ACCELERATING THE EUROPEAN

RENEWABLE ENERGY *TRANSITION*

LUT UNIVERSITY &
GREENS/EUROPEAN
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EXECUTIVE SUMMARY

While the detrimental impacts of climate change are unravelling around the world, a geopolitical crisis at the heart of Europe has brought to the forefront another dimension to the complexities of the energy transition. Energy security and energy independence have preceded to shape future energy decisions, not only in Europe but across the world. Europe has been at the forefront in driving the transition towards sustainable energy adoption as well as enhancing climate mitigation. The energy transition towards higher shares of renewable energy is already well underway in many European countries, particularly in the power sector. The European Commission has envisaged a long-term climate neutrality vision with the European Green Deal. However, compounding crises including the Russian invasion of Ukraine have accentuated the cost to the European economy that is coupled with a centralised energy system highly dependent on imported fossil fuels. In this context, accelerating the energy transition across the European Union (EU) is essential for enhancing energy security, ensuring long-term price stability and mitigating climate change. Amidst the current gloom and doom, there is a long-term opportunity for Europe to emerge as a global leader with an accelerated transition towards a highly efficient energy system based on 100% renewables, which will enable a range of benefits, not only for its economy but also for other economies around the world.

This research study, undertaken by LUT University and commissioned by The Greens / European Free Alliance, presents a first of its kind technology-rich, multi-sectoral, multi-regional cost optimisation driven analyses of energy transition pathways for the EU and its member states. Energy transition pathways for the EU are explored in three distinct scenarios:

- **REFERENCE (REF)** scenario: a slower energy transition in line with the climate neutrality objective by 2050 of the current Green Deal.
- **RENEWABLE ENERGY SYSTEM – 2040 (RES-2040)** scenario: an accelerated energy transition towards a highly efficient and 100% renewables based integrated energy system across the European Union by 2040.
- **RENEWABLE ENERGY SYSTEM – 2035 (RES-2035)** scenario: a rapid energy transition in the next decade resulting in a highly efficient and 100% renewables based integrated energy system across the European Union by 2035.

This study presents a techno-economic blueprint demonstrating cost optimal pathways of transitioning the power, heat, transport and industry sectors towards an integrated, efficient and sustainable energy system across the EU embedded within Europe in the mid- to long-term, from 2035 to 2050.

Some of the key trends and insights that emerge from the study are:

Electrification and efficiency are primary drivers

A fundamental shift towards high levels of electrification across end-uses shapes the energy transition from the present decoupled energy system, which is based on high shares of fossil fuels that are mostly imported in the case of Europe. Electrification across the energy sector drives renewable energy uptake and efficiency gains in the three scenarios: RES-2035 with 100% renewables in 2035, RES-2040 with 100% renewables in 2040 and REF scenario with over 98%[1] renewables in 2050 (refer Table ES-1). The Figure ES-1 indicates the primary energy supply in the three scenarios for years in which a fully renewable and highly efficient energy system is reached in each scenario, 2035 for the RES-2035 scenario, 2040 for the RES-2040 scenario and 2050 for the REF scenario. Furthermore, despite an overall increase in the demand for energy services across the power, heat, transport and industry sectors, the primary energy demand reduces with higher shares of electrification. Improving rates of building renovation along with shifts in transport towards electric mobility as well as modal shifts towards increasing use of rail enables reducing both final and primary energy in the three scenarios. This indicates highly sector coupled and efficient energy systems in the future.

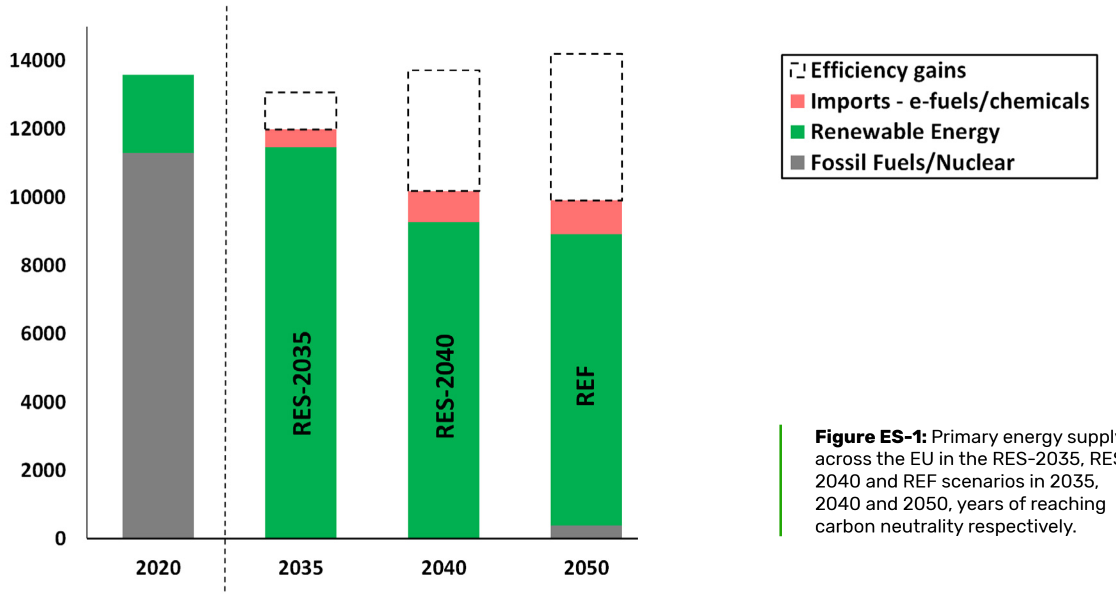

Figure ES-1: Primary energy supply[2] across the EU in the RES-2035, RES-2040 and REF scenarios in 2035, 2040 and 2050, years of reaching carbon neutrality respectively.

Some shares of imports of e-fuels and e-chemicals[3] from other European countries ensure a cost optimal energy system across the European Union in the three scenarios (refer Table ES-1).

Solar and wind emerge as the prime sources of electricity generation

Solar photovoltaics and wind power become the most dominant sources of electricity generation with the highest levels of cost competitiveness across the three scenarios by 2050. Solar PV

1 A share of less than 2% nuclear power remains as a result of nuclear power plants operating until end of their technical lifetimes across the European Union. However, newly built nuclear is not considered due to prohibitive costs along with environmental and social concerns. Existing construction sites with high probability for finishing the plant are assumed to be commissioned.

2 The primary energy does not include fossil feedstock for industry and ambient heat.

3 These are synthetic fuels and chemicals produced from renewable electricity.

provides the largest capacities over the course of the energy transition, from nearly 3 TW in the REF scenario in 2050 to over 4.5 TW in the RES-2035 scenario in 2035. Wind power has installed capacities ranging from nearly 800 GW in the REF scenario in 2050 to over 1000 GW in the RES-2035 scenario in 2035. Utility-scale solar PV as well as PV prosumers (residential, commercial and industrial) contribute 50-54% (refer Table ES-1) of the electricity in 2050 across the three scenarios. While wind power contributes around 40% (refer Table ES-1) of the electricity in 2050 across the three scenarios.

Heat pumps coupled with electric heating are the prime sources of heat

Heat pumps along with electric heating, both at the individual and district level, are the prime sources of heat and critical to replace fossil fuels in the heat sector across the European Union. In addition, this enables improving efficiency and, coupled with continually growing rates of building renovation across the European Union, massive gains in lowering the primary energy are achieved. Heat pumps along with electric heating provide 50-60% of the heat by 2050 across the three scenarios (refer Table ES-1).

Electricity, heat and gas storage are critical for stability and flexibility

Energy storage plays a critical role in the transition of the energy system towards high shares of renewables by providing stability and flexibility. Combinations of storage technologies cover the energy demand throughout the transition period, with batteries providing the bulk of the electricity storage. Thermal energy storage provides heat for industry and space heating, while methane and hydrogen storages provide fuel for flexible electricity and heat generation in proximity of the demand for all energy sectors. Hydrogen storage also provides flexibility that enables harmonising variable renewable electricity with production of hydrogen-based fuels and chemicals and reduce curtailment.

Sector coupling enhanced by e-hydrogen, e-fuels and e-chemicals

A critical aspect in enabling high shares of renewables penetration in energy systems is the production of synthetic fuels and chemicals from renewable electricity. Fuel conversion technologies such as water electrolysis, methanation, Fischer-Tropsch, Haber-Bosch, methanol synthesis, and others supply renewables-based fuels and chemicals through the energy transition, mainly to cover demand from the transport and industry sectors. Fossil fuels and feedstock in marine and aviation transportation and industry sectors are replaced by e-fuels and e-chemicals in varying rates across the three scenarios.

Energy costs

A shift to higher shares of renewables in the energy system results in stable levelised costs of energy, defined as total annualised energy system cost divided by the total final energy demand, across the three scenarios by 2050 (refer Table ES-1). A trend develops where the levelised cost of energy shares become increasingly dominated by capital costs, as fuel costs decline through the transition period. The levelised cost of electricity and levelised cost of heat decline through the transition across the three scenarios (refer Table ES-1).

Carbon dioxide emissions

The most important result of the energy transition is that CO_2 emissions[4] can be reduced from over 2,500 mega tonnes CO_2 ($MtCO_2$) in 2020 across the energy system to zero by 2035 in the RES-2035 scenario, zero by 2040 in the RES-2040 scenario and zero[5] by 2050 in the REF scenario in comparison to 1990 levels (see Figure ES-2).

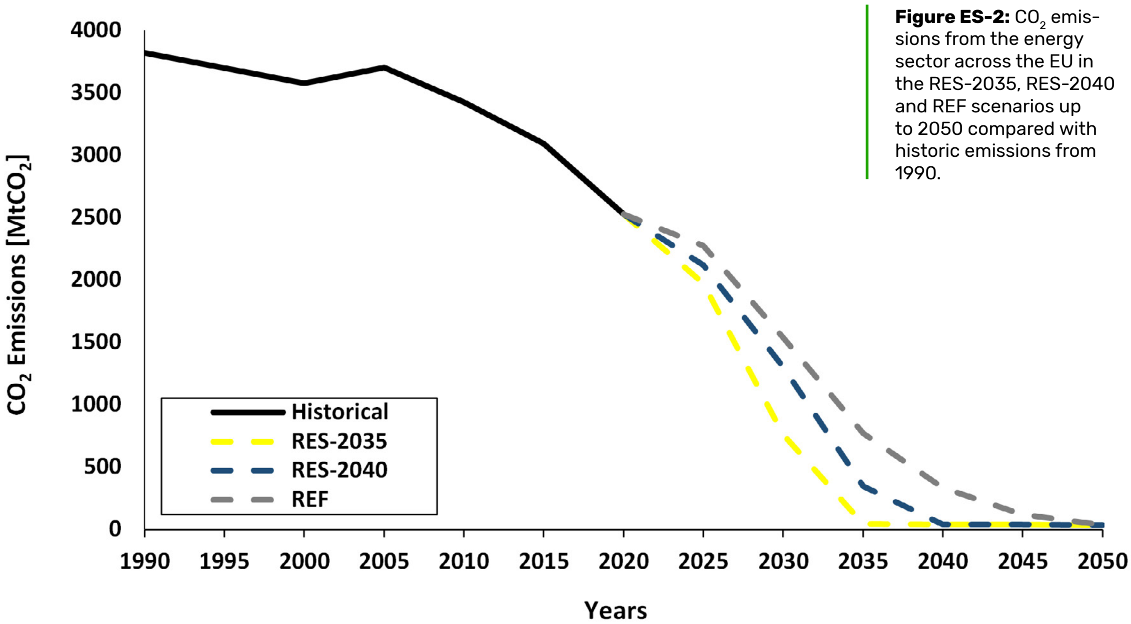

Figure ES-2: CO_2 emissions from the energy sector across the EU in the RES-2035, RES-2040 and REF scenarios up to 2050 compared with historic emissions from 1990.

Results from this research clearly indicate that a low ambition pathway is not only a burden for the entire society with the younger generation vulnerable to higher CO_2 emissions, but it is also the least secure option due to its reliance on imported fossil fuels beyond 2030. Whereas an accelerated ambitious climate mitigation pathway is realistic, leading to zero CO_2 emissions by 2040 and just a marginal increase in unit energy cost compared to the energy system in 2020, with a range of other benefits including a highly efficient energy system requiring less primary energy. Similarly, a rapid energy transition pathway with zero CO_2 emissions by 2035 is technically feasible and enhances energy security across the European Union but requires massive investments in the next few years accompanied by drastic measures in revamping energy policies.

4 Direct CO_2 emissions from the utilisation of fossil fuels in the power, heat, transport and industry sectors across the EU. Feedstock-related CO_2 emissions in industry are included with their CO_2 emissions shares in production. CO_2 emissions from other non-energy sources are not considered.

5 Some residual CO_2 emissions remain from limestone usage in the cement industry, and these are expected to be abated by natural climate solutions or capture and storage solutions.

KEY PARAMETERS	UNITS	REF		RES-2040		RES-2035	
		2030	2050	2030	2050	2030	2050
Primary Energy Demand	TWh	11 808	9 907	11 617	10 087	11 980	11 482
Final Energy Demand incl ambient heat for heat pumps	TWh	10 577	10 158	10 574	9 890	10 843	9 885
Final Energy Demand excl ambient heat for heat pumps	TWh	9 366	8 639	9 289	8 517	9 333	8 783
Electrification	%	32%	83%	38%	88%	60%	91%
RE supply share	%	49%	99%	56%	100%	75%	100%
RE share electricity	%	79%	98%	82%	100%	98%	100%
Solar PV capacity	GW	725	2900	968	3437	2018	4497
Wind power capacity	GW	479	791	535	864	950	1213
Solar PV supply	TWh	915	3527	1215	4242	2616	5551
Wind power supply	TWh	1625	2813	1852	3101	3173	4185
Solar PV supply share	%	24%	50%	29%	54%	41%	54%
Wind power supply share	%	43%	40%	44%	39%	50%	40%
Heat pumps/electric heat supply share	%	53%	62%	52%	56%	52%	53%
e-fuels/chemicals imports	TWh	1	527	43	328	574	0
LCO Energy	€/MWh	59	45	61	49	68	57
LCO Electricity[6]	€/MWh	73	44	72	44	52	43
LCO Heat[7]	€/MWh	43	24	45	23	43	27
CO_2 emissions reduction compared to 1990 levels	%	60%	100%	65%	100%	80%	100%

Table ES-1: Key parameters in 2030 and 2050 for the three energy transition scenarios across the EU.

The daunting task of limiting global warming to 1.5°C, enhancing energy security and enabling energy independence, requires transformative systemic changes driven by sustainable economic development across the different regions of the world. In this regard, the European Union is well positioned to pursue a leadership role by reducing CO_2 emissions rapidly within the continent as well as providing impetus for rapid implementation of sustainable energy technologies globally. As this study has highlighted, this is both technologically feasible as well as economically viable.

6 LCOE: Levelised cost of electricity

7 LCOH: Levelised cost of heat

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1 INTRODUCTION

Exacerbating climate impacts, ongoing global pandemic and ensuing geopolitical crises have exposed the vulnerabilities of a centralised energy system heavily reliant on fossil fuels. In Europe, the current Russian invasion of Ukraine adds new levels of concern and uncertainty, resulting in volatile energy costs across economies that remain profoundly intertwined with imports of fossil fuels[1]. In the absence of alternatives, increasing fossil fuel prices inflict energy scarcity and pose challenges to industrial competitiveness across Europe. While citizens are concerned about their growing energy bills and risks posed by climate change as warned in the recent report of the Intergovernmental Panel on Climate Change (IPCC)[2]. The United Nations (UN) report[3], calls for global greenhouse gas (GHG) emissions to be reduced by 7.6% each year between 2020 and 2030, to get on track to keep the 1.5°C temperature limit of the Paris Agreement. The European Commission (EC) has envisaged a strategic long-term vision with the European Green Deal[4], which outlines feasible pathways for Europe to lead the transition towards a climate-neutral economy by 2050 in line with the objectives of the Paris Agreement. In principle, the broad-ranging pathways in the long-term strategy are highly commendable, as they target some fundamental aspects: increased energy efficiency; increased use of renewables; a clean and connected mobility system; a competitive circular economy industry; connected high-standard infrastructures; a boost in the bioeconomy and natural carbon sinks. However, the timelines of the proposed vision are deemed unambitious and incongruent with the level of economic development in Europe[5]. The multifaceted challenges of enhancing energy security, enabling price stability and ensuring sustainable development present an opportunity for the European Union (EU) to pursue a global leadership role in becoming the world's first zero GHG emissions continent and help drive the rest of the world towards climate-neutrality well before 2050. Along these lines, this research study by LUT University commissioned by The Greens / European Free Alliance envisions energy system transition pathways for the EU within the European continent, with different levels of ambition. It analyses the development of the European energy system in three distinct scenarios:

- **THE REFERENCE SCENARIO (REF)** reaching 98% renewables, and in which CO_2 emissions are reduced to zero in 2050
- **THE RENEWABLE ENERGY SYSTEM – 2040 (RES-2040)** fully renewable scenario, in which CO_2 emissions reach zero by 2040
- **AND THE RENEWABLE ENERGY SYSTEM – 2035 (RES-2035)** fully renewable scenario, in which CO_2 emissions reach zero by 2035

From niche beginnings, primarily in Europe, renewable energy technologies have emerged as the most preferred power generation sources globally and disrupted energy markets fundamentally. The growing uptake of renewable energy in Europe and across the world has opened new avenues with increased participation of citizens and companies in shaping energy choices enabled by the decentralised nature of renewables, particularly solar photovoltaics (PV) and wind power. Renewable energy contributed around 20% of the total energy supply across the EU in 2020[6] (see Figure 1). Accordingly, fossil fuels and nuclear contributed about 80% of EU's total energy supply in 2020[6], with both being mostly imported. The EU relied on energy imports of around 58% in 2020, with 24% coming from Russia[6] (see Figure 1). The EU imported around 40% of its natural gas, more than 25% of its oil and about 50% of its coal consumptions from Russia in 2020[1]. In the case of natural gas, some of the EU member states are even far more reliant on imports from Russia. This innate reliance on imports of Russian fossil fuels is viewed as an underlying factor in the ongoing geopolitical crisis due to the Russian invasion of Ukraine. Juxtaposing renewables and Russian fossil fuel imports, the EU currently gets more energy from Russia than locally generated renewable energy. This poses serious challenges to long-term energy security, at the same time presents a tremendous opportunity for a rapid energy transition with excellent renewable resources across the EU.

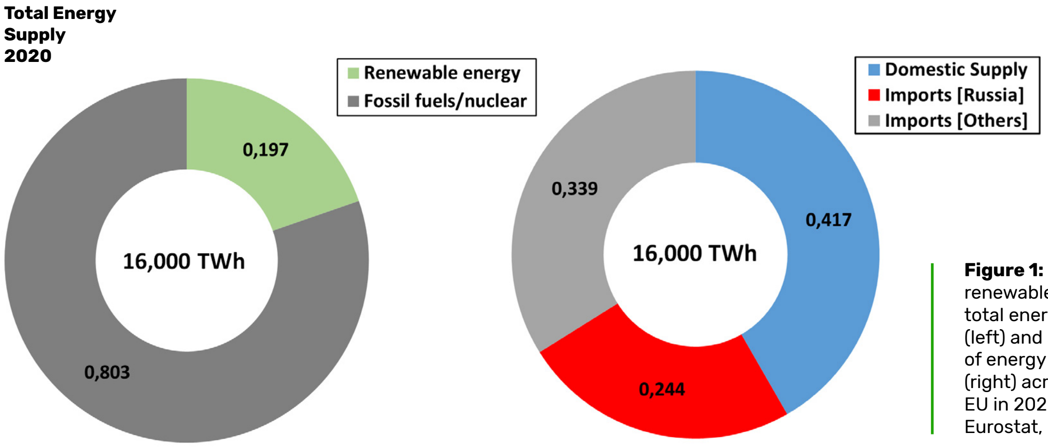


Figure 1: Share of renewable energy in total energy supply (left) and shares of energy imports (right) across the EU in 2020. Source: Eurostat, 2021[7]

The power sector is leading the way through the transition as solar and wind power increasingly replace coal, fossil gas, and nuclear energy as the world's most preferred energy sources[8]. The key driver is the rapidly declining cost for renewable energy technologies in the last decade[9]. Cost reductions, particularly in solar PV and wind power, have been consistent over the last few years and are set to continue into the next decade. In the case of solar PV, costs between 20-30 €/MWh are already prevalent in regions with good resources and enabling regulatory and institutional frameworks[9]. Surprisingly, costs below 20 €/MWh are not impossible anymore, even if they were unthinkable just a few years ago[9]. For example, record-low auction prices for solar PV in Chile, Mexico, Peru, Saudi Arabia, the United Arab Emirates, India and recently in Germany have seen a levelised cost of electricity as low as 25 €/MWh[10]. Amidst these developments, the European energy system is well poised to take advantage with almost 35% of electricity from renewable sources, as indicated by Figure 2.

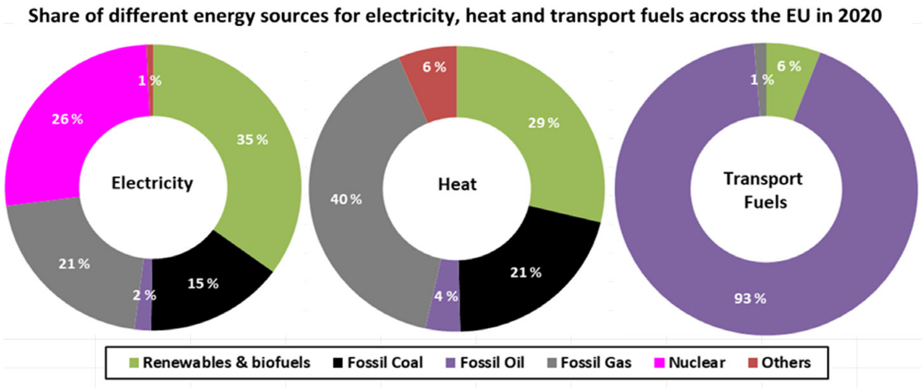


Figure 2: Shares of renewable energy in gross final energy consumption of electricity, heat and transport fuels across the EU in 2020. Source: Eurostat, 2021[17].

Despite the growth of renewables in the power sector across Europe, the remaining energy sectors are still lagging behind. Heat consumption across Europe remains heavily based on fossil fuels, primarily imported natural gas (see Figure 2), while around 15% of the renewable heat comes from bio resources. However, there is increasing adoption of renewables in various heating processes. Renewable energy can serve thermal demand when supplied by electricity, either directly or using heat pumps[11]. Furthermore, electrification of heating is on the rise, using wind electricity for Power-to-Heat applications, heat pumps in district heating networks and increasingly using electricity from solar PV for heat to increase self-consumption rates in the face of reductions in feed-in tariffs and growing retail electricity prices[11]. District heat systems supply about 11% of global space and domestic hot water heating and are particularly suitable for use in densely populated regions that have an annual heating demand of four or more months, such as in the northern latitudes of Asia, Europe and North America[12]. In many regions in the world, renewable based district heating with seasonal storage is already a viable option[11].

Energy for the transport sector across the EU is heavily reliant on fossil oil with 93% of the supply in 2020 (see Figure 2), which is mostly imported. Moreover, it is both the largest individual sector in terms of overall EU GHG emissions and the only sector with rising emissions. The transport sector comprises several modes, namely road, rail, marine and aviation across passenger and freight categories[13,14]. There is a rapid shift towards electrification in the transport sector with the evolution of the electric car market across the EU. There were over 16.5 million electric cars on the roads worldwide at the end of 2021[15], following a decade of rapid growth. Nearly 10% of global car sales were electric in 2021[15]. Global electric car registrations increased by 41% in 2020[16], despite the pandemic-related disruptions in car sales, which dropped by 16% around the world[16]. Europe overtook the People's Republic of China as the world's largest EV market for the first time. Further, registrations of electric buses and trucks expanded across major markets, reaching global stocks of 600,000 and 31,000 respectively[16]. In Europe, electric car sales increased by nearly 70% in 2021 to 2.3 million[17], though about half of which were plug-in hybrids. Overall, electric cars accounted for 17% of total European sales in 2021[17], but there were significant differences across markets with the highest shares in Norway at 72%, Sweden at 45% and the Netherlands at 30%[17]. The penetration of this technology in the transport sector could reach the same level as the PV penetration in the power sector, in the coming years and possibly evolve even faster[18]. Likewise, marine transportation has options with increasing availability of alternative fuels such as biofuels in existing engines, which could be an immediate option, thereafter use of electricity-based synthetic fuels, such as e-ammonia, e-methanol and Fischer-Tropsch based e-fuels[19]. The production and use of sustainable aviation fuels, specifically bio-based jet fuel or synthetic e-kerosene jet fuel apart from direct electrification for short-distance flights can propel the aviation sector towards being more sustainable[20], whereas rail transportation with already a high share of electricity use is well underway for maximum electrification[12]. In addition, synthetic fuels, including hydrogen and e-diesel could cover the non-electrified rail transport. Modal shift from aviation and road transportation to rail will contribute to emissions reduction and increase the overall energy efficiency of the transport sector, though it will require investments in railway infrastructure, especially in densely populated areas.

