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RESEARCH ARTICLE

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Reflecting the energy transition from a European perspective and in the global context—Relevance of solar photovoltaics benchmarking two ambitious scenarios

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Abstract

Multiple energy-related crises require a fast transition towards a sustainable energy system. The European Green Deal aims for zero CO_2 emission by 2050, while accelerating climate change impacts obligate a faster phase-out of fossil fuels. Energy transition studies for Europe at and near 100% renewable energy are used as a benchmark for two newly introduced scenarios for Europe reaching zero CO_2 emissions by 2050 and 2040. A technology-rich energy system model was applied in hourly resolution for Europe in 20 interconnected regions and in full sector coupling covering all energy demands. The results reveal a cost-neutral energy transition towards 2050 based on declining levelised cost of electricity and a pathway with 9% higher energy costs leading to 17% lower total CO_2 emissions with an accelerated energy transition by 2040. The two scenarios find shares of solar photovoltaic (PV) in total generation of 61%–63% by 2050, the highest ever estimated for Europe, still below the highest global average shares ranging between 75% and 77% form three independent studies. The central energy system components are solar PV, wind power, batteries, electrolysers and CO_2 direct air capture for carbon capture and utilisation. The core characteristic of the European energy future may be best described by a power-to-X economy, which may evolve on the global scale to a solar-to-X economy.

KEYWORDS

100% renewable energy, energy transition, Europe, power-to-X economy, solar PV, wind power, zero CO_2 emissions

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1 | INTRODUCTION

The energy transition in Europe is not only a response to multiple crises but also taking advantage of enormous opportunities. Scientific research on the energy transition towards 100% renewable energy (RE) systems in Europe was started by Bent Sørensen in 1975 with the first ever scientific paper on the topic for the case of Denmark.[1,2] This involved propagating wind power for electricity supply, solar energy for heat supply and electricity-based e-hydrogen for all remaining energy demand. Sørensen already based the necessity of the transition on risks posed by climate disruptions, limitation of fossil and nuclear fuels and their degrading quality and the need for high levels of energy security achievable with a 100% RE system. The first scientific global 100% RE system transition analysis was published in 1996, again by Sørensen,[3] and clearly addressed the necessity of a radical turn in energy policy due to climate change and presenting scenarios with up to 77% of solar photovoltaic (PV) share in global electricity supply. The outstanding potential and role of solar PV was confirmed in the meantime based on state-of-the-art methodology.[4,5]

The pioneering analysis of Sørensen positioned Denmark as a global leader in energy transition research, with three international leading research hubs in the field of 100% RE systems research at Aalborg University, Aarhus University and Danish Technical University.[2,6,7] Consequently, Denmark was the first country in the world with a 100% RE target set in 2011[8] and had the highest wind power share in electricity supply across the world with 44% in 2021,[9] led by pioneering ventures in offshore energy islands,[10] establishing the world market leader, Vestas, in wind power,[11] transitioning the first major fossil fuels company to renewable energy with Ørsted succeeding DONG[12] and starting the fuel transition in the marine industry with e-methanol-based shipping pushed by the global shipping container market leader Maersk.[13] Denmark showcases enormous opportunities for the energy transition towards 100% RE, which requires strong policy vision focussed on real solutions, strong stakeholder commitments and continued execution of measures to achieve the long-term target.

The development in the European solar PV industry,[14] however, showcases how massive policy failures can destroy leadership, economic development, industrial opportunities, burden energy security and thus contribute to energy crises. Europe, in particular Germany, has been one of the three historic leaders in the public and private research of solar PV, next to the United States and Japan.[15] This led to outstanding leadership in the 2000s with the political innovation of Feed-in Tariff programmes first in Germany, then across entire Europe.[16,17] The market shares of Europe in the global PV deployment reached more than 80% in 2000s,[18] documenting the outstanding role of Europe in catalysing the dawn of the Solar Age.[16,17] However, political recklessness resulting in unclear industrial PV policies combined with continued ignorance of the climate emergency led to the collapse of the European solar PV industry, massive loss of jobs in the PV industry and a decline in PV deployment. This collapse was even supported by barriers that were introduced to slow down the energy transition. In the face of the historic energy crisis and energy security threat in 2022, it has to be noted that massive political failures in the 2010s in Europe, and in Germany, its largest economy, have exacerbated the energy crisis in the early 2020s. Substantially higher solar PV and wind power capacities across Europe would have enabled a more resilient and sustainable energy system. The dimensions of energy security substantially correlate with sustainable energy supply.[19,20] The role of oil and gas majors remains unclear, while a mismatch between their discourse, actions and investments is evident.[21] Li *et al*.[21] conclude that until actions and investments are brought into alignment with discourse, assertions of greenwashing appear well-founded. Their role in abetting policy ambiguity remains to be investigated; however, the fact that the biggest American and European oil and gas majors have spent millions lobbying to delay or weaken effective climate policy is well documented.[21,22]

The climate emergency has emerged as the major threat for civilisation.[23] The carbon budget of a 1.5°C target at 67% probability, as aimed for in the Paris Agreement,[24,25] is expected to be used already by around 2030.[26] Anthropogenic climate change is understood in a very high level of detail,[27] whereas the energy-industry transition research as summarised in the recent 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)[28] still lacks vital insights regarding highly renewable and sustainable energy transitions,[2] with distorted policy recommendations as the consequence. The global response to this emergency needs a higher level of ambition in climate targets and increased focus on low-cost and sustainable energy system solutions, which can be showcased in ambitious energy transition scenarios.

