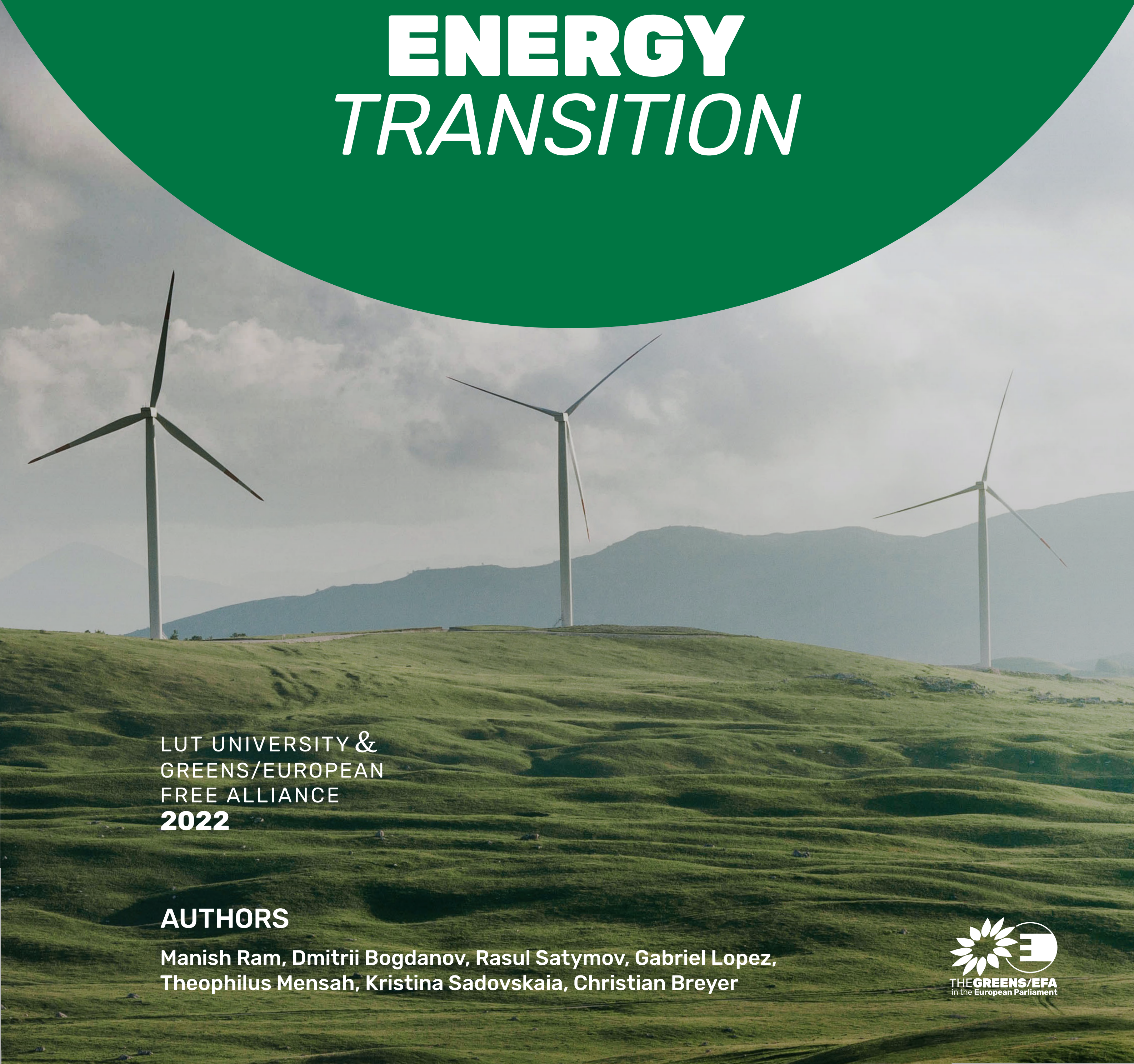
POLICY MAKER SUMMARY

ACCELERATING THE **EUROPEAN RENEWABLE ENERGY** *TRANSITION*



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THE GREENS/EFA
in the European Parliament

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The European Union (EU) is in the midst of an energy conundrum, with challenges ranging from ensuring supply to mitigating climate change but also issues of affordability and security. The EU faces the daunting task of formulating a long-term climate neutrality vision without impeding the short-term energy security within its borders and beyond. There are ongoing discussions on the levels of ambition envisioned within the European Green Deal, given that the energy transition towards higher shares of renewable energy is already well underway in many European countries, particularly in the power sector. There is an opportunity for Europe to emerge as a global leader with an accelerated transition of its energy system towards 100% renewables, which enables a range of benefits not only for its economy but also for other economies around the world. In this context, the **Greens/European Free Alliance (Greens/EFA) tasked LUT University (LUT)** with the research objective to explore and determine energy transition pathways across Europe with varying levels of ambition to achieve an energy efficient and fully renewable energy system aligned with climate neutrality.

The overall aim of this research is to present the most viable and feasible techno-economic options by determining the least cost energy mixes with the transitioning of the power, heat, transport and industry sectors towards an integrated energy system across Europe in the long term. This research presents first of its kind **technology-rich, multi-sectoral, multi-regional and cost-optimal** analyses with high spatial (27 member states derived from 20 regions across Europe) and temporal (hourly) resolutions of energy transition pathways for the EU.

