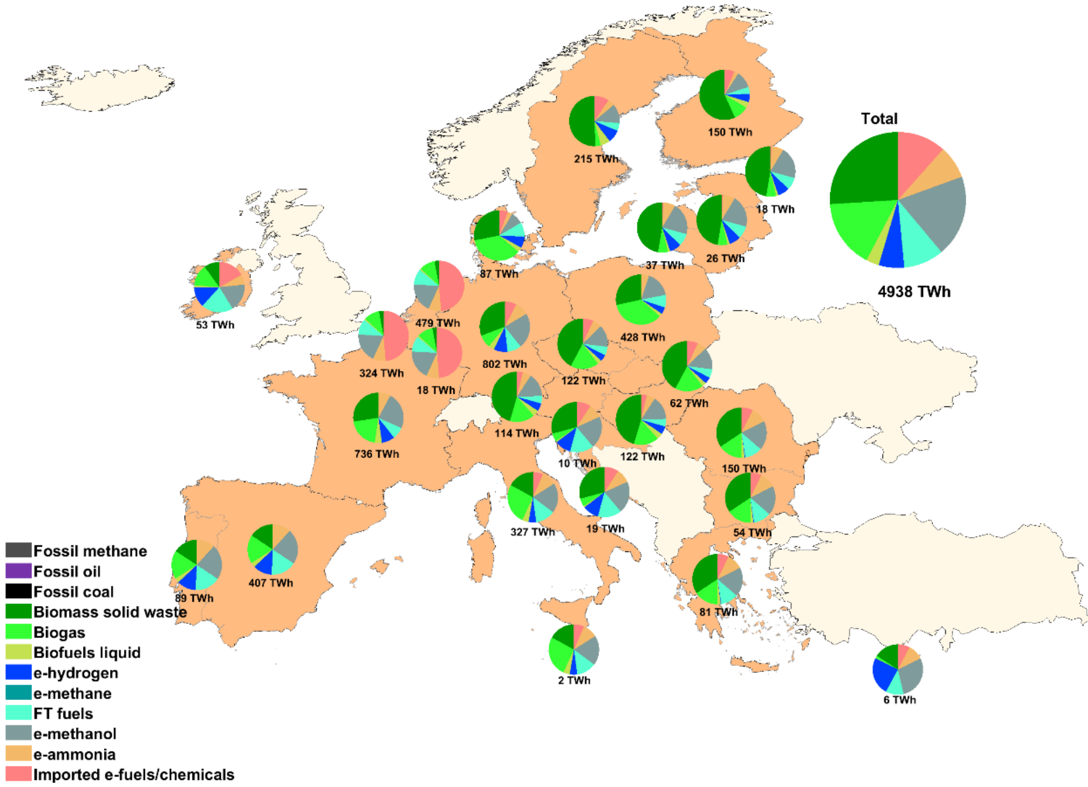


Figure C2.24: Regional fuels and chemicals supply in 2050 across the EU (RES-2040).

The electricity network is robust and rapidly developing across the EU and beyond covering Europe. With energy resources distributed across the region, electricity trade is 1308 TWh in 2050 across Europe in the RES-2040 scenario (see Figure C2.25), representing less than 17% of total electricity generation in EU. Net exporters and importers emerge across Europe to enable a cost optimal energy mix for the whole region.

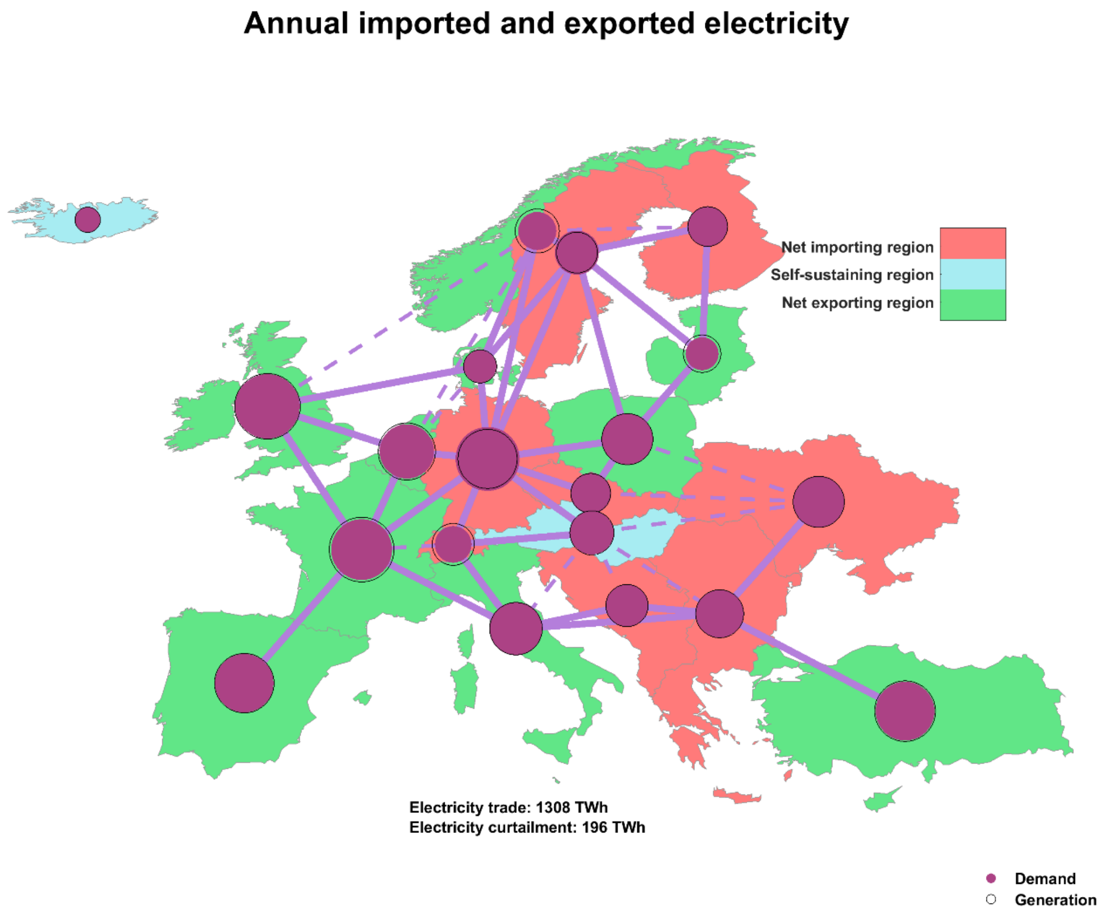


Figure C2.25: Regional electricity trade with net-importers and net-exporters in 2050 across Europe. Solid and dashed lines indicate used and not used interconnections, respectively (RES-2040).

The RES-2040 scenario results in a completely coupled energy system in 2040, which is largely based on renewable electricity and further develops to 2050, as shown in Figure C2.26. The energy system in the RES-2040 scenario is almost completely sector coupled and has plenty of flexibility options, in batteries for short-term storage, gas storage for seasonal variations and a mix of power-to-heat, power-to-gas, power-to-fuels and power-to-chemicals. The power, heat, transport and industry sectors have diversified energy sources.

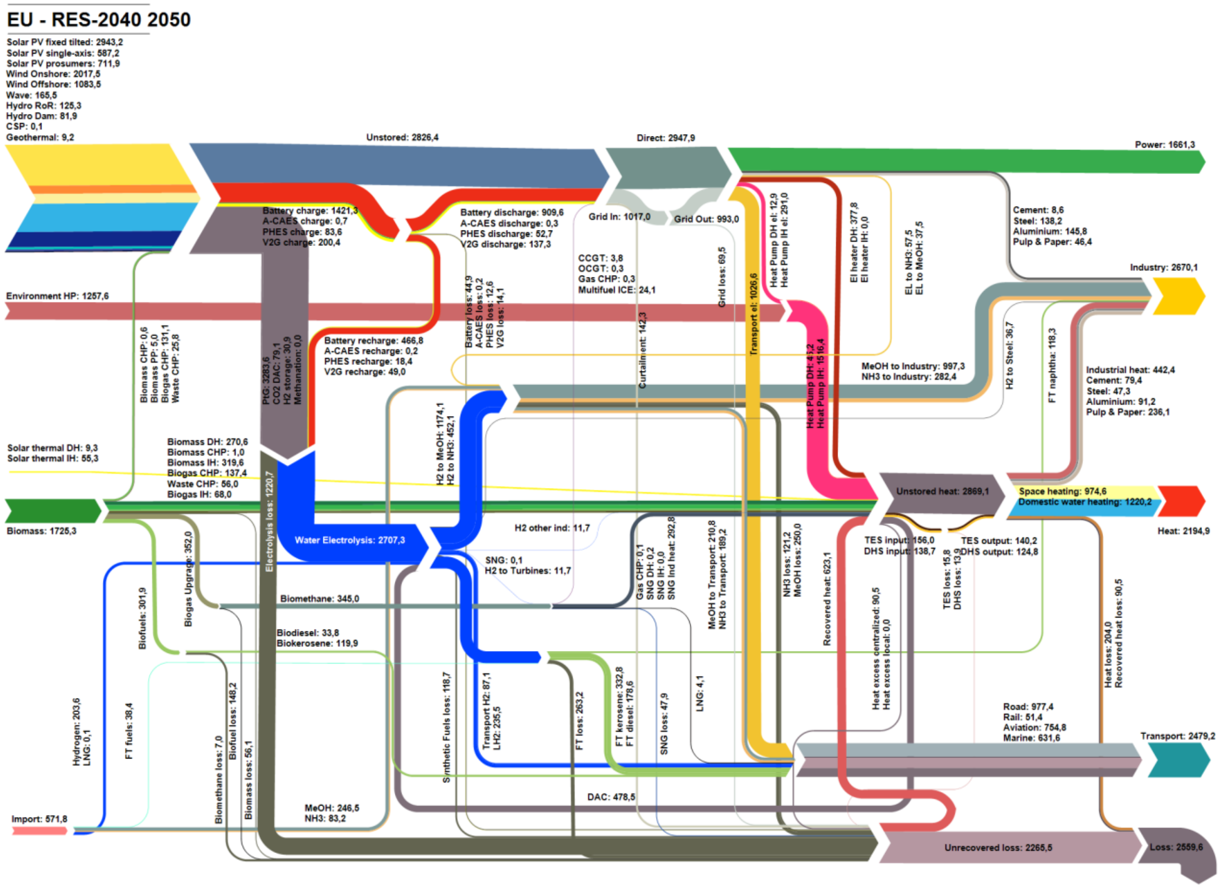


Figure C2.26: Energy flows of the EU energy system in 2050 (RES-2040).

C3. RES-2035 Scenario

Energy Demand

In the RES-2035 scenario, the uptake of renewables is relatively faster as compared to the other scenarios, which also influences the change in resource efficiency through rapid electrification. Efficiency measures such as improving building renovation rates, modal shift of transport towards electrified rail use and more conscious use of energy enable further gains in final and, consequently, primary energy. This eventually determines the levels of primary energy demand as shown in Figure C3.1.