Recent political and industrial activities aim for a restart and raised level of ambition, first initiated by massive pressure from civil society in particular the youth to tackle climate change,[29,30] and second by gravely endangered energy security due to the Russian war in Ukraine.[31] The European Green Deal,[32] Renewable Energy Directive (REDII),[33] revamped EU Emissions Trading System (EU ETS),[34] revised energy efficiency directive with emphasis on heating and cooling along with net-zero energy buildings[35] and zero-emission vehicles by 2035[36] showcase on the European level a mostly awaited change in aims, direction and execution. The legislative proposals in the 'Fit for 55' package[37] and further extraordinary measures under REPowerEU[38] document accelerated emphasis in reaching the targets. The revision of the REDIII[39] is the key policy initiative to enable the transition to a 100% RE supply across the EU before 2050. Also, on national levels, a focus on real solutions helps to concentrate on the relevant measures, increase the level of ambition and identify required capacities and derive respective measures, as documented on the case of Germany in a newly formulated energy strategy.[40] Specifically for the solar sector, the EU Solar Strategy[41] set out by the European Commission in May 2022 under REPowerEU[38] establishes a 750 GW solar target by 2030, indicating a more prominent role for solar in the EU. This is supported by several dedicated initiatives addressing rooftop solar (European Solar Rooftop Initiative[41]), domestic manufacturing (EU Solar PV Manufacturing Alliance[41]) and tackling other existing challenges such as access to finance, permitting, utility-scale PV deployment, efficient solar energy distribution and establishment of a resilient supply chain. Driven by the need to address long-term energy security coupled with the urgency of mitigating climate change, the EU will need to pursue higher ambition, and this research is an effort to present ambitious energy transition scenarios for Europe.

The role of solar PV is vital in enabling the visions of the EU to become a climate neutral economy before 2050 as highlighted by Jäger-Waldau *et al*.[42] In this context, the aim of this paper is to reflect the role of solar PV for the European energy transition within the global context. This is enabled by estimating a cost-optimised share of solar PV in electricity generation and primary energy supply in Europe. Solar PV and wind power are the least cost electricity supply options with the potential to serve all final energy demands via sector coupling[43–46] and power-to-X technologies.[46–51] The approach in this research is a combination of (i) an overview on PV shares in highly RE system studies for Europe; (ii) two ambitious scenarios for Europe based on 100% RE by 2040 and 2050 applying the LUT Energy System Transition Model[5,46]; and (iii) scenarios benchmarked with existing scientific literature and in the context of global findings. The novelty of this research is the development of a zero CO_2 emission transition scenario for Europe by 2040 based on 100% RE and the consequent focus on the role of solar PV for achieving such an ambitious target.

2 | LITERATURE OVERVIEW ON 100% RENEWABLE ENERGY SYSTEM TRANSITION FOR EUROPE

The definition of 'Europe' varies with different studies; however, it typically comprises the European Union, and often Switzerland, Norway and some Southeast European countries, along with Turkey, Ukraine and Iceland. In total, 93 studies in scientific journals on highly RE scenarios for Europe are known, thereof all identified ones until mid-2021 are listed in Khalili and Breyer.[6] From these, 16 studies describe a pathway from the present up to 100% RE in the future, typically around 2050 (Table 1, Figure 1). Of these, seven studies describe the entire energy system, whereas 16 studies all cover the power sector, and no single study describes the energy industry with details for the industry system. Only one study within the seven is in multi-node (30) and hourly resolution,[61] however lacking concrete data for benchmarking. Remarkably, despite the 93 studies identified for Europe, with the first published in 1997 by Sørensen,[68] the first study describing a transition pathway was published in 2017 by Pleßmann and Blechinger[67] for the European power sector. The first study considering all energy demands in Europe was published by Löffler *et al*.[65] in 2019, but for limited temporal resolution, which was overcome in 2020 by Victoria *et al*.[61] Transition scenarios describing zero-emission pathways are of highest importance for stakeholders and policymakers in identifying evolutionary measures and capacities to reach with the aim of 100% RE across Europe. Several power sector transition studies find near 100% RE power systems by 2035 and 2040. For all energy sectors analyses, only one study shows a pathway for 100% RE by 2040.[61]

Almost all the used energy system models belong to the most used models for 100% RE system studies in total, as LUT-ESTM, GENeSYS-MOD, PyPSA and TIMES belong to the 10 most used energy system models for 100% RE system studies.[69] LUT-ESTM and PyPSA are in hourly resolution, and both are rated very high in overall model functionality.[70] PyPSA is open-source[71] and currently only applied to Europe, but the model is planned to expand to cover Africa and the entire world,[2] whereas LUT-ESTM is not yet open-source and applied for a broad variety of countries and regions all around the world including global studies.[2,17,72] PyPSA and LUT-ESTM are capable of more detailed industry inclusion for 100% RE systems,[46,48] whereas LUT-ESTM has not yet been applied with this functionality for Europe, and PyPSA not yet for 100% RE studies. GENeSYS-MOD and TIMES are also open-source, whereas TIMES is not free. The four main models differ in their level of details for e-fuels and e-chemicals, as GENeSYS-MOD is limited to e-hydrogen,[59] TIMES can model e-hydrogen, e-methane and e-liquids,[4] PyPSA covers e-hydrogen, e-methane and e-liquids[48] and LUT-ESTM includes e-hydrogen/LH2, e-methane/liquefied natural gas (LNG), e-liquids, e-ammonia and e-methanol.[46] PyPSA is able to combine various CO_2 sources and CO_2 demands as raw material and sequestration,[48] whereas this is limited in LUT-ESTM to direct air capture (DAC) but prepared for diversified CO_2 sources[73] and realised for CO_2 removal.[74]

Most studies with available results find variable RE (VRE) shares in electricity supply between 80% and 90% for Europe (Figure 1), whereas the shares of solar PV and wind power vary significantly. Two studies showcase the VRE share in total primary energy demand (TPED) between 65% and75% in 2045 and 2050.[63,65] This study finds shares of about 94% and 84% for VRE shares in electricity supply and TPED, respectively, the highest among all studies.

The shares of solar PV in electricity generation from the different pathway studies according to Table 1 range between 19% and 37%, considering studies published since 2017, and 28% in average, excluding studies from the LUT team. The LUT team finds PV shares of 41%–47% in power sector studies[64,66] prior to this research, and 61%–63% in this research. Victoria *et al*.[61] find a solar PV share of 56%. The difference in PV shares is driven by PV capital expenditures (capex), the capex of the most important supporting technologies batteries and electrolysers and the extent of sector coupling, as well as on the level of PV prosumer.[75,76] In addition, the consideration of diversified PV system technologies influences the PV shares, in particular single-axis tracking PV and whether rooftop and ground-mounted is individually optimised within energy system models.