The energy transition across Europe and in particular across the EU is explored in three distinct scenarios with the following boundary parameters and conditions[1]:

- REFERENCE SCENARIO [REF]: the energy system across the EU continues with current market and agreed policy trends 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, ramping up efficiency in buildings by doubling current renovation rates and 100% RE by 2050, enabling carbon emissions reduction of nearly 40% by 2030, compared to 2020 and around 60% compared to 1990 levels[2]. This scenario is not compatible with the ambitious climate target of limiting temperature rise to below 1.5°C. Fossil fuels are completely phased out by 2050, while existing nuclear power plants operate until end of technical lifetimes with no new constructions across the EU.

- RENEWABLE ENERGY SYSTEM - 2040 SCENARIO [RES-2040]: increased efforts by all member states to drive the renewable energy share in final energy demand across the EU to 56%[3] in 2030 and 100% by 2040, ramping up efficiency in buildings by tripling current renovation rates of 1% per annum and enabling energy related carbon emission reductions of around 50% by 2030 compared to 2020 and 65% compared to 1990 levels, further on to zero energy related carbon emissions by 2040. Fossil fuels and nuclear power plants are completely phased out by 2040 across the EU.

1 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.

2 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.

3 This includes ambient heat used by heat pumps.

- **RENEWABLE ENERGY SYSTEM - 2035 SCENARIO [RES-2035]:** with increased impetus the EU takes a global leadership role in mitigating climate change and enabling higher levels of energy security across Europe. Thereby driving the renewable energy share in final energy demand across the EU to around 75% in 2030 and 100% by 2035, ramping up efficiency in buildings by four times the current renovation rates of 1% per annum and enabling energy related carbon emissions reduction of 70% by 2030 compared to 2020 and 78% compared to 1990 levels, further on to zero emissions by 2035, which is compatible with the climate target of limiting temperature rise to below 1.5°C as defined in the Paris Agreement. 100% renewable energy across the power sector in all EU member states in 2030 and all other sectors towards 100% renewables by 2035. Fossil fuels and nuclear power plants are rapidly phased out by 2035 across the EU.

The major trends and insights that emerge from the three energy transition scenarios are:

High shares of renewables enable high levels of electrification in future energy systems

A fundamental shift towards high levels of electrification shapes the energy transition from the present energy system across the EU, which is based on about 80% fossil fuels and nuclear in 2020. Electrification across the energy sector, comprising of power, heat, transport and industry results in the highest share of 87% for the RES-2035 scenario in 2035, 85% in the RES-2040 scenario in 2040 and 83% in the REF scenario in 2050 (see Fig. ES1). The uptake of renewable energy drives electrification and integration of the different energy sectors with a 100% renewable energy system across the EU by 2035 in the RES-2035 scenario, by 2040 in the RES-2040 scenario and by 2050 in the REF scenario (see Fig. ES1). In addition, direct electrification drives energy efficiency in most of the sectors.

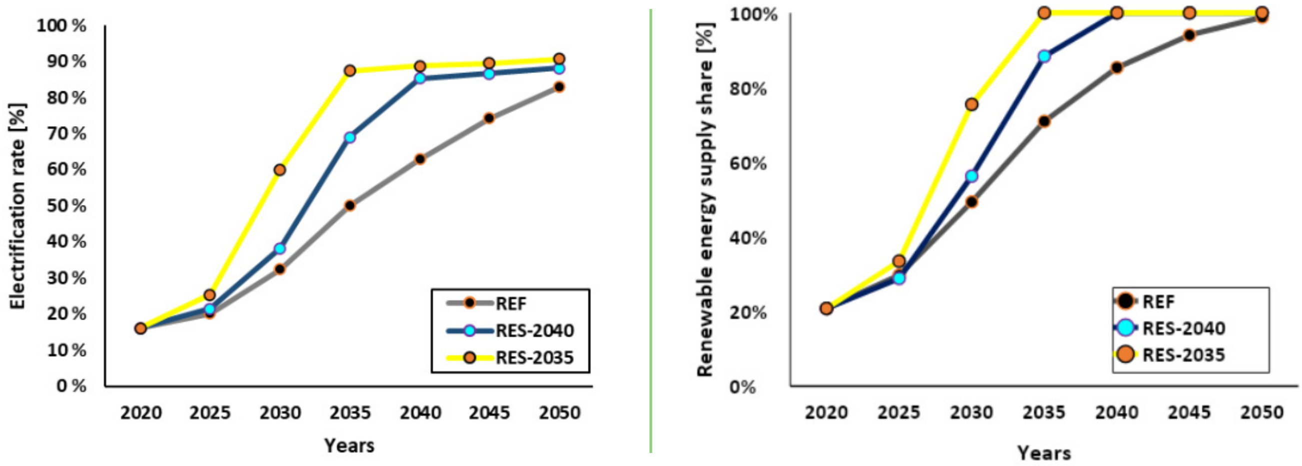

Fig ES1: Electrification rates (left) and shares of renewable energy (right) in the 3 scenarios.