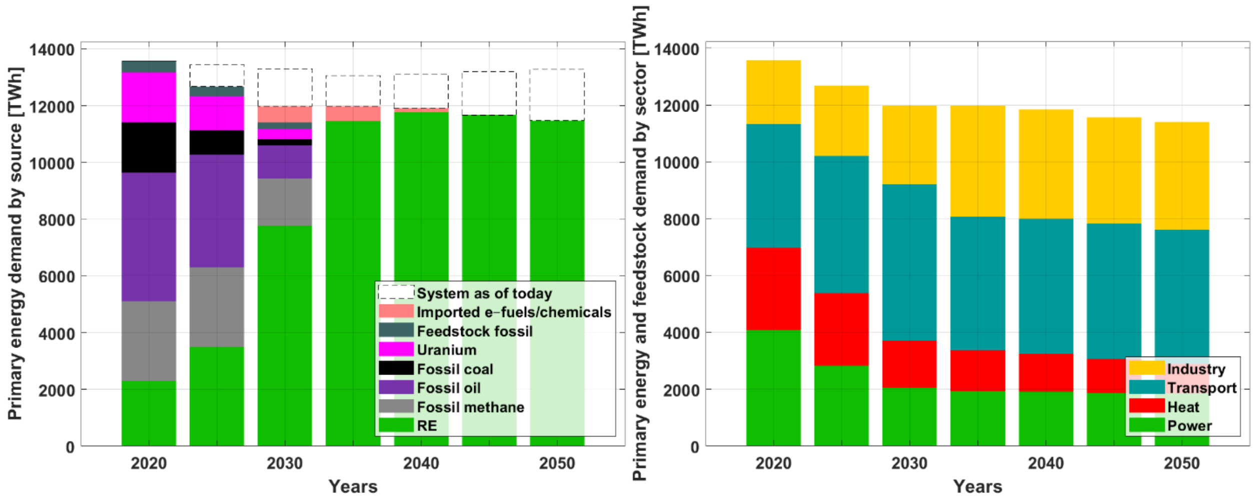
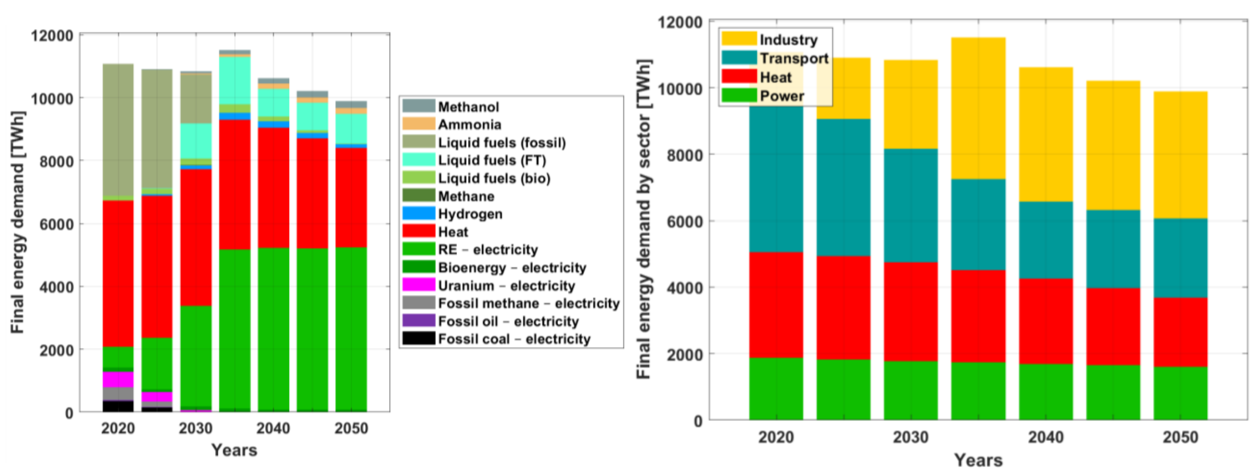


Figure C3.1: Primary energy demand according to sources (left) and on a sectoral basis (right), during the energy transition from 2020 to 2050 across the EU (RES-2035).

The primary energy demand decreases from over 13,750 TWh in 2020 to around 11,500 TWh by 2050 across the EU as shown in Figure C3.1. The gain in efficiencies compared to the 'system as of today' is due to electrification of the heat, transport and industry sectors, while the growth in demand for energy services continues. The final energy declines from about 11,000 TWh in2020 to just under 10,000 TWh in 2050, despite a high level of energy services, with peak in 2035 mainly for the production of e-fuels as shown in Figure C3.2. The different fuels that constitute the final energy demand[1] transition from mostly fossil fuels in 2020 to renewable electricity, heat, e-fuels and e-chemicals by 2035.



[1] Including the ambient heat for heat pumps

Figure C3.2: Final energy demand[1] according to sources (left) and on a sectoral basis (right), during the energy transition from 2020 to 2050 across the EU (RES-2035).

Sectoral Outlook

Energy supply is mainly through electricity and heat, as accelerated levels of electrification are achieved through the transition. An increasing amount of electricity generation is needed along with heat, storage and supply of fuels and chemicals and to cover the future energy demand.

Electricity

The electricity generation capacity across the EU satisfies demand from all energy sectors including power, heat, transport and industry. The total installed capacity grows massively from about 750 GW in 2020 to over 6000 GW by 2050 as shown in Figure C3.3. In the initial period of the transition, a larger share of wind power capacities is installed up to 2030, but in the later part of the transition solar PV dominates the shares of installed capacities reaching over 4500 GW by 2050. On the other hand, the shares of fossil fuels and nuclear power decline through the transition, with complete phaseout by 2035.

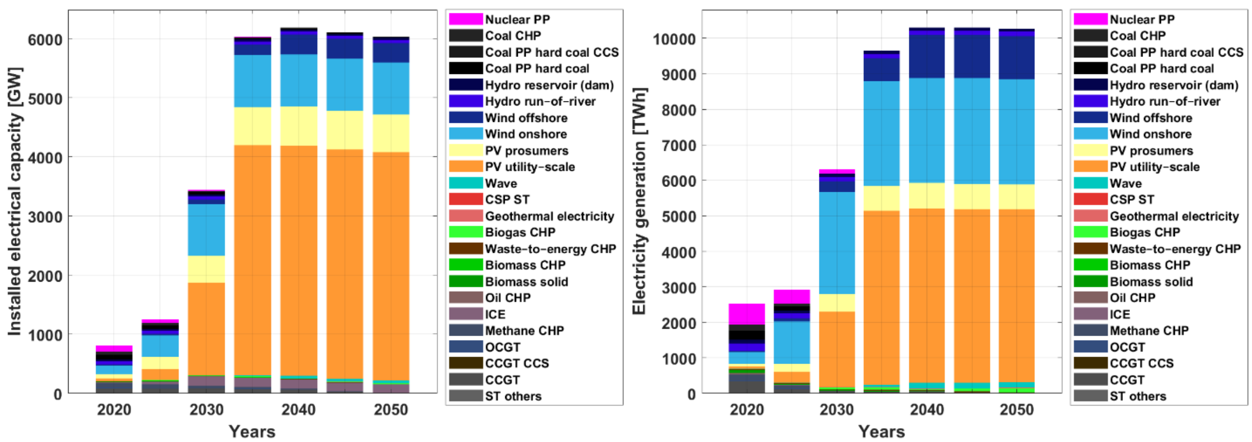


Figure C3.3: Technology-wise installed capacities (left) and technology-wise electricity generation (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Electricity generation from the various technologies to cover the demand of power, heat, transport and industry sectors is shown in Figure C3.3. Solar PV supply increases through the transition along with wind power, wave power and electricity from waste and residual biomass up to 2050.

Heat

In the heat sector, heat pumps, electric heating, and biomass-based heating constitute the majority of installed capacity by 2050, also shown in Figure C3.4. A decrease in total installed capacity of heating technologies occurs mainly due to efficiency gains with heat pumps and electric heating, as fossil fuels recede from the energy system. The key driver is the increase in building renovation rate to four times the current rate and linear increase of industrial heat efficiency to 3% per annum until 2030. Heat pumps play a significant role through the transition with a share of over 50% of heat generation by 2050 on both the district and individual levels, as indicated in Figure C3.4. On the other hand, fossil gas-based heating decreases through the transition from over 75% in 2020, to almost zero by 2050. Moreover, fossil fuels

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[1] Including the ambient heat for heat pumps

based heat generation declines through the transition period as coal-based combined heat and power (CHP) and district heating (DH) are replaced by heat generation from heat pumps, waste-to-energy CHP, biomass-based DH, and individual heating (IH).

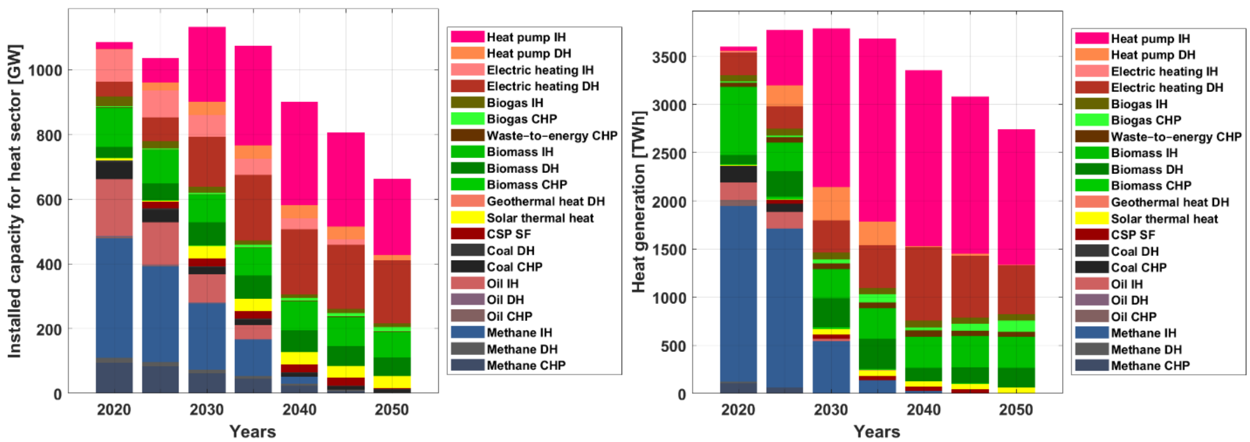

Figure C3.4: Technology-wise heat generation capacities (left) and technology-wise heat generation (right) during the energy transition from 2025 to 2050 across the EU (RES-2035).

Electricity, Heat and Gas Storage

Energy storage technologies play a critical role in enabling a secure energy supply across the EU, fully based on renewable energy across different sectors. The installed electricity storage capacity increases from just 0.4 TWh in 2020 to nearly 5 TWh by 2050, as shown in Figure C3.5. Utility-scale and prosumer batteries with major shares of vehicle-to-grid dominate, some PHES remains through the transition. Utility-scale and prosumer batteries contribute a major share of the electricity storage output with hydrogen and methane based output contributing beyond 2035, as highlighted by Figure C3.5. In addition, vehicle-to-grid, PHES contributes some shares through the transition.