Absolute solar PV electricity generation differs widely among the identified studies not only due to sectoral coverage from power sector to all sectors but also due to the geographic coverage of Europe ranging from European Union to entire Europe including Ukraine and Turkey. PV electricity generation in power sector studies is between 760 and 2750 TWh with an average of 1776 TWh, and in all sector studies, the range is found to be 480–2800 TWh with an average of 1760 TWh. This is a surprising result, as electrification of heat and transport demands should lead to substantially higher demands in studies covering all sectors compared with just power sector studies.

TABLE 1 Overview on all 100% RE system transition studies for Europe published in scientific journals. RE shares of at least 95% are considered for near 100% RE cases. All used models are of optimisation type, and all studies describe pathways. Results of this study are added for comparison. Energy sectors comprise power (P), heat (H), transport and industry (I).

Authors	Year	Model	Temporal resolution	Sectors	Regions	Electricity generation		Generation share		TPED share		RE share	Target year[b]
						PV [TWh]	Wind [TWh]	PV	Wind	PV	Wind		
This study—Moderate	2022	LUT-ESTM	Hourly	All	20	10,600	5630	61%	33%	54%	29%	99.5%	2050
This study—Leadership[a]	2022	LUT-ESTM	Hourly	All	20	12,345	6400	63%	32%	56%	29%	100%	2040
Rodrigues *et al.*[52]	2022	REMIND, PRIMES, TIMES	Time slices	All	11	1550	2940	29%	55%	n/a	n/a	96%	2050
Backe *et al.*[53]	2022	EMPIRE	Hourly	P,H	35	2050	3550	28%	49%	n/a	n/a	97%	2050
Hainsch *et al.*[54]	2022	OSeMOSYS - GENeSYS-MOD	Time slices	All	-	n/a	n/a	n/a	n/a	n/a	n/a	95%	2050
Backe *et al.*[55]	2022	EMPIRE	Hourly	P	35	765	2365	19%	58%	n/a	n/a	100%	2050
Holz *et al.*[56]	2021	EMPIRE	Hourly	P,H,I	-	2140	890	55%	23%	n/a	n/a	96%	2050
Löffler[57]	2021	OSeMOSYS - GENeSYS-MOD	Time slices	P	30	1730	860	37%	50%	n/a	n/a	100%	2050
Lehtveer *et al.*[58]	2021	H2D	Annually	All	12	480	1600	19%	64%	n/a	n/a	98%	2050
Hainsch *et al.*[59]	2021	OSeMOSYS - GENeSYS-MOD	Time slices	P,H	17	2160	3360	30%	47%	n/a	n/a	96.0%	2050
Pietzcker *et al.*[60]	2021	LIMES-EU	Time slices	P	29	1870	2310	32%	39%	n/a	n/a	99.8%	2050
Victoria *et al.*[61]	2020	PyPSA	Hourly	All	30	3360	2025	56%	34%	n/a	n/a	98%	2040
Ringkjob *et al.*[62]	2020	TIMES	Time slices	All	28	970	1870	25%	47%	n/a	n/a	97%	2050
Auer *et al.*[63]	2020	OSeMOSYS - GENeSYS-MOD	Time slices	All	30	2800	3950	35%	50%	31%	44%	100%	2045
Child *et al.*[64]	2019	LUT-ESTM	Hourly	P	20	2340	1900	41%	33%	n/a	n/a	99.8%	2035
Löffler *et al.*[65]	2019	OSeMOSYS - GENeSYS-MOD	Time slices	All	17	2330	3080	n/a	n/a	28%	37%	97%	2050
Child *et al.*[66]	2018	LUT-ESTM	Hourly	P	20	2750	1960	48%	34%	n/a	n/a	99.8%	2035
Pleßmann and Blechinger[67]	2017	elesplan-m	Hourly	P	18	1200	3800	20%	64%	n/a	n/a	98%	2040

Abbreviations: LUT-ESTM, LUT Energy System Transition Model; PV, photovoltaic; RE, renewable energy; TPED, total primary energy demand.

[a]Higher generation leads to excess e-fuels, which are assumed to be exported.

[b]Target year when the near 100% RE system status is achieved.

The results of this study are 10,600–12,345 TWh, which is several factors higher. Details and reasons for the substantial difference are presented in the results and discussion sections.

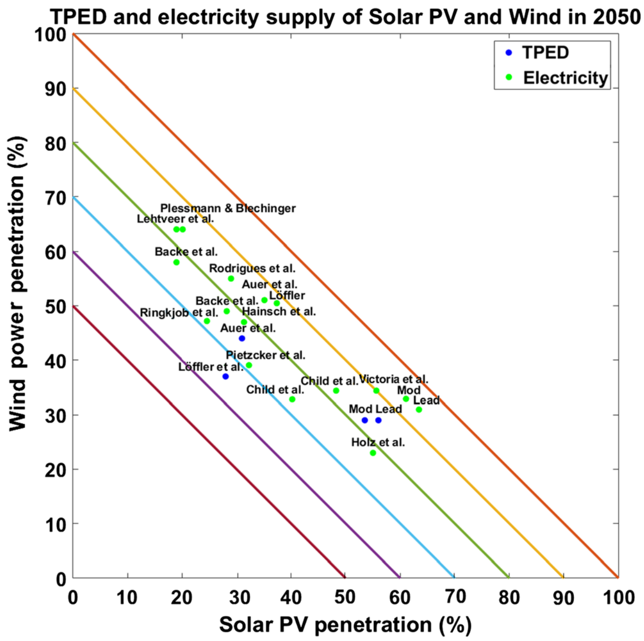

FIGURE 1 Shares of solar photovoltaic (PV) and wind power in 100% renewable energy (RE) scenarios for Europe in electricity generation and in total primary energy demand (TPED) in the year 2050. Results of Table 1 are displayed. Only a few studies exist for PV shares higher than 40%, while they are from only three different teams. Regional coverage of Europe varies across studies but includes at least the European Union. [Colour figure can be viewed at wileyonlinelibrary.com]

3 | METHODOLOGY

The energy transition has been modelled by applying the LUT Energy System Transition Model,[5,46] covering residential, commercial and industrial use of electricity and heat, and the transport sector energy demand. Thus, the model accounts energy related CO_2 emissions for power, heat and transport sectors. The cost-optimised modelling was conducted in 5-year steps, with each modelled year in hourly resolution to ensure the supply–demand balance at each hour. More detailed explanation is presented below.