These recent trends across the different sectors show clearly that growth in renewable energy, electrification along with efficiency measures is on the rise across the EU. Nevertheless, current growth rates are insufficient to achieve the levels of defossilisation necessary in the mid- to long-term that will ensure climate mitigation as well as energy independence. Significant additional electrification of the heat, transport, and industry sectors and integration with the power sector will be required. In this regard, rapid growth in renewable electricity along with efficiency measures must continue to accelerate the energy transition and pathways to make this possible have to be explored.

Recent research indicates that achieving 100% renewable energy and zero GHG emissions is possible, and most likely before the mid of this century[14,21–27]. Europe has emerged as the preferred region for 100% renewable energy studies, as Hansen et al.[28] conclude that Europe is the most well researched region in terms of 100% renewable energy systems and transitions. With a matured renewable energy industry and being a leading hub for research and innovation, this is a positive indicator for progressive policy development. Child et al.[29] have listed out some of the key peer-reviewed journal publications on 100% renewable energy driven systems for Europe. Brown et al.[30] and Victoria et al.[31] demonstrate the development of a networked and sector-coupled European energy system under limited carbon budget constraints, while Connolly et al.[32] highlight a smart energy system for Europe with limited bioenergy use and high electrification. Plessmann and Blechinger[33] focus on the European power supply system and demonstrate the techno-economic feasibility of reaching the EU's mitigation targets by 2050, they also show that a transition from conventional fossils-nuclear to renewables-based power supply systems is possible for the EU even with a politically driven nuclear power phase-out. Löffler et al.[34] highlight multiple pathways for the European energy system until 2050, focusing on one of the major challenges of the low-carbon transition: the issue of unused capacities and stranded assets, concluding that there is a need for strong, clear signals from policy makers in order to combat the threat of shortsighted planning and investment losses. Furthermore, the common themes that emerge from all these studies indicate that 100% renewable energy scenarios are both technologically feasible and cost competitive across Europe[29,35].

For the most part, the power, heat, transport and industry sectors have traditionally relied on separate infrastructures and different fuels. As a result, separate regulations and policy regimes govern each energy use. Electrification is disrupting these sectoral barriers, mainly due to high technical efficiencies, comparably lower costs and the availability of prospective power-to-X technologies. These power-to-X technologies include power-to-heat (electric heat pumps[36,37]), power-to-hydrocarbons (hydrogen[38,39], methanation[38–41], synthetic fuels[41–43], synthetic chemical feedstock[44–47]), a directly or indirectly electrified transport sector[13,48] (battery electric vehicles[49,50], marine[51,52], aviation[42]), power-to-water (reverse osmosis desalination[53]), and power for negative emissions technologies[54,55], but also sustainable or non-avoidable carbon capture and utilisation (CCU)[56].

Widescale adoption of electro-mobility, heat pumps and electrolysers for the production of green hydrogen will drive the overall electricity consumption and peak demand up, reinforcing the need for increased efficiency measures across Europe[57]. In consideration of these recent trends, decision-makers across Europe and specifically the EU, increasingly seek out energy transition analyses on high geo-spatial and temporal resolutions, along with robust technical and economic insights. Circumstantially, this research study presents energy transition pathways for the EU encompassing the broader European continent. The three distinct scenarios enable and prompt a comprehensive discourse on setting ambitious targets within and beyond the European Green Deal framework, that envisions securing long-term energy independence and striving towards global leadership on climate mitigation.

2 METHODS:

Modelling the integrated European energy system transition

The LUT Energy System Transition Model (LUT-ESTM)[14,58] is applied across an integrated energy system covering the energy demand from the power, heat, transport and industry sectors as shown in Figure 3. Agricultural energy demand is included in the aforementioned sectors. The unique features of the LUT-ESTM enable cost optimal energy system transition pathways on high levels of geo-spatial and temporal resolutions. Furthermore, capabilities of the LUT-ESTM to analyse energy systems in an hourly resolution for an entire year enables uncovering crucial insights particularly with respect to storage and flexibility options, most relevant to future energy systems. The weather data from 2005 is considered as a reference in this study, which represents a resource year around the average for a solar PV and wind power based energy system in Europe. The LUT-ESTM with its comprehensive list of energy technologies (over 120 different energy technologies across different sectors, end uses and applications) is ranked amongst the most robust tools for the analyses of long-term energy transition pathways[59].

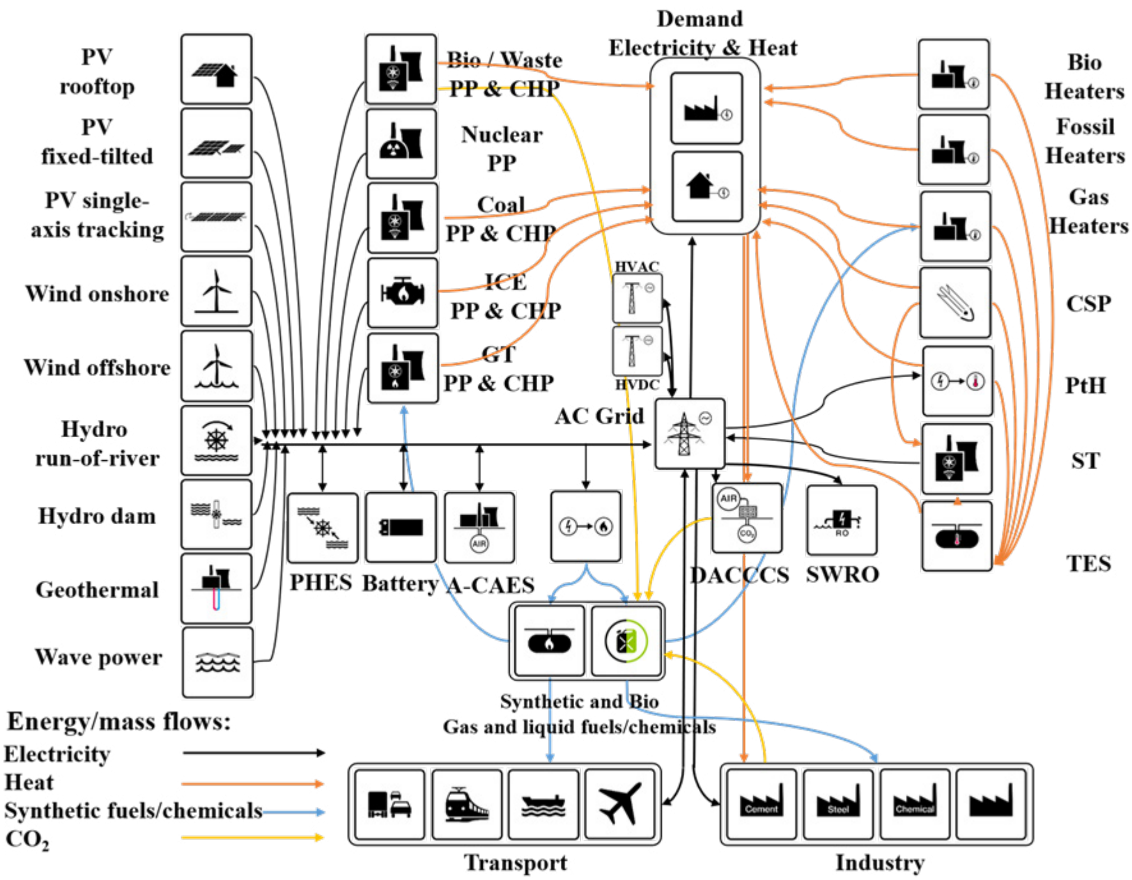


Figure 3: Schematic representation of the LUT Energy System Transition Model.

Energy system simulations in the LUT-ESTM are carried out in a **2-stage approach.** In an initial stage, the prosumer simulations determine a cost effective share of prosumers across Europe[29] through the transition from 2020 to 2050, in five-year intervals.

- **Prosumer modelling**

Prosumers are considered as both producers and consumers of energy (both electricity and individual heating) and play a vital role in the integrated energy system[11]. The energy system transition analyses consist of distributed self-generation and consumption of residential, commercial and industrial PV prosumers, which are simulated with a different sub-model describing the PV prosumer and battery capacity development. PV prosumers have the option to install their own rooftop PV systems either with or without lithium-ion batteries. PV prosumers can also draw power from the grid in order to fulfil their energy demands[11], while having the option to feed-in surplus electricity into the grid. The target function for PV prosumers is the minimisation of the cost of consumed electricity, calculated as a sum of self-generation, annual costs and the cost of electricity consumed from the grid, minus the cost of electricity sold to the grid. Similarly, prosumers can also fulfil their individual heating demand. This is enabled by fossil and biofuel-based boilers, solar thermal collectors, direct electric heating and heat pumps utilisation for residential domestic hot water demand and space heating demand where applicable. Residential thermal energy storage is preferred in the energy system, if it is economically feasible in given geographic conditions. Space heating demand varies across the different regions of Europe depending on climatic and weather conditions. A partial self-supply to cover the electricity demand of individual heating pumps and heating rod systems is taken into account, if it is economically viable for prosumers.

In a second stage, post the determination of prosumer penetration, the overall energy system is simulated for a cost optimal energy mix across the integrated energy sectors and corresponding time steps.

- **Energy system modelling**

The model has integrated all crucial aspects of the power, heat, transport and industry sectors' energy demands, including non-energetic feedstock for some of the key industries. For every time step (in 5-year intervals between 2020 and 2050), the model defines a cost optimal energy system structure and operation mode for the given set of constraints: power demand, process heat demand for industry, space and domestic water heating[60]. Energy and feedstock demand is considered for the cement, steel, chemicals, pulp and paper, aluminium and other industries[58]. The industry sector is enabled to be fully based on renewable energy and feedstock as a crucial element of the transition. Transportation demand is derived for the modes: road, rail, marine (including inland waterways), and aviation for passenger and freight transportation. The road segment is subdivided into passenger Light Duty Vehicles (LDV), passenger two-wheelers/three-wheelers (2W/3W), passenger bus, freight Medium Duty Vehicles (MDV), and freight Heavy Duty Vehicles (HDV). The other transportation modes are comprised of demand for freight and passengers. The demand is estimated in passenger kilometres (p-km) for passenger transportation and in (metric) ton kilometres (t-km) for freight transportation. Further information and data for transportation demand along with fuel shares and specific energy demand are provided in Khalili et al.[13]. The target of the optimisation is the minimisation of total energy system cost.

The energy technologies modelled are:

- **electricity generation technologies: renewable energy (RE), fossil, and nuclear technologies;**
- **heat generation technologies: renewable and fossil;**
- **energy storage technologies: electricity, heat, gas and CO_2 storage technologies;**
- **V2G: vehicle-to-grid technology, smart EV charging;**
- **Power-to-Fuels, Power-to-Chemicals : synthetic e-fuels and e-chemicals production;**
- **electricity transmission technologies.**

A detailed overview of the methodology along with the technical and financial assumptions that are considered in modelling the European power, heat, transport and industry sectors are available in the Annex. These are based on the detailed description of the model applied to the global power sector in Bogdanov et al. (2019)[61] and all energy sectors in Bogdanov et al. (2021)[14,58].

Energy resources

The generation profiles for optimally fixed-tilted and single-axis tracking PV, concentrating solar thermal power (CSP) and wind power are calculated according to Bogdanov and Breyer[62], the single-axis tracking PV capacity factors are based on Afanasyeva et al.[63] (see Figures A5 and A6 in the Annex). The hydropower feed-in profiles are computed based on daily resolved water flow data for the year 2005[64]. The potentials for sustainable biomass and waste resources were obtained from Bunzel et al.[65] and further classified into categories of solid wastes (99 TWh), residues from forestry, agriculture and pulp and paper industry (1100 TWh) and biogas (739 TWh). Geothermal energy potential is estimated according to the method described in Aghahosseini and Breyer[66].

Regional modelling: 3-step approach

In order to achieve robust energy system analyses for Europe and correspondingly for the 27 EU member states, a three-step modelling approach is adopted (see Figure 4). The first two steps represent the hierarchical approach to energy system optimisation as defined in Bogdanov et al.[67] for the case of Japan. The step three enables further disaggregation of the regional results to retrieve the country-specific results for representative energy transition pathways.

STEP 1: Europe is categorised in four macro regions, which are Nordic, West, Central and Southeast. Energy transition pathways in three distinct scenarios are simulated for these interconnected macro regions of Europe and the results serve as a guiding reference for the next step. The four macro regions are further comprised of 19 regions across Europe. Iceland is not connected to the integrated European power grid and modelled as an energy island. The composition of the four macro regions and the corresponding 19 regions of Europe plus Iceland are as follows:

- **NORDIC:** Norway, Denmark, Sweden, Finland and a Baltic region that includes the countries of Estonia, Latvia and Lithuania;

- **WEST:** Iberian peninsula region with Portugal, Spain and Gibraltar, France together with Monaco and Andorra, Italy together with San Marino, Vatican and Malta, British Isles region comprised of the United Kingdom and the Republic of Ireland, Benelux region comprising Belgium, the Netherlands and Luxembourg;

- **CENTRAL:** Germany, Poland, a region comprising Czech Republic and Slovakia, a region with Austria and Hungary, a region with Switzerland and Liechtenstein;

- **SOUTHEAST:** A region that includes the Western Balkan countries of Slovenia, Croatia and Bosnia and Herzegovina, Serbia, Montenegro, Macedonia, Kosovo and Albania, a region including Eastern Balkan countries of Romania, Bulgaria and Greece, a region with Ukraine and Moldova, a region with Turkey and Cyprus;

- **ICELAND**

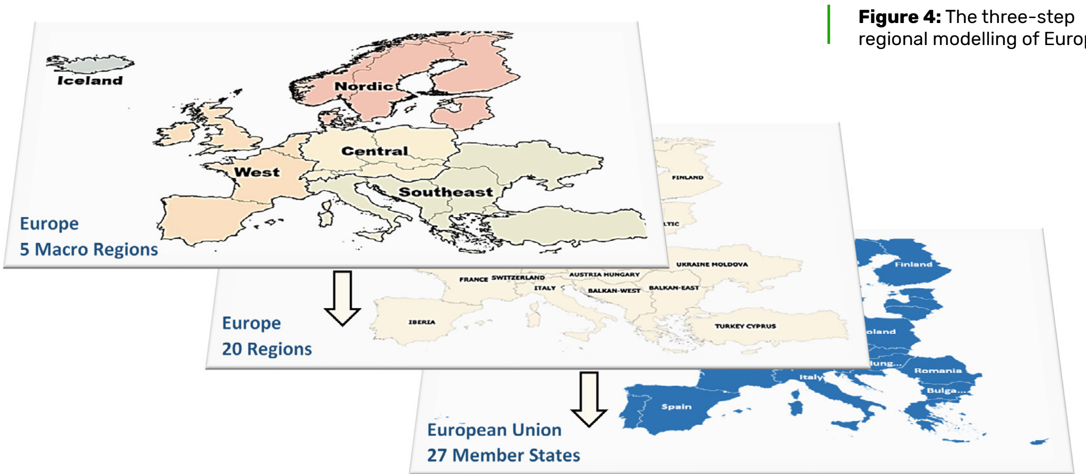


Figure 4: The three-step regional modelling of Europe.

STEP 2: Europe is further disaggregated from 4 macro regions to 19 regions across Europe, plus Iceland. Wherein some of the smaller countries have been merged with larger countries to form sizeable local regions. This reflects the highly interconnected energy infrastructure across Europe, as the energy transition is envisioned on a regional basis. The energy system transition is simulated for the whole of Europe, which is structured into 20 interconnected regions. These interconnections follow the interconnected patterns of the 5 macro regions, as electricity is predominantly exchanged within regional electricity pools. The 20 regions are interconnected with optimised transmission networks and Iceland remains as an isolated region. Cost optimised transition pathways for an integrated European energy system are modelled for three distinct scenarios.

STEP 3: The results from the simulations of the 20 regions of Europe serve as the basis for determining the energy transition pathways of the 27 EU member states. A per capita approach is adopted to disaggregate data of regions that comprise smaller member states of the EU. Aggregated results of the 27 member states are presented for the EU in three distinct scenarios.

Scenarios: Reference, Renewable Energy System - 2040 and Renewable Energy System - 2035

The LUT-ESTM can be applied to generate wide-ranging energy scenarios across the different regions of the world on a global-local scale. However, the objective of this study is to highlight energy scenarios in context to achieving the goals of the Paris Agreement of achieving net zero carbon emissions[8] from the energy system, in a technically feasible and economically viable manner. Therefore, three distinct scenarios are envisioned for an integrated energy sector combing the power, heat, transport and industry demands for the case of Europe and correspondingly the EU, from the current system in 2020 towards cost optimal energy systems with varying features up to 2050. The energy transition across Europe and in particular across the EU is explored in three distinct scenarios with the following boundary parameters and conditions[9]:

REFERENCE (REF): In this scenario, the European energy system is set on a minimum ambition pathway, wherein the current market and agreed policy trends continue up to 2030 with a requirement of at least 40% renewable energy, but the modelling results in 49% renewable energy of the final energy demand across the EU. Efficiency improvements in buildings across the EU witness doubling of the current rate of 1% per annum and linear increase of industrial heat efficiency to 1.5% per annum by 2030 and remains until 2050. In the transport sector, a slower rate of electrification of road transport leads to a longer presence of internal combustion engines (ICE) in road transport by 2050. Fuels for marine and aviation transportation encounter a slow transition away from fossil fuels by 2050. Slower growth of rail capacities across the EU with 5% every 10 years for both passenger and freight. Nuclear power plants continue to operate until the end of their technical lifetimes, but no new constructions of nuclear power plants are added to the system, while existing construction sites are assumed to be commissioned based on their probability of completion in the foreseeable future. New coal plants are not allowed due to climate regulation, whereas new gas-fired power plants are allowed, but with the obligation and abilities to switch to non-fossil fuels during the transition. The transmission grid expansion rate and corresponding interconnections across the EU are assumed to increase three folds in the next 25 years. The climate neutrality vision of the EC[68] by 2050 is achieved, as CO_2 emissions are zero by 2050 and reduced by at least 55% in 2030 below 1990 levels. Eventually, this scenario is not compatible with the ambitious goal of the Paris Agreement of limiting mean global temperature rise to below 1.5ºC. This scenario poses higher risks for energy security with continual reliance of imported fossil fuels in the mid-term.

RENEWABLE ENERGY SYSTEM - 2040 (RES-2040): In this scenario, the European energy system is set on an accelerated energy transition pathway. Increased efforts by all member states to drive the renewable energy share in final energy demand across the EU to 56%[10] in 2030 and 100% by 2040 is envisioned. Ramping up efficiency in buildings by tripling current renovation rates

8 The focus of this research is on carbon dioxide (CO_2) emissions from the consumption of fossil fuels in the energy-industry sectors across the EU and entail some uncertainties when compared to emissions levels in 1990.

9 No major changes are assumed in terms of consumer preferences across the scenarios, rather higher levels of energy services are assumed to be met in the future with correspondingly higher levels of energy efficiency.

10 This includes ambient heat used by heat pumps.

of 1% per annum and linear increase of industrial heat efficiency to 2.2% per annum by 2030 and remains until 2050 is considered. Wherein the current fossil fuels and nuclear power plants are phased out by 2040 and no new constructions of nuclear power plants are considered. New coal plants are not allowed due to climate regulation, whereas new gas-fired power plants are allowed, but with the obligation and abilities to switch to non-fossil fuels during the transition. The use of crops-based biofuels is eliminated from the EU energy system by 2030. The transmission grid expansion rate and corresponding interconnections across the EU are assumed to increase five times in the next 20 years. Accelerated electrification of transport is considered with some modal shift towards rail. Accelerated growth of rail capacities across the EU with 10% every 10 years for both passenger and freight is also considered. This scenario enables energy related carbon emissions reduction of at least 65% compared to 1990 levels, which is compatible with the climate target of limiting temperature rise to below 1.5°C as defined in the Paris Agreement with energy related carbon emissions reduced to zero already in 2040 across the EU. This scenario presents prospects of enhancing energy security and pursuing energy independence across the EU.

RENEWABLE ENERGY SYSTEM - 2035 (RES-2035): In this scenario, the European energy system is set on a high ambition and rapid energy transition pathway. With increased impetus the EU takes a global leadership role in mitigating climate change and enabling higher levels of energy security across Europe. Wherein the current fossil fuels and nuclear power plants are phased out by 2035 and no new constructions are considered. New gas-fired power plants are allowed, but with the obligation and abilities to switch to non-fossil fuels before 2035. The use of crop-based biofuels is eliminated from the EU energy system by 2030. The renewable energy share in final energy demand across the EU is expected to increase rapidly to around 75% in 2030 and 100% by 2035, which entails ramping up efficiency in buildings with four times the current renovation rates of 1% per annum and the linear increase of industrial heat efficiency to 3% per annum by 2030 that remains until 2050. There are no limitations on the transmission grid expansion rate and corresponding interconnections across the EU, but not exceeding doubling of capacities in the next five years. Enabling energy related carbon emissions reduction of at least 75% compared to 1990 levels, further on to zero emissions by 2035. This is highly compatible with the ambitious climate target of limiting temperature rise to well below 1.5°C. 100% renewable energy across the power sector in all EU member states in 2030 and all other sectors towards 100% renewables by 2035. Rapid electrification of transport is considered with modal shift towards rail. Rapid growth of rail capacities across the EU with 15% increase every 10 years for both passenger and freight transportation are considered. Substantial investments in railway infrastructure are required for this capacity increase, though, detailed quantification is beyond the modelling details of this study. Furthermore, as this scenario achieves zero CO_2 emissions and 100% renewables by 2035, it presents an opportunity for Europe to proceed with additional CO_2 emissions reduction and thereby becoming a negative CO_2 emissions continent. This is primarily driven by additional capacities to produce renewables based synthetic fuels for defossilisation of the transport and industry sectors beyond 2035. This leads to an opportunity to produce additional volumes of renewables based synthetic fuels for exports from 2035 to 2050. This effectively leads to negative CO_2 emissions in Europe since the carbon for the exported synthetic fuels is extracted from air in Europe but released in importing countries; the effect is zero for the sum of the exporting and importing countries. This scenario not only ensures higher levels of energy security but also positions the EU to export climate friendly technologies to other parts of the world and enhance global mitigation efforts.

The results are visualised and presented in five-year intervals through the transition from 2020-2050 for an integrated energy system transition across the EU in three distinct scenarios, REF, RES-2040 and RES-2035 (see Annex). Furthermore, the results are highlighted from an integrated energy system perspective as well as from a sectoral perspective for the power, heat, transport and industry sectors across the three scenarios respectively.

3 RESULTS:

Integrated energy system transition across the European Union

The energy transition from the present disjunctive state of the power, heat, transport and industry sectors in 2020, towards an integrated energy system fulfilling the energy and feedstock demand across the EU up to 2050, enforces some fundamental disruptions. In general, an increasing rate of sector coupling through the transition period from 2020-2050 is assumed in this study, which leads to a highly integrated energy system by 2050, with varying levels of efficiency gains across the three scenarios.

Long-term energy demand and supply

The development of the energy demand from 2020 to 2050 depends on several factors. First, the share of RE in energy supply, as defossilisation, allows to drastically reduce energy losses in power generation. Second, the level of sector coupling between the power, heat, transport and industry sectors, which depends on the adoption of different energy technologies. Third, the rate of electrification in the heat, transport and industry sectors, which depends on technological adoption, switch in powertrains and evolution of production processes respectively. Fourth, member states decisions on energy pricing shall favour emission-free electricity and should avoid extra surcharges on electricity prices in comparison to other energy carriers. In addition, the rate of improvements in building renovation rates increase efficiency across applications and drive down the primary energy further. Lastly, the rate of adoption of synthetic fuels that are primarily based on renewable electricity[43]. The development of primary energy consumption[11] across the three scenarios, from an energy carrier perspective is shown in Figure 5.