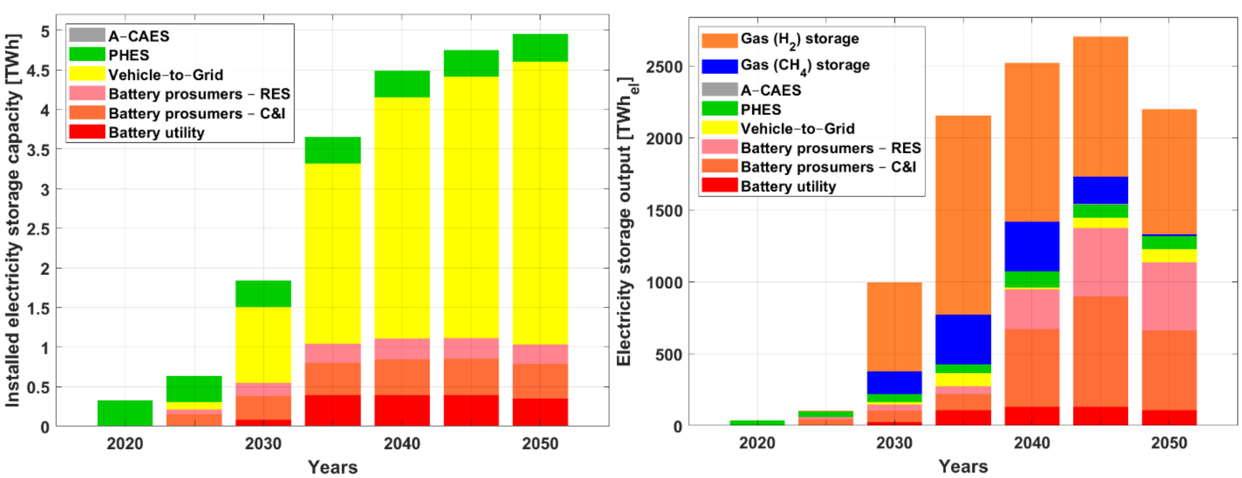

Figure C3.5: Installed electricity storage capacities (left) and electricity storage output (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Heat storage plays a vital role in ensuring that the heat demand is covered in all sectors. The installed heat storage grows substantially from 2030 onwards, installed capacities are dominated by gas storage (hydrogen and methane), as shown in Figure C3.6. This substantial capacity addition is mainly to provide seasonal storage across the EU covering the heat demand in the absence of fossil fuels. The present fossil gas storage capacity across the EU is around 1000 TWh[54], a doubling of this gas storage would be needed for an integrated energy system by 2035. Thermal energy storage emerges with heat storage output from 2030 until 2050, as shown in Figure C3.6. Hydrogen gas storage contributes a majority of the heat storage output from 2035 to 2050 along with some shares of biomethane, covering predominantly the seasonal demand, which is covered by fossil gas before 2030.

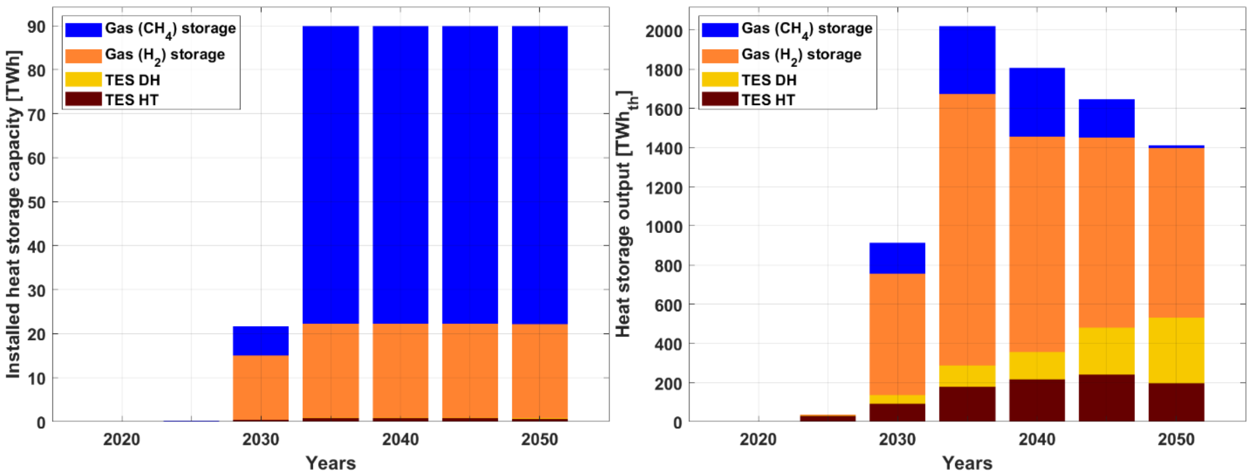

Figure C3.6: Heat storage installed capacities (left) and heat storage output (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Transport and Industry

The final energy demand of the transport sector across the EU is almost twice the energy demand from the power sector at around 4400 TWh in 2020. However, this demand declines through the transition to around 2000 TWh by 2050, as shown in Figure C3.7. This is achieved mainly due to efficiency gains brought about by electrification of the sector, mainly road transport. On the other hand, the energy and feedstock demand for the industry sector grows through the transition driven by production of sustainable chemicals and fuels, as shown in Figure C3.7.

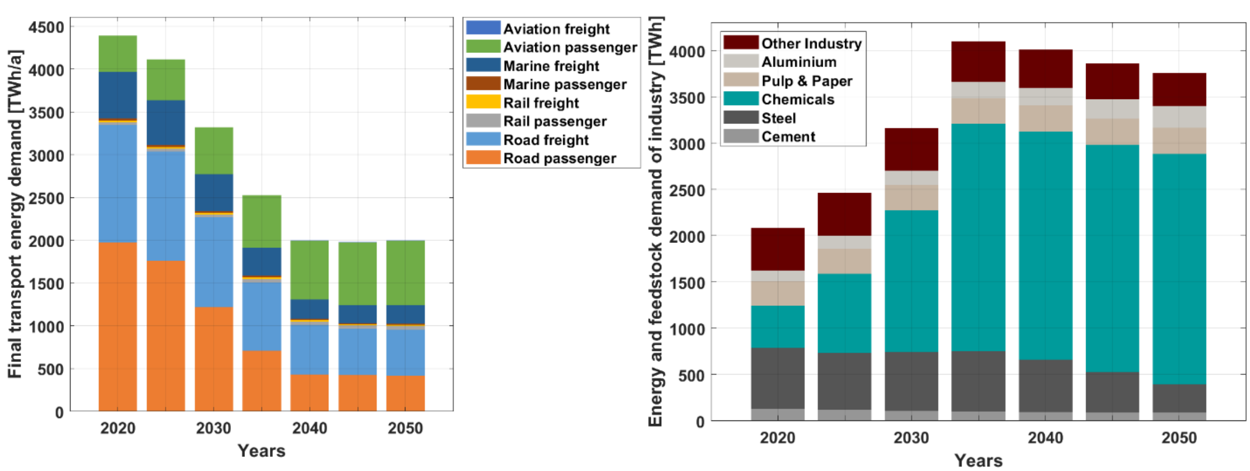

Figure C3.7: Final energy demand for transport (left) and energy and feedstock demand[1] for various industries (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

[1] Including the ambient heat for heat pumps

The road transport energy demand declines through the transition with massive gains from high levels of direct electrification, whereas the final energy demand increases for aviation in the last few years, not only due to a continuous transportation demand, but also driven by increasing specific energy demand due to production of synthetic e-fuels. Energy demand for the rail mode remains fairly stable through the transition, as it already at a high level of electrification across the EU. The development of the final energy demand for the different transport modes through the transition is shown in Figure C3.7. The low efficiency of the present transport sector is highlighted by the projection of an about 80% increase in transportation demand, but declining final energy demand for the transport sector.

Electrification of Heat, Transport and Industry Sectors

The heat, transport and industry sectors undergo a significant transformation in the course of the energy transition, as high levels of electrification (direct and indirect) lead to higher demand for electricity and a rapid decline in demand for fossil fuels.

The share of electricity in the final energy demand for heat increases substantially with about 2100 TWh by 2050, while the share of fossil fuels in the final energy demand declines to zero by 2035 from nearly 2400 TWh in 2020, as shown in Figure C3.8.

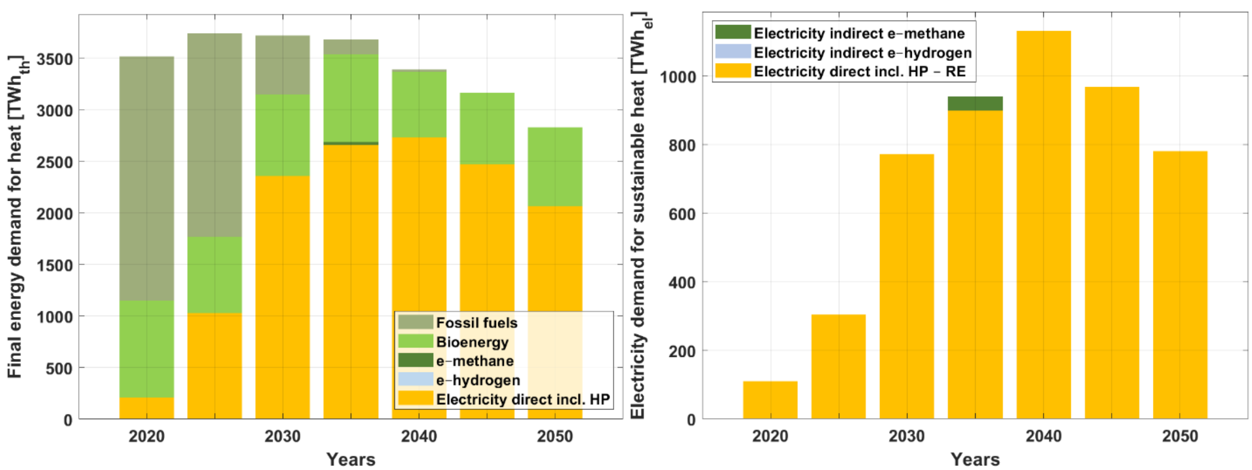

Figure C3.8: Final energy demand for heat[1] (left) and electricity demand for sustainable heat (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Electricity demand to provide sustainable heat increases through the transition to around 780 TWh_{el} by 2050, with a peak of over 1100 TWh_{el} in 2040.

Fossil fuels consumption in the transport sector across the EU is seen to decline through the transition from about 95% in 2020 to zero by 2035. On the other hand, liquid fuels produced by renewable electricity contribute around 30% of final energy demand in 2050. In addition, hydrogen constitutes around 15% of final energy demand in 2050 along with e-methanol and e-ammonia, as shown in Figure C3.9. Sustainable biofuels from waste and residual biomass contribute some shares as part of renewable liquid fuels. Electrification of the transport sector creates an electricity demand of about 4200 TWh_{el} by 2050. In the initial periods demand is driven by electrification of road transport, while marine and aviation drive the electricity demand for e-fuels synthesis in 2030s and 2040s, as the massive demand for synthetic e-chemicals and liquid e-fuels kicks in from 2030 onwards up until 2050, as indicated in Figure C3.9.