3.1 | LUT Energy System Transition Model

The LUT Energy System Transition Model (LUT-ESTM)[5,46] is applied across an integrated energy system covering demand from the power, heat and transport sectors as shown in Figure 2. The unique features of the model enable to determine cost optimal energy system transition pathways with a high level of geo-spatial and temporal resolution. Furthermore, the capability to model in an hourly resolution for an entire year enables the uncovering of crucial insights, particularly with respect to storage and flexibility options, which are most relevant for future energy systems. The LUT-ESTM is ranked as one of the most developed energy system models[70,77] and is among the two most used models for 100% RE system studies.[69]

The simulations are carried out in a two-stage approach. In an initial stage, the prosumer simulations determine a cost-effective share of prosumers and the structure of prosumers power and heat supply systems across Europe through the transition from 2020 to 2050, in 5-year intervals. At the second stage, the model defines the structure and hourly operation of the centralised energy system for each 5-year

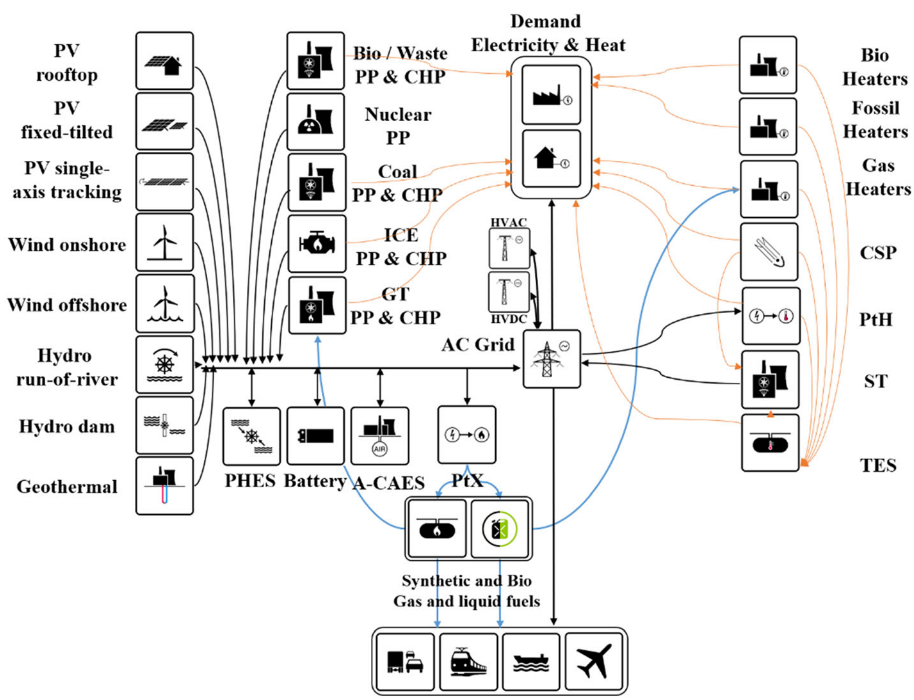

FIGURE 2 Schematic representation of the LUT Energy System Transition Model (LUT-ESTM).[5,46] AC, alternating current; A-CAES, adiabatic compressed air energy storage; CHP, combined heat and power; CSP, concentrating solar thermal power; GT, gas turbne; HVAC, high voltage alternating current; HVDC, high voltage direct current; ICE, internal combustion engines; PHES, pumped hydro energy storage; PP, power plant; PtH, power-to-heat; PtX, power-to-X; PV, photovoltaic; ST, steam turbine; TES, thermal energy storage. [Colour figure can be viewed at wileyonlinelibrary.com]

interval of the transition considering the technology-rich portfolio of generation, storage, transmission and power-to-X technologies.

The technologies modelled are:

- electricity generation technologies: renewable energy, fossil and nuclear technologies;
- heat generation technologies: renewable and fossil;
- energy storage technologies: electricity, heat and gas storage technologies;
- power-to-fuels technologies: synthetic e-fuel production; and
- electricity transmission technologies.

The detailed description of the model is provided in Supporting Information S1 (Section A).

3.2 | Scenarios and data

The energy system transition has been carried out for the whole of Europe, which is structured into 20 regions. Some of the smaller countries have been merged with larger countries to form sizeable local regions, as the energy transition is envisioned on a regional basis. The composition of the regions is as follows and shown in Figure 3:

- Northern: Norway, Denmark, Sweden, Finland and a Baltic region that includes the countries of Estonia, Latvia and Lithuania;
- Western: 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 and Benelux region comprising Belgium, the Netherlands and Luxembourg;
- Central: Germany, Poland, a region comprising Czech Republic and Slovakia, a region with Austria and Hungary and a region with Switzerland and Liechtenstein;
- Southeast: a region including the Western Balkan countries of Slovenia, Croatia and Bosnia and Hertzegovina, Serbia, Montenegro, Macedonia, Kosovo and Albania, a region including Eastern Balkan countries of Romania, Bulgaria and Greece, a region with Ukraine and Moldova and a region with Turkey and Cyprus; and
- Iceland

The 20 regions are interconnected with optimised transmission networks, and Iceland is considered as an isolated region. Cost optimised transition pathways for an integrated European energy system in the interconnected 20-node resolution are modelled for three distinct scenarios.