The high levels of electrification and renewable energy penetration enable a fundamental shift in the energy system being dominated **by molecules from fossil fuels to electrons from renewable electricity,** also providing energy efficiency gains.

A transformation in primary energy consumption across the EU

Despite an overall increase in the demand for energy services across the power, heat, transport and industry sectors, the primary energy consumption[4] reduces with higher shares of electrification due to increase in efficiencies. The energy transition results in highly sector coupled and efficient energy systems based on renewable electricity in the future across the EU. The primary energy consumption declines from about 13,200 TWh in 2020 to nearly 9,200 TWh by 2050 in the REF scenario, about 9,500 TWh by 2040 in the RES-2040 scenario[5] and nearly 12,000 TWh by 2035 in the RES-2035 scenario (see Fig. ES2). In the case of RES-2040 and RES-2035 scenarios, primary energy consumption continues to decline with higher efficiency gains until 2050.

In summary, the drive towards low-cost electrification and enhanced sectoral integration leads to a strong electricity demand growth, and renewable electricity emerges as the prime energy carrier in future energy systems, reaching 100% rapidly by 2035 in the RES-2035 scenario, by 2040 in the RES-2040 scenario and almost 100% in the REF scenario by 2050 (with a few nuclear power plants still in phase out mode). Some shares of imports of e-fuels and e-chemicals enable cost effective 100% renewable energy systems across the EU[6]. These shares of imports of e-fuels and e-chemicals are significantly lower compared to the current imports of fossil fuels across the EU.

Fig ES2: Development of the primary energy consumption in the 3 scenarios through the transition.

4 Primary energy consumption does not include non-energy feedstock for industry and ambient heat from the environment for example in heat pumps.

5 In addition, the energy system utilises about 1700 TWh of ambient heat, about 150 TWh of feedstock comprising e-fuels and e-chemicals and about 40 TWh of biochar for the steel industry in 2040.

6 The shares of imports of e-fuels and e-chemicals in primary energy consumption: in the REF scenario is 0% in 2030 and 8% in 2050, in the RES-2040 scenario is 1% in2030 and 3% in 2050 and in the RES-2035 scenario is 8% in 2030 and 0% in 2050.

Efficiency gains drive an integrated energy system across the EU

Initially the primary energy demand represents the current compartmentalised energy system, which is dominated by fossil fuels that are inefficiently converted to electricity for the power sector, heat for heating applications in the heat sector and as combustible fuel for energy in the transport sector. The primary energy demand evolves during the transition to represent an increasingly integrated energy system, which is enabled by electrification and sector coupling. Electrification is primarily driven by the switch from fossil fuels and nuclear based electricity generation to renewables based electricity in the power sector, internal combustion engines to electric powertrains in the transport sector and electric heating coupled with heat pumps in the heat sector. Optimal use of renewable energy and efficient operation of the energy system is ensured by sector coupling, converting renewable electricity to heat and fuels, in particular in times of high and moderate inelastic energy demand. High levels of efficiency gains from electrification, building renovation and sector coupling enable a decrease in the primary energy demand of an integrated energy system in the short term as well as 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 dependent on the scale and rate of the transition. An accelerated shift to renewables for defossilisation does imply additional energy consumption required to produce e-fuels and e-chemicals which are needed to reduce emissions in the hard-to-abate sectors in the short term. This leads to lesser efficiency gains in terms of overall energy consumption. However, it also places the EU in a prime technology position to be able to turn into a technology exporter of e-fuels and e-chemicals in the mid-term. While in the long-term, advancing electrification of all the processes and reduction of e-fuels utilisation will allow to further increase energy efficiency of the integrated EU energy system.

A transformation in electricity supply across the EU

Solar PV and wind power emerge as the dominant sources of electricity generation due to their cost competitiveness across the three scenarios. Solar PV 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, and also the largest generation shares of over 50% in the REF scenario in 2050 to 54% in the RES-2035 scenario in 2035 (see Fig. ES3). The other power pillar of the energy transition, 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 and accounts for 38% to 41% of generation shares across the three scenarios, with complementary shares from other renewables such as hydropower, wave energy and bioenergy. On the other side, fossil fuels are completely eliminated from the EU energy system in all three scenarios, while nuclear power plants continue to operate until end of technical lifetimes in the REF scenario and are phased out by 2040 in the RES-2040 scenario and by 2035 in the RES-2035 scenario. New constructions of nuclear power are not considered in all the three scenarios, as nuclear power is not cost competitive with renewable electricity generation and have the most lengthy construction times across the EU. The results of this research further substantiate that nuclear power is not a cost effective option and does not feature in rapid energy transition pathways owing to its extensively complex budget overruns and perpetual construction times, but also poses sustainability and security issues.