[1] Including the ambient heat for heat pumps

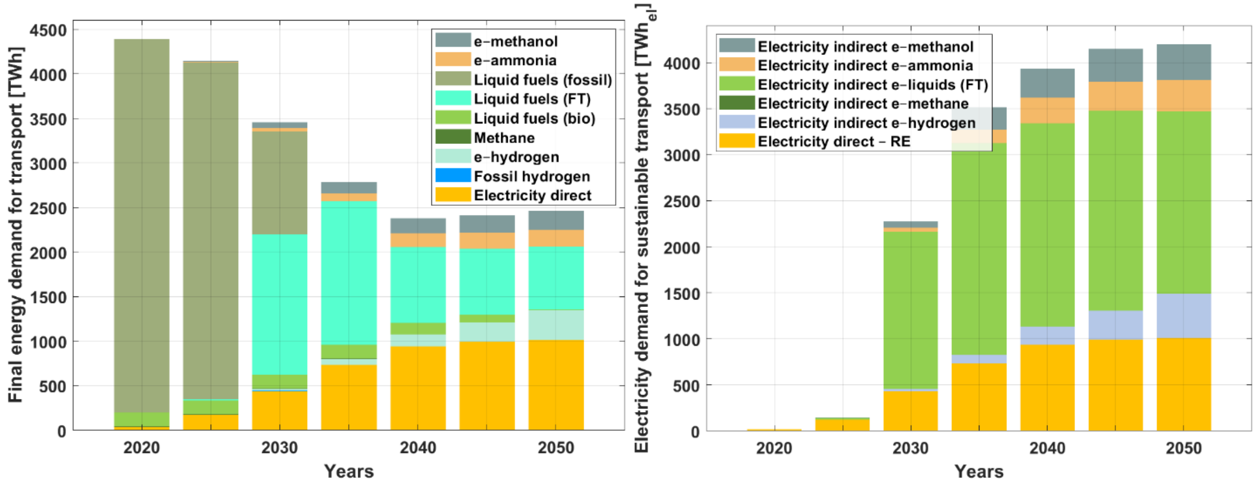

Figure C3.9: Final energy demand for transport (left) and electricity demand for sustainable transport (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

As renewable electricity use in the industry sector grows, fossil fuels are replaced by green e-hydrogen and other e-fuels and e-chemicals in 2035 and beyond, as shown in Figure C3.10. Electrification of the industry sector creates an electricity demand of about 2600 TWh_{el} by 2050. The massive demand for green e-hydrogen kicks in from 2030 onwards up until 2050, mainly for the production of sustainable e-chemicals, as indicated in Figure C3.10.

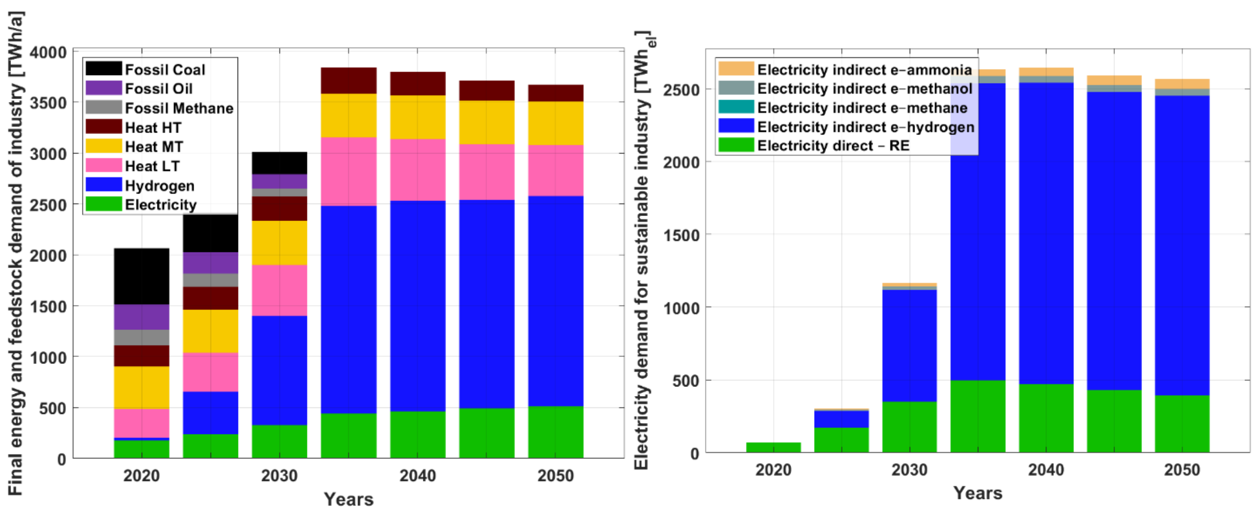

Figure C3.10: Energy and feedstock demand for industry[1] (left) and electricity demand for sustainable industry (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Fuels, Chemicals and Carbon Supply

An essential aspect in the transition of the transport sector towards higher electrification completely based on high shares of renewable energy is the production of synthetic fuels and chemicals: e-hydrogen, e-methane, Fischer-Tropsch fuels, e-methanol and e-ammonia. As indicated in Figure C3.11, fossil fuels are completely replaced by a combination of sustainable fuels and chemicals by 2035. Additionally, CO_2 direct air capture, which is vital in the production of synthetic e-fuels, supplies up to over 600 $MtCO_2$ by 2050, as

[1] Including the ambient heat for heat pumps

shown in Figure C3.11. Some CO_2 buffer storage, which stores CO_2 from DAC systems to be utilised in the production of e-fuels and e-chemicals, complements CO_2 supply in the energy system.

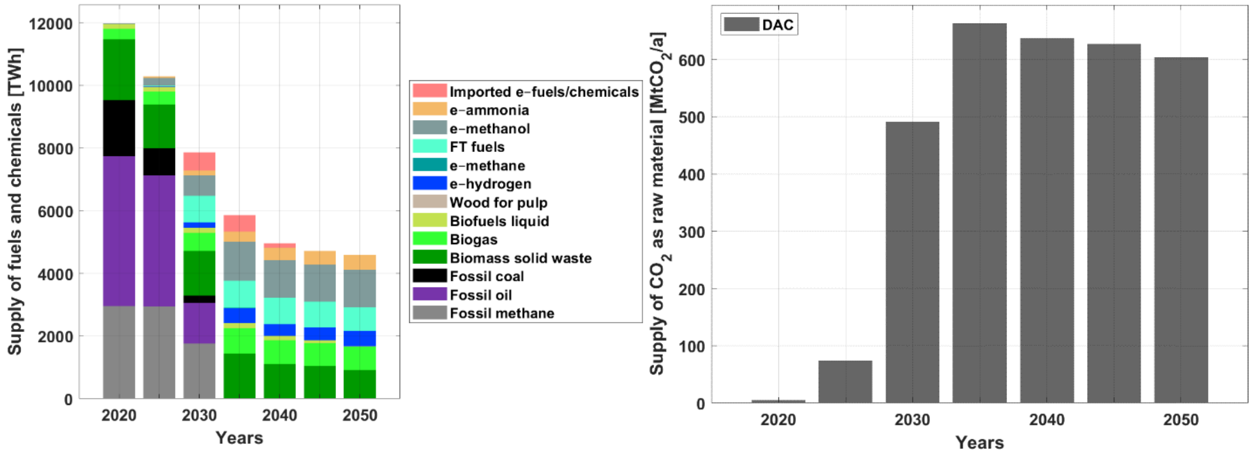

Figure C3.11: Supply of fuels and chemicals (left) and CO_2 as raw material (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Costs and Investments

The total annual costs decline from about 720 b€ in 2030 to about 550 b€ in 2050 through the transition period and are well distributed across the major sectors of power, heat, transport and industry across the EU. As indicated in Figure C3.12, 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 the EU rapidly.

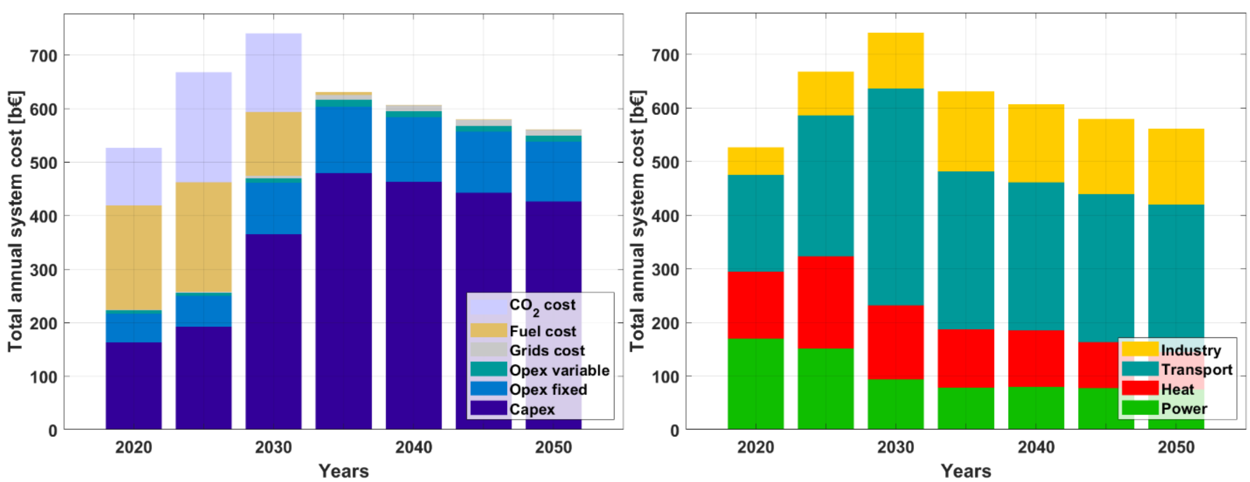

Figure C3.12: Annual energy system costs composed of different parameters (left) and of different sectors (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

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 source[55]. As indicated in Figure C3.13, levelised cost of energy remains stable at around 62 €/MWh by 2050 and is increasingly dominated by capital costs as fuel costs continue to phase out through the transition period, which could mean increased self-reliance in terms of energy for the EU by 2035. Capital costs are well spread across a range of technologies with major investments for solar PV, wind power, batteries, heat pumps, and synthetic e-fuel and e-chemicals conversion technologies up to 2050, as shown in Figure C3.13.