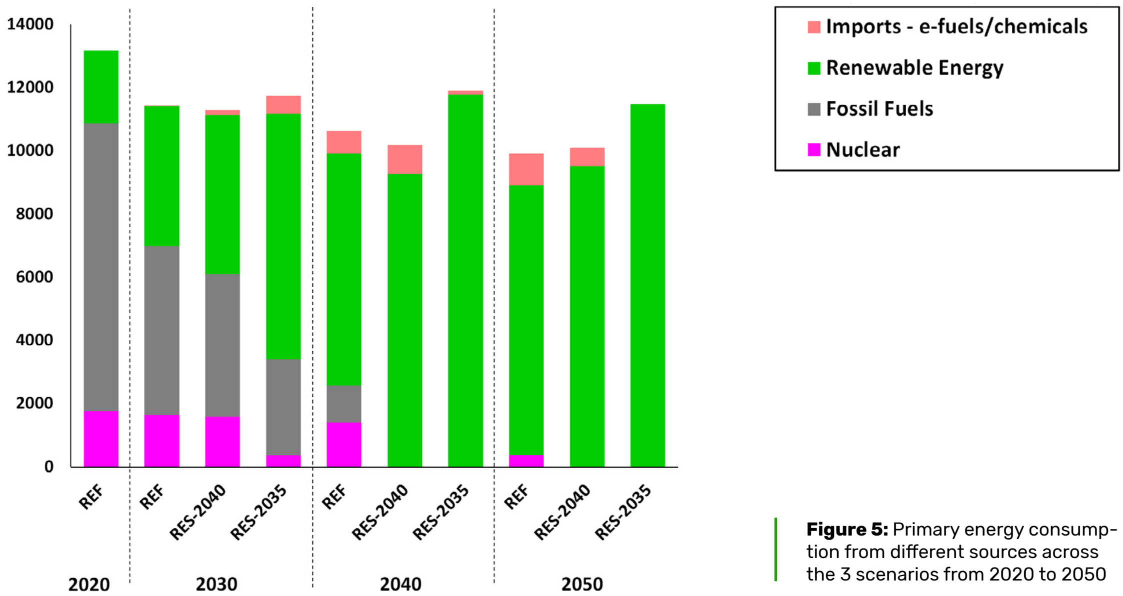


Figure 5: Primary energy consumption from different sources across the 3 scenarios from 2020 to 2050

11 Primary energy consumption does not include ambient heat from heat pumps and geothermal technologies.

Electrification is a growing trend that is predominantly reflected in the heat, transport and industry sectors, wherein electricity demand is growing as applications, and services are increasingly electricity-based[69]. Electricity supply from solar PV, wind power and hydropower is accounted as primary energy according to international standards[70,71]. A growing shift towards electrification is observed across all the three scenarios in varying levels and rates. Low-cost solar PV and wind power drive renewable electricity use across the different sectors. In the REF scenario, renewables reach 96% of primary energy consumption by 2050 (see Figure 5). While in the RES-2040 scenario, renewable energy is 100% by 2040. In the RES-2035 scenario, rapid electrification leads to 100% renewable energy consumption by 2035. On the contrary, energy from fossil fuels and nuclear rapidly decline to zero by 2035 in the RES-2035 scenario, to zero by 2040 in the RES-2040 scenario and to nearly zero by 2050 in the REF scenario that has some remaining shares of nuclear power from plants operating until end of technical lifetimes. Further details for the individual scenarios are presented in the Annex. From a sectoral point of view, the shares of primary energy demand for the transport and industry sectors increase across the three scenarios through the transition, while primary energy demand for the heat and power sectors declines in the three scenarios with increasing efficiency measures, building renovation rates and adoption of technologies with higher energy conversion efficiencies.

Across all three scenarios, the final energy demand slightly decreases by 2050 in comparison to 2020 (see Figure 6). This stability in final energy demand across the three scenarios is due to efficiency gains from high levels of electrified end use of energy and ensuing efficiency measures. Electricity and heat in terms of final energy grow in share across the three scenarios, while the share of fuel in final energy declines. This is predominantly due to the replacement of fossil fuels by renewables-based electricity and heat, sustainable synthetic fuels and some shares of residual biomass and waste. On a sectoral note, the share of transport in final energy declines as the shares of industry grow. This is on account of the high share of electric vehicles in transportation that leads to increased efficiency along with shift towards higher use of electrified rail and lesser demand by 2050. While the industry sector requires more electricity to produce e-chemicals. The details of final energy demand across each of the scenarios is presented in the Annex.

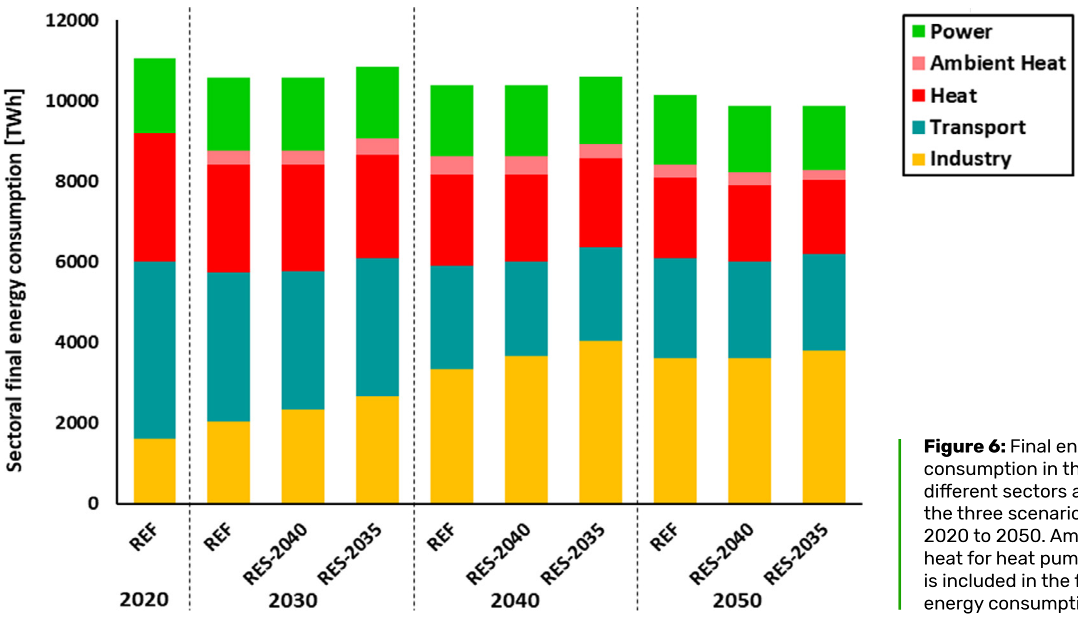


Figure 6: Final energy consumption in the different sectors across the three scenarios from 2020 to 2050. Ambient heat for heat pumps is included in the final energy consumption.

Penetration of renewables is not just a matter of replacing hydrocarbons with zero-carbon sources of energy supply, it also represents a significant change in resource efficiency. This is illustrated by the overall electrification across the power, heat and transport sectors, while the final energy consumption remains steady and also declines through the transition until 2050, as shown in Figure 6. The decline in final energy consumption is despite a steady growth in energy services, which is reflected by the growth in power and heat demand as well as transportation demand in terms of passenger and freight travel, as shown in the Annex.

Switching from today's energy system dominated by fossil fuels to a fully renewables-based energy system, largely utilising renewable electricity from solar PV and wind power, along with efficiency measures means untapping a tremendous efficiency potential.

- In the **power sector,** fossil fueled power plants are inefficiently converting hydrocarbons into electricity, while emitting CO_2, NOx, SOx and other pollutants produced during combustion. Their efficiencies typically range from 37% to 60%, depending on the fuel and power plant type. In nuclear power plants only 35% of the energy of the fission reaction is transformed into electricity, and the remaining 65% is lost. Similarly, uranium enrichment for nuclear electricity production is a very inefficient process, as further energy is required in mining and processing uranium, which finally increases the total loss. In addition, causing adverse environmental and social issues encompassing the handling and disposal of spent fuel[72]. Conversely, renewables-based electricity allows for a much more efficient use of energy compared to using conventional sources. The energy output of direct renewable electricity sources, such as solar PV, wind power and hydropower, is 100% primary energy according to international standards.

- In the **heat sector,** conventional energy supply achieves higher efficiencies – combined heat and power (CHP) can go beyond 80% efficiency, whereas a gas boiler has an efficiency close to 100%. However, the use of heat pumps allows for much higher efficiencies, referenced to the electricity input, since additional heat is taken from the environment as part of the process. For this reason, their efficiency, called coefficient of performance, is usually in the range of 3 to 4, i.e., the heat supplied is higher by this factor than the electricity required.

- Electrification is a disruptive efficiency trend also in the **transport sector.** The best internal combustion engines (ICE) used in conventional road vehicles have an average annual efficiency of 20-30%, while the fleet average is substantially lower, because the biggest portion of energy is lost as waste heat and the real driving profiles do typically not allow the most efficient operation points. In contrast, electric vehicles achieve a much higher efficiency than conventional cars: the efficiency of an electric motor is around 85%, while regeneration allows to save energy from deceleration and further increases efficiency, especially in urban terrains. Electricity-based production of synthetic fuels enables indirect electrification of the remaining heat and transport sectors where direct electrification is more difficult. Electricity, water and air can be converted to synthetic hydrocarbon fuels, such as e-kerosene jet fuel, with an average efficiency of around 50%, which is only slightly less than converting raw biomass into refined biofuels.

- The **industry sector** with different industries is expected to realise significant efficiency improvements as the current inefficient processes, predominantly based on fossil fuels, are replaced with advanced and highly efficient technologies in the coming years. In the chemical industry, fossil fuel feedstock is replaced by renewable electricity, water and air during the transition to produce the required bulk feedstock chemicals[73,74]. In the steel industry, the emphasis is on recycling used steel and steel products and where recycling is not feasible, direct electricity and hydrogen is used as a feedstock replacing coal in steel production[75,76]. In the electricity intensive aluminium industry, processes remain unchanged with the emphasis on recycling of aluminium, which drastically reduces the electricity demand during the transition. The pulp and paper industry uses biomass as feedstock, with low process related emissions, wherein the electricity and heat demands are covered by increasing levels of renewable electricity, similar to the aluminium industry.

To highlight the efficiency gains from increased levels of electrification and improving building renovation rates, the three scenarios are compared to respective low electrification scenarios in which the primary energy demand grows through the transition with the same levels of energy use and technologies as of 2020, as shown in Figure 7.

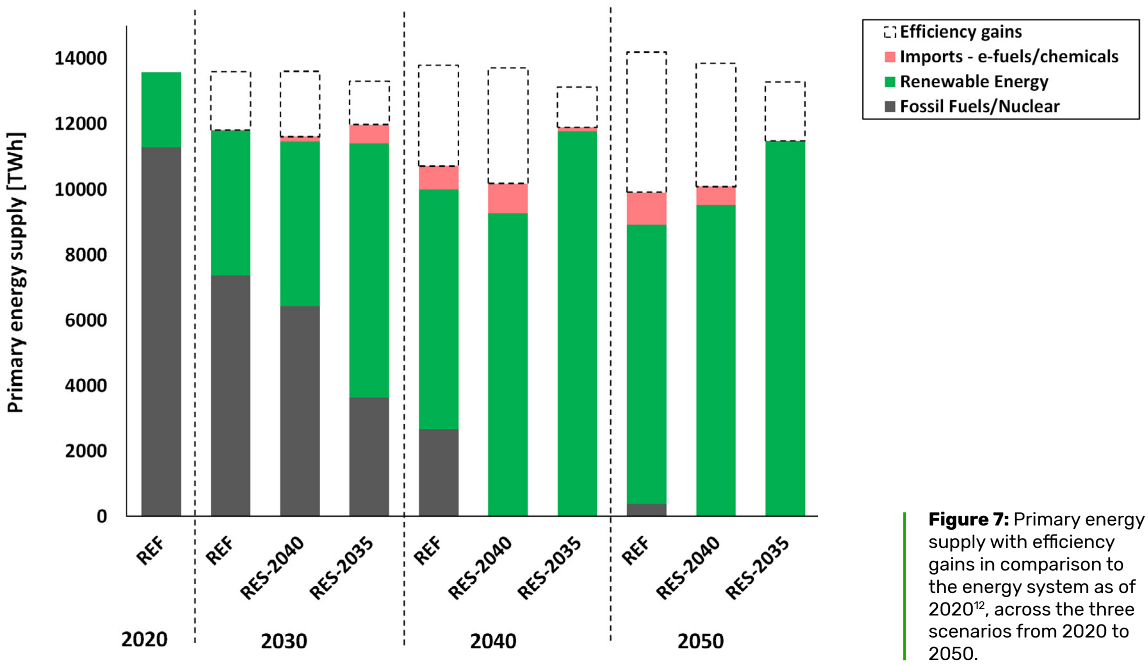


Figure 7: Primary energy supply with efficiency gains in comparison to the energy system as of 2020[12], across the three scenarios from 2020 to 2050.

12 Efficiency gains are derived from the comparison of primary energy development in the three scenarios to an assumed development of the energy system with the static efficiency status as in 2020 until 2050.

The REF scenario has the highest shares of efficiency gains in primary energy by 2050, as compared to the low electrification scenario in which the current system is projected to continue until 2050. The RES-2040 scenario has the most efficiency gains by 2040 and the RES-2035 scenario has lower shares of efficiency gains in primary energy. This is due to the advanced production of e-fuels and e-chemicals by 2035 in the RES-2035 scenario. Unlike the other scenarios, the RES-2035 scenario fully relies on local e-fuels and e-chemicals production in 2050 across the EU.

This indicates that future energy systems with high shares of renewables will have high conversion efficiencies and deliver high levels of energy services with lower levels of primary energy input. To enable cost optimal energy transitions across the EU, imports of e-fuels and e-chemicals from other European countries as well as outside Europe are realised. However, the shares of imports are low and encourage deployment of renewables beyond the EU. 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. Increasingly levels of recycling and overall circular economy contribute to increased energy efficiency, such as secondary steel and aluminium, also higher rates of plastics, paper and cardboard recycling, with only small fraction utilised in waste-to-energy operation.

The current energy system of the EU is rather disintegrated and segmented, which is dominated by fossil fuels that are inefficiently converted to electricity in the power sector, heat for heating applications in the heat sector, as combustible fuel for energy in the transport sector and as fuel and feedstock in industrial processes in the industry sector. During the transition, the energy system evolves towards higher levels of sectoral integration, which is enabled by electrification, adoption of storage and power-to-X technologies. Electrification is primarily driven by the switch from fossil fuels and nuclear based electricity generation to renewables-based electricity in the power sector, electric heating coupled with geothermal heat pumps in the heat sector, internal combustion engines to electric drivetrains in the transport sector and process conversions from fossil fuels and feedstock to direct electricity along with e-fuels and e-chemicals in the industry sector. Sector coupling enhances the efficient operation of the energy system, which is driven by power-to-heat, power-to-mobility, power-to-gas, power-to-fuels and power-to-chemicals. Renewables-based electricity, which is a primary source of energy, emerges as the key energy carrier. It is utilised for electricity in the power sector, generating heat applicable in the heat sector and providing electricity for direct use as well as production of synthetic fuels (e-hydrogen, e-methane, e-kerosene jet fuel, e-fuels, e-methanol and e-ammonia) in the transport and industry sectors along with high temperature applications in the heat sector. Renewable electricity based hydrogen emerges as the second most important energy carrier through the transition, mainly for the production of synthetic fuels and chemicals. Natural heat from the environment in the form of geothermal heat and bioenergy from biomass and organic waste provide some shares of primary energy for electricity, heat, transport and industry use. High levels of efficiency gains from electrification and sector coupling not only enable a decrease in the primary energy demand of an integrated energy system but also adoption of efficient processes in the long term. This is captured by the final energy demand, which represents the energy demand at the consumption end. In the current decoupled and fossil fuels heavy energy system, a higher level of primary energy is required to meet the final energy demand, whereas in a highly electrified and sector coupled energy system a lower level of primary energy is required to meet the final energy demand, which is almost the same by 2050 (see Figures 5-7).

Energy supply across the EU is heavily dominated by fossil fuels (about 80%) in 2020, with around 20% share of renewable energy (refer Figure 1). However, the share of renewable energy grows substantially through the transition period up to 2050, but in varying pathways across the three scenarios as illustrated in Figure 8.

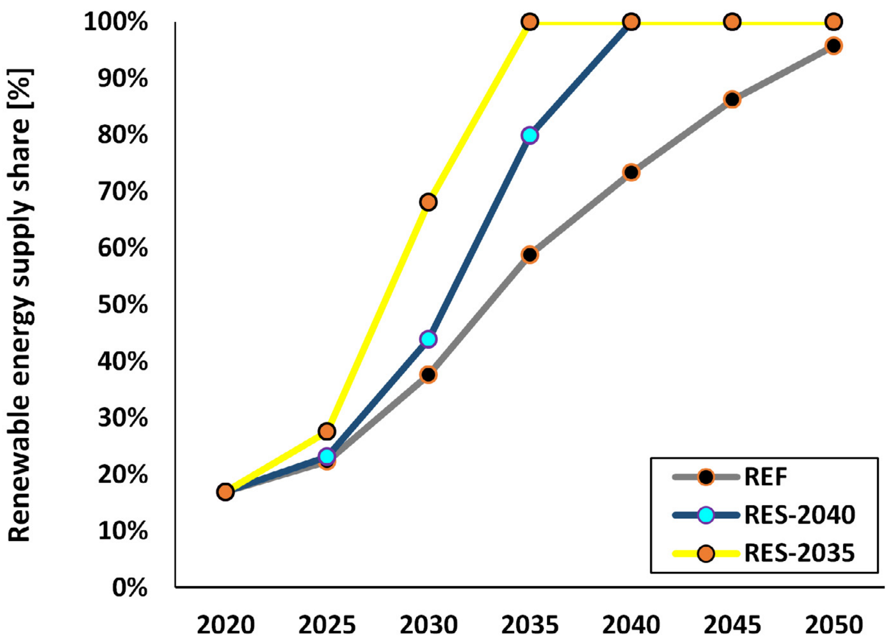


Figure 8: Share of renewable energy in primary energy supply across the three scenarios from 2020 to 2050.

The RES-2035 scenario displays a rapid transition pathway for the EU, in which renewable energy supplies 100% of the energy in 2035 and continues to supply the integrated energy system until 2050. In the RES-2040 scenario, renewable energy growth is accelerated through the transition reaching 100% by 2040. In the REF scenario, renewable energy is on a low-growth trajectory reaching about 98% supply by 2050, with just some remaining and gradually phasing out shares of nuclear. A few European countries have witnessed rapid growth of renewables in the past decade, with 9 of the top 10 countries worldwide with the highest share of electricity from wind power and solar PV situated in Europe[77]. This reinstates the possibility for rapid deployment of renewables across the EU to provide energy for an increasingly integrated energy system.

Sectoral Outlook

Different trends in the power, heat, transport and industry sectors across the EU in the three scenarios emerge through the transition. As the sectors transition towards higher shares of renewables in the energy supply mix, different technologies have different roles in ensuring the operational stability of the integrated energy system. A closer look at the individual sectors provides further insights into the energy transition across the EU towards high shares of renewable energy in the three scenarios.

Electricity Supply

The transition of the power sector across the EU is already well underway with around 35% of electricity being generated by renewables (refer Figure 2). This trend continues across the three scenarios in varying levels of electricity generation from renewable sources, as shown in Figure 9.

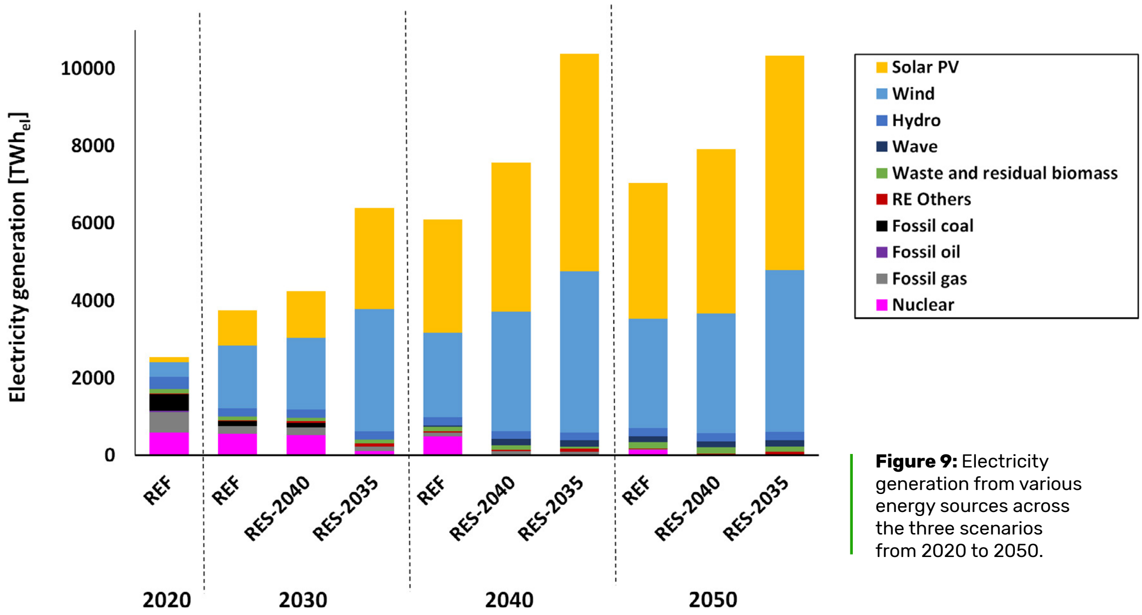


Figure 9: Electricity generation from various energy sources across the three scenarios from 2020 to 2050.

Increasing shares of electrification lead to higher levels of electricity generation with nearly 3-5 times in 2050 compared to 2020 levels across the three scenarios, as highlighted in Figure 9. In the REF scenario, the installed capacities of renewables grow at a slower rate with about 3960 GW and generation of renewable electricity reaches over 7,000 TWh by 2050. In the RES-2040 scenario, an accelerated growth in renewables capacities of 4550 GW delivers nearly 8,000 TWh of electricity by 2050. In the RES-2035 scenario, a rapid growth in capacities up to 2035 with over 6000 GW ensures 100% renewable electricity delivering over 10,000 TWh in 2050. Wind power delivers the most electricity in the mid-term up to 2030 in the three scenarios, whereas solar PV emerges as the prime source of electricity from 2040 onward with better cost competitiveness in the three scenarios. In 2050, solar PV delivers nearly 50% of electricity in the REF scenario, around 54% in both the RES-2040 and the RES-2035 scenarios. Further, solar PV prosumers including residential, commercial and industrial contribute significant shares of solar generation, around 20% in the REF scenario, 17% in the RES-2040 scenario and 12% in the RES-2035 scenario in 2050. Solar PV prosumers too enable an efficient energy system across the EU, as electricity is generated at the sites of consumption with reduced transmission and distribution losses. On the other hand, fossil fuels based electricity generation is completely phased out in the three scenarios, most rapidly in the RES-2035 scenario by 2030 followed by the RES-2040 scenario in 2040 and by 2050 in the REF scenario. Similarly, nuclear power is phased out in both the RES-2040 and RES-2035 scenarios by 2040 and 2035 respectively. While in the REF scenario, nuclear power plants remain operational until end of technical lifetimes and contribute minor shares of electricity in 2050. However, in all three scenarios, nuclear power is deemed uncompetitive with low-cost renewable electricity and it poses grave environmental and social risks[72,78,79] that are well documented across the EU and the world. Installed capacities and corresponding electricity generation in each scenario are presented in the Annex.

Heat Supply

Heat is a vital energy form for the EU, predominantly for space heating and domestic hot water. In 2020, about 30% of heat supply is provided by renewables, which is mainly bioenergy. On the other hand, fossil gas provides the majority with over 40% (see Figure 2). A combination of direct electric heating and indirect via heat pumps is increasing in shares across many EU countries owing to the substantial efficiency gains and as affordable alternatives to imported fossil gas[80,81.] Building renovations driven by efficiency standards that are expected to continually improve through the transition enable rapid adoption of efficient and sustainable heating across the building sector in the EU countries. This trend is observed across the three scenarios with heat generation capacities and the corresponding heat generation through the transition, as highlighted in Figure 10.

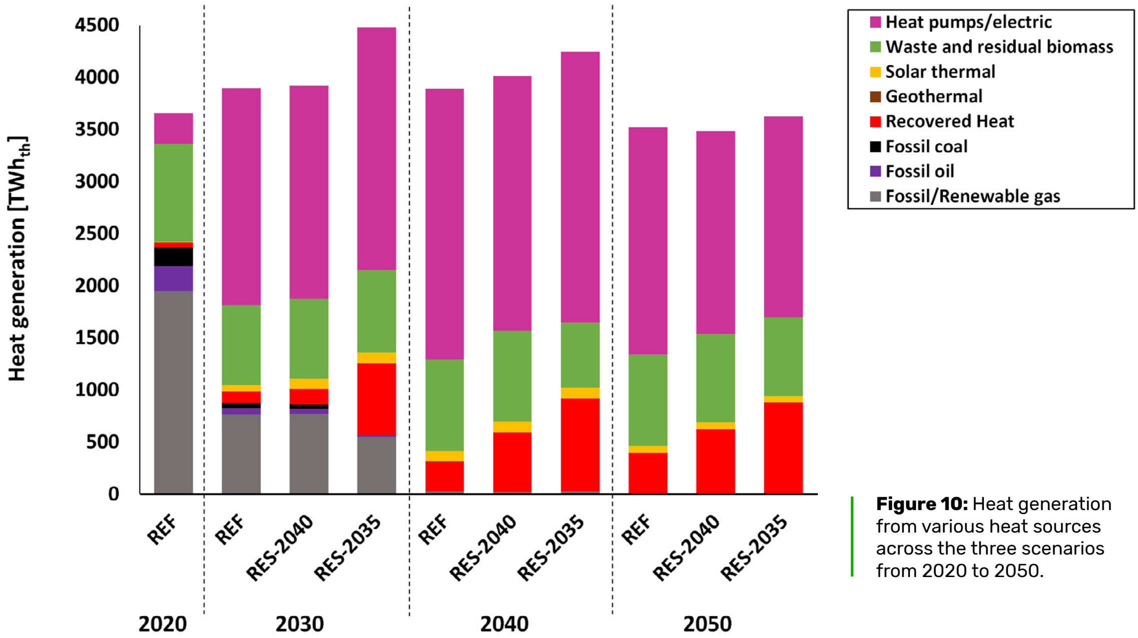


Figure 10: Heat generation from various heat sources across the three scenarios from 2020 to 2050.