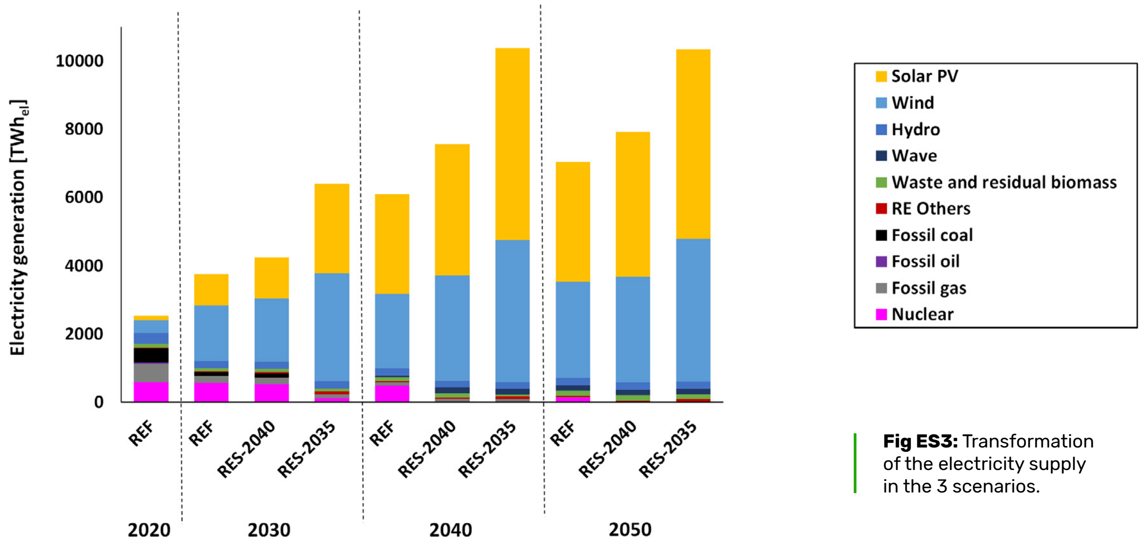

Fig ES3: Transformation of the electricity supply in the 3 scenarios.

Electricity emerges as the prime energy carrier across the different energy sectors leading to an increase in electricity supply from current levels of over 2530 TWh in 2020 to over 2.5 times by 2050 (7050 TWh) in the REF scenario, about 3 times by 2040 (7550 TWh) in the RES-2040 scenario and almost 4 times increase by 2035 (9700 TWh) in the RES-2035 scenario (see Fig. ES3).

A transformation in heat supply across the EU

The current heat sector across the EU is strongly dominated by fossil gas with over 65% supply share, which is mostly imported. A combination of direct and indirect electric heating is foreseen to take over through the transition with around 70% heat supply in all three scenarios (see Fig. ES4), owing to substantial efficiency gains of these heat pumps and electricity-coupled solutions.

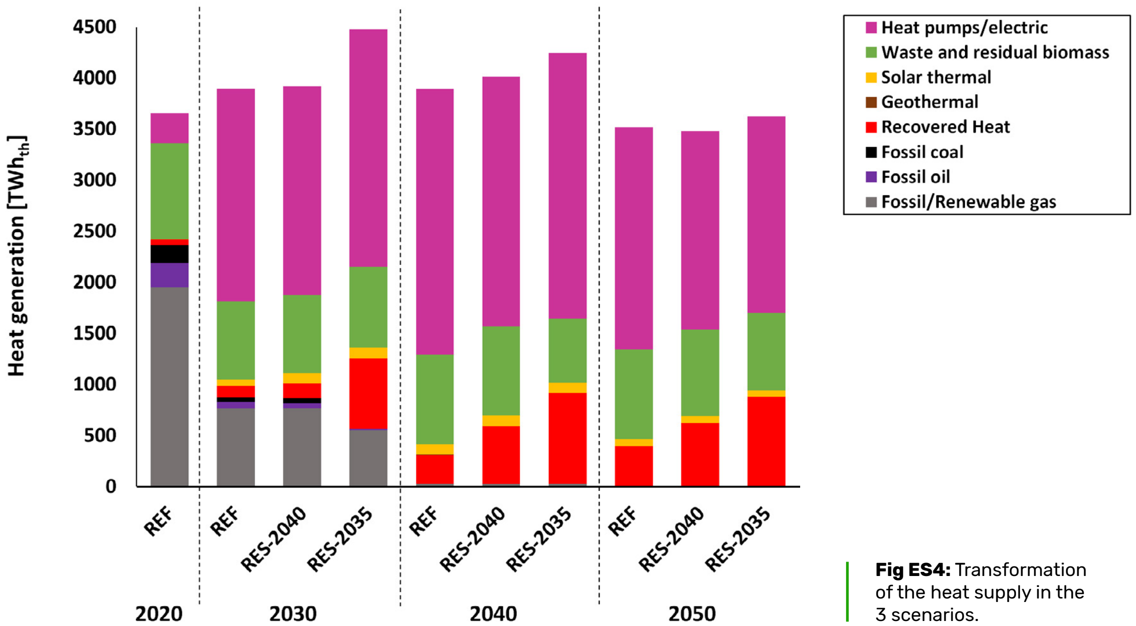

Fig ES4: Transformation of the heat supply in the 3 scenarios.

Renewables-based electric heating (direct) and heat pumps (indirect) are expected to comprise the majority of heat generating capacities through the transition, complemented by a small but steady share of other renewables, primarily sustainable bioenergy and some solar thermal. Recovered heat, which utilises waste heat from different processes to cover demand plays a vital role in the transition and further enhances efficiency of the EU energy system. Heat supply across the three scenarios remains at the current levels (see Fig. ES4) despite declining heat demand for space heating and domestic hot water, which is primarily due to significant efficiency gains from the new heating technologies as well as enhanced building standards across the EU. A rapid transition away from imported fossil gas across the EU is feasible and viable as highlighted by the RES-2035 scenario, thereby enhancing energy security and climate mitigation.