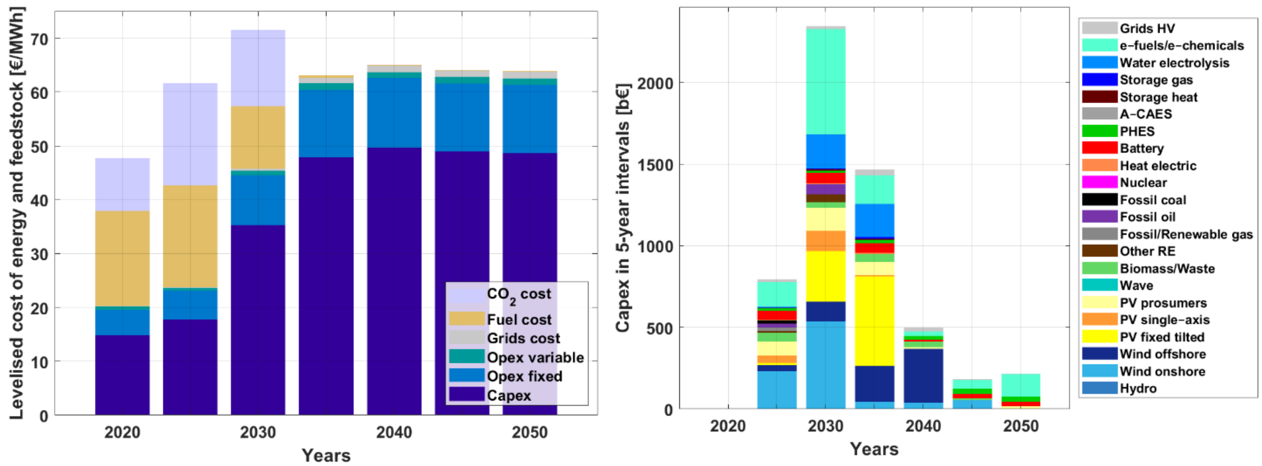

Figure C3.13: Levelised cost of energy (left) and capital expenditures in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Capital expenditures are well spread across a range of power generation technologies with the majority share in wind power up to 2030, beyond which solar PV dominates investments up to 2035, as shown in Figure C3.14. The LCOE of the power sector decreases substantially from around 84 €/MWh in 2020 to around 41 €/MWh by 2050, as shown in Figure C3.14. LCOE is predominantly comprised of Capex as fuel costs decline through the transition.

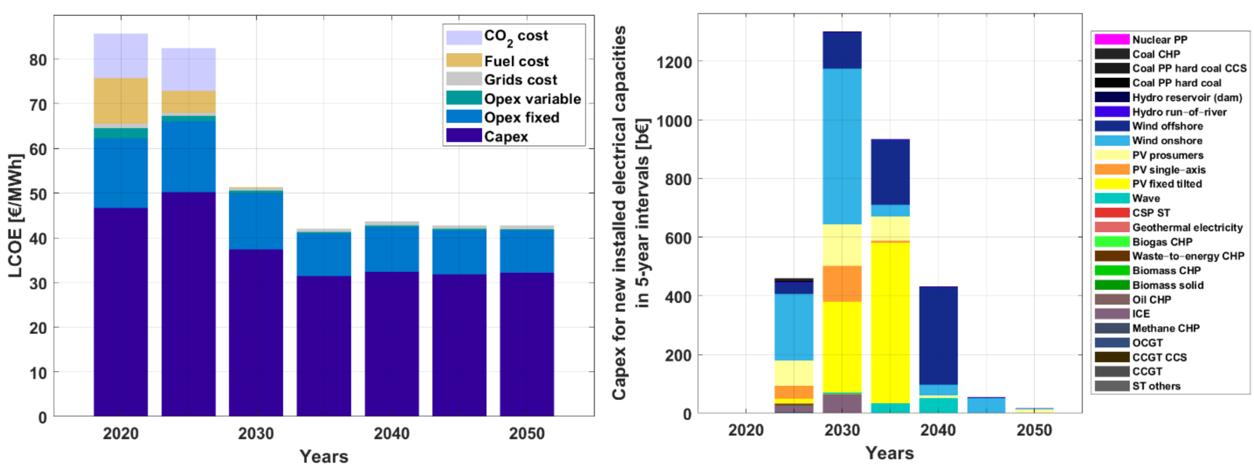

Figure C3.14: Levelised cost of electricity (left) and capital expenditures for electricity generation in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

Investments in the heat sector are mainly in heat pumps and some shares in biomass heating up to 2050, also shown in Figure C3.15. The steep increase in heat pump investments in the initial five-year period and 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. The LCOH of the heat sector, after an initial increase, declines from about 50 €/MWh in 2025 to around 27 €/MWh by 2050, as shown in Figure C3.15. The LCOH is predominantly comprised of Capex as fuel costs decline through the transition. Rapid electrification and improvements in building renovation rates with efficiency gains enables the LCOH to decline in a stable manner up to 2050.

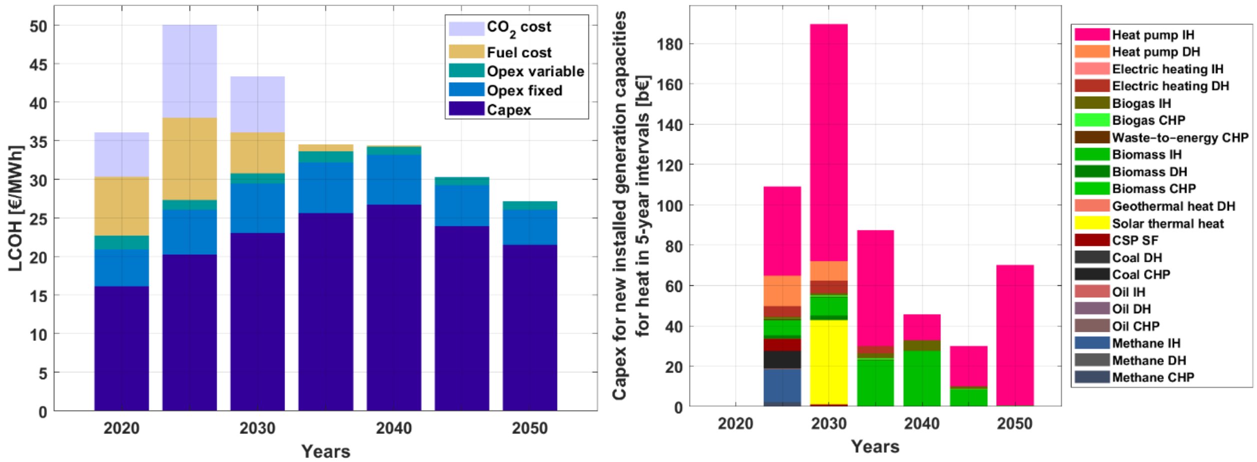

Figure C3.15: Levelised cost of heat (left) and capital expenditures for heat generation in five-year intervals (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

The total annual energy costs for transport after initial increase, decline to about 170 b€ by 2050, as shown in Figure C3.16. During the same period, passenger transportation services increase by more than 50% and freight services by 25%, while energy demand decreases. This is primarily due to efficiency gains through electrification of the sector resulting in lower annual system costs. Furthermore, annual system costs transit from being heavily dominated by fuel costs in 2020 to a very diverse share of costs across various technologies for electricity, synthetic e-fuels and sustainable biofuel production by 2035 and beyond. Similarly, the final energy cost of energy and feedstock for the industry sector after initial increase, declines to about 90 b€ by 2050, driven by process changes as shown in Figure C3.16.

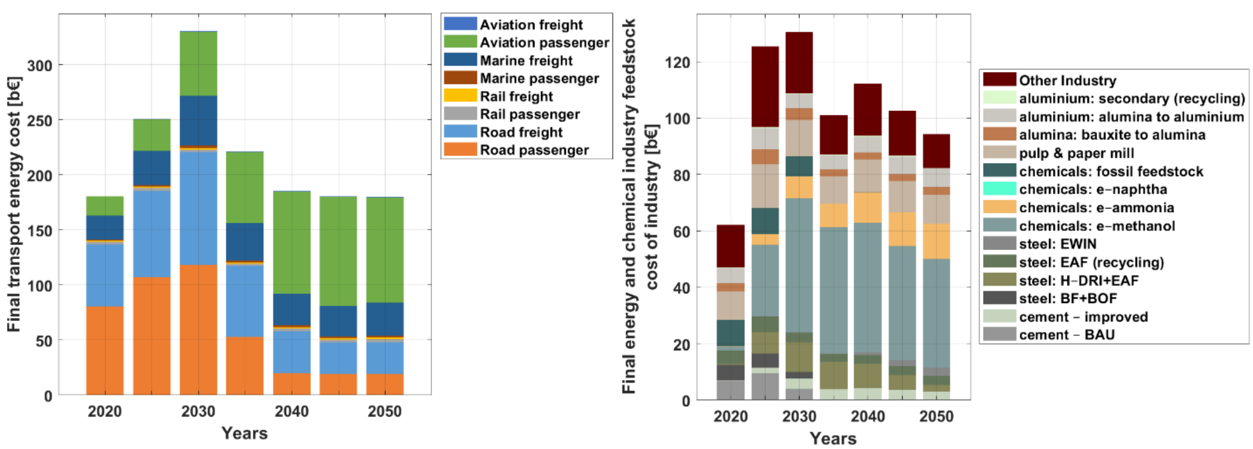

Figure C3.16: Final transport energy costs for different modes (left) and final energy and chemicals feedstock costs of different industries and processes (right) during the energy transition from 2020 to 2050 across the EU (RES-2035).

CO_2 Emissions

The results of the energy transition towards high shares of renewable energy indicate a sharp decline in CO_2 emissions, reaching almost zero by 2035, across the power, heat, transport and industry sectors across the EU as shown in Figure C3.18. The power and heat sectors undergo a deep defossilisation, whereas for the transport sector it is rather slow. In the industry sector, CO_2 emissions reduction are rather slow with some residual emissions from limestone use in the cement industry from 2035. However, this emission is mitigated through natural climate or capture and storage solutions.