Across the three scenarios, heat pumps with electric heating deliver the majority of heat generation by 2050, a slightly declining share of bioenergy fully shifting to waste and residual biomass contributes heat along with recovered heat. Recovered heat is the waste heat from different thermal processes including the production of e-fuels and e-chemicals captured to cover heat demand. Utilisation of recovered heat is crucial to enhance efficiencies through the transition. Enhanced efficiency standards of buildings driven by continually improving renovation with different rates across the three scenarios ensure growing efficiency gains from improved and electrified heating. Existing building renovation rate of around 1% across the EU is expected to double in the REF scenario, triple in the RES-2040 scenario and quadruple in the RES-2035 scenario by 2030 and continue towards 2050. The increase in building renovation rates leads to efficiency improvements in space heating, due to different assumptions on the renovation rates the per capita space heating demand reduces by 1.1% per annum in the REF scenario, 1.6% per annum in the RES-2040 scenario and 2.1% per annum in the RES-2035 scenario by 2030 and continues until 2050. Similarly, industrial heat efficiency rate increases linearly to 1.5% per annum in the REF scenario, 2.2% per annum in the RES-2040 scenario and 3% per annum in the RES-2035 scenario by 2030 and continues until 2050. On the contrary, fossil fuels based heat declines across the three scenarios, rapidly to zero in the RES-2035 scenario by 2035, zero share in the RES-2040 scenario by 2040 and reaching zero by 2050 in the REF scenario. These results indicate that the heating sector is poised for higher shares of heat pumps and electric heating along with some water and residual biomass based heat, complemented by efficiency measures, renovation rates and recovered heat. The growth of these technologies across the EU has the potential to displace imported fossil gas, predominantly from Russia and enable pathways towards energy independence. Installed capacities and corresponding heat generation in each individual scenario are presented in the Annex.

Transport and Industry

The transport sector across the EU is undergoing some significant changes: electrification, digitalisation, automation, modal shifts and the sharing economy are fast transforming transport services[82]. In Europe, electric car sales increased by nearly 70% in 2021 to 2.3 million, about half of which were plug-in hybrids[17]. However, BEVs are expected to emerge as the dominant technology for road transport as plug-in hybrids are neither cost effective nor energy efficient in the long term, as this can be already observed in Norway. This trend will predominantly affect the energy demand for road transportation across the three scenarios. The final energy demand for road passenger and freight transport declines significantly through the transition across the three scenarios, as illustrated in Figure 11, while the final energy demand for aviation passenger transportation increases marginally through the transition across the three scenarios, mainly driven by the production of synthetic e-kerosene jet fuel as shown in Figure 11.

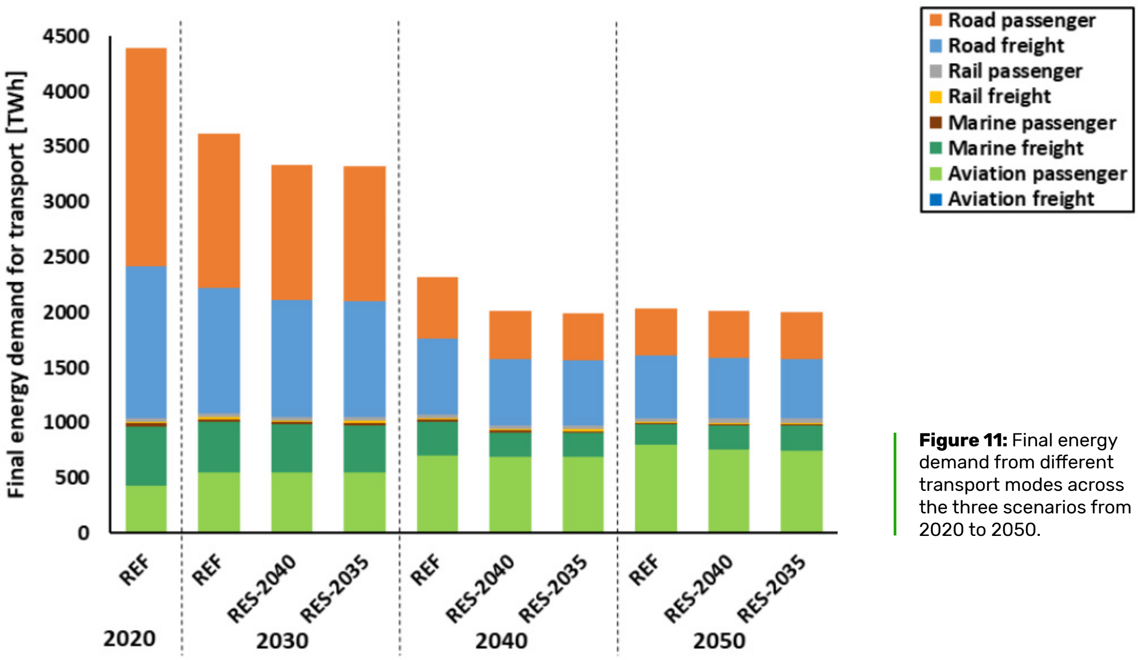


Figure 11: Final energy demand from different transport modes across the three scenarios from 2020 to 2050.

The contrasting trends in the development of the final energy demand are because of the level of direct electrification possible in the different transport modes as well as the modal shifts mainly towards electrified rail. Road transportation has a high level of direct and rapid electrification in the RES-2040 and RES-2035 scenarios. While slightly lower levels and slower electrification in the REF scenario, resulting in slightly higher final energy demand as shown in Figure 11. Aviation transport, mainly passenger, has a growing final energy demand across the three scenarios from 423 TWh in 2020 to 793 TWh (REF), 750 TWh (RES-2040) and 748 TWh (RES-2035) by 2050, as additional electricity is required for the production of renewable e-fuels. Furthermore, direct electrification of short hauls across all modes including electric ferries, electric aircrafts emerge as viable options during the transition for ships from 2025 onwards and for airplanes from 2035 onwards. Modal shift towards increasing use of high speed rail across the EU for both passenger and freight is an attractive proposition[83]. The modal shift in passengers is 90% from road and 10% from aviation in all the three scenarios. However, the growth in rail capacities across the EU is 5% every 10 years in the REF scenario, 10% every 10 years in the RES-2040 scenario and 15% every 10 years in the RES-2035 scenario in both passenger and freight rail. By 2050 in the REF scenario 49 600 mil p-km (0.5% of total road demand) and 74 800 mil t-km (2.1% of total road demand) are shifted to rail from road transport and 42 400 mil p-km (1.2% of total aviation demand) and 11 700 mil t-km (9.4% of total aviation demand) from aviation. By 2050 in the RES-2040 scenario the increased rail infrastructure development leads to higher modal shifts: 143 200 mil p-km (1.4%) and 162 800 mil t-km (4.6%) are shifted from road transport and 52 800 mil p-km (1.4%) and 21500 mil t-km (17%) from aviation. Only in RES-2035 the rail infrastructure exceeds the overall transportation demand growth: 248 500 mil p-km (2.4%) and 261 900 mil t-km (7.5%) are shifted from road transport and 64 500 mil p-km (1.8%) and 32 483 mil t-km (26%) from aviation. In this sense, transportation by the rail mode emerges as the most effective across the EU and is expected to play a significant role in strengthening the EU transport system, its resilience, and its reliability[84].

Various industries that form the industry sector across the EU are critical to the economies of the member states, which not only provide employment to millions but also value added products that are used in other sectors. However, these energy-intensive industries emit significant CO_2 emissions as they use fossil fuels for energy and as feedstock. The transition of these industries is enabled by change in sources of energy as well as change in processes resulting in fossil fuels independent industries in the three scenarios. The transition leads to growing demand from these industries in all three scenarios, particularly the chemicals industry as illustrated in Figure 12.

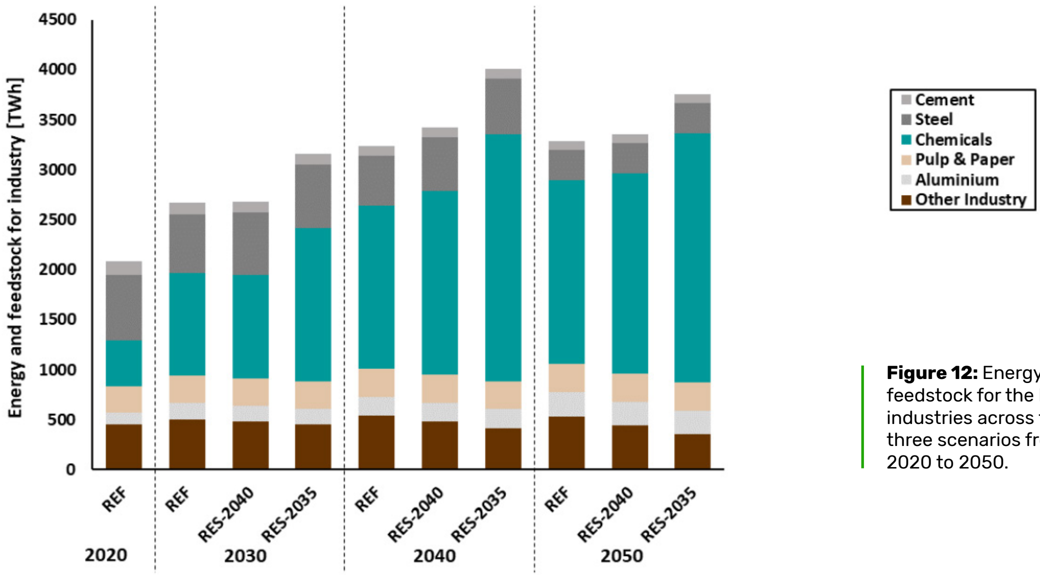


Figure 12: Energy and feedstock for the key industries across the three scenarios from 2020 to 2050.

The global growth of the chemical industry until 2050 is projected at about 1.8% annually[85]. The chemical industry can transition to being more sustainable by switching from fossil fuels to renewable electricity based power-to-chemicals solutions. The two main chemicals that can serve as the feedstock chemicals by 2050 are ammonia and methanol[73,86]. The chemicals industry requires the most energy input, predominantly for the production of e-hydrogen enabling the transition to sustainable chemicals. Other industries of steel, cement and others have a declining energy demand with electrification of processes (see Figure 12). Electricity evolves to be the main primary energy input, while most electricity is required for hydrogen production, mainly for chemicals, but also for green steel and partly for cement. The energy demand remains rather stable for the pulp and paper, aluminium and other industries through the transition in the three scenarios. In the REF scenario, a 100% renewables-based industry transition occurs by 2050, by 2040 in the RES-2040 scenario and by 2035 in the RES-2035 scenario. Refer to the Annex for details on each scenario.

Defossilisation of the energy supply

Changing energy mix coupled with increasing electrification and improving efficiency result in a transition of the volumes as well as the types of fuels and chemicals across the three scenarios. The total supply of fuels and chemicals is reduced by over 55% by 2050 compared to 2020 levels in the three scenarios (see Figure 13). Moreover, a fundamental shift from fossil fuels to renewable electricity based synthetic fuels and chemicals takes shape with varying rates in the three scenarios. Fuels from waste and residual biomass enhance the transition to sustainable fuels and chemicals with growing supply shares in the three scenarios (see Figure 13). However, the volumes of total supply slightly decline through the transition as they are limited by stringent sustainability and biodiversity limits, utilising only residual biomass and waste across the EU. The major demand for biomass shifts from individual heating, which is the prime consumer of biomass in 2020, to utilisation in power generation, individual heating, centralised district heating systems, advanced (2nd gen) biofuels synthesis and biomethane production in approximately even shares. In the RES-2040 scenario 349 TWh of biomass and waste is utilised for power generation, 323 TWh for centralised heating, 376 TWh for individual heating, 337 TWh for advanced biofuels synthesis and 467 TWh for biomethane production which is later used for power generation and as marine transport fuel in 2040. Some shares of imports of e-fuels and e-chemicals enable a cost-effective transition across the EU in the three scenarios, also in avoiding excess capacities around 2050 while e-fuels and e-chemicals investments outside the EU and Europe can be triggered by imports.

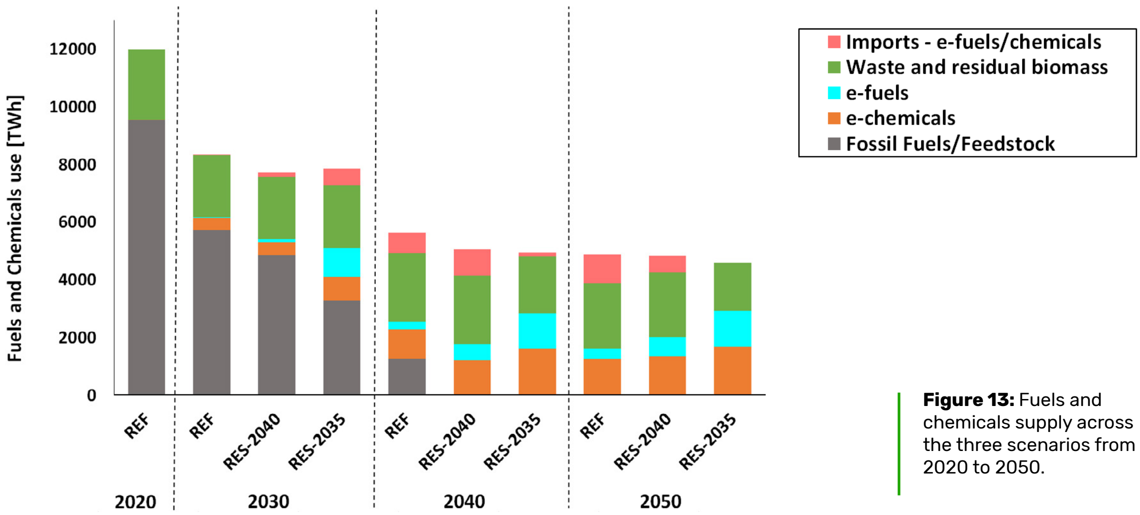


Figure 13: Fuels and chemicals supply across the three scenarios from 2020 to 2050.

In the REF scenario, e-fuels and e-chemicals conversion technologies play a significant role and the supply shares of e-fuels and e-chemicals increase significantly from 2040 onwards. While in the RES-2040 and RES-2035 scenarios, the production of e-fuels and e-chemicals are ramped up faster and have prominent supply shares by 2030. Imports of e-fuels and e-chemicals, mostly from neighbouring European countries but also from outside Europe enable a cost-effective transition and prevent inefficient capacity expansion as well as land utilisation across the EU. Imports kick in beyond 2040 increasing up to 2050 in the REF scenario, while in the RES-2040 and RES-2035 scenarios, imports begin in 2030, in RES-2035, e-fuels imports peak in 2030s and later decline by 2050 and energy supply of the EU becomes fully self-sufficient. Accordingly, supply shares of fossil fuels diminish steadily through the transition from a majority of the supply in 2020 to reach zero by 2050 in the REF scenario while declining rapidly by 2040 and 2035 in the RES-2040 and RES-2035 scenarios, respectively. Further details on the supply of fuels and chemicals in each of the scenarios are presented in the Annex.

The production of e-fuels and e-chemicals requires a steady and sustainable supply of carbon dioxide (CO_2) as a vital ingredient. In this study, CO_2 is sourced from Direct Air Capture (DAC), as this is the most feasible option from a long-term perspective and has a potential role in climate mitigation[54]. However, sustainable point sources of CO_2 could have a potential role in the short-term until the 2030s across the EU. The CO_2 supply in each of the three scenarios is presented in the Annex.

The overall increase in electrification along with improving efficiency levels drives down the consumption of all fuels by over 55% in all three scenarios and is the prime driver for the defossilisation of the EU's energy system.

Electrification across the heat, transport and industry sectors

Electrification along with improving efficiency levels across the different energy sectors and applications is a growing trend across Europe, which is currently taking place through a mix of direct and indirect substitutions[57]. Direct substitution involves the proliferation of electric vehicles in the transport sector and the adoption of highly efficient electric heating systems like heat pumps in buildings and some parts of industry. Solar PV prosumers with electricity generation at the sites of consumption lead to reduced transmission and distribution losses, thereby enabling more efficient energy system across the EU. On the other hand, indirect substitution involves a switch to synthetic fuels, which are produced by electrolysis, methanation and Fischer-Tropsch synthesis using renewable electricity, to provide energy for heat, transport and as many industrial processes as possible, that otherwise would rely on fossil fuels. Measures in reducing overall need for energy driven by building renovation rates, modal shifts towards highly efficient rail, efficient use of recovered heat, efficient EVs and smart charging as well as other measures play a vital role in aiding electrification and integration of the EU energy system.

The significant growth in electricity supply (mainly from renewables) for the different sectors across the three scenarios is highlighted in Figure 14. From just a few hundred TWh in 2020[13], electricity supply grows massively especially in the transport and industry sectors in the three scenarios. With a rapid transition and corresponding electrification, the electricity supply growth

13 The direct electricity consumption of the industry sector is allocated in the power sector, therefore the displayed extra electricity consumption in 2020 is low.

is the highest in the RES-2035 scenario with about 7000 TWh by 2040, followed by the RES-2040 and REF scenarios with around 5000 TWh and 4000 TWh in 2050 respectively (see Figure 14). However, this growth in electricity supply leads to overall decrease in final energy consumption with significant gains in efficiency enabled by the phase-out of inefficient use of fossil fuels and corresponding adoption of highly efficient processes, increasing renovation rates in buildings and overall electrification of the energy system. It is possible to have more energy with less resources across the EU.

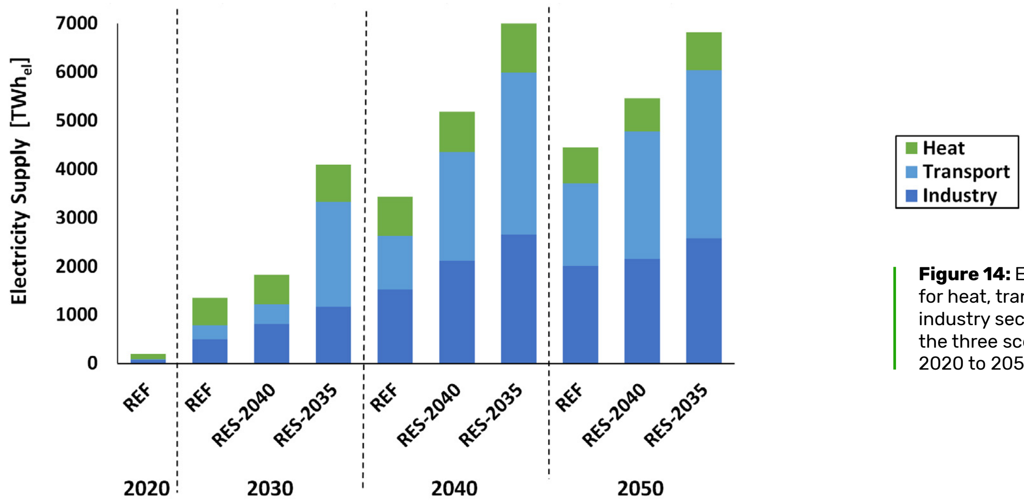


Figure 14: Electricity for heat, transport and industry sectors across the three scenarios from 2020 to 2050.

Electricity usage in the heat, transport and industry sectors increases through the transition across the three scenarios, in the form of direct electricity as well as indirect electricity in the production of e-hydrogen, synthesis of e-fuels and e-chemicals (see Figure 15). In the REF and RES-2040 scenarios direct electricity and some shares of e-hydrogen enable the transition in the mid-term until 2030. While in the RES-2035 scenario, e-fuels along with e-hydrogen and direct electricity are ramped up rapidly by 2030. Consequently, the RES-2035 scenario has the highest shares of electricity supply for e-hydrogen and e-fuels up to 2050, followed by the RES-2040 and REF scenarios (see Figure 15).

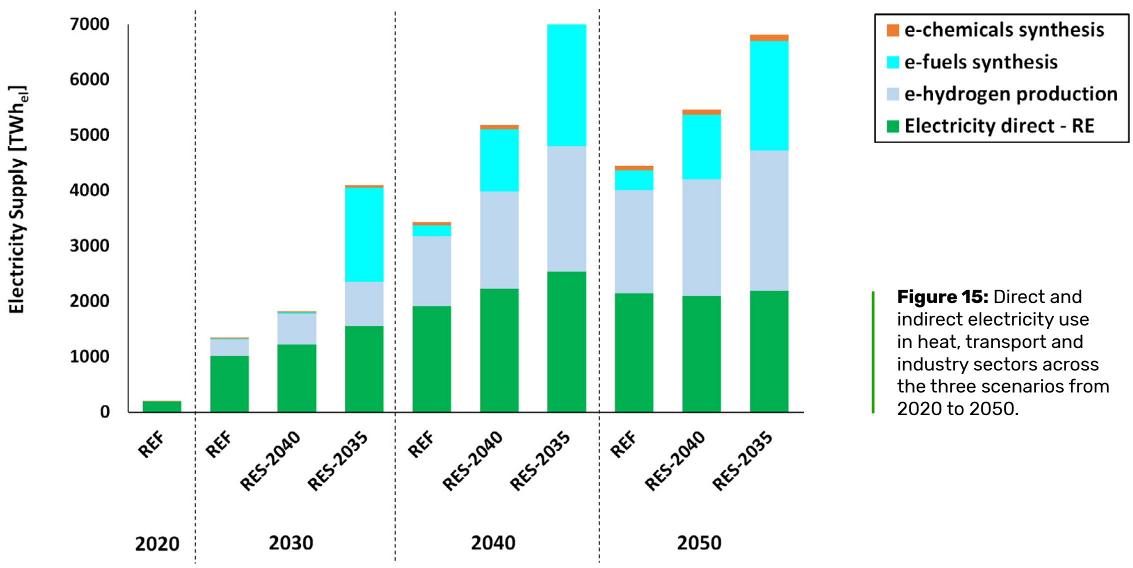


Figure 15: Direct and indirect electricity use in heat, transport and industry sectors across the three scenarios from 2020 to 2050.

Direct electricity is predominantly for road and rail transport modes, while electricity for the production of e-hydrogen and synthesis of e-fuels and e-chemicals enables the shift in marine and aviation modes. In the industry sector, electricity supply for the production of e-hydrogen and e-chemicals synthesis plays a vital role in the shift to sustainable chemicals production, steel, and partly cement production. Some minor shares of electricity enable the synthesis of e-ammonia and e-methanol through the transition in the three scenarios.

In the transport sector, renewable electricity drives the electrification in the initial periods of the transition, after which renewable electricity based e-hydrogen and e-fuels provide the majority of the energy across the three scenarios (refer Annex). Renewable electricity based e-hydrogen and e-fuels play an important role in providing a vital source of energy for transport modes that cannot be directly electrified as well as for hard-to-abate industries, which further enable the integration of the transport and industry sectors. Further details of the heat, transport and industry sectors for each scenario are presented in the Annex.

The drive towards electrification and higher levels of efficiency enhances sectoral coupling, as low-cost renewable electricity emerges as the prime energy carrier in future energy systems. To enable the integration of high shares of renewable electricity in the future energy system, storage technologies are critical through the transition.

Storage for electricity, heat and gas

To realise an energy transition towards a fully sustainable and integrated energy system across the EU, the development and adoption of storage technologies is vital[87]. Renewable electricity generation is inherently intermittent and is dependent on regional as well as seasonal weather patterns, which vary starkly across Europe. Therefore, to ensure a functionally stable and reliable energy system across the EU, energy storage technologies are expected to be the key enablers. Integrating high shares of variable renewable electricity across the power, heat, transport and industry sectors will require electricity, heat and gas storage technologies. In this study, a range of electricity, heat and gas storage technologies are part of the energy system across the EU (see Figures 16 and 17).

Electricity storage technologies play a vital role in enabling the transition towards high shares of renewable energy across the three scenarios, as shown in Figure 16. As the shares of solar PV and wind power increase significantly beyond 2030, the role of storage is crucial in providing uninterrupted electricity supply, across the three scenarios. Batteries, both for utility and prosumers emerge as the preferred option in the long-term beyond 2040. Vehicle-to-grid, which is another form of battery storage also contributes some shares beyond 2040 along with some shares of pumped hydro energy storage through the transition across the EU. The details of each scenario are presented in the Annex.

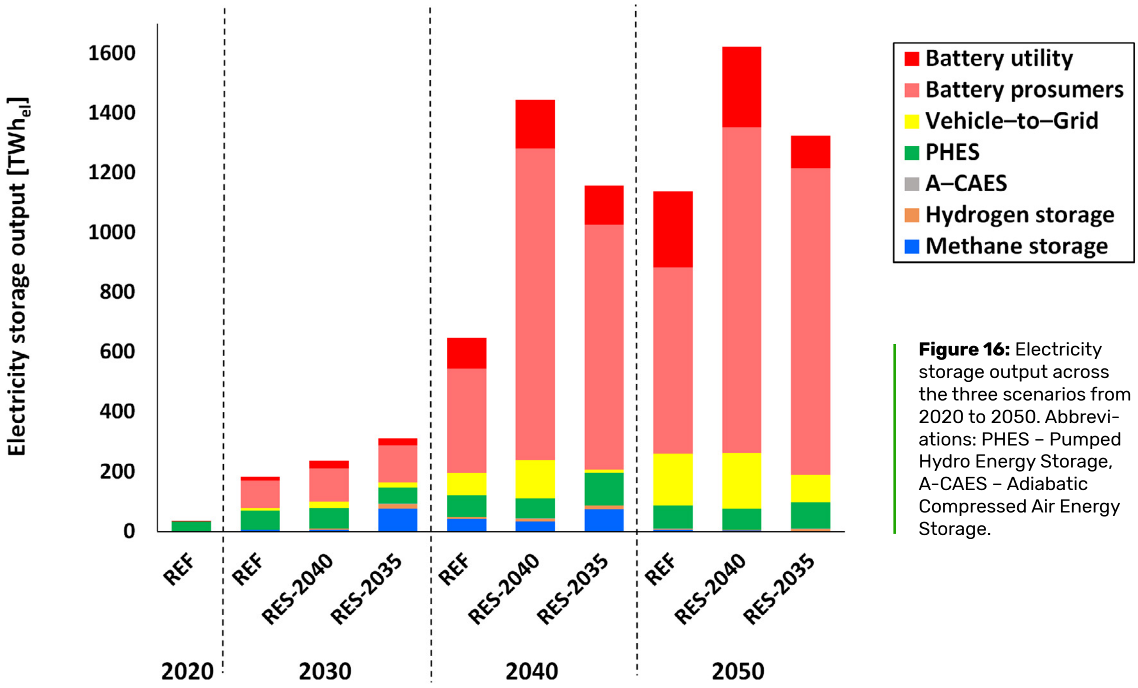


Figure 16: Electricity storage output across the three scenarios from 2020 to 2050. Abbreviations: PHES – Pumped Hydro Energy Storage, A-CAES – Adiabatic Compressed Air Energy Storage.