A transformation in fuels and chemicals use across the EU

Fossil fuels currently dominate energy and feedstock supply to the transport and industry sectors across the EU. The transport sector gets about 8% of the energy from renewables, mainly biofuels and some shares of electricity. With the energy transition, direct electrification emerges as the most efficient solution to decarbonise the road transport mode, while aviation and marine transport modes rely heavily on renewable electricity based synthetic fuels in the three scenarios.

The industry sector includes energy and feedstock supply to the cement, steel, chemicals, aluminium, pulp and paper, and other industries. The industry sector is currently dominated by fossil fuels across the EU. However, a complete transformation of the industry sector is realised in all three scenarios with direct electrification of some industrial processes such as steel production and with the adoption of sustainable processes enabled by **renewable electricity based e-fuels (e-hydrogen, e-methane and Fischer-Tropsch fuels) and e-chemicals (e-ammonia and e-methanol).**

Massive electrification, predominantly in road transport and some industries drastically reduces the fuels and chemicals use by about 60% in the REF and RES-2040 scenarios by 2050 and 2040 respectively, and by about 50% in the RES scenario by 2035 (see Fig. ES5). The remaining fossil fuels are predominantly replaced by e-fuels and e-chemicals with some shares of imports in the three scenarios, while sustainable biowaste-based fuels are needed in enabling the transition to 100% renewable energy systems across the EU (see Fig. ES5).

A fundamental transformation from a compartmentalised energy sector to an integrated energy system enabled by low-cost renewable electricity emerges in the three scenarios. Direct electrification in heat, transport and industrial activities along with indirect electrification through the production of e-fuels and e-chemicals couple the different energy sectors towards higher levels of efficiency and economic benefits.

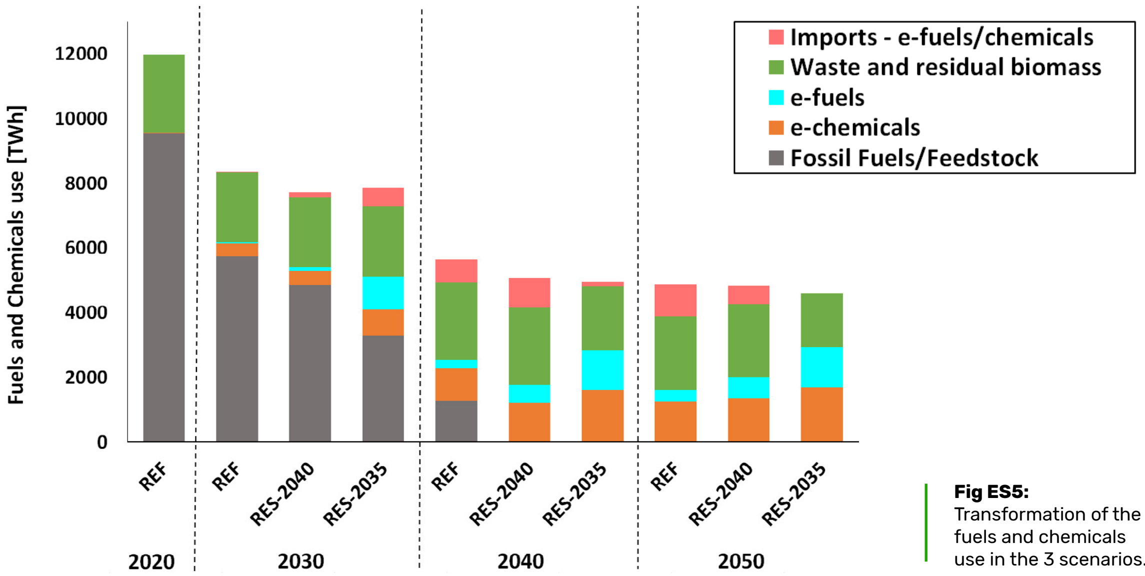

Fig ES5: Transformation of the fuels and chemicals use in the 3 scenarios.

High sustainability standards for bioenergy across the EU

Bioenergy plays a role in the generation of electricity and heat along with the production of fuels. However, all bioenergy sources considered in this research are well within the sustainability limits of biodiversity across the EU. Bioenergy sources are mainly wastes and residues and do not consider energy crops either locally from within the EU or from elsewhere in the form of imports beyond 2030. Bioenergy use is assumed for its highest value for the entire energy system.

Energy storage emerges as the vital component in 100% integrated renewable energy systems

Energy storage plays a critical role in the transition of the energy system towards high shares of renewables by providing stability and flexibility. Further, energy storage technologies enable the integration of the energy system with vehicle-to-grid, coupling the power and transport sectors, while gas (methane and hydrogen) storage complements power-to-gas solutions. Combinations of storage technologies cover the energy demand throughout the transition period, with batteries (utility and prosumers) providing the bulk of the electricity storage needs in the three scenarios (see Fig. ES6). While gas storage technologies are an indispensable part of the energy transition in the context of providing seasonal energy for heating mainly from biomethane, particularly in winter across the EU. Hydrogen storage plays more of a buffering role for the various power-H2-X solutions. Thermal energy storage (TES), both high temperature and district heating ensure stable and reliable heat supply through the transition in the three scenarios.