3.2.1 | Laggard

In this scenario, the European energy system is set on a minimum ambition pathway, wherein the current and upcoming fossil fuels and nuclear power plants are not phased out and continue operating until end of its technical lifetime. In the transport sector, a slower rate of electrification of road transport leads to a longer presence of internal combustion engines (ICEs) in road transport by 2050. Fuels for marine and aviation transportation are still 50% fossil by 2050 due to a

FIGURE 3 Europe, constituted by the corresponding 20 regions. [Colour figure can be viewed at wileyonlinelibrary.com]

delayed transition. Substantial new nuclear power plants, as well as new fossil plants, are added to the system according to scenarios of European Commission (EC).[78] The EC's vision of climate neutrality by 2050 is not achieved, as GHG emissions reduction are at 90% below 1990 levels. Medium GHG cost development is considered with present values in 2020 to 150 €/tCO_2 by 2050. Finally, the ambitious goal of the Paris Agreement of limiting mean global temperature rise to below 1.5°C is violated.

3.2.2 | Moderate

In this scenario, the European energy system is set on a medium ambition pathway, wherein the current fossil fuel power plants are phased out by 2050 and no new nuclear power plants are considered, with existing and under construction plants operating until end of their technical lifetimes. New coal plants are not allowed due to climate regulation, whereas new gas-fired power plants are allowed, but with the obligation to switch to non-fossil fuels during the transition. The EC's vision of climate neutrality by 2050 is achieved, as GHG emissions are zero in 2050. Medium GHG cost development is considered with present values in 2020 to 150 €/tCO_2 by 2050. Finally, the less ambitious goal of the Paris Agreement of limiting mean global temperature rise to below 2°C is more likely achievable than the more ambitious target of 1.5°C.

3.2.3 | Leadership

In this scenario, the European energy system is set on a high ambition pathway, wherein the current fossil fuels and nuclear power plants are phased out by 2040 and no new plants are considered. New gas-fired power plants are allowed, but with the obligation to switch to non-fossil fuels before 2040. The EC's vision of climate neutrality by 2050 is achieved well before by a decade, as GHG emissions are zero in 2040. High GHG cost development is considered with present values in 2020 to 200 €/tCO_2 by 2040. Finally, the ambitious goal of the Paris Agreement of limiting mean global temperature rise to below 1.5°C is more likely to be achieved. Furthermore, as this scenario achieves zero GHG emissions and 100% renewables by 2040, it presents an opportunity for Europe to proceed with additional GHG emissions reduction and thereby becoming a negative CO_2 emission continent. This is primarily driven by additional capacities to produce renewable electricity-based synthetic e-fuels for defossilisation of the transport sector by 2040. This leads to an opportunity to produce additional volumes of e-fuels from 2045 to 2050. As remaining combustion vehicles in the stock are continued to be phased out beyond 2040, European demand for liquid fuels declines. The continued production of e-fuels leads to significant volumes for the export of e-fuels that enable displacement of fossil fuels in other regions, which further reduces GHG emissions globally and places Europe in a leadership position. This effectively leads to negative CO_2 emissions in Europe because the carbon for the e-fuels is mainly extracted from air.

All scenarios share the same assumptions on the energy demand in power, heat and transport sectors and the RE potentials. Detailed information on demand, transport technology shares and RE potential is presented in the Supporting information (Figures A5–A8). The weighted average cost of capital (WACC) is set to real 7% for the entire transition and investments in all technologies, except high risk nuclear and coal for which WACC is set to 10%. The currency value is considered for 2020. This study was carried out before the high inflation of 2022 hits the markets. However, inflation impacts all investments, and fossil fuel prices escalate even faster, thus, the structural results of the study remain valid, while it might be expected that most prices rebalance in near future after the exogenic shocks are absorbed. A detailed description of the financial and technical assumptions, including capital and operational expenditures, lifetime and efficiencies for all technologies, as well as costs of fuels, and their sources, is presented in the Supporting information (Tables B1–B5).

4 | RESULTS

The results are presented for the two main scenarios, Moderate (Mod) and Leadership (Lead), which lead to zero CO_2 emissions in the energy system by 2050 and 2040, respectively, and they are compared with a less ambitious scenario named Laggard (Lag), which does not aim for 100% RE or for zero CO_2 emissions by 2050, while it is close to the aims of the European Green Deal. The energy transition from the present disjunctive state of the power, heat and transport sectors in 2020, towards an integrated and sector-coupled energy system fulfilling the energy demand from power, heat and transport across Europe in 2050 enforces some fundamental changes. In general, an increasing rate of sector coupling through the transition period from 2020 to 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. The details of each individual scenario are presented in Supporting Information S1 (Section C).

4.1 | Final energy demand

Phasing in 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, where the final energy demand remains steady and even declines in two of the scenarios through the transition until 2050, as shown in Figure 4. The decline in final energy demand occurs despite a steady growth in energy services, which is reflected by the growth in power and heat demands as well as transportation service demand in terms of passenger and freight travel, as shown in the Supporting information (Figures A5–A7). Assumptions for efficiency improvements for heat demand are conservative in this study, whereas efficiencies may be ramped up faster for space heating and industrial process heat. Development of the final energy demand across the three scenarios from an energy carrier and sectoral perspective is shown in Figure 4.

4.2 | Primary energy demand

The development of the primary energy demand from 2020 to 2050 depends on several factors. First is the level of sector coupling between the power, heat and transport sectors, which depends on adoption of different technologies. Second is the rate of electrification in the heat and transport sectors, which depend on technology and powertrain assumptions, respectively. Last is the rate of adoption of e-fuels that are primarily based on electricity.[50,79,80] The development of primary energy demand across the three scenarios, from a sectoral as well as an energy carrier perspective, is shown in Figure 5. From a sectoral point of view, the primary energy demand for the transport sector grows across the three scenarios through the transition. This is largely driven by the increase in demand for transportation services, while powertrain changes and corresponding efficiencies lead to a decline in primary energy demand for road and rail transportation and increase in primary energy demand for marine and rail transportation. Conversely, primary energy demand for the heat and power sectors declines.