Heat storage plays a vital role in covering the heat demand across the three scenarios through the transition, as shown in Figure 17. Further details for each individual scenario are presented in the Annex.

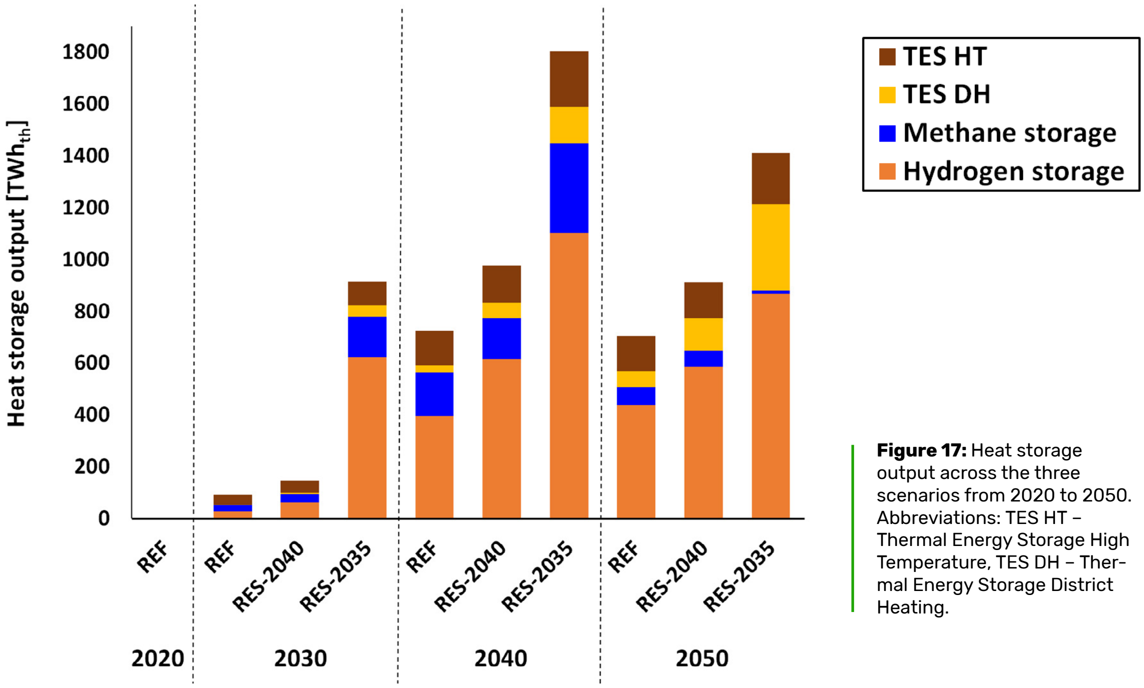


Figure 17: Heat storage output across the three scenarios from 2020 to 2050. Abbreviations: TES HT – Thermal Energy Storage High Temperature, TES DH – Thermal Energy Storage District Heating.

A major share of the heat storage is provided by renewables-based hydrogen storage across the three scenarios (see Figure 17). The methane and hydrogen storage can be discharged to provide fuel for heating, running power plants, buffer hydrogen for e-fuels production, or provide feedstock for industry. This is influenced by seasonal demand to cover heat, power, e-fuels, and industrial feedstock requirements during the winters across the EU. While thermal energy storage

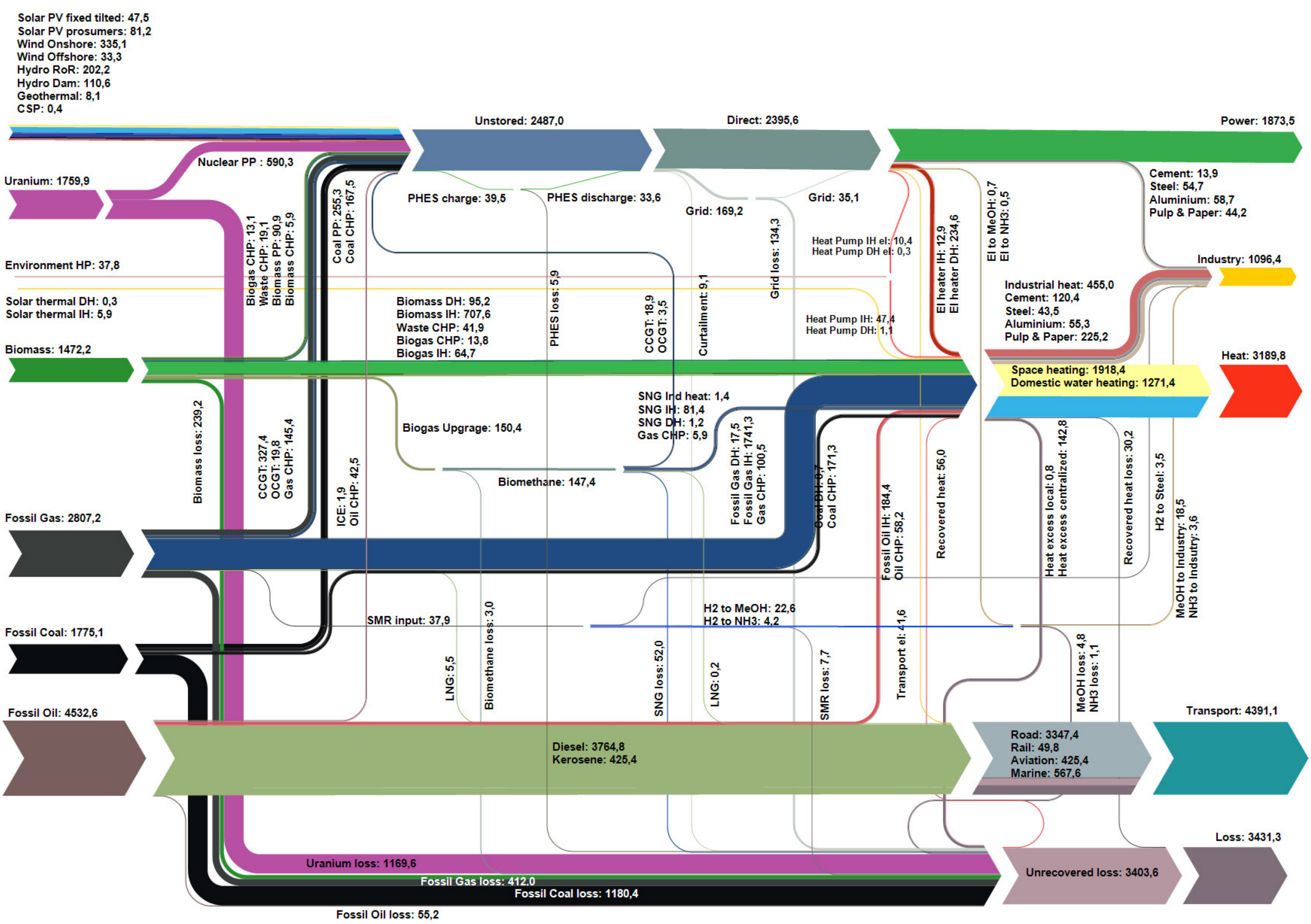
(TES), both high temperature (HT) as well as district heating (DH) provide significant shares in the later stages of the transition, as shown in Figure 17. The RES-2035 scenario has higher shares of heat storage with rapid growth, while the REF and RES-2040 scenarios have lower shares through the transition. Further details for each individual scenario are presented in the Annex.

The results indicate that electricity and heat storage options have a more prominent role for accelerating the transition, as they provide a bridging solution for power, heat, transport and industry sectors.

Sector coupling and flexibility in the energy system

Sector coupling has been much vaunted in recent times across Europe as a key enabler in the pursuit of GHG emissions reduction in the energy sector[30,88]. Moreover, it can be a cost-efficient means of integrating the energy system, by valuing synergy potentials and interlinkages between different uses, applications and sectors. The impacts of sector coupling across the three scenarios are highlighted in the Figures 19-21, which show energy flows in the EU energy system in 2050 for the REF, RES-2040 and RES-2035 scenarios respectively. These are compared to the current EU energy system in 2020, which is rather sector decoupled as shown in Figure 18.

Figure 18: Energy flows of the EU energy system in 2020.



The current energy system is supply-driven, centralised and mostly decoupled, which complements the use of fossil fuels and nuclear as the dominant energy sources. The energy flows of the EU energy system in 2020, as shown in Figure 18, are highly resource intensive and inefficient with a high share of energy loss on the level of final energy, but even more inefficient in the step from final energy to energy services, in particular in the transport sector. The power sector is the most diversified, in terms of energy sources and the transport sector particularly road, aviation and marine are the least diversified with almost complete reliance on fossil fuels as the energy source. The heat sector is diversified partly, but still heavily relies on fossil gas as the energy source. This indicates that the current EU energy system is inherently less diversified, decoupled, inflexible and hugely dependant on imported energy sources. However, recent developments in the power sector and the emergence of low-cost renewable electricity as the prime energy carrier has set the direction towards a more decentralised, sector coupled, flexible and demand-oriented energy system.

In this study, sector coupling involves the integrated use of different energy infrastructures and carriers, in particular electricity, heat, e-fuels and e-chemicals. This is enabled both on the supply side, with the conversion of renewable electricity to heat, e-hydrogen, e-methane, e-kerosene jet fuel, e-fuels and e-chemicals, and the demand side, with electrification of endues and storage for cost effective management of energy use. Several studies[27,30,57,89,90] show that sector coupling can lower the overall costs of the energy transition, as validated by the results of this study. The resulting energy systems across the three scenarios in 2050 are illustrated by mapping the energy flows in the system for REF (Figure 19), RES-2040 (Figure 20) and RES-2035 (Figure 21).

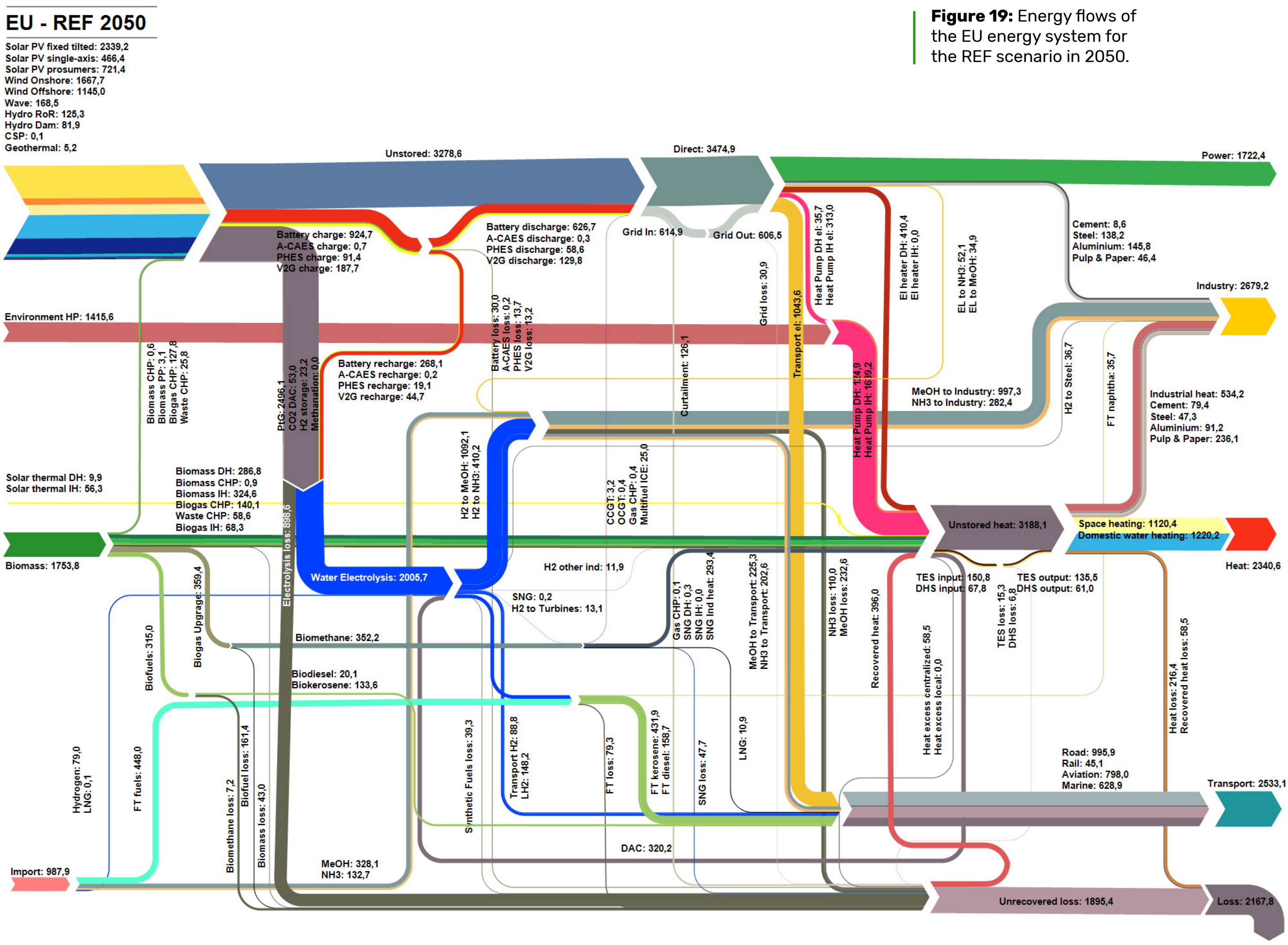


Figure 19: Energy flows of the EU energy system for the REF scenario in 2050.

In the REF scenario, the energy system is highly sector coupled with flexible storage options, as shown in Figure 19. However, it still has some shares of nuclear 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 19.

The RES-2040 scenario results in a completely coupled energy system in 2040 (see Figure 20), which entirely based on renewable electricity and further develops to 2050. 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.

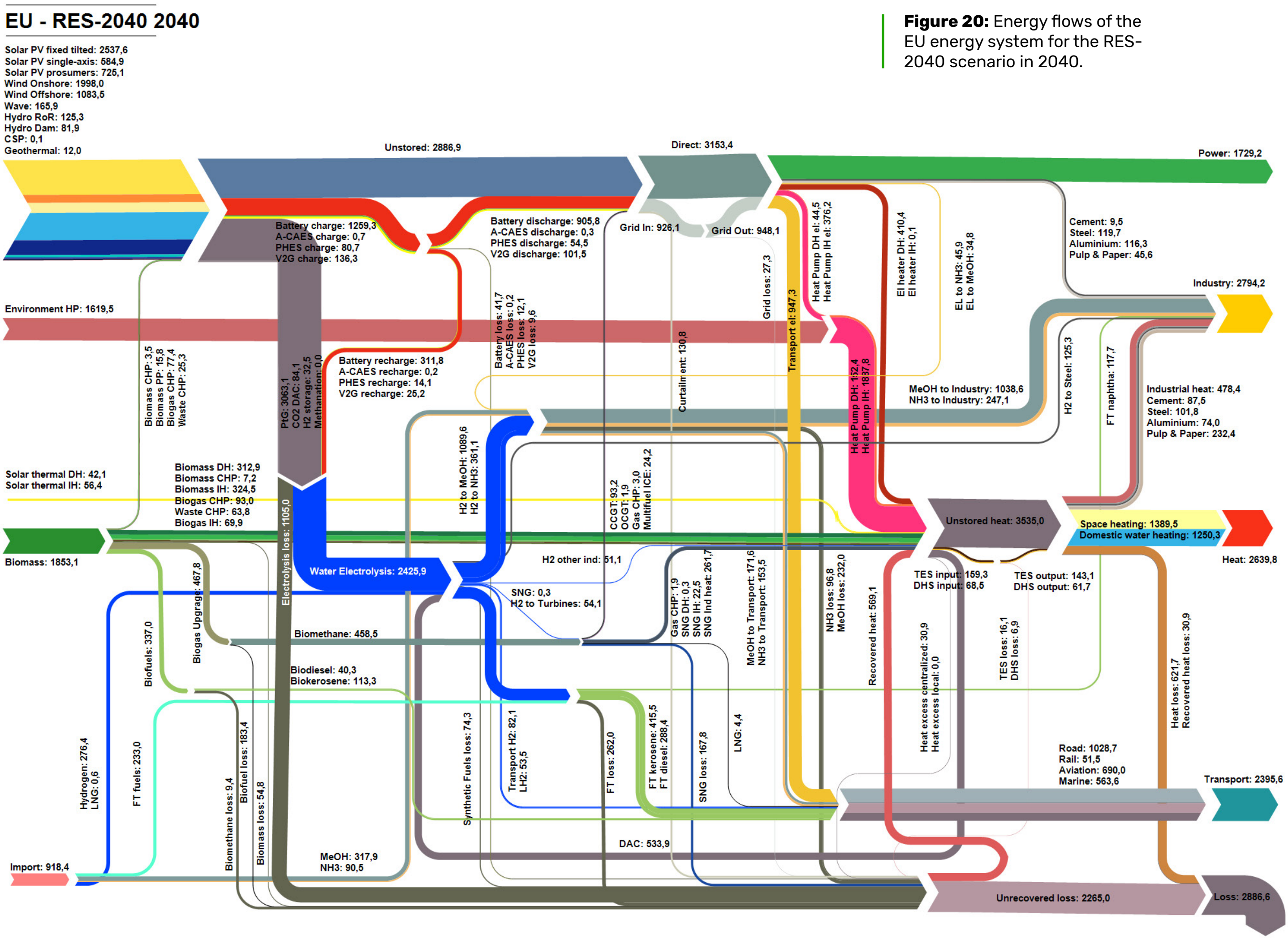


Figure 20: Energy flows of the EU energy system for the RES-2040 scenario in 2040.

The RES-2035 scenario results in a completely sector coupled and integrated energy system in 2035 (see Figure 21) and develops further until 2050. The energy system in the RES-2035 scenario has highly diversified power, heat and transport sectors, as shown in Figure 21. However, a majority of the heat is from highly efficient heat pumps that use naturally available heat, and renewable electricity based synthetic fuels meet a majority of transport energy demand. Storage technologies play a vital role in providing flexibility to the system, which enables higher levels of electrification and sector coupling. The energy system receives substantial flexibility from large electrolyser capacities, which are needed for e-hydrogen, e-kerosene jet fuel, e-ammonia and e-methanol, mainly for marine and aviation transportation and industry sectors, but also for high-temperature applications. These energy carriers can be stored until they are used. The high flexibility of electrolysers enables the efficient uptake of variable electricity generation from solar PV and wind power, which along with vehicle-to-grid effectively reduces the demand for electricity storage.

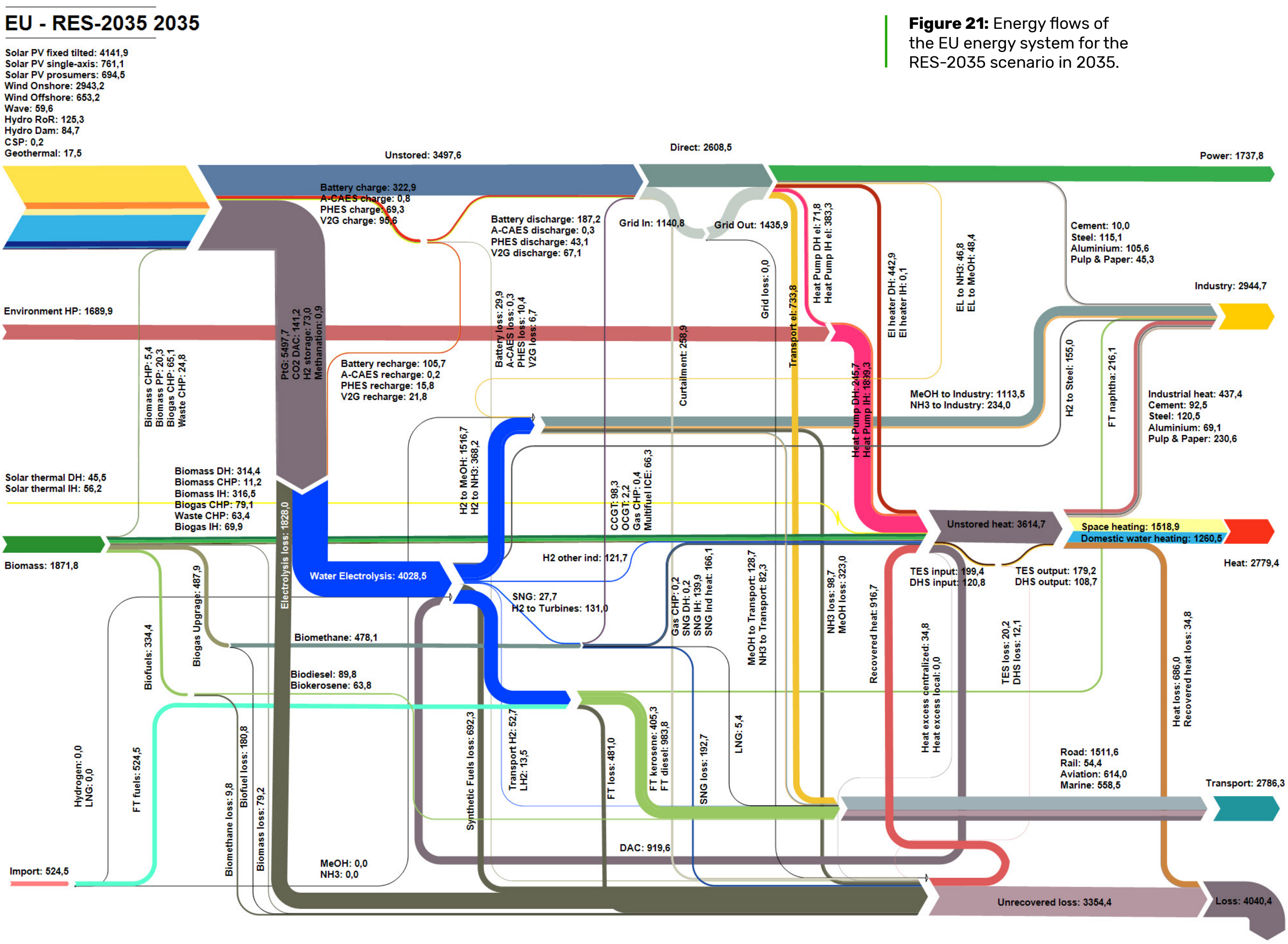


Figure 21: Energy flows of the EU energy system for the RES-2035 scenario in 2035.

4 COST AND BENEFITS:

of the integrated European energy system transition

Cost of energy is a key deciding factor for determining the viability of energy scenarios, roadmaps and pathways. Renewable energy generation, electricity and heat storage technologies along with renewable electricity based synthetic fuels evolve to become the key elements of energy supply system in the first half of the 21st century across the EU. To enable robust comparisons of energy costs and investment requirements through the transition, the real value of the Euro (€) in 2020 is assumed for the transition period until 2050, thus without considering inflation. Initially, annual energy system costs increase up to 2030 and further decline up to 2050 in all three scenarios (see Figure 22). The annual energy system costs indicate the cost benefits of operating highly renewables-based energy systems, as the costs in the RES-2035 and RES-2040 scenarios decline steadily from 2040 onward as the energy system is based on 100% renewables already since 2035 and 2040 respectively. Overall, the annual energy system costs in 2050 are in close range to currents costs in 2020 in the three scenarios, indicating that a transition towards 100% renewables has long-term cost benefits across the EU. Considering current fossil fuel prices across the EU, the annual energy system costs could be much higher, and the cost benefits of rapid transition much greater.