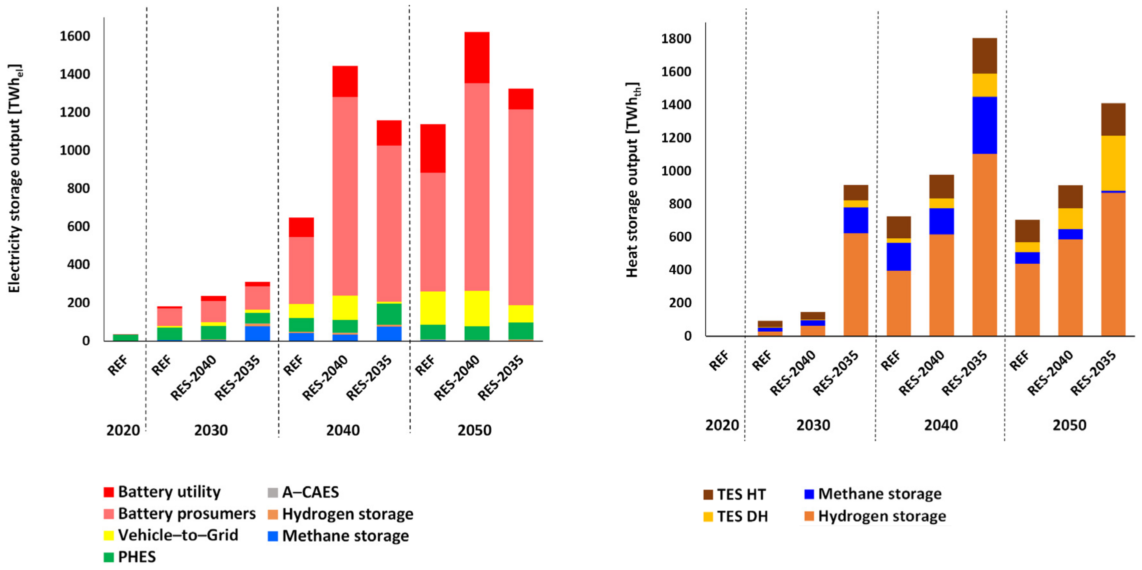

Fig ES6: Electricity storage output (left) and heat storage output (right) through the transition in the 3 scenarios.

A highly integrated approach with full sector coupling and high electrification rates delivers the most efficient and cost-effective energy system, keeping the growth of electricity, gas and heat storage outputs up to about 20-30% of primary energy demand in the three scenarios. Therefore, energy storage technologies are vital in ensuring efficient and cost-effective energy systems in the future.

Massive investments are needed for a rapid energy system transition across the EU

The cost of energy is among the key deciding factors in determining the viability of energy scenarios, blueprints, roadmaps, and pathways. The widespread apprehension on the costs of ambitious energy transition pathways towards 100% renewables remain, even across the EU. However, this research indicates that costs in the most ambitious RES-2035 scenario with 100% renewables across the EU will only be 10-12% higher than those in 2020. Furthermore, the RES-2040 scenario costs are only about 4-5% higher than in 2020. However, volatility of fossil fuel prices can induce much higher spikes in energy system costs. Considering the current energy prices of fossil fuels, 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[7] that are embedded in volatile global markets leads to additional economical as well as environmental risks. However, achieving the most ambitious scenario entails ramping up investments in renewable energy and sustainable technologies across the EU in **this decade with over 2900 billion € by 2030** (see Fig. ES7). Correspondingly, these investments spur economic activity, create jobs, enable meeting both the targets of European climate-neutrality and the Paris Agreement, while ensuring higher levels of energy security across Europe. The energy transition is not only about direct investments

7 Average energy prices for coal, fossil oil and fossil gas during the winter of 2021/2022 across the EU are considered for the EU energy system in 2025, and for 2030, the cost of fossil gas is assumed at 30% cost levels of the average price during the winter 2021/2022 due to uncertainties from increased LNG imports and long-term market distortions.

but also per-unit-generation cost: when looking at the levelised cost of energy (LCOEnergy) in the long-term, the REF scenario yields a LCOEnergy of 45 €/MWh in 2050, the RES-2040 scenario results in a LCOEnergy of 52 €/MWh in 2040 and the RES-2035 scenario has a LCOEnergy of 55 €/MWh in 2035[8] (see Fig. ES7). These are rather competitive to current LCOEnergy of 48 €/MWh in 2020. This indicates that an accelerated energy transition towards 100% renewable energy is an economically more attractive proposition than moving slowly. Capital costs increasingly dominate LCOEnergy in the three scenarios, as fuel costs lose importance through the transition period with the phase-out of fossil fuels and nuclear.