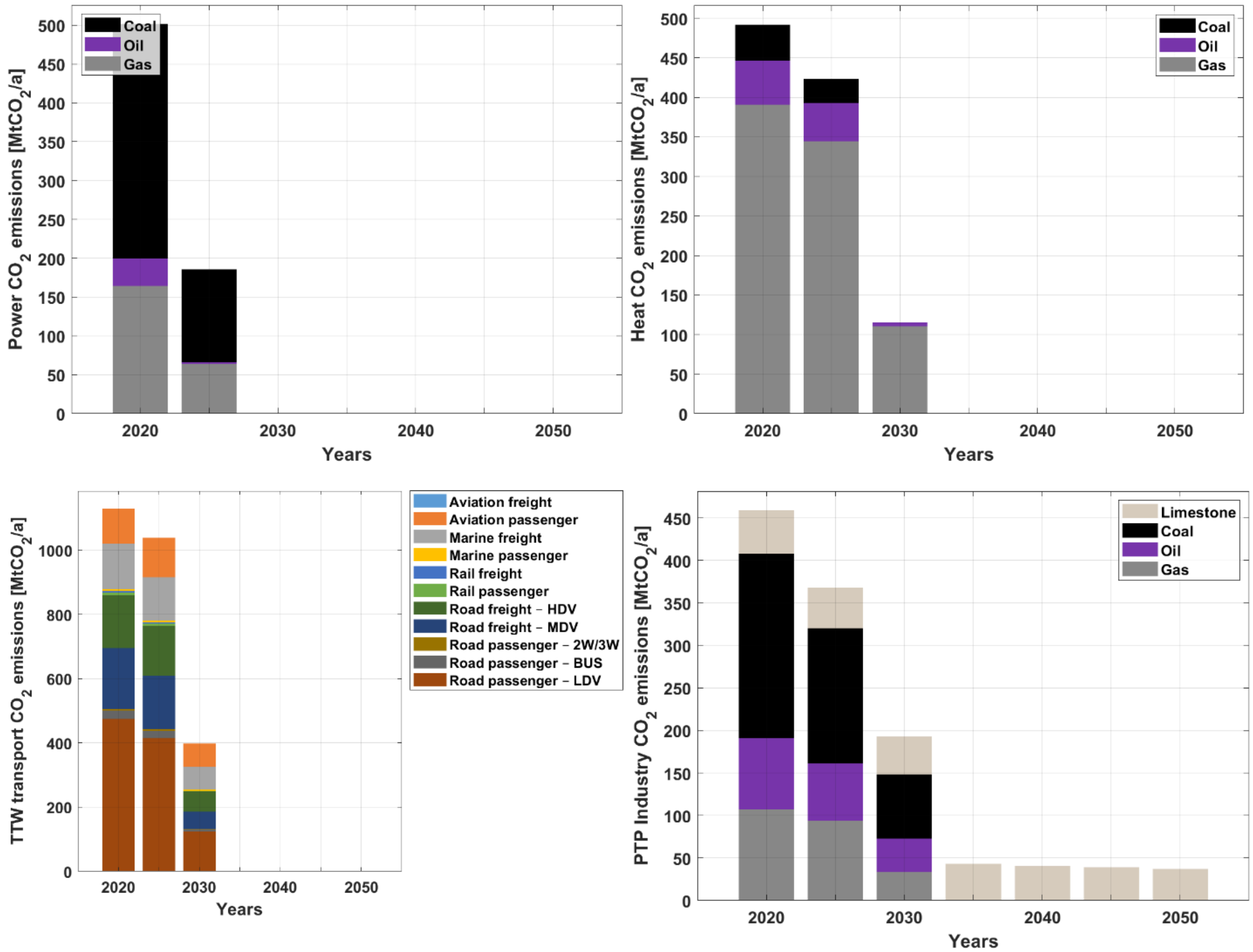

Figure C3.17: CO_2 emissions in the power sector from different fuels (top left), CO_2 emissions in the heat sector from different fuels (top right), CO_2 emissions in the transport sector from different modes (bottom left) and CO_2 emissions in the industry sector from different fuels (bottom right), during the energy transition from 2020 to 2050 across the EU. Tank to Wheel (TTW) and Plant to Product (PTP) considers CO_2 emissions from readily available fuels and does not consider CO_2 emissions from the upstream production and delivery of fuels (RES-2035).

CO_2 emissions from the power sector decline through the transition from around 500 $MtCO_2$/a in 2020 to zero by 2030 as shown in Figure C3.17. Similarly, CO_2 emissions from the heat sector decline through the transition from over 480 $MtCO_2$/a in 2020 to zero by 2035 as shown in Figure C3.17. CO_2 emissions from the transport sector decline through the transition from around 1100 $MtCO_2$/a in 2020 to zero by 2035 and CO_2 emissions from the industry sector decline through the transition from over 450 $MtCO_2$/a in 2020 to nearly zero by 2035, with some residual emissions from limestone, as shown in Figure C3.17.

Regional Outlook

The regional distribution of electricity generation capacities, electricity generation, heat generation capacities, heat generation, electricity storage output, heat storage output, supply of fuels and chemicals across the EU, and electricity exchange across the European network are illustrated in the Figures C3.18 to C3.25. Further information during the different years of the transition for the 27 EU member states is provided in a supplementary data file.

Power generation capacities are distributed throughout the EU, with major shares of solar PV in the Southern member states, while wind power has major shares in the northern and western members states of the EU in 2050 (see Figure C3.18). PV prosumers are a relevant energy system feature in all member states. The total power generation capacity installed across the EU in the RES-2035 scenario in 2050 is 6035 GW.

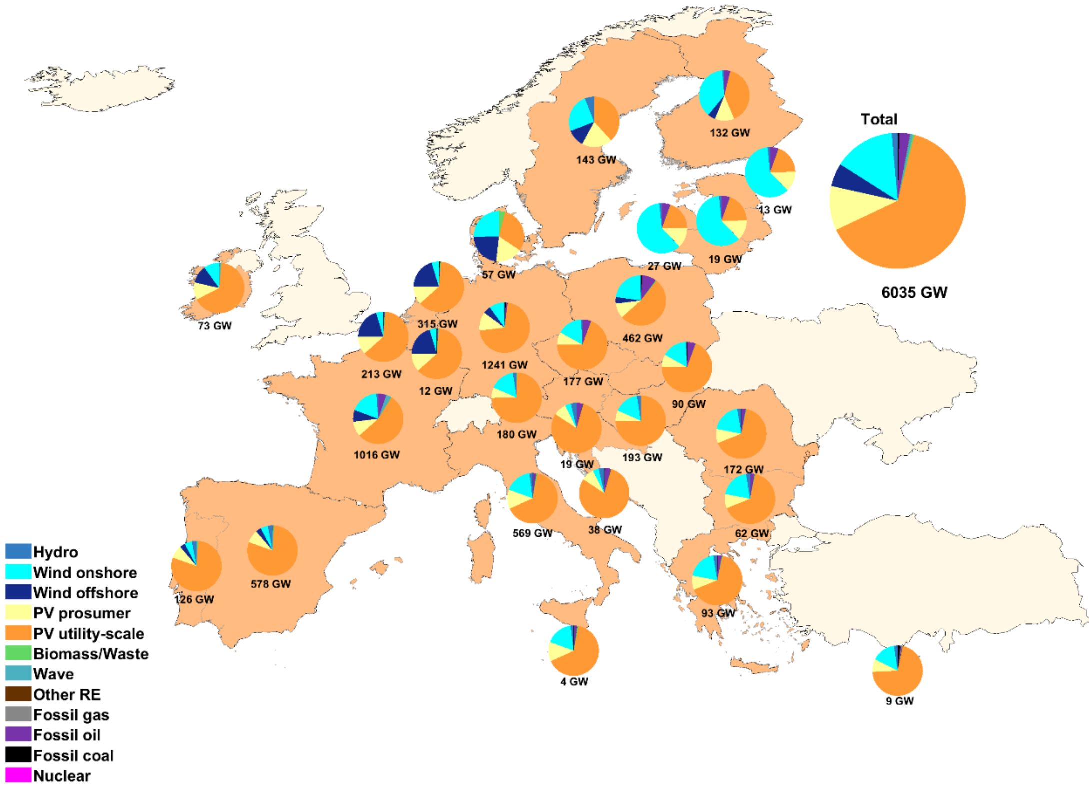

Figure C3.18: Regional electricity generation capacities in 2050 across the EU (RES-2035).

Similarly, electricity generation shares vary across the EU, with total generation of 10,302 TWh in the RES-2035 scenario in 2050. Solar PV generation shares dominate in the southern and western member states, while wind power has the major shares in the northern and Baltic member states (see Figure C3.19). PV prosumers are a relevant energy system feature in all member states. From a EU energy system point of view, the southern and northern member states have great complementarity in terms of resources.

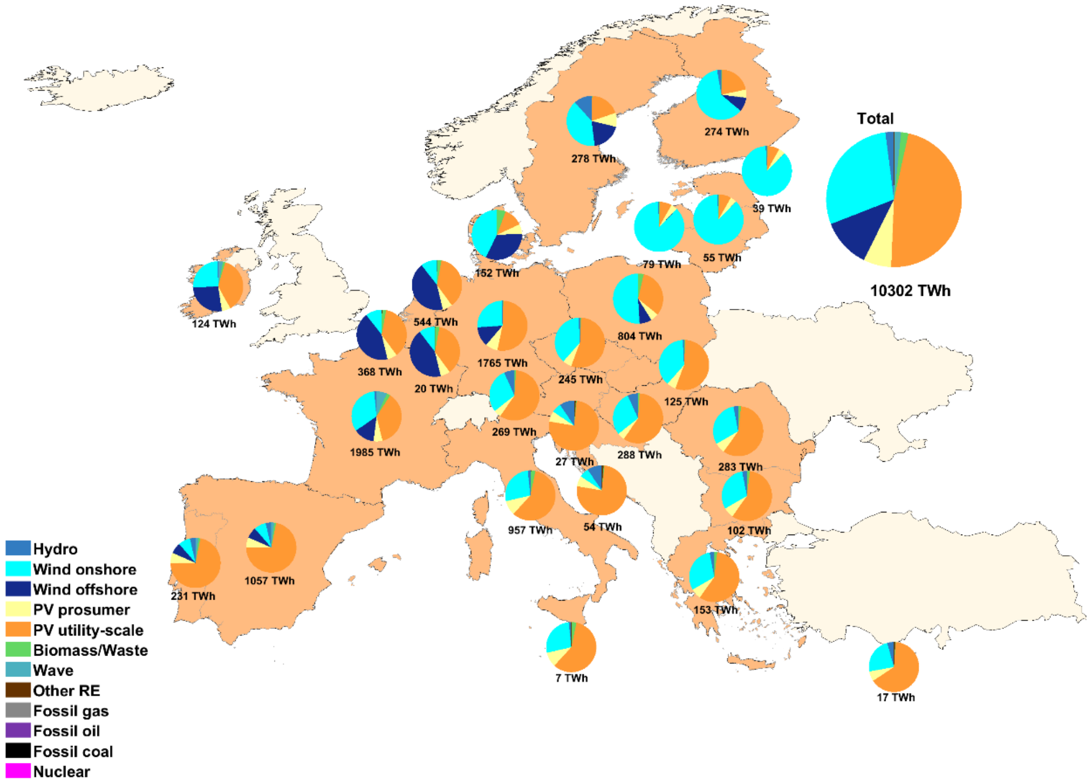

Figure C3.19: Regional electricity supply in 2050 across the EU (RES-2035).

Heat generation capacities are about 633 GW across the EU in the REE-2035 scenario in 2050 and well distributed across the member states. Heat pumps and electric heating are the major heat sources in 2050 and are predominant in the southern and western member states. While higher shares of bioenergy provide heat in the northern and Baltic states along with minor shares across the rest of the EU (see Figure C3.20).