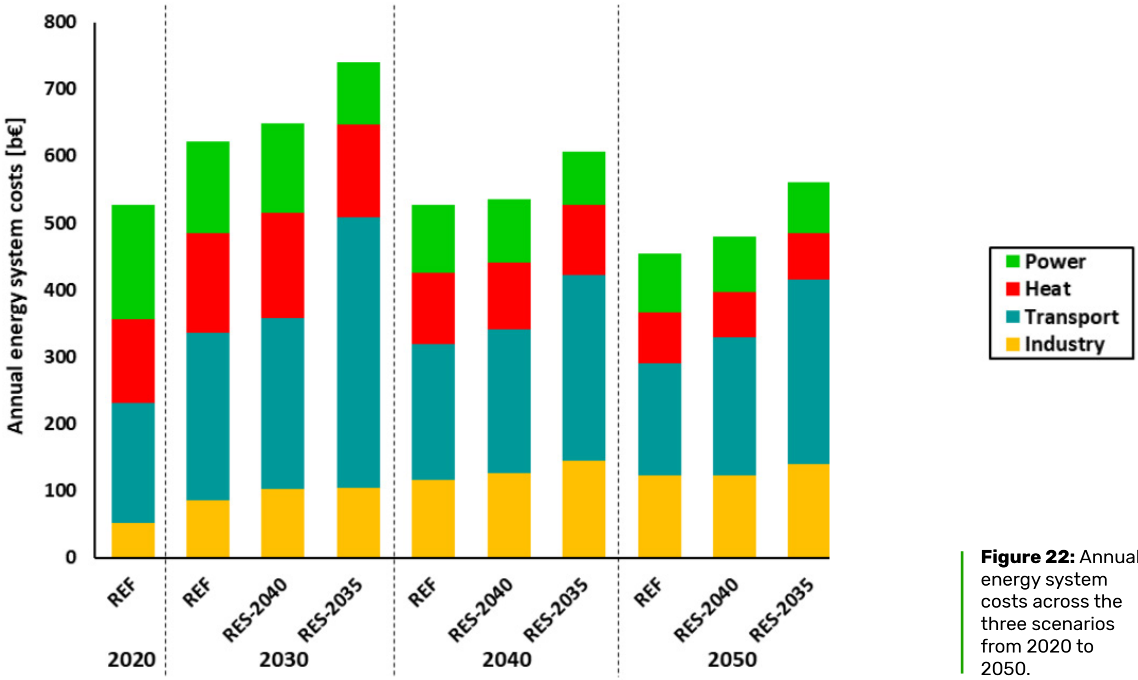


Figure 22: Annual energy system costs across the three scenarios from 2020 to 2050.

Investments, which are capital expenditures for installed capacities of energy technologies that occur in every 5-year interval from 2020 to 2050 are highlighted for the three scenarios in Figure 23. These indicate the distinctive pathways for the three scenarios, wherein the RES-2035 scenario requires massive scaling of investments in the short-term until 2030 and 2035, which yields greater benefits in the long-term by 2050 with minimal investments required. The RES-2040 scenario requires more investments in the short to mid-term of the transition from 2035 onward, as it reaches close to 100% renewables in 2040. Similarly, in the REF scenario investments are more evenly distributed through the transition, as higher shares of renewables deliver energy in 2050. These trends clearly highlight the importance of timely investments, with higher investments in the next couple of decades for an accelerated energy transition across the EU, which has significant benefits in the long-term. Lower energy costs, better economic prospects, significantly higher employment generation[91–93], higher levels of energy security, and progressive leadership on climate action are just some of these benefits with the RES-2035 and RES-2040 scenarios. The REF scenario entails investments in the later stages of the transition and therefore delays the prospects of advancing the benefits of the energy transition across the EU and beyond. However, this delayed transition requires lower capital infusion through the transition but results in higher requirements in the later periods in 2045 and 2050 as seen in Figure 23.

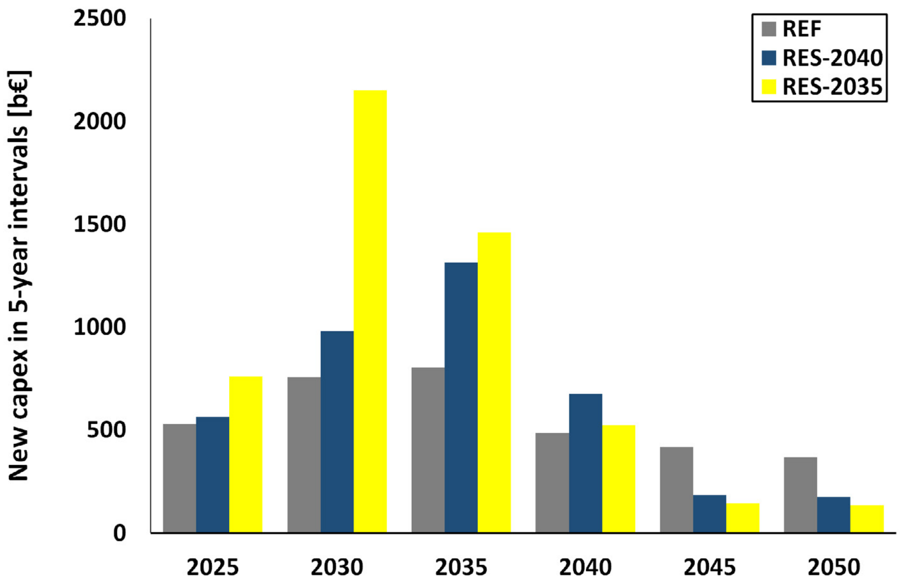


Figure 23: Capital expenditures in 5-year intervals across the three scenarios from 2020 to 2050.

Investments in the form of capital expenditures are mainly in solar PV, wind power, batteries, heat pumps and technologies in the value chain of renewables-based synthetic fuels and chemicals production. Technology-wise capital expenditures are presented for each scenario in the Annex.

The levelised cost of energy, after an initial increase, declines across the three scenarios through the transition up to 2050, as shown in Figure 24. The total system wide levelised cost of energy is the lowest in the REF scenario by 2050 at about 50 €/MWh, followed by the RES-2040 scenario with a slightly higher levelised cost of energy of about 54 €/MWh. While in the RES-2035 scenario, the levelised cost of energy is higher at 64 €/MWh in 2050 but provides a higher level of energy security with 100% of the energy sourced within Europe. This corroborates that an accelerated energy transition towards 100% renewable energy is an attractive proposition from an energy security perspective, while levelised costs of energy are not too high compared to costs in 2020. However, the current volatility in fossil fuel prices have already led to increasing costs of energy across the EU. In this context, an accelerated energy shift towards renewables may even be the most cost-effective option in the short to mid-term. Furthermore, costs induced by climate inaction are not considered in this study, while there is growing evidence that climate inaction can induced high economic costs[2,94].

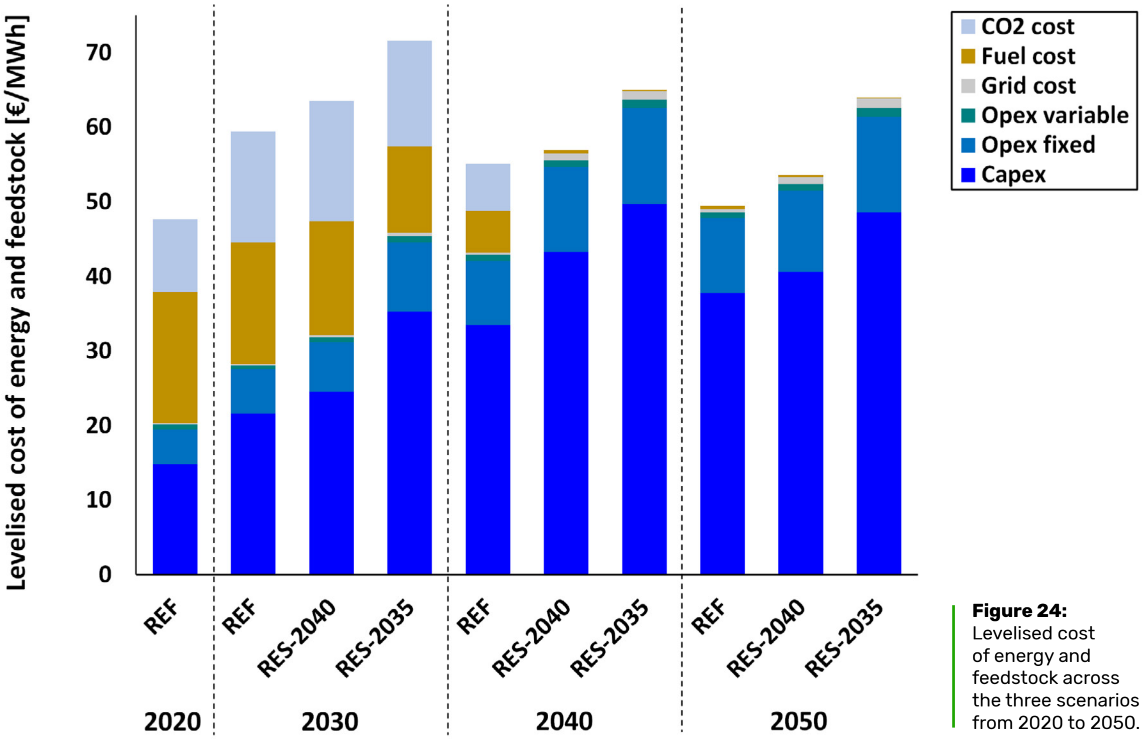


Figure 24: Levelised cost of energy and feedstock across the three scenarios from 2020 to 2050.

In the long-term, levelised cost of energy is increasingly dominated by capital costs as fuel costs loose importance through the transition period, which could mean increased levels of energy security across Europe by 2050. Furthermore, the levelised cost of energy consists of all aspects of the energy system with electricity and heat as the primary sources of energy generation. Therefore, the levelised cost of electricity and heat respectively are vital indicators of costs in the energy transition. CO_2 costs are reflected in the levelised cost of energy and increase in the initial period up to 2030 and the cost of emitted CO_2 varies across the three scenarios (see Table B4 in the Annex). Higher CO_2 emissions costs coupled with increasing costs of fossil fuels (see Table B3 in the Annex) renders fossil fuels uncompetitive and therefore most new investments across the three scenarios are in renewables through the transition.

The levelised cost of electricity (LCOE) decreases substantially across the three scenarios through the transition until 2050, as shown in Figure 25.

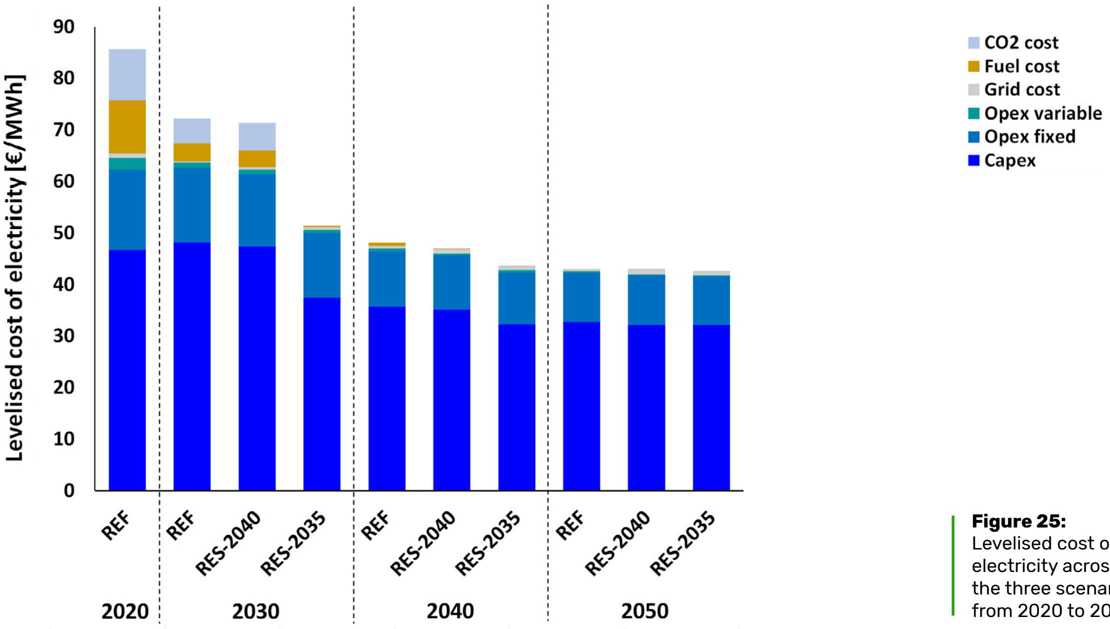


Figure 25: Levelised cost of electricity across the three scenarios from 2020 to 2050.

In the three scenarios, the LCOE declines by about 50% in 2050 compared to 2020 levels. This indicates that electricity from renewable sources is set to emerge as the most economical across the EU. The share of fuel costs declines through the transition, as the shift towards electrification results in capital expenditures driven energy system costs. The resulting cost beyond 2050 will further decline in the following periods by about 15%, which is mainly a consequence of major re-investments in the periods after 2050 with lower capital costs in and beyond 2050. Further, capex reductions are expected making overall energy costs in the second half of the century extremely low-cost, which might lead to a cost decline of more than 15%.

The levelised cost of heat (LCOH), after an initial increase, declines through the transition across the three scenarios until 2050 (see Figure 26). The levelised costs in the heat sector decline from around 36 €/MWh in 2020 to around 24 €/MWh, in the REF scenario, to around 23 €/MWh in the RES-2040 scenario and to about 27 €/MWh in the RES-2035 scenario, by 2050. The LCOH is predominantly comprised of capital expenditures as fuel costs decline through the transition (see Figure 26). Despite a substantial increase in heat demand across the EU, mainly driven by industrial process heat and increased space heating driven by more space per person, the LCOH declines substantially by 2050. This is attributed to the increased levels of electrification in the heating sector.

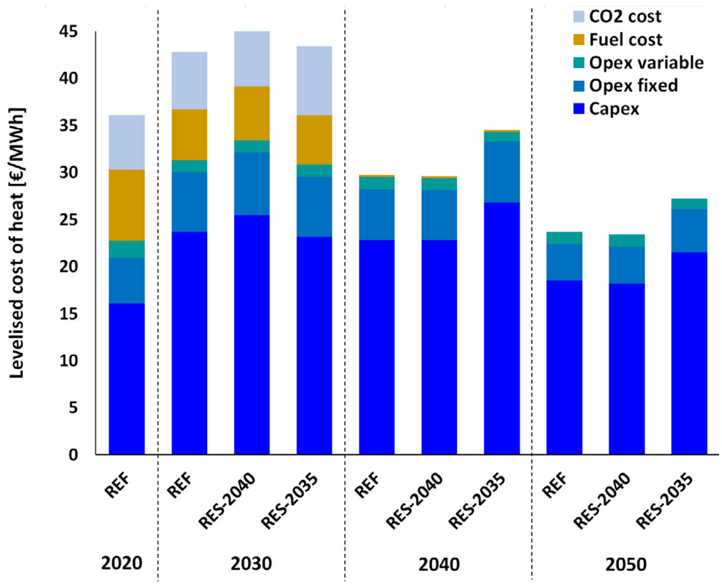


Figure 26: Levelised cost of heat across the three scenarios from 2020 to 2050.

This research shows that there are huge cost benefits of transitioning towards 100% renewable energy across Europe, more so in an accelerated energy transition pathway reaching 100% renewables by 2040. The levelised cost of energy of a 100% renewable energy system shows further decline from 2040 to 2050, indicating that a low-cost energy future will be driven by renewables. As highlighted by a latest report[95], in deregulated markets such as the EU, coal faces imminent economic obsolescence through market forces and similarly for other fossil fuels.

This research indicates that the most ambitious RES-2035 scenario with 100% renewables across the EU by 2035 costs only 10-12% more than the 2020 energy system costs, and further, the RES-2040 scenario costs are only about 4-5% higher than the 2020 energy system costs. However, the Russian invasion of Ukraine has propelled already high energy prices even higher across the EU and beyond. It is expected to inflate energy bills, hitting consumers across the EU the hardest[1]. The increased volatility of fossil fuel prices can induce much higher spikes in energy system costs. Considering the current energy prices of fossil fuels applying average prices of the winter 2021/2022 for the near future, the total EU energy system costs in 2025 and 2030 would be nearly 70% and 2% higher, respectively, in comparison to costs in 2020. Therefore, relying on imported fossil fuels that are embedded in volatile global markets leads to additional economical as well as environmental risks.

However, achieving the most ambitious RES-2035 scenario entails ramping up investments in renewable energy and sustainable technologies across the EU in this decade with over 2900 b€[14] by 2030 (see Figure 23). In the RES-2040 scenario, over 1500 b€ of investments are needed by 2030 and about 1300 b€ by 2030 in the REF scenario. Moreover, cumulative investments in the long-term up to 2050 are 3.4 t€[15] in the REF scenario, 3.9 t€ in the RES-2040 scenario and 5.2 t€ in the RES-2035 scenario.

Stranded assets become an increasingly vital economic issue, in the times of climate emergency. Languid investment policies of power and heat companies and lack of clear governmental regulations lead to growing risks, and economic burdens of avoidable losses. The scale of stranded assets depends on the scenario definitions. In the REF scenario, all fossil fuel based electricity and heat supply is eliminated by 2050, nuclear capacities are assumed to operate until end of technical life, while existing construction sites as of 2020 are considered to be finished, but no new constructions are assumed to be commissioned, due to unsound economics and stringent sustainability constraints. In the RES-2040 scenario, it is assumed that all fossil and nuclear operations are ceased by 2040, and existing construction sites are assumed to be terminated before 2025. The resulting stranded capacities in the RES-2040 scenario are 24.9 GW of coal power plants and 5.9 GW of coal CHP plants in 2040. The stranded capacities in the RES-2035 scenario are 30.8 GW of coal power plants, 10.4 GW of coal CHP plants, 22.7 GW of coal district heating plants in 2035, and 4.5 GW of nuclear capacities not older than 40 years in 2040, when nuclear power plants operation is halted. No nuclear refurbishment investments have been assumed in the three scenarios, so that no respective losses are allocated to stranded assets. Nuclear refurbishment investments can account for about 1-2 b€ per reactor for up to 20 years of lifetime extension[96]. The economic losses are estimated based on the total historic capital expenditures for the capacities and the corresponding shares of remaining years of operational lifetime, during which the capacities are stranded, due to decommissioning before the end of their technical lifetime. The respective stranded asset losses for the REF scenario are 12.2 b€ in total, thereof 9.9 b€ for coal power plants

14 b€: Billion Euros.

15 t€: Trillion Euros.

and 2.3 b€ for coal CHP plants. The stranded asset losses for the RES-2040 scenario are 30.9 b€ in total, thereof 20.5 b€ for coal power plants, 6.7 b€ for coal CHP plants, 0.4 b€ for coal district heating plants, and 3.3 b€ for nuclear power plants. In the RES-2035 scenario, the stranded asset losses would be around 100 b€ with 49 b€ for coal power plants, 21 b€ for coal CHP plants, 2.3 b€ for coal district heating and about 27 b€ for nuclear power plants until 2035. In the case of fossil gas based individual heating, the cost of these assets being stranded are roughly 18 b€ by 2040 in the RES-2040 scenario and 90 b€ by 2035 in the RES-2035 scenario, while being phased out in the REF scenario by 2050. These stranded asset losses are rough estimates and could increase when complexities and additional costs of individual power plants are considered. However, these costs are fully allocated to the respective scenarios, which are borne by the operators of the respective plants. If these stranded asset costs are not included, the scenarios would result in lower respective energy costs. However, this remains an aspect of debate: from what point onwards, unwilling investors have to fully incorporate the risks of new investments in highly unsustainable technologies?

Carbon dioxide emissions

The results of the energy transition indicate a sharp decline in CO_2 emissions until 2050, across the power, heat, transport and industry sectors in the three scenarios as shown in Figure 27. The CO_2 emissions across the EU energy sector is over 2500 $MtCO_2$ in 2020, it undergoes a rapid decline to zero by 2035 in the RES-2035 scenario, an accelerated decline to zero by 2040 in the RES-2040 scenario and a steady decline to zero by 2050 in the REF scenario. The costs of CO_2 emissions play a vital role in driving down emissions and the costs for each scenario is highlighted in Table B4 in the Annex.

There are some minor shares of unabated CO_2 emissions from the limestone utilisation in cement production reflected in the industry sector emissions in the three scenarios. However, these residual CO_2 emissions can be mitigated with either natural climate solutions such as carbon sinks, afforestation or through carbon capture and storage solutions. These mitigation actions are reflected in overall systems costs and in terms of CO_2 emissions costs in the three scenarios.

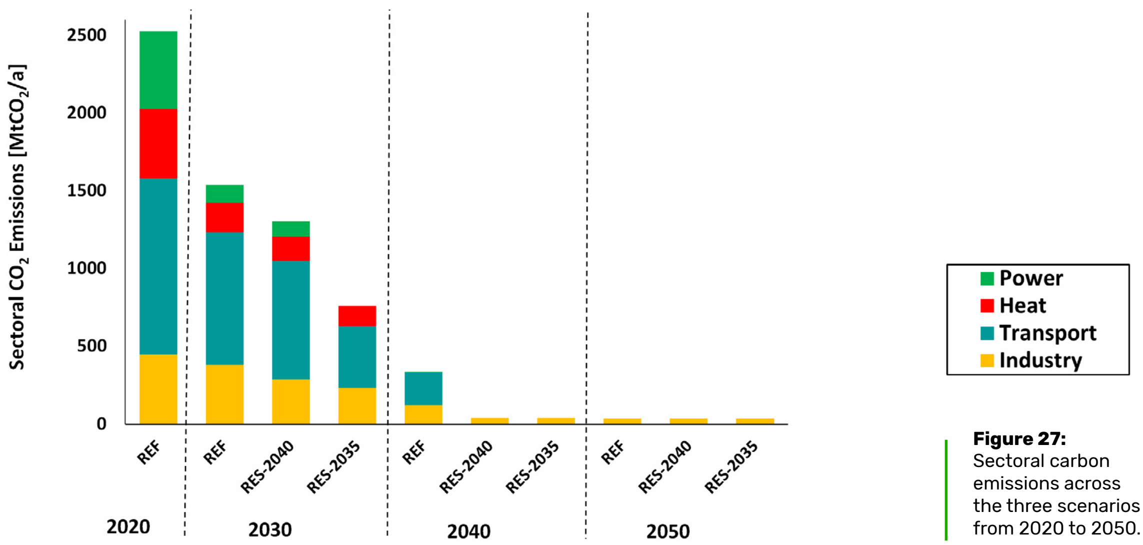


Figure 27: Sectoral carbon emissions across the three scenarios from 2020 to 2050.

The remaining cumulative CO_2 emissions across the EU comprise of around 22 $GtCO_2$ in the RES-2035 scenario, about 27 $GtCO_2$ in the RES-2040 scenario and around 33 $GtCO_2$ in the REF scenario, from 2020 to 2050 (see Figure 28). The additional cumulative CO_2 emissions resulting from the REF scenario in comparison to the RES-2035 scenario is around 11 $GtCO_2$ across the EU by 2050.

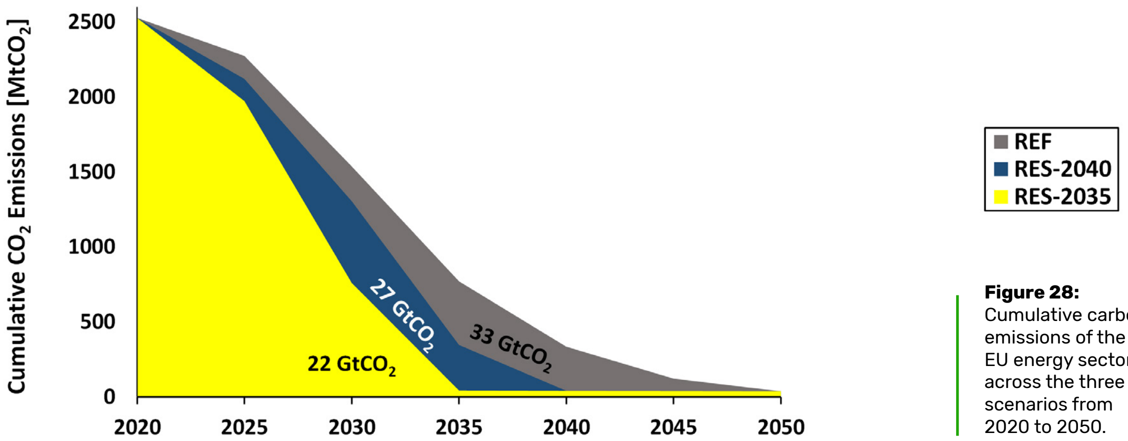


Figure 28: Cumulative carbon emissions of the EU energy sector across the three scenarios from 2020 to 2050.

The RES-2035 scenario is the most in adherence to the ambitious Paris Agreement target of 1.5ºC, with zero CO_2 emissions by 2035 and more than 75% reduction by 2030 in comparison to 1990 levels. The RES-2040 scenario results in zero CO_2 emissions by 2040 and about 65% reduction by 2030 in comparison to 1990 levels, placing it in the more likely achievable target for limiting global temperature rise to 1.5ºC compared to pre-industrial levels. Whereas the REF scenario, results in the reduction of CO_2 emissions to zero by 2050 and around 60% by 2030 in comparison to 1990 levels (refer Figure ES-2). This certainly limits possibilities of achieving the Paris Agreement, given the levels of economic growth and capabilities of the EU. In addition, it redeems this as an unfair effort by the developed member countries of the EU in comparison to some of the developing and least developed countries around the world.