4.3 | Electricity generation and capacities

Increased levels of electrification lead to higher levels of electricity generation and corresponding generation capacities, which is highlighted in Figure 6. In the Laggard scenario, the installed capacities of renewables grow at a slower rate and generation of renewable electricity reaches over 11,500 TWh by 2050. In the Moderate scenario, a steady growth in renewable capacities delivers around 17,180 TWh of electricity by 2050. In the Leadership scenario, a rapid growth in capacities up to 2040 ensures 100% renewable electricity. Solar PV shares in electricity generation are 61% and 63% by 2050, whereas the share in primary energy supply reaches 54% and 56%, respectively. These scenarios represent the highest reported value for Europe and are a consequence of cost optimisation, latest solar PV cost assumptions[81] and consequent sector coupling in utilisation of

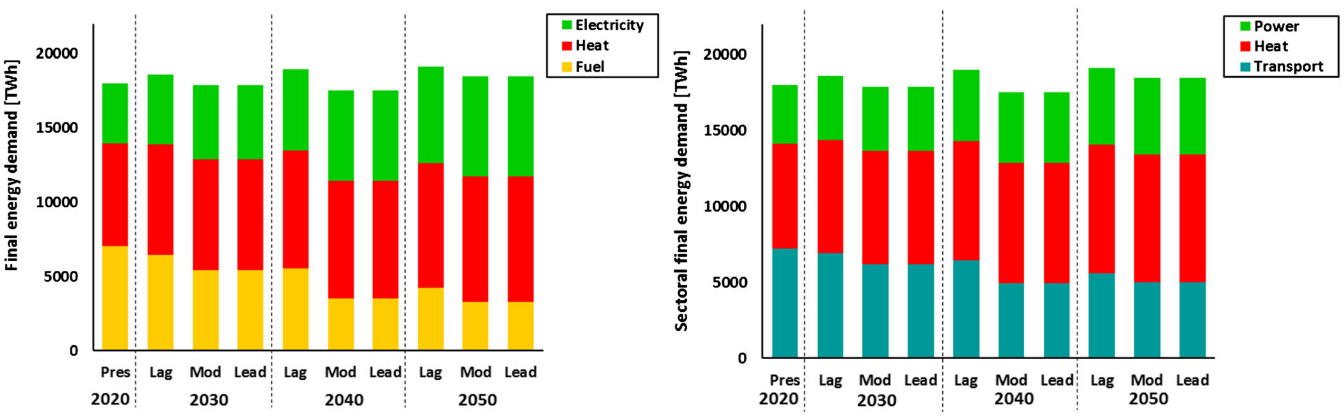

FIGURE 4 Final energy demand across the three scenarios according to energy carriers (left) and according to different sectors (right) from 2020 to 2050. [Colour figure can be viewed at wileyonlinelibrary.com]

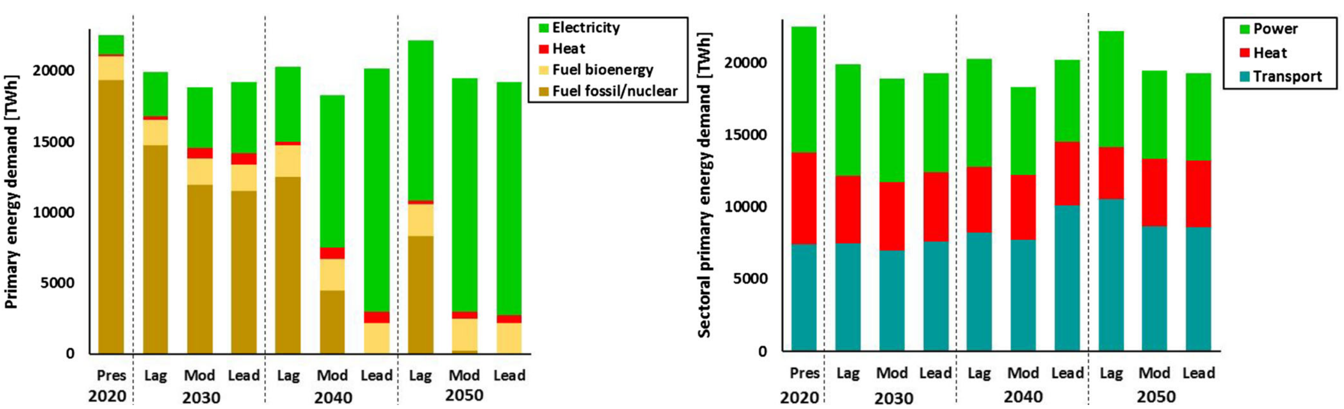

FIGURE 5 Primary energy demand according to energy carriers (left) and according to different sectors (right) across the three scenarios from 2020 to 2050. [Colour figure can be viewed at wileyonlinelibrary.com]

power-to-X technologies. In addition, the Laggard scenario with less ambition was investigated, with the findings indicating that the Moderate scenario is the least cost option for Europe (Figure 14).

4.4 | Regional distribution of installed capacities and generation in 2050

Electricity generation capacities are installed across Europe to satisfy the energy demand for power, heat and transport up to 2050. Solar PV capacities are predominantly in the southern regions of Europe that have better solar resources through the year, whereas wind power capacities are mainly in the northern and western regions of Europe that have much better wind conditions, as shown in Figure 7. Overall, solar PV and wind power capacities, along with some hydropower capacities, constitute the majority of installed capacity in 2050 across Europe in both the Moderate and Leadership scenarios. The only difference being the total capacities installed in the two scenarios, with close to 9950 GW installed in the Moderate scenario, whereas around 11,500 GW capacity is installed in the Leadership scenario. As the Leadership scenario is on a more progressive pathway, achieving 100% RE by 2040 leads to additional capacities that power the production of e-fuels that can be exported in 2050. The Leadership scenario has around 2500 TWh higher electricity generation due to the exported e-fuels in 2050.