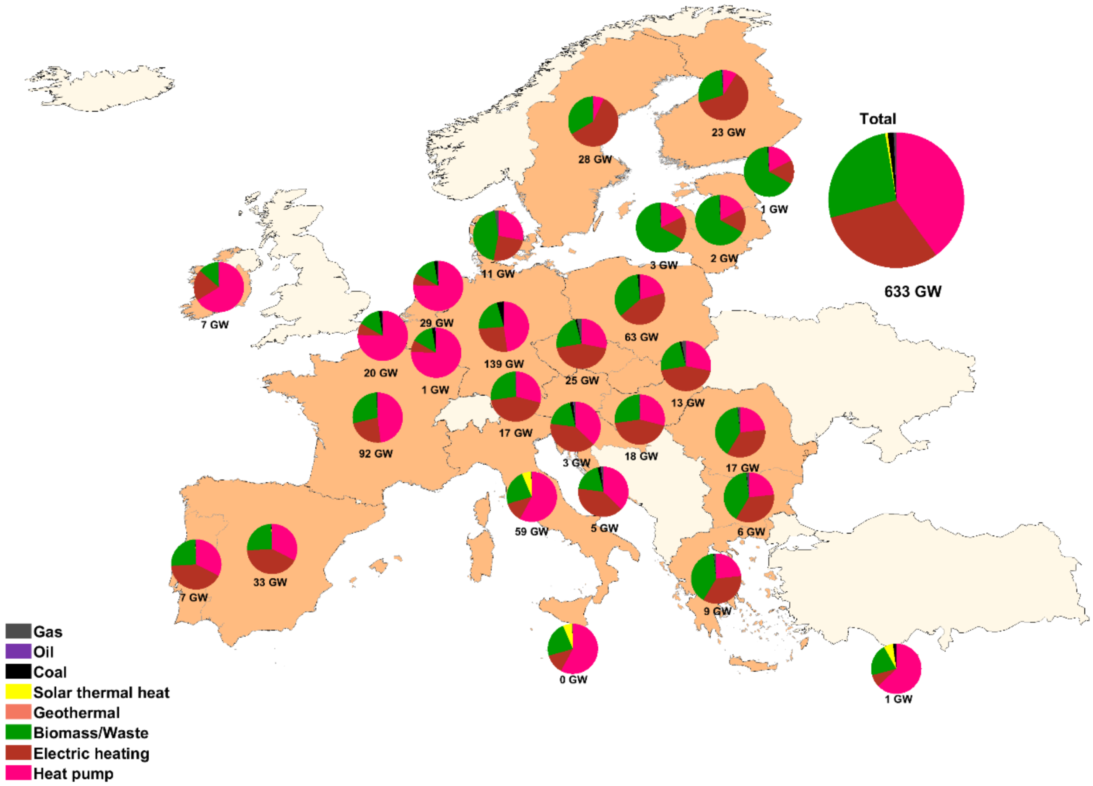

Figure C3.20: Regional heat generation capacities in 2050 across the EU (RES-2035).

Total heat generation across the EU is 2690 TWh in the RES-2035 scenario in 2050. Major share is from heat pumps and electric heating across most states, while bioenergy contributes most of the heating in the eastern and Baltic states of the EU (see Figure C3.21).

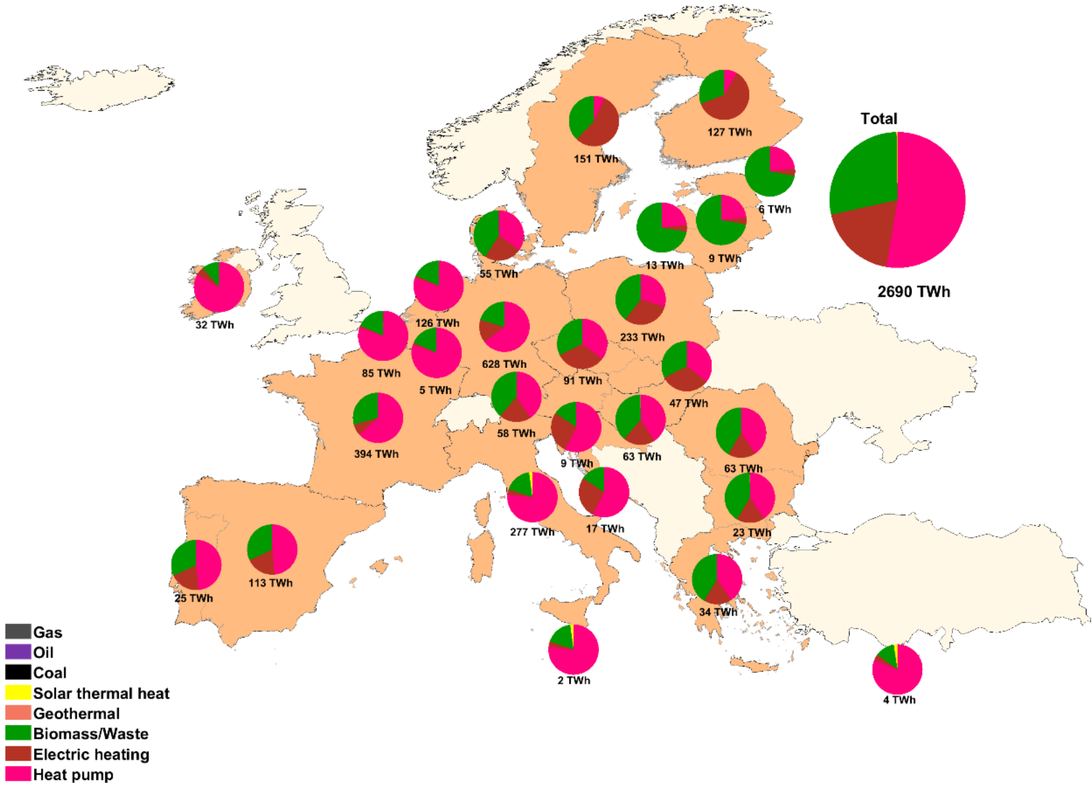

Figure C3.21: Regional heat supply in 2050 across the EU (RES-2035).

Batteries (prosumers and utility-scale) along with vehicle-to-grid emerge as the dominant electricity storage sources across the EU in 2050, with 1344 TWh of storage output in the RES-2035 scenario. Prosumer batteries dominate across the EU, with some shares of utility scale batteries, vehicle-to grid and pumped hydro energy storage across the EU (see Figure C3.22).

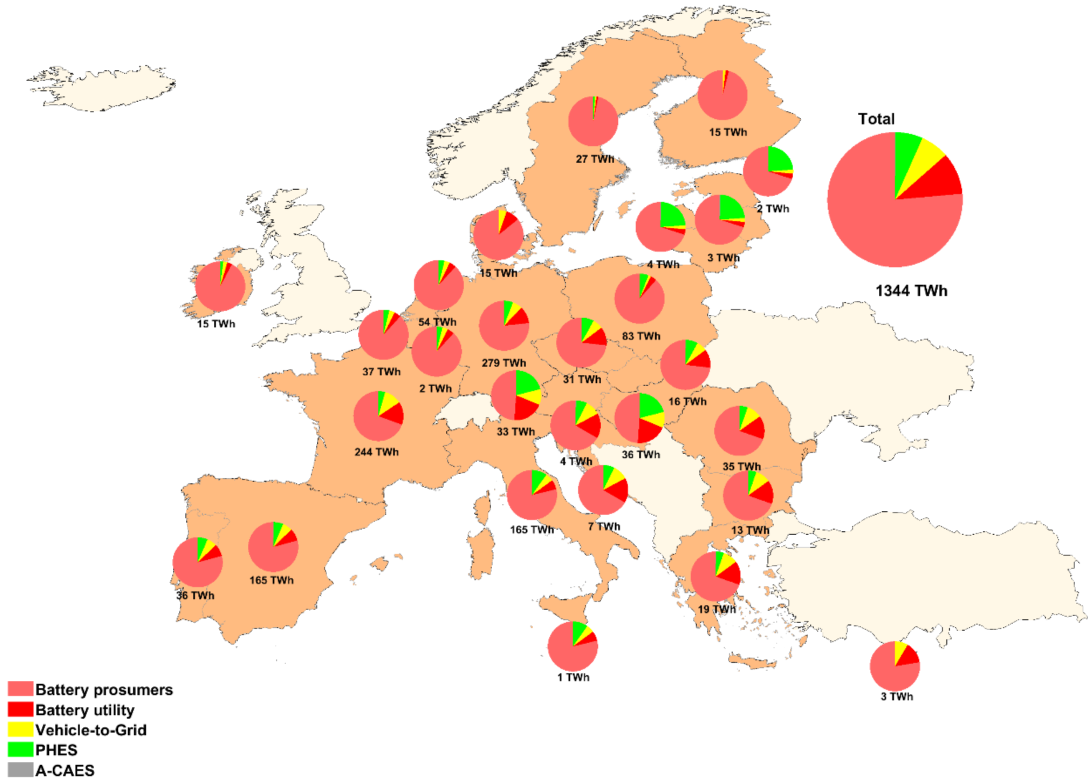

Figure C3.22: Regional electricity storage output in 2050 across the EU (RES-2035).

Heat storage output is 1412 TWh in 2050 across the EU in the RES-2035 scenario. It is well distributed across the member states and hydrogen storage provides the bulk of the heat across members states in 2050. While thermal energy storage provides major shares of the heat in some member states with high temperature heat. Some shares of biomethane storage output contribute across the EU for seasonal heat (see Figure C3.23).

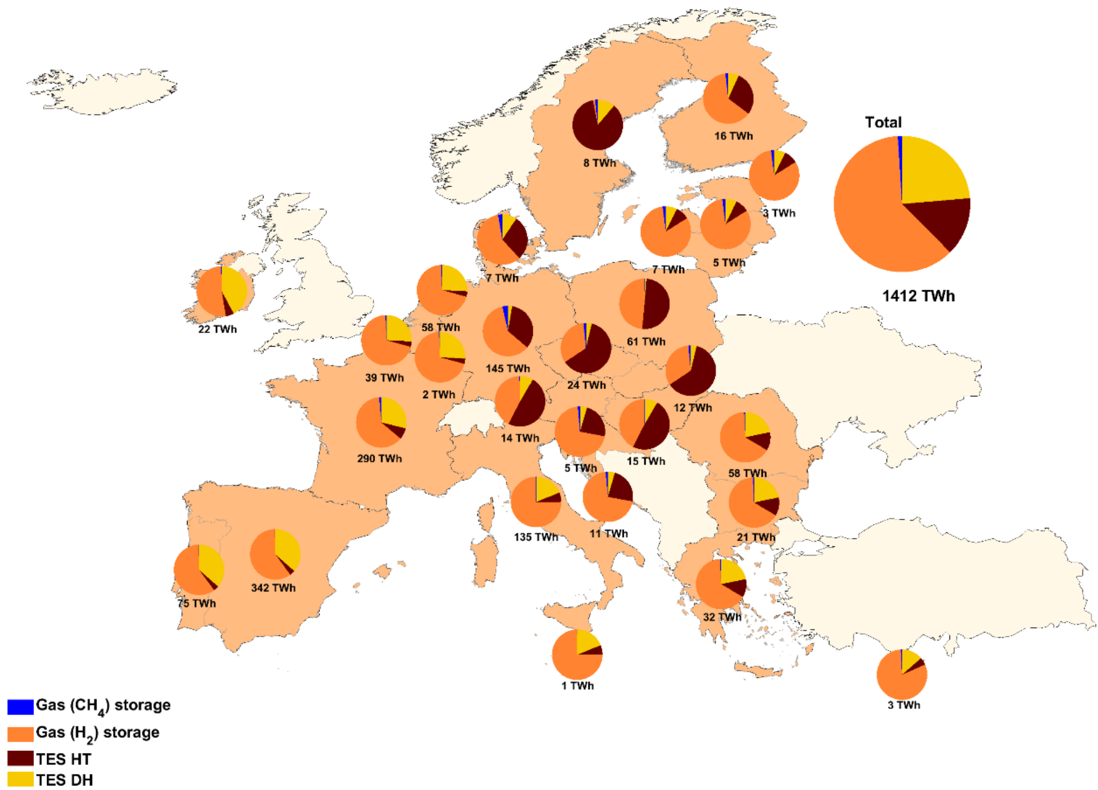

Figure C3.23: Regional heat storage output in 2050 across the EU (RES-2035).