Climate mitigation is the most important issue of current times, the urgency was heightened by the findings of the IPCC[97], which stated that extra warming on top of the approximately 1°C we have seen so far would amplify the risks and associated impacts, with implications for the world and its inhabitants. Additionally, latest research indicates a coupling of major global climate change tipping points[98], which further stresses the importance of not violating the 1.5°C target. The daunting task of limiting warming to 1.5°C would require transformative systemic changes, integrated with sustainable development across the world. In this regard, the onus is on the EU to take on a leadership role by reducing CO_2 emissions rapidly within the continent as well as to act as a catalyst for rapid implementation of sustainable energy technologies globally. As this research has highlighted, this is both technologically feasible as well as economically viable for all member countries of the EU and rest of Europe.

5 REGIONAL OUTLOOK

Europe is amongst the most interconnected regions in the world, with robust energy infrastructure connecting the different countries and the members of the EU pursuing a common goal of creating an Energy Union. As far as renewable energy resources are concerned, Europe has a good mix of significant wind potential in the northern and western regions (including the United Kingdom and Ireland) complemented with excellent solar potential in the southern member countries of the EU and Turkey. Other forms of renewable resources are also well distributed throughout the continent, which influence the regional energy mix of the various countries and regions within Europe. The RES-2040 scenario, being both ambitious as well as the most plausible with regard to achieving ambitious climate mitigation targets across the EU, regional insights for this scenario is further explored. However, regional insights for each of the scenario is presented in the Annex.

Electricity generation capacities are installed across the EU to satisfy the energy demand from power, heat, transport and industry up to 2050. Solar PV capacities are predominantly in the southern countries of the EU that have better solar resources through the year with solar PV prosumers spread across the EU. While wind energy capacities are mainly in the northern and western countries of the EU that have much better wind conditions for both onshore and offshore (see Figure 29).

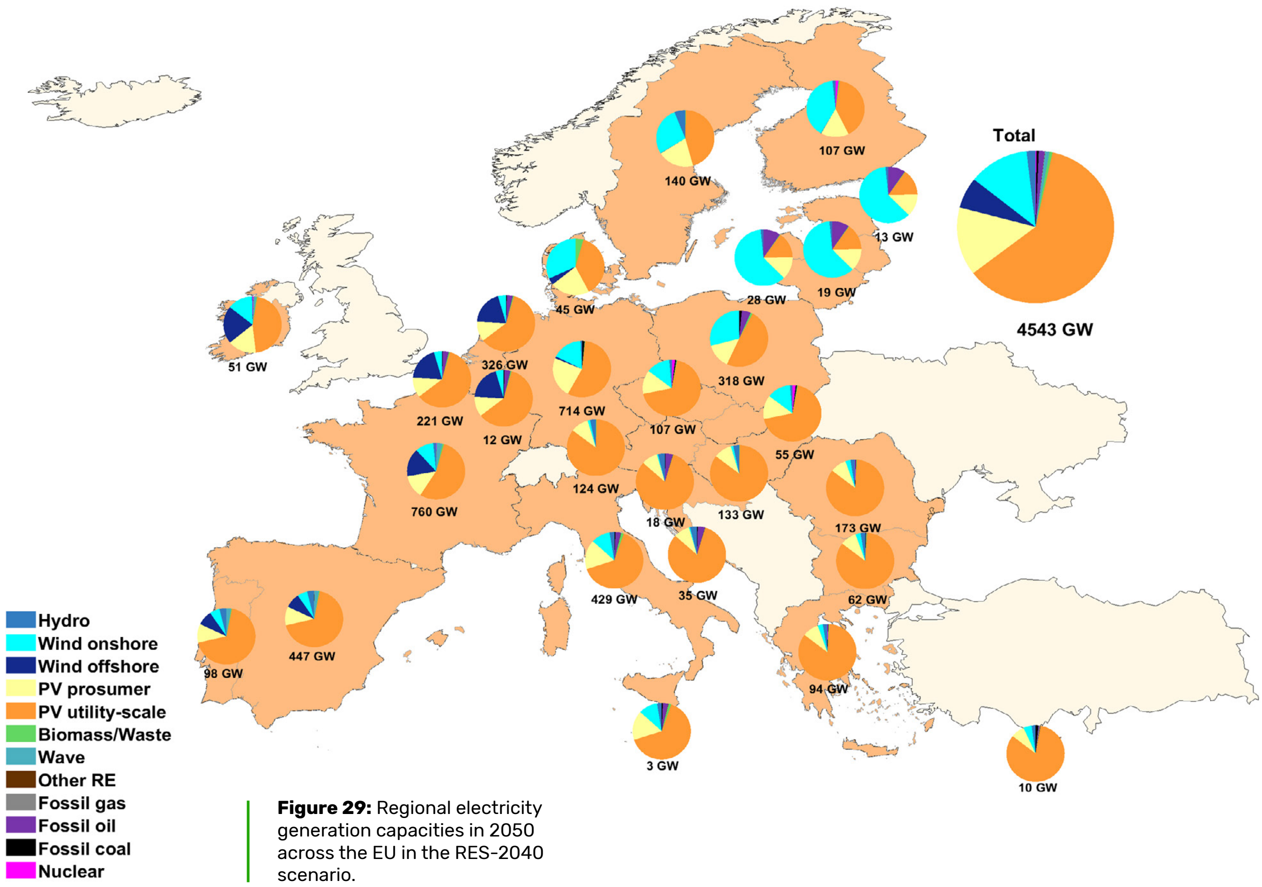


Figure 29: Regional electricity generation capacities in 2050 across the EU in the RES-2040 scenario.

Overall, solar PV and wind power capacities along with some hydropower and wave power capacities constitute the majority of installed capacity at 4543 GW in 2050 across the EU in the RES-2040 scenario. As the RES-2040 scenario is on a more progressive pathway, achieving 100% renewables by 2040 leads to additional capacities, powering the production of synthetic fuels and chemicals until 2050.

Similarly, higher shares of solar PV generation are in the southern countries and higher shares of wind power are in the northern and western countries of the EU (see Figure 30). Solar PV prosumers do contribute some vital shares across the EU and complement utility-scale solar PV generation. This could enhance the complementarity of solar PV and wind power in an interconnected European energy system. The electricity generation across the power, heat, transport and industry sectors of the EU are predominantly from solar PV and wind power in the RES-2040 scenario in 2050, as shown in Figure 30. Solar PV, which supplies an average of 54% of electricity across the EU, has higher shares in the southern countries of the EU. While wind power, which contributes an average of 40% across the EU, has much higher supply shares in the northern and western countries of the EU. Overall, solar PV and wind power generate most of the electricity needed across the EU in 2050 with high complementarity between the different regional electricity pools (see Figure 30).

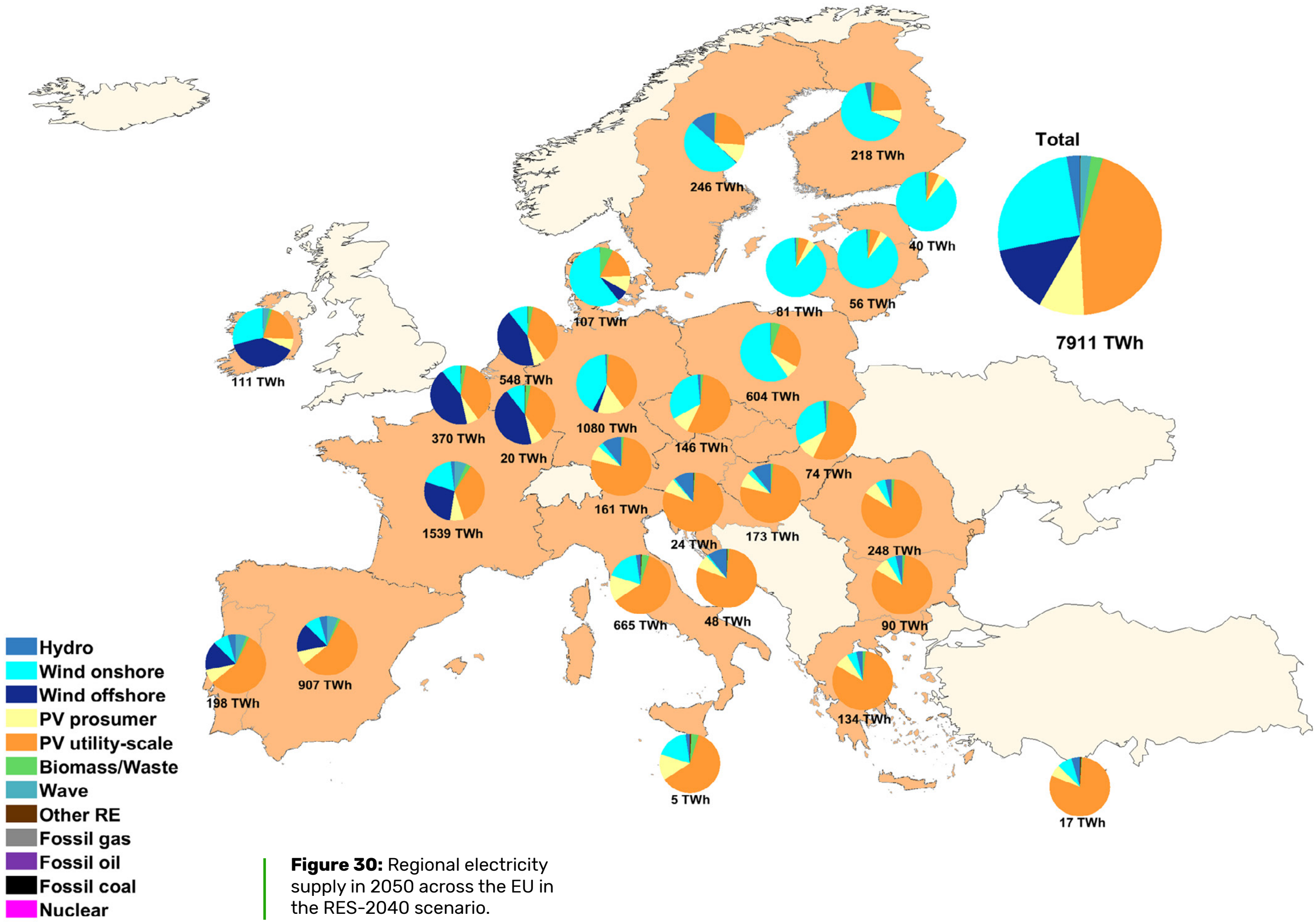


Figure 30: Regional electricity supply in 2050 across the EU in the RES-2040 scenario.

Heating demand across the EU transitions from heavily reliant on imported fossil gas towards heat pumps combined with electric heating and some shares of waste and residual biomass based heating. Heat pumps and electric heating capacities are spread across the EU with major capacities in central and norther countries, while waste and residual biomass based heating capacities are mainly in the northern countries of the EU. The total heating capacities across the EU in the RES-2040 scenario are 650 GW in 2050 (see Figure 31). Heat pumps emerge as the prime heating technology across the EU by 2050. Minor shares of solar thermal capacities are present in Portugal, Spain, Italy and Greece, which are countries with excellent solar resources on an annual basis.

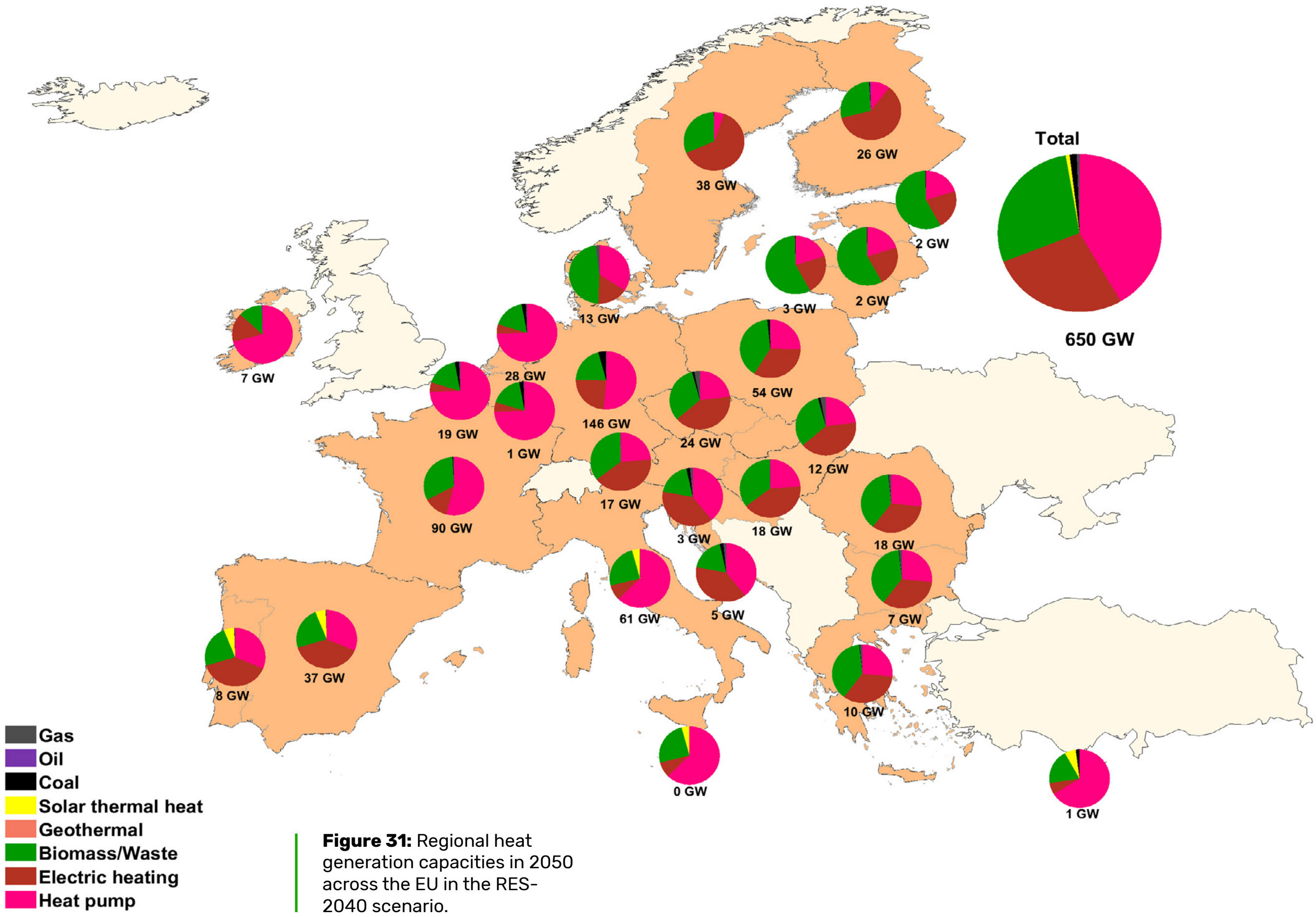


Figure 31: Regional heat generation capacities in 2050 across the EU in the RES-2040 scenario.

Heat generation across the EU meets demand comprised of domestic hot water, space heating and industrial process heat. Likewise, heat pumps generate most of the heat needed across the EU by 2050 in the RES-2040 scenario resulting in higher efficiency gains. Heat generation from heat pumps coupled with electric heating have major shares in the western, central and southern countries of the EU, while waste and residual biomass based heating supplies major shares in the eastern and northern countries of the EU (see Figure 32). Minor shares of solar thermal heat contribute in the southern countries of the EU.

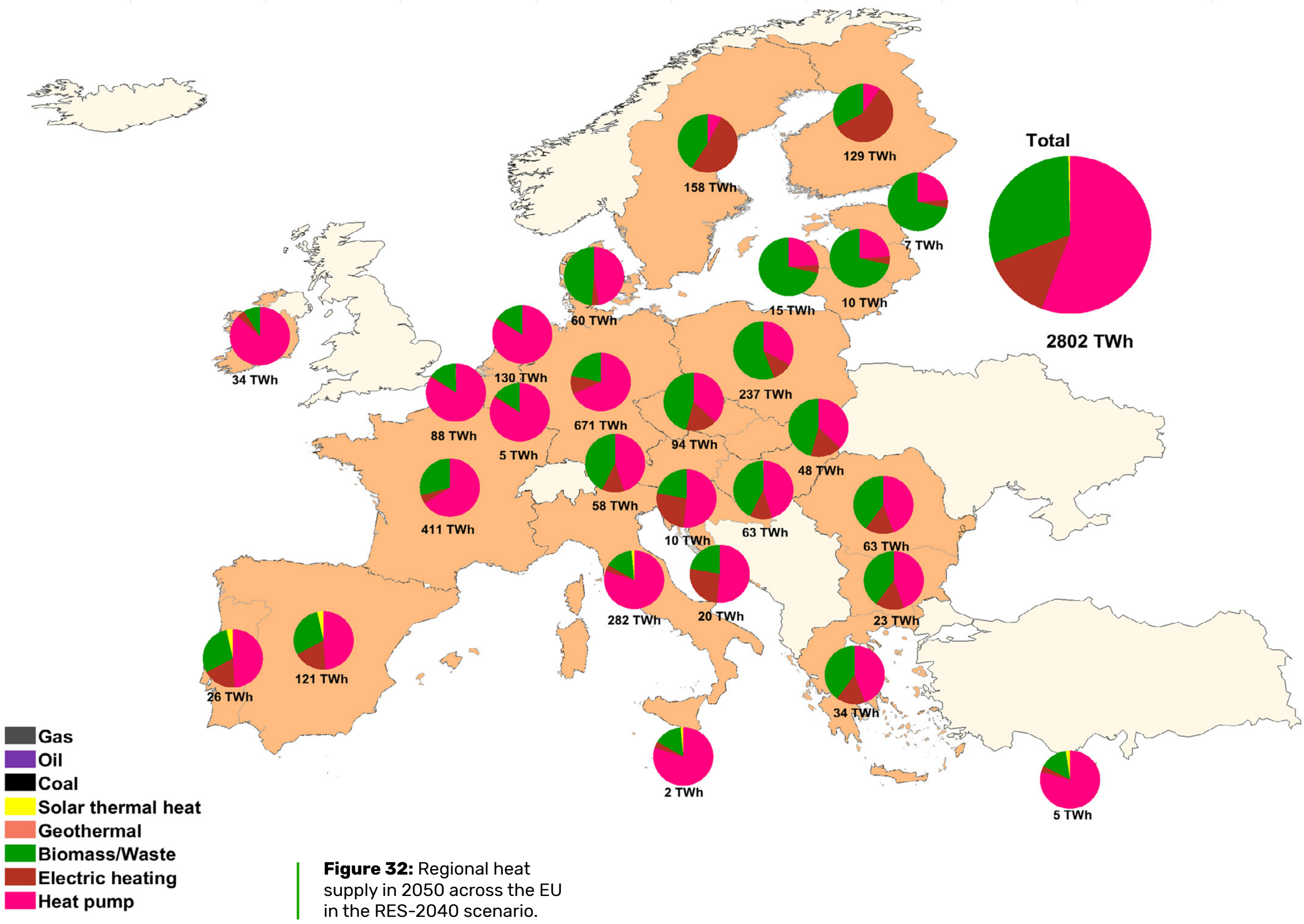


Figure 32: Regional heat supply in 2050 across the EU in the RES-2040 scenario.

Electricity storage output across the integrated power, heat, transport and industry sectors of the EU is predominantly from batteries (comprising utility-scale, residential, commercial and industrial prosumers) along with battery based vehicle-to-grid and some shares of PHES in 2050, as shown in Figure 33. Prosumer batteries, which supply major shares of the storage output across the EU, are higher in the southern countries. The total electricity storage output in 2050 across the EU in the RES-2040 scenario is 1634 TWh, majority of which is in the central and southern countries (see Figure 33).

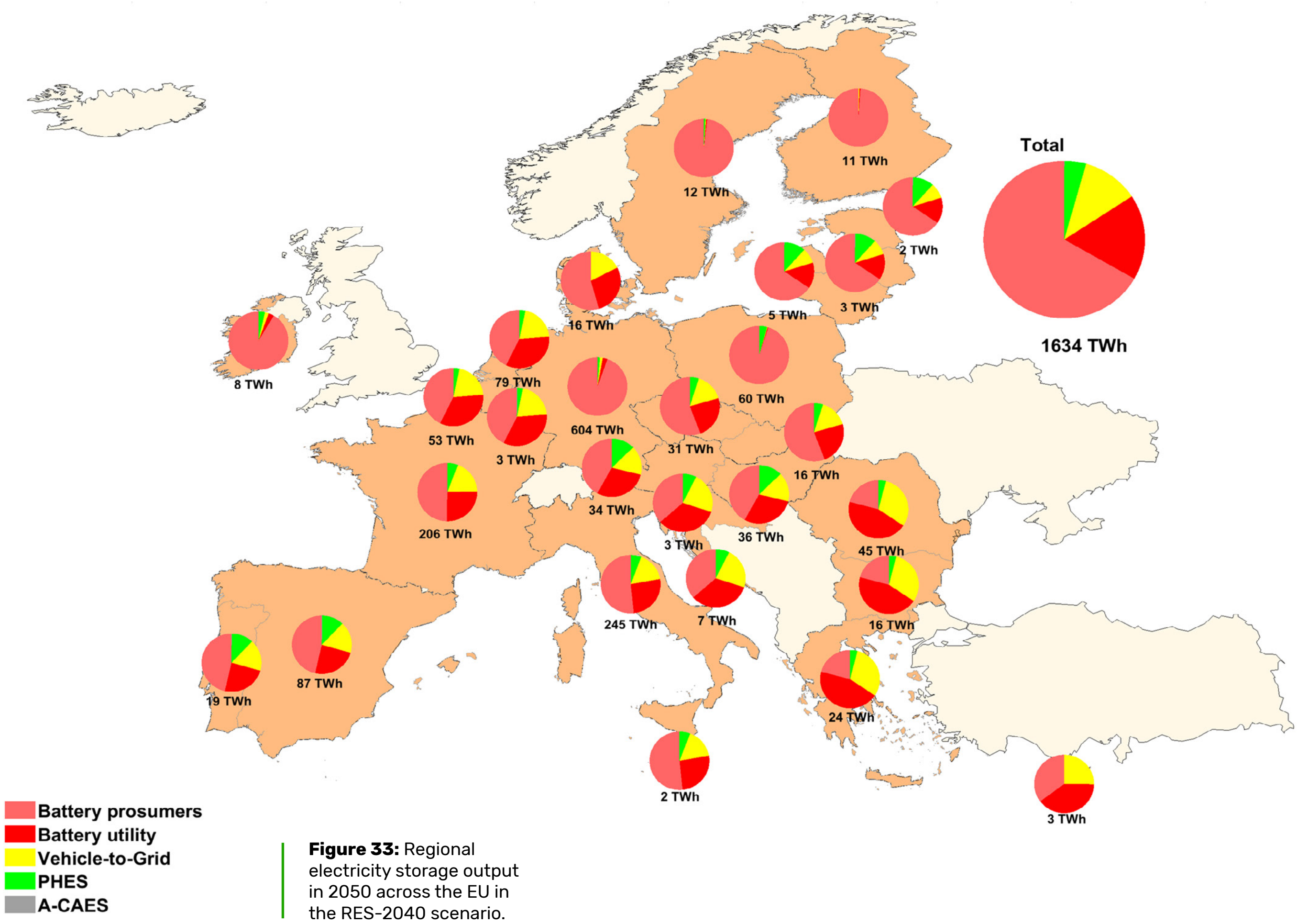


Figure 33: Regional electricity storage output in 2050 across the EU in the RES-2040 scenario.

Heat storage plays a vital role in ensuring stable energy supply across the EU, predominantly in the winters when there is a huge demand for heating in the northern countries. Hydrogen and biomethane along with thermal energy storage (district and individual levels) supplies heat across the EU, in the RES-2040 scenario (see Figure 34). Thermal energy storage has higher output shares in some of the countries like Sweden and Finland, while hydrogen and biomethane storage output has higher shares in other countries such as France and Germany, as shown in Figure 34. Overall, heat storage output is 914 TWh in 2050 across the EU in the RES-2040 scenario.