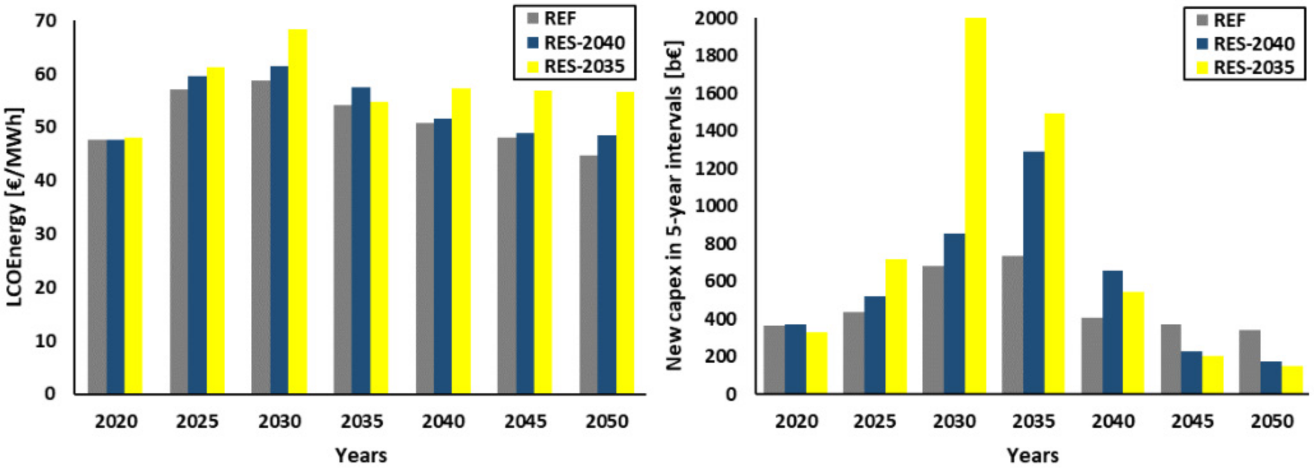

Fig ES7: Levelised cost of Energy (left) and new capital expenditures (right) through the transition in the 3 scenarios. Capital expenditures comprise the respective 5-year period.

In summary, **the pace of the energy transition across the EU is directly decided by the rate of capital diffusion into renewable energy and sustainable technologies in the next few years.** This clearly serves as an indication to policy and decision makers about prioritising capital allocation. An accelerated energy transition across the EU could potentially enable a green economic recovery from the effects of the pandemic, ensure high levels of energy security with locally sourced renewable energy, displacing costly fossil fuels imports, gain energy independence from Russia, and drive down carbon emissions as well as associated pollution stabilising the climate and a better environment.

8 The real value of the Euro (€) in 2020 is assumed for the transition period until 2050, without the consideration of inflation. This enables robust comparisons of energy costs and investment requirements through the years.

An accelerated energy transition triggers the sharpest decline in carbon emissions across the EU

An accelerated energy transition towards 100% renewables triggers a steep decline in CO_2 emissions from the energy system across the EU. CO_2 emissions decline in the three scenarios, from about 2500 million tonnes of CO_2 ($MtCO_2$) in 2020 to nearly zero by 2035 in the RES-2035 scenario, nearly zero by 2040 in the RES-2040 scenario and nearly zero by 2050 in the REF scenario (remaining are limestone-related CO_2 emissions from cement industry, which can be mitigated with carbon capture and storage or natural climate solutions, while the energy related emissions reduce to zero) (see Fig. ES8). The remaining cumulative CO_2 emissions comprise around 22 giga tonnes of CO_2 ($GtCO_2$ from 2020 to 2035 in the RES-2035 scenario, around 27 $GtCO_2$ from 2020 to 2040 in the RES-2040 scenario and 33 $GtCO_2$ from 2020 to 2050 in the REF scenario (see Fig. ES8).

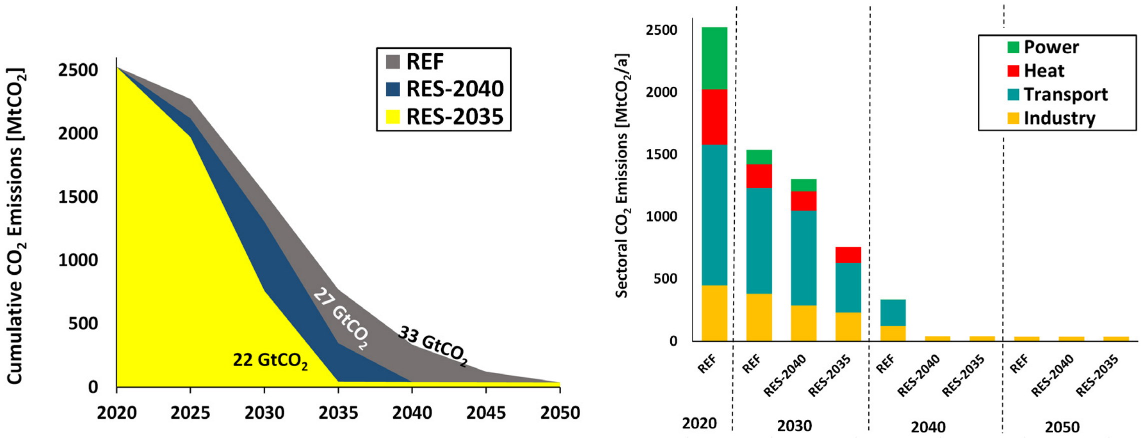

Fig ES8: Cumulative CO_2 emissions (left) and sectoral CO_2 emissions (right) through the transition in the 3 scenarios.