Supply of fuels and chemicals is well distributed across the EU with 4595 TWh in the RES-2035 scenario in 2050. Waste and residual biomass contribute the major share of fuels, while e-fuels and e-chemicals are well distributed across the EU (see Figure C3.24). There are no imports of e-fuels and e-chemicals in the RES-2035 scenario in 2050. Imports of e-fuels and e-chemicals play a vital role in the transition and peak in 2035 and phased out by 2050 in the RES-2035 scenario. This is due to cost effective ramping of renewables and production of e-fuels and e-chemicals within the EU, and ongoing reduction of fuels demand from vehicle stocks beyond 2035. The EU can benefit from favourable renewable energy resources in neighbouring countries and beyond in the short to mid-term, while moving towards self-sufficiency and energy independence in the long-term.

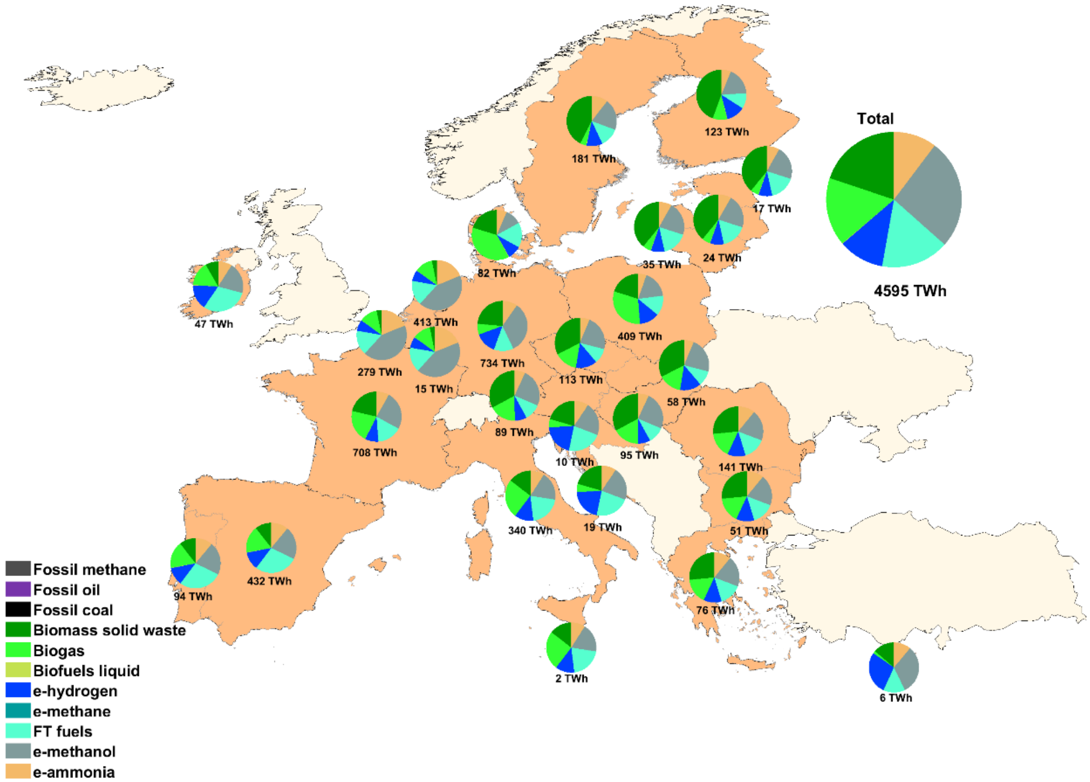

Figure C3.24: Regional fuels and chemicals supply in 2050 across the EU (RES-2035).

The electricity network is robust and rapidly developing across the EU and beyond covering Europe. With energy resources distributed across the region, electricity trade is 1342 TWh in 2050 across Europe in the RES-2035 scenario (see Figure C3.25), representing 13% of total electricity generation in EU. Net exporters and importers emerge across Europe to enable a cost optimal energy mix for the whole region.

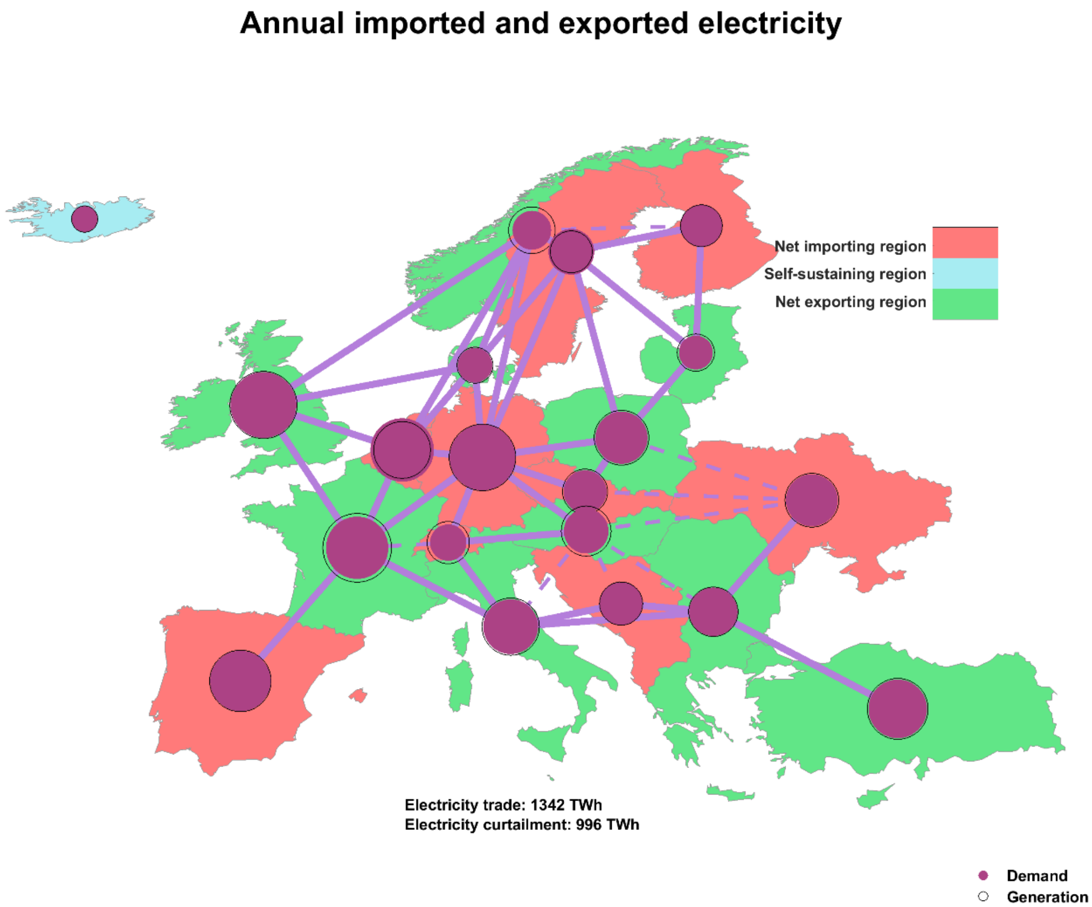

Figure C3.25: Regional electricity trade with net-importers and net-exporters in 2050 across Europe. Solid and dashed lines indicate used and not used interconnections, respectively (RES-2035).

The RES-2035 scenario results in a completely sector coupled and integrated energy system in 2035 and develops further until 2050, as shown in Figure C3.26. The energy system in the RES-2035 scenario has highly diversified and self-reliant power, heat and transport sectors across the EU, as shown in Figure C3.26.

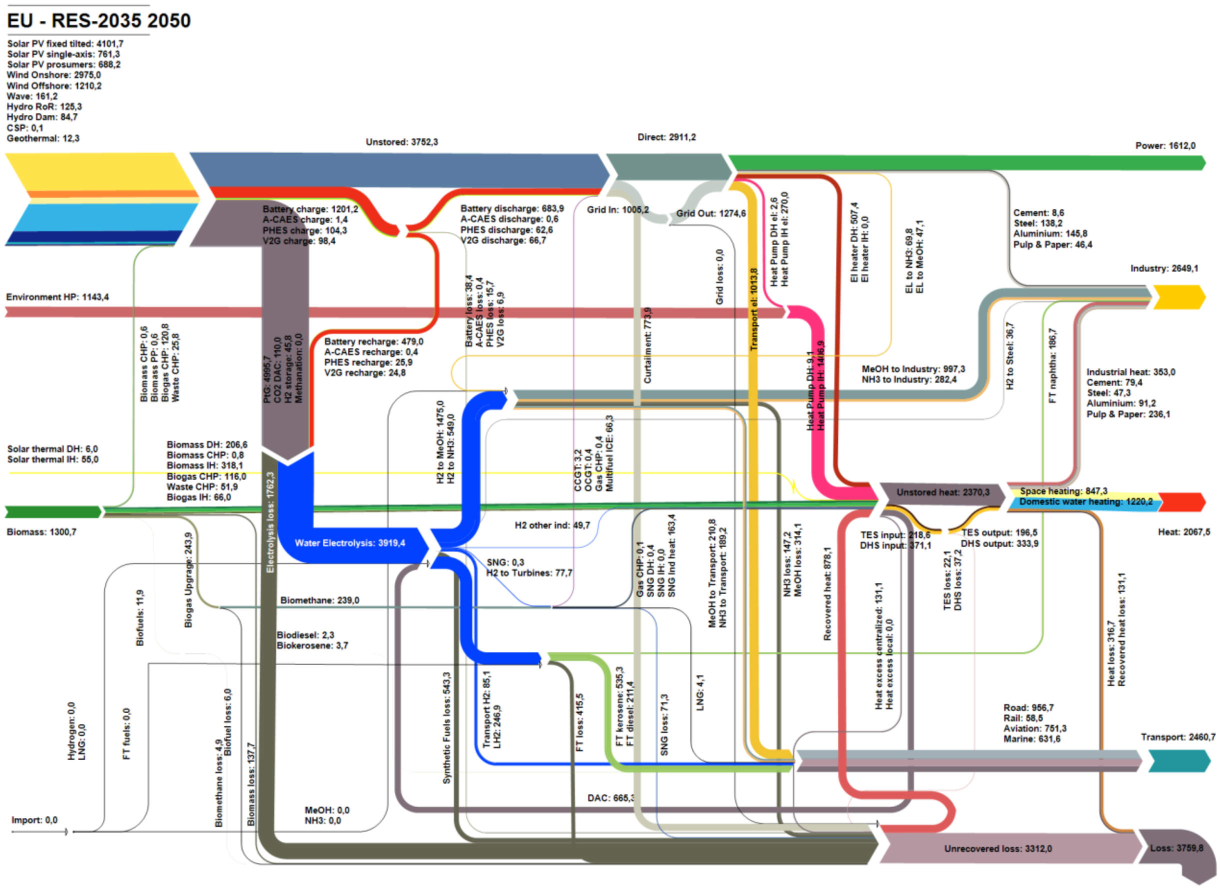

Figure C3.26: Energy flows of the EU energy system in 2050 (RES-2035).

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