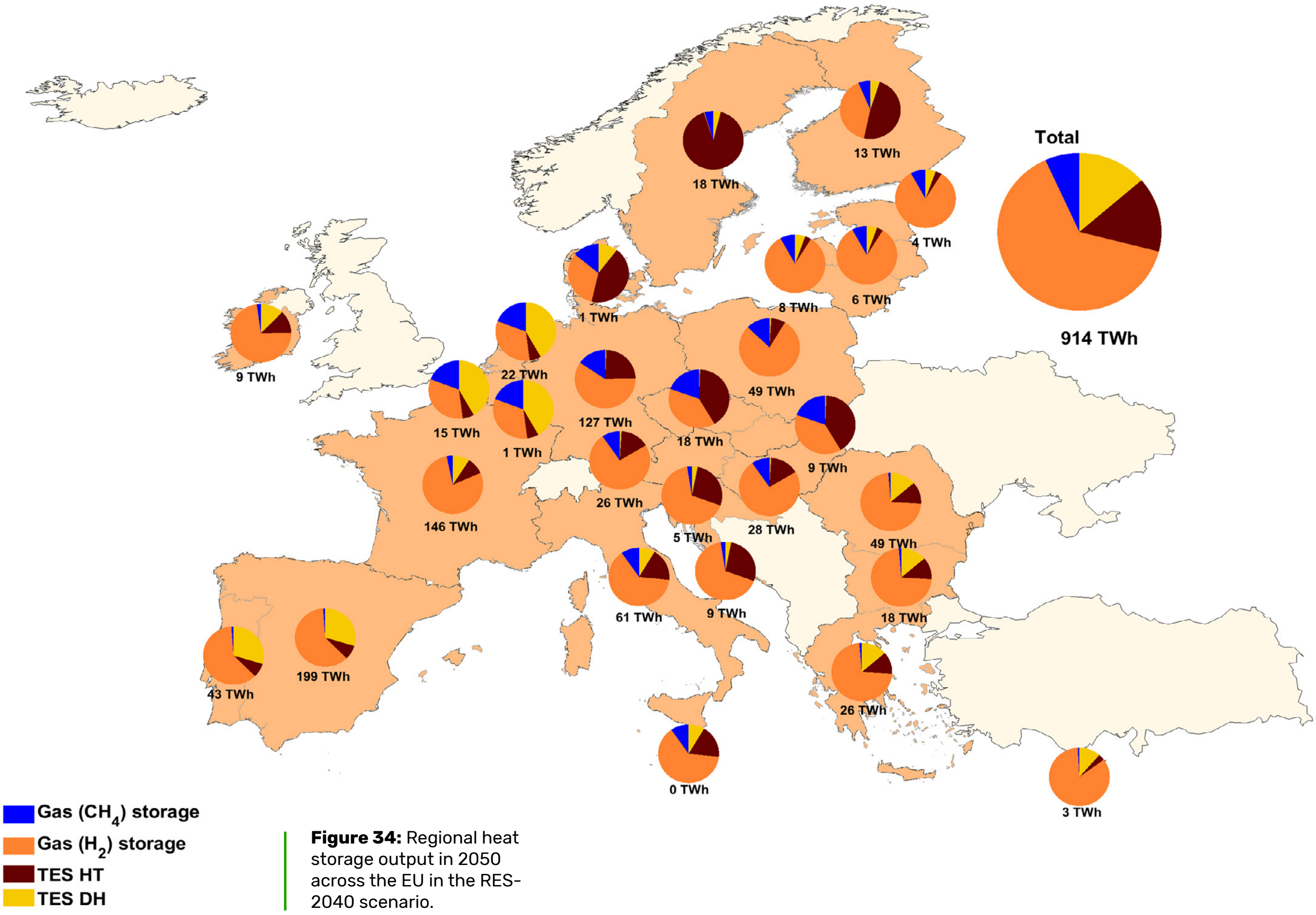


Figure 34: Regional heat storage output in 2050 across the EU in the RES-2040 scenario.

The total supply of fuels and chemicals including imports of e-fuels and e-chemicals is 4938 TWh in 2050 across the EU in the RES-2040 scenario. Central and southern countries of the EU emerge as the production hubs of e-fuels and e-chemicals, that play a critical role in the transition particularly in marine and aviation transportation and industry sectors. The north-western port countries of the EU emerge as the import hubs for e-fuels and e-chemicals (see Figure 35). Waste and residual biomass based fuels are spread around the EU, with major shares in the eastern and northern countries of the EU. Overall, the EU can transition from heavily fossil fuels import reliant to locally produced green fuels and chemicals by 2050.

Electrolysers play a vital role not only in the production of synthetic fuels, but also in enhancing the flexibility and integration of energy systems. Installed capacities of electrolysers are for each scenario are presented in the Annex.

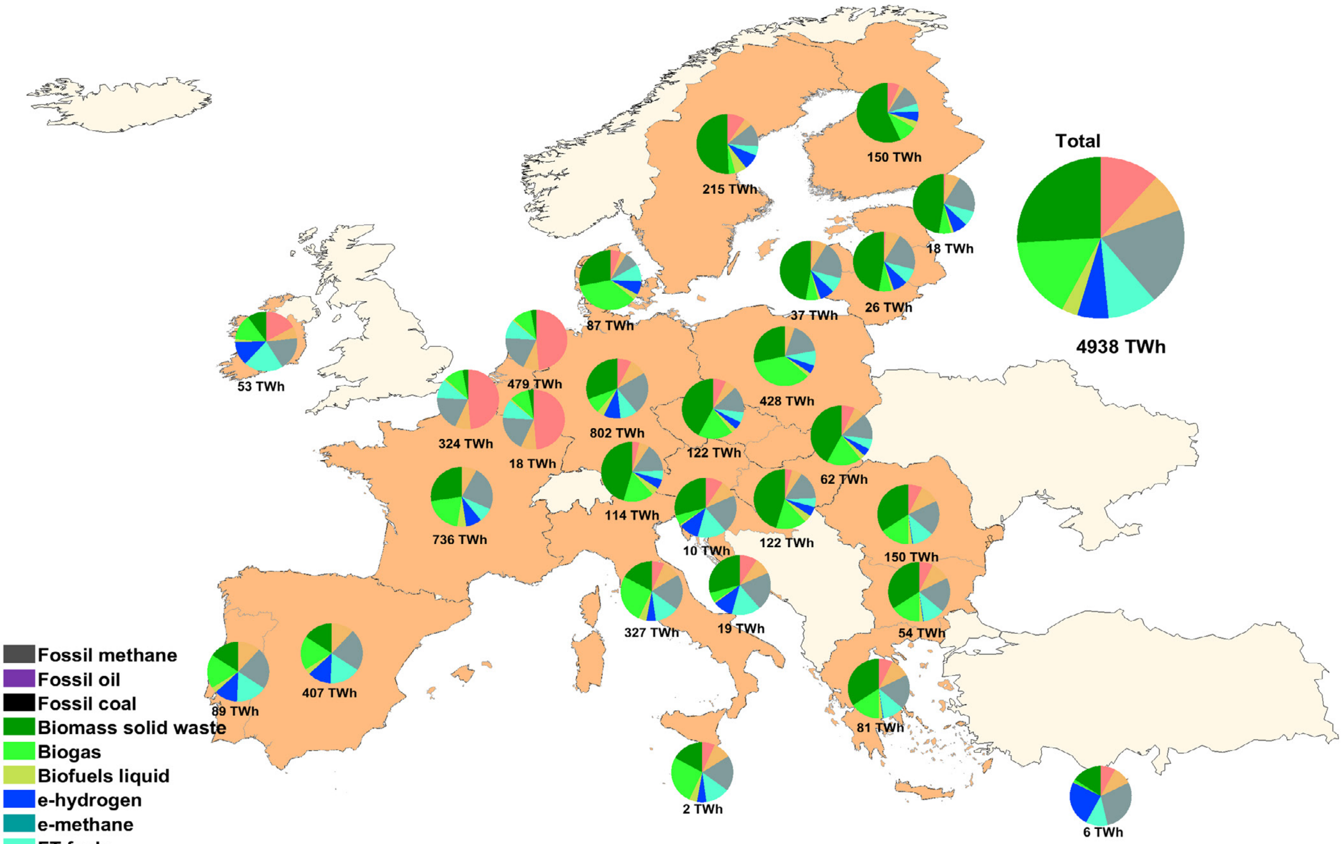


Figure 35: Regional fuels and chemicals supply in 2050 across the EU in the RES-2040 scenario.

Transmission interconnections between the 20 regions across Europe play a vital role in optimal usage of local resources and enable lowering costs of energy across Europe. Integration of the energy system with high levels of electrification, sector coupling and storage technologies lead to optimised electricity trade across the 20 regions, at around 1308 TWh in 2050 for the RES-2040 scenario (see Figure 36). Moreover, demand and generation are well synchronised across the 20 regions, indicating higher utilisation of local resources to meet annual energy demand. About 17% of the generated electricity is traded across the interconnected regions, indicating that about 83% of electricity is generated within the regions where demands originate. Electricity is mainly imported from Turkey, Norway and the United Kingdom, while there are no electricity imports from Russia. This enables a highly decentralised energy system design coupled with an interconnected and cost optimised European energy system. Curtailed electricity is less than 3% in the cost-optimised solution for the RES-2040 scenario with 100% renewable energy supply that is enabled by the strong sector coupling of the entire energy system. Countries and regions with good solar and wind resources emerges as net-exporters, while some of the Northern, eastern and central regions are net-importers.

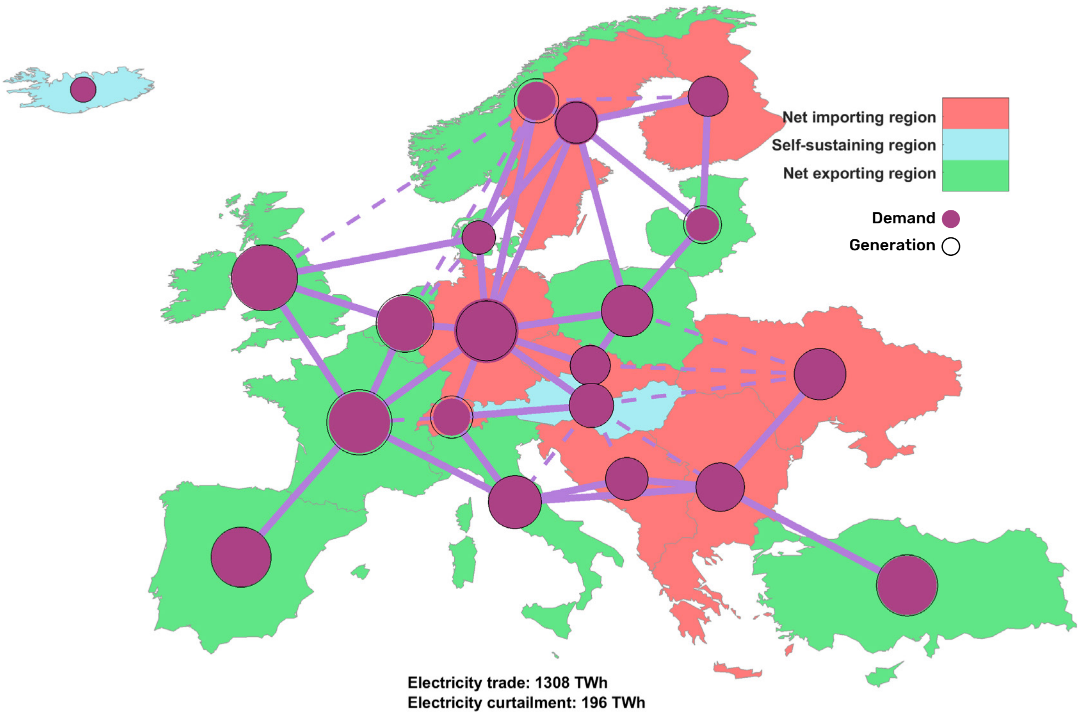


Figure 36: Regional electricity trade with net-importers and net-exporters in 2050 across Europe in the RES-2040 scenario.

The regional insights across electricity, heat, storage, fuels and chemicals along with the electricity network suggest that an integrated energy system serving the power, heat, transport and industry sectors across Europe with 100% renewable energy is both technically robust and economically lucrative. Countries across the EU can develop cost optimal energy systems based on local resources along with integration into the wider European energy network. Thereby reducing reliance on imported fossil fuels and ensuring energy security across Europe with a highly decentralised, integrated and independent energy system.

6 CONCLUSIONS

This study along with other research studies indicate that a 100% renewable energy system across Europe will not only ensure meeting the Paris Agreement, but also bring about a multitude of socio-economic benefits to the European as well as global society[99–101]. Several research studies have shown that renewables have been creating employment over the last couple of decades across the EU[102] and have the potential to create far more additional jobs in the coming decades with the transition towards higher shares of renewable energy[91–93]. However, innovative policies, incentives and financial mechanisms need to be pursued vigorously both in the context of addressing climate change and enabling energy security. Some of the key trends and insights from the three energy transition pathways explored in this study have some valuable indicators for advancing energy policies and regulations across the EU.

Electrification and efficiency measures across energy services

A paradigm shift is observed across the three scenarios, wherein low-cost renewable electricity emerges as the prime energy carrier of the future and along with e-hydrogen drive fossil fuels out of integrated energy systems. In a highly digitalised future with strong climate policies, electrification of energy services will be pervasive in Europe[17] as well as globally[103]. Primarily, fossil and nuclear fuels used in the energy sector are substituted by technologies directly extracting electricity and heat from the environment, in particular solar PV, wind power and heat pumps. As highlighted by the results, electric vehicles will largely replace fossil-fuelled 2-wheelers, 3-wheelers, cars, buses and trucks quite rapidly as current trends indicate[17]. While heat pumps and electric heating increasingly substitute oil and gas heating systems and boilers in buildings and industries across the EU. Solar PV prosumer at the residential, commercial and industrial levels contribute vital electricity and improve efficiency of the energy system with generation at the sites of consumption, thereby reducing transmission and distribution losses. In addition, efficiency measures in particular building renovation rates, which increase through the transition in the three scenarios boost the adoption of efficient usage of electricity and heat across the buildings sector of the EU. Low-cost electricity from renewables is used to produce e-hydrogen, e-kerosene jet fuel, e-ammonia and e-methanol for applications where direct electrification is challenging or impossible. The advantages of widespread electrification are clear and compelling, as substantial efficiency gains are observed through the transition across the three scenarios in terms of primary energy consumption. These findings indicate that energy policies should consider electrification as well as efficiency improvements across the different energy services in tandem.

Local resource driven energy systems

Another critical aspect of this research is capturing the regional variation as well as the potential for localised energy systems across the EU through the transition. Renewable energy resources are well distributed across Europe, but different resources are available in different proportions across the different countries and regions. Therefore, the results of this research enable energy transition pathways that maximise utilisation of locally available renewable resources in a cost optimal manner. Wind power is the most dominant source of energy in the initial periods of the transition up to 2030s, after which solar PV emerges as the prime source of energy until 2050 as the costs of solar PV become highly competitive. Solar PV prosumers further enable localisation of electricity generation across the EU. Hydropower, waste and residual biomass-based energy, wave power and geothermal energy play a complementary role in electricity generation, while dispatchability, where available, is extremely valuable. Heat pumps further complement these, which emerge as the dominant heat source that uses thermal energy from the environment as the prime resource. Bioenergy and renewables-based synthetic fuels provide steady shares of heat through the transition. Results from the three scenarios suggest that prosumers with solar PV, batteries and individual heat pumps emerge as enablers of cost optimal solutions. Emergence of prosumers across the EU needs to be hastened, along with building efficiency measures policies that include battery storage in building as well as vehicle-to-grid solutions across buildings in the EU.

Flexible and integrated energy systems

To complement the high levels of electrification along with renewable energy penetration, storage technologies play a vital role in providing system stability, flexibility and cross-sectoral integration. Batteries, both utility-scale and prosumers emerge as the prime electricity storage technology through the transition across the three scenarios, complemented by some shares of pumped hydro energy storage. From a seasonal perspective, hydrogen and methane storages play a vital role in covering the seasonal heat demand that is strongly prevalent in the EU. In addition, thermal energy storage provides a viable source of heat storage and adding to the flexibility of the system via power-to-gas and power-to-heat processes. As storage solutions are critical to enabling energy transitions across the EU, comprehensive policy is needed to boost adoption of storage technologies across the EU.

It is evident that a complete substitution of hydrocarbons by renewable electricity is not technically feasible, as electricity cannot be directly used in some sectors such as aviation (for long distance flights) or marine transportation and some industries. Thus, renewable electricity based synthetic fuels are essential to fulfil this demand via the power-to-fuels and power-to-chemicals processes. FT-fuels, hydrogen and liquefied gases (methane and hydrogen) are a viable alternative to fossil fuels and have a vital role through the transition. A critical integration of the production process of synthetic fuels with renewable energy generation along with innovative heat management increases the overall flexibility of the transport sector and reduces the need for high levels of curtailment and storage. Electrolysers emerge as a central component through the energy transition, as most power-to-X processes begin with the production of e-hydrogen by electrolysers that is further processed into FT-fuels and liquefied hydrogen. In addition, electrolysers are utilised to produce e-methanol and e-ammonia that are vital in achieving a sustainable chemical industry across the EU, while they are also used as marine fuels. Declining investment costs of electrolysers lead to increased flexibility in operation of electrolysers, which synchronise with the variability of electricity generation from solar and wind resources. This indirectly reduces the storage demand in the power sector and leads to the least cost operation of the entire energy system. The most important energy carriers in future energy systems are electricity, based on renewables, followed by hydrogen, produced from renewable electricity, while the latter is typically further converted into fuels and chemicals of interest. Sector coupling and power-to-X solutions are going to drive an integrated energy system development, which require comprehensive and cross-sector policies to be enacted across the countries of the EU. Similarly, policies regulating different industries across the EU will need to be revamped to boost process changes towards adopting electrification and sustainable feedstock, particularly in cement, steel and aluminium production.

Direct air capture (DAC) technology is increasingly being seen as a vital component, which is necessary to achieve in the first phase, zero CO_2 emissions, and in the second phase, negative CO_2 emissions[54,55,104]. As further highlighted by the results, DAC plays a key role in the production process of synthetic fuels. Moreover, DAC has several key features, in particular a very good area footprint for large-scale deployment, no major conflicts with land use, and an excellent match to the renewables based energy systems of the future[54,74], which are mainly based on solar PV and wind power as highlighted by the results. This technology can be further pursued to enable higher levels of carbon capture and utilisation and in processes where carbon can be utilised as an input product, which will boost mitigation efforts in achieving the goals of the Paris Agreement. Thereby, policies to boost the adoption of DAC along with the production of synthetic fuels and chemicals need to be enacted across the EU.

Overall, the trend across the three scenarios indicates that the current decoupled, centralised and fossil fuels based energy system transits towards a decentralised and integrated energy system with high levels of sector coupling. The various storage technologies and power-to-X technologies, complemented by high levels of electrification enable a highly integrated and efficient energy system in the future.

Cost optimal energy transition pathways

Envisioning energy transition pathways that consider a majority of the critical influencing factors are crucial in informing and shaping energy decisions. Costs are always one of the key factors to influence policy making across the board, and therefore, cost optimal energy transition pathways have significant potential to inform policy and decision makers, who are often concerned about costs of energy. In this context, the results highlight that from a levelised cost of energy perspective, the three scenarios show steady energy costs in the long-term, despite accelerated and rapid energy transitions. Concerning the levelised cost of electricity and heat, the three scenarios show substantial decline with respect to energy costs in 2020, which are much higher with the current fossil fuel prices. From an annual energy system cost perspective, costs remain stable and decline through the transition for increased levels of energy services. High level of investments in the form of capital expenditures are required across the three scenarios in varying rates, enabling strong economic stimuli with the creation of jobs, welfare and high level of services at low energy costs[105]. In addition, enhancing climate mitigation along with reduction in air pollution across the EU.

In general, these trends define energy transition pathways that are taking shape in the EU as well as globally. However, the three scenarios and the corresponding effects define plausible energy transition pathways for the EU and Europe.

THE REF SCENARIO: The results highlight an energy transition pathway that reduces CO_2 emissions across the EU energy sector to zero by 2050 with about 98% renewable energy in 2050. However, this is deemed unambitious with respect to the global efforts required to limit temperature rise to 1.5°C, with the levels of technological and economic development across the EU. Despite the cost advantage of renewables, fossil fuels and nuclear continue to supply energy as they are not phased out in a timely manner. This also leads to a slower growth rate of renewables and slows down emerging trends such as electrification, sector coupling and overall integration of the energy sector. In consideration of these aspects, this scenario leads to a slow transformation of the European energy system with no cost benefits, resulting in higher risks of security with continued reliance on energy imports in the mid-term. Additional risks of stranded assets and divestments, as fossil and nuclear continue to supply energy. Continued impacts of air pollution, with slower decline rates with the persistence of fossil fuels deep into the transition period. Overall, this scenario underlines an energy transition pathway that does not bring benefits to the European continent, nor does it justify Europe's progressive position globally.

THE RES-2040 SCENARIO: The results present an energy transition pathway that reaches zero CO_2 emissions across the EU energy system by 2040. This scenario advances the climate neutrality vision set by the EU for 2050 and is in the range of the global efforts required to limit temperature rise to 1.5°C. While this is a commendable effort reflecting the capabilities of the EU being a highly developed and progressive continent, it could be further hastened to address the looming energy security issue and decouple from imported fossil fuels across the EU. The cost advantage of renewables over fossil and nuclear fuels enables an accelerated transition to 100% renewables by 2040. A steady growth rate of renewables emerges along with storage technologies that enable trends such as electrification, sector coupling and complete integration of the energy sector by 2040. The accelerated transition enables a lower costing scenario, as annual energy costs decline through the transition in comparison to current levels. Moreover, the levelised costs of energy, electricity and heat are lower. This scenario leads to an accelerated transformation of the European energy system with lesser risks of security as reliance on energy imports declines through the transition. Some risks of stranded assets and divestments are posed by persisting nuclear power plants. Impacts of air pollution are reduced with decline in fossil fuels through the transition. Overall, this scenario underlines an energy transition pathway that does bring numerous benefits to the European continent. However, it still does not justify Europe's progressive position, as this opens opportunities for other major countries like China and India to leapfrog into a Leadership position, in terms of global climate action.

THE RES-2035 SCENARIO: The results present a rapid energy transition pathway that reaches zero CO_2 emissions across the European energy system by 2035. This scenario is more advanced than the climate neutrality vision set by the EU for 2050 and is in the ambitious range of global efforts required to limit temperature rise to 1.5°C. This scenario portrays efforts that are very much in synchronisation with the capabilities of the EU being a highly developed and progressive continent. The cost advantage of renewables over fossil and nuclear fuels enables a rapid transition to 100% renewables by 2035, under high carbon costs. In addition, existing fossil fuels and nuclear power are phased out in a rapid manner for achieving high levels of sustainability. A rapid growth rate of renewables emerges along with storage technologies that amplify trends such as

electrification, improving efficiency levels, sector coupling and complete integration of the energy sector by 2035. The levelised costs of energy, electricity and heat are quite stable through the transition. This scenario leads to a rapid transformation of the European energy system with far lesser risks of security, as reliance on energy imports decline steeply and exports of renewables-based synthetic fuels could take shape beyond 2035. Consequently, the EU would be on a net-negative CO_2 emissions level from the energy system , since the production of synthetic fuels and chemicals would require carbon that would be extracted from the air. This effectively leads to negative CO_2 emissions in Europe, since the carbon for the exported synthetic fuels is extracted from the air in Europe but released in the importing countries; the net effect is zero for the sum of the exporting and importing countries. Far lesser risks of stranded assets and divestments can be stated, with no new fossil and nuclear investments. Impacts of air pollution are reduced at a faster rate with steep decline in fossil fuels by 2035. Overall, this scenario underlines an energy transition pathway that brings numerous benefits to the European continent and beyond. It places the EU in a progressive position, as this opens opportunities for catalysing other countries and regions to adopt a rapid energy transition strategy and propel itself as a global climate leader.
A society that does not have access to abundant, reliable, cheap and sustainable energy stakes its economic and social progress, and this concern in the current context of the ongoing Russian invasion of Ukraine affects Europe as a whole. It is a pan-European matter more than an issue that only touches individually the interests of the member states. A net-zero EU is an evolving process. However, the ongoing energy crisis is the impetus to accelerate Europe's energy transition. The direction is clearly irreversible with more deployment of renewables at a much faster pace, by ensuring swift permitting and licencing procedures at the EU level. In the wake of the crisis, immediate plans to progressively replace gas boilers with high-efficiency heat pumps and support the development of European sustainable heating is vital. Promoting prosumers along with renovating and electrifying Europe's residential buildings is crucial. Enabling more efficient and electrified transport systems across the EU with emphasis on high-speed rail is vital along with driving efficiency measures. As highlighted in the study, energy interconnections and electricity infrastructure to provide flexibility and reliability of the EU energy system that enables optimising the use of renewable and other resources will be critical for ensuring stable energy costs. A Europe that swiftly builds up renewable energy technologies, which electrifies heating, transport and industry, and which diversifies supplies of fuels and chemicals is a more sustainable, more citizen-friendly and more independent Europe emerging as a global climate leader.

ABBREVIATIONS

A-CAES	Adiabatic compressed air energy storage
BECCS	Bioenergy carbon capture and storage
BEV	Battery electric vehicle
CAES	Compressed air energy storage
CAPEX	Capital expenditures
CCS	Carbon capture and storage
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CSP	Concentrated solar thermal power
DAC	CO2 Direct air capture
DACCS	Direct air carbon capture and storage
DH	District heating
FCEV	Fuel cell electric vehicle
FLH	Full load hours
FT	Fischer-Tropsch
GHG	Greenhouse gas
GT	Gas turbine
GW	Gigawatt
HDV	Heavy duty vehicle
HT	High temperature
HVAC	High voltage alternating current
HVDC	High voltage direct current
ICE	Internal combustion engine
IEA	International Energy Agency
IH	Individual heating
LCOC	Levelised cost of curtailment
LCOE	Levelised cost of electricity
LCOH	Levelised cost of heat
LCOS	Levelised cost of storage
LCOT	Levelised cost of transmission
LCOW	Levelised cost of water
LDV	Light duty vehicle
LH2	Liquefied hydrogen
LNG	Liquefied methane
LT	Low temperature
MDV	Medium duty vehicle
MED	Multiple-effect distillation
MSF	Multi-stage flash
MT	Medium temperature
MW	Megawatt
OCGT	Open cycle gas turbine
OPEX	Operational expenditures
PHEV	Plug-in hybrid electric vehicle
PHES	Pumped hydro energy storage
PP	Power plant
PtG	Power-to-gas
PtH	Power-to-heat
PtL	Power-to-liquids
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable energy
ST	Steam turbine
TES	Thermal energy storage
TPED	Total primary energy demand
TW	Terawatt
TTW	Tank-to-wheels
V2G	Vehicle-to-grid

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