The presented scenarios for energy system transition pathways across the EU are compatible with the Paris Agreement, with the RES-2035 scenario highlighting an accelerated pathway for achieving the ambitious target of limiting temperature rise to below 1.5°C and **setting the EU on course for global leadership.** While the RES-2040 scenario shows a slightly lesser ambitious pathway of likely limiting warming to 1.5°C and the REF scenario is the least ambitious, above a 1.5°C warming.

In summary, results from this research indicate that a low ambition pathway across the EU is a burden for its society not only from climate change and economic perspectives but also raises the risks of energy insecurity. The results affirm that a highly ambitious energy transition pathway towards 100% renewables by 2040 is technically feasible and economically viable. This could be further accelerated with strongly pressuring policy measures by 2035. These call for significant scaling of investments, but with the benefit of stable per unit energy costs. With the promise to locally produced sustainable energy, the elimination of the dependence on fossil fuels imports becomes a reality and most importantly we will be on track to realise the 1.5°C climate target of the Paris Agreement.

Annex

Annex with more detailed results on the development of renewable energy shares in the energy system, electricity generation, efficiency standards, also for sub-sectors of building, heat, transport and power are provided in the annex data file. The results are emphasised for the central RES-2040 scenario.

Table A1: Primary energy demand and final energy consumption across the EU in the RES-2040 scenario.

	PRIMARY ENERGY DEMAND AND FINAL ENERGY CONSUMPTION[9] ACROSS THE EU-27						
	2020	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PED (TWH)	13 197	12 808	11 216	10 688	9 648	9 623	9 621
PED (MTOE)	1 135	1 101	964	919	830	827	827
FEC (TWH)	11 058	10 469	9 289	8 692	8 548	8 499	8 517
FEC (MTOE)	951	900	799	747	735	731	732

Table A2: Renewable energy shares in final energy consumption of the EU member states in the RES-2040 scenario.

	RENEWABLE ENERGY SHARES IN FINAL ENERGY CONSUMPTION [%]						
	2020	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
AUSTRIA	38%	34%	61%	92%	100%	100%	100%
BELGIUM	10%	16%	47%	89%	100%	100%	100%
BULGARIA	26%	35%	55%	87%	100%	100%	100%
CROATIA	21%	43%	62%	91%	100%	100%	100%
CYPRUS	20%	24%	57%	90%	100%	100%	100%
EU-27	**21%**	**29%**	**56%**	**88%**	**100%**	**100%**	**100%**

9 Primary Energy Demand (PED) and Final Energy Consumption (FEC) are defined according to Eurostat: https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-11

	RENEWABLE ENERGY SHARES IN FINAL ENERGY CONSUMPTION [%]						
	2020	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CZECH REPUBLIC	22%	27%	52%	79%	100%	100%	100%
DENMARK	33%	47%	65%	92%	100%	100%	100%
ESTONIA	34%	47%	68%	92%	100%	100%	100%
FINLAND	33%	48%	75%	91%	100%	100%	100%
FRANCE	20%	32%	54%	83%	100%	100%	100%
GERMANY	18%	25%	58%	90%	100%	100%	100%
GREECE	26%	35%	55%	87%	100%	100%	100%
HUNGARY	38%	34%	61%	92%	100%	100%	100%
IRELAND	15%	24%	57%	89%	100%	100%	100%
ITALY	20%	20%	50%	89%	100%	100%	100%
LATVIA	34%	47%	68%	92%	100%	100%	100%
LITHUANIA	34%	47%	68%	92%	100%	100%	100%
LUXEMBOURG	10%	16%	47%	89%	100%	100%	100%
MALTA	20%	20%	50%	89%	100%	100%	100%
NETHERLANDS	10%	16%	47%	89%	100%	100%	100%
POLAND	13%	39%	65%	93%	100%	100%	100%
PORTUGAL	20%	25%	53%	88%	100%	100%	100%
ROMANIA	26%	35%	55%	87%	100%	100%	100%
SLOVAKIA	22%	27%	52%	79%	100%	100%	100%
SLOVENIA	21%	43%	62%	91%	100%	100%	100%
SPAIN	20%	25%	53%	88%	100%	100%	100%
SWEDEN	44%	44%	65%	89%	100%	100%	100%
EU-27	**21%**	**29%**	**56%**	**88%**	**100%**	**100%**	**100%**

Table A3: Renewable energy shares in different energy segments across the EU in the RES-2040 scenario.

	RENEWABLE ENERGY SHARES [%] ACROSS EU-27						
	2020	2025	2030	2035	2040	2045	2050
ELECTRICITY SUPPLY	39%	59%	81%	95%	100%	100%	100%
BUILDINGS	35%	42%	77%	96%	100%	100%	100%
HEATING	33%	36%	75%	96%	100%	100%	100%
INDUSTRY[10]	0%	31%	75%	95%	100%	100%	100%
TRANSPORT	4%	6%	17%	72%	100%	100%	100%

10 Green Hydrogen (H_2) for non-energy use in industry.

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