Similarly, higher shares of solar PV generation are in the southern regions, and higher shares of wind power are in the northern and western regions as highlighted in Figure 8. The electricity generation supplying demand across the power, heat and transport sectors of Europe is predominantly from PV and wind power in both the Moderate and Leadership scenarios in 2050, as shown in Figure 8. Solar PV, which supplies an average of 61% in the Moderate scenario and 63% in the Leadership scenario, is more common in the southern regions of Europe. Wind power, which contributes an average of 33% in the Moderate and 33% in the Leadership scenario, is mainly found in the northern and western regions of Europe. Other regional insights on

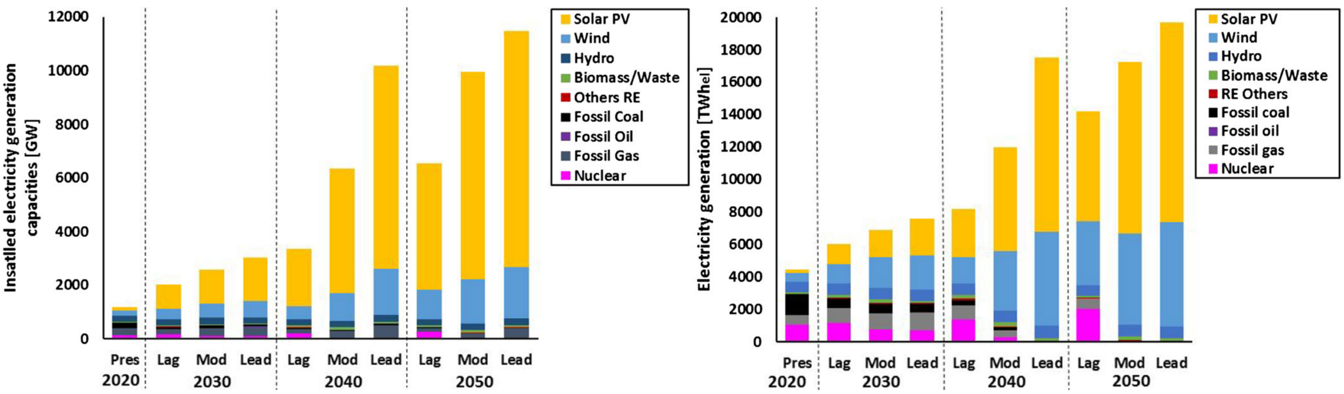

FIGURE 6 Installed electricity generation capacities (left) and electricity generation (right) from various energy sources across the three scenarios from 2020 to 2050. PV, photovoltaic; RE, renewable energy. [Colour figure can be viewed at wileyonlinelibrary.com]

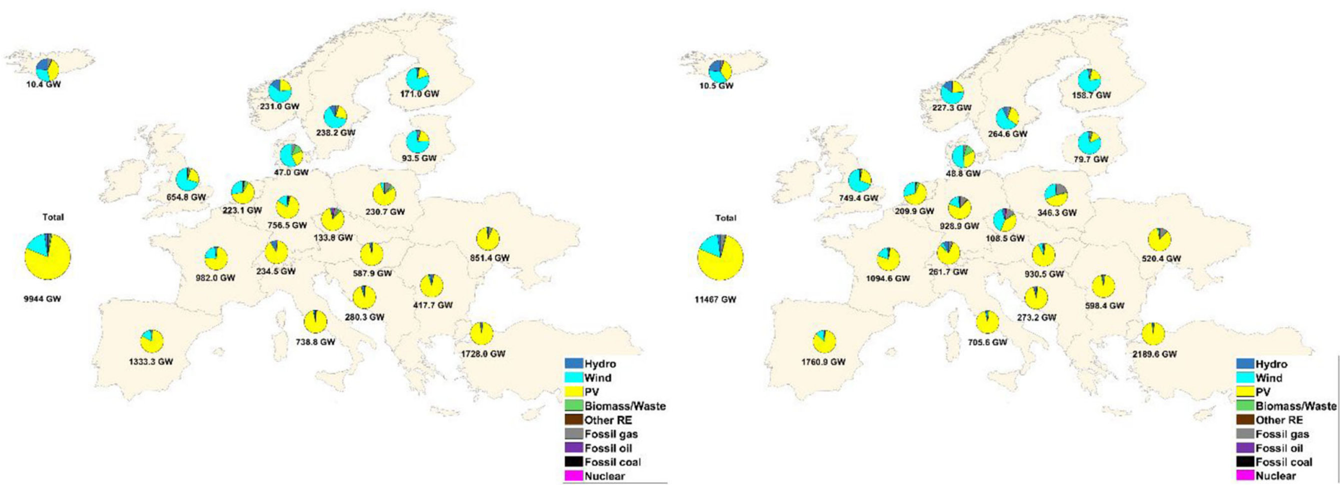

FIGURE 7 Regional electricity generation capacities in 2050 across Europe, in the Moderate (left) and Leadership (right) scenarios. PV, photovoltaic; RE, renewable energy. [Colour figure can be viewed at wileyonlinelibrary.com]

the distribution of storage and electricity exchange within Europe are highlighted in Supporting Information S1 (Section C4).

4.5 | Electricity storage and its share in demand

As the shares of solar PV and wind power increase significantly beyond 2030, the role of storage is crucial in providing uninterrupted energy supply across the three scenarios. The ratio of electricity demand covered by electricity storage increases through the transition to around 15% in the Laggard scenario, nearly 24% in the Moderate scenario and over 20% in the Leadership scenario by 2050, as highlighted in Figure 9. The Leadership scenario has a more rapid uptake of renewables and phase out of fossil fuel and nuclear power with a higher level of sector coupling by 2040, which indicates the need for lesser electricity storage. In the three scenarios, utility-scale and prosumer batteries contribute a major share of the electricity storage output with over 95% of electricity storage by 2050, whereas pumped hydro energy storage (PHES) contributes through the transition with minor shares. Demand response and sector coupling are the most important elements to limit storage demand. The assumed demand response options in the applied scenarios are from heat pumps and thermal energy storage on a district heat level along with electrolysers and hydrogen buffer storage that decouple VRE generation and the near baseload synthesis demand. Smart electric vehicle charging and vehicle-to-grid are not applied in this study, which have the potential to further reduce the storage demand.

4.6 | Heat supply

Across the three scenarios, heat pumps with electric heating form the majority of heat generating capacities by 2050, a steady share of bioenergy capacities contributes heat. Fossil fuels-based heat declines

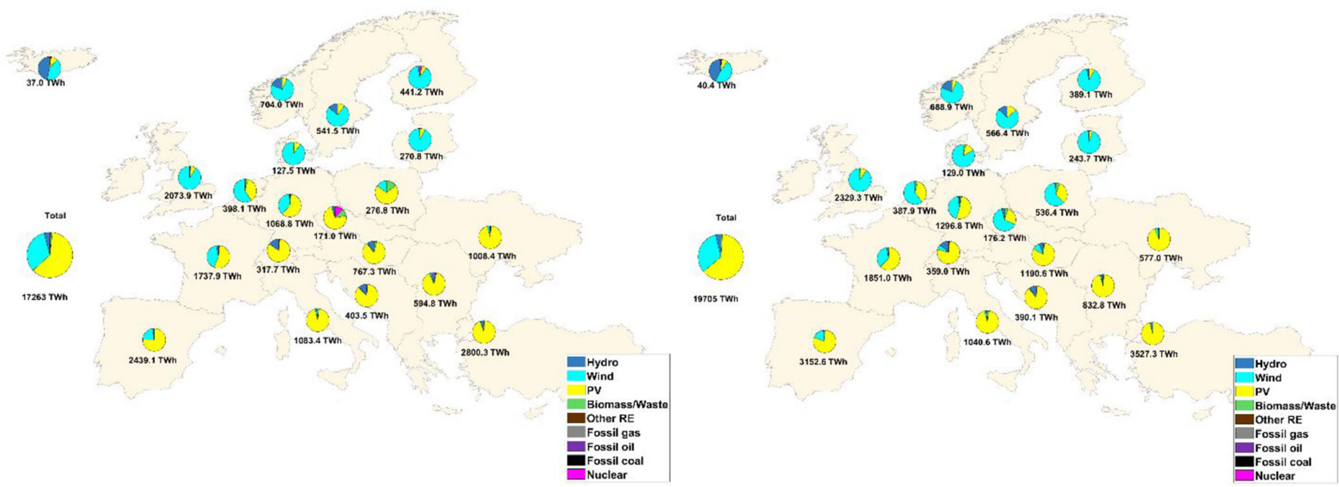

FIGURE 8 Regional electricity generation in 2050 across Europe, in the Moderate (left) and Leadership (right) scenarios. PV, photovoltaic; RE, renewable energy. [Colour figure can be viewed at wileyonlinelibrary.com]

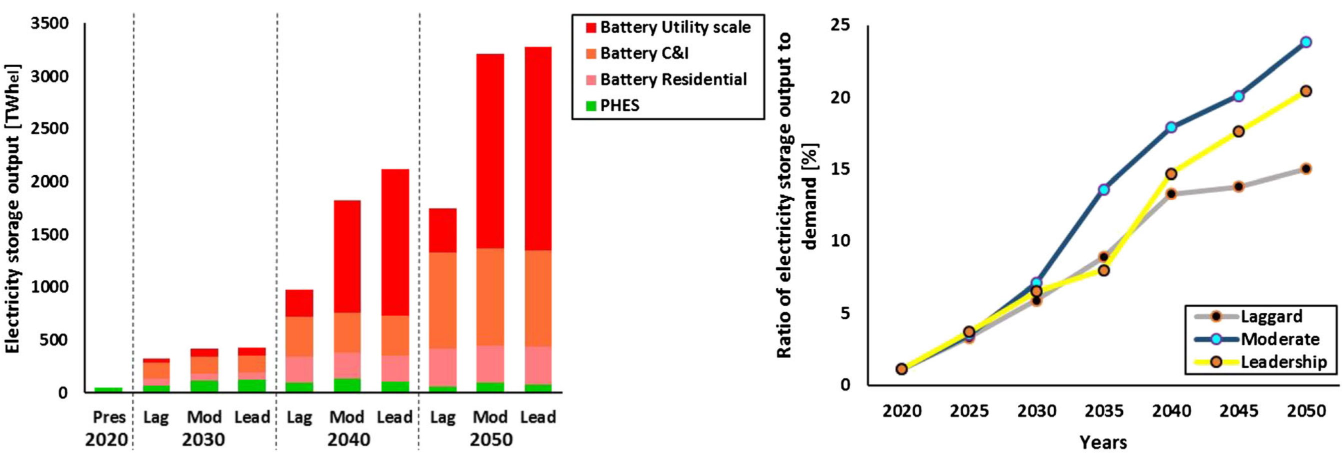

FIGURE 9 Electricity storage output (left) and ratio of electricity storage to demand (right) across the three scenarios from 2020 to 2050. C&I, commercial and industrial; PHES, pumped hydro energy storage. [Colour figure can be viewed at wileyonlinelibrary.com]

across the three scenarios, with zero share in the Leadership scenario by 2040, zero share in the Moderate scenario by 2050 and some minor shares for industrial process heat in the Laggard scenario by 2050. Renewable electricity-based e-hydrogen and e-methane contribute towards industrial process heat in the latter stages of the transition across all three scenarios (see Figure 10). These results indicate that the heating sector is poised for higher shares of heat pumps and electric heating along with some e-fuels by 2050.

4.7 | Transport demand and fuels

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. Road transport has a high level of direct electrification in the Leadership and Moderate scenarios, whereas slightly lower levels in the Laggard 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, as additional electricity is required to produce e-fuels.

The changing energy mix in the energy carrier demand in the transport sector across the three scenarios through the transition is highlighted in Figure 11. In the Leadership scenario, renewables-based electricity, e-hydrogen and electricity-based Fischer-Tropsch liquid (e-FTL) fuels provide the majority of the energy by 2040, with minor shares of renewables-based methane, composed by biomethane and e-methane, and biofuels. The Moderate scenario is quite close to the Leadership scenario by 2050, but substantial differences around 2040. In the Laggard scenario, renewables-based electricity, hydrogen, methane, e-FTL fuels and biofuels with some shares of fossil fuels meet the final energy demand by 2050. Fossil fuel consumption in the transport sector across the three scenarios declines through the transition from about 95% in 2020 to zero by 2040 in the Leadership scenario, zero by 2050 in the Moderate scenario and about 26% in the Laggard scenario.

4.8 | Electrification of energy system

Electrification 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. Direct substitution involves the phase-in of electric vehicles in the transport sector and the adoption of electric heating systems like heat pumps in buildings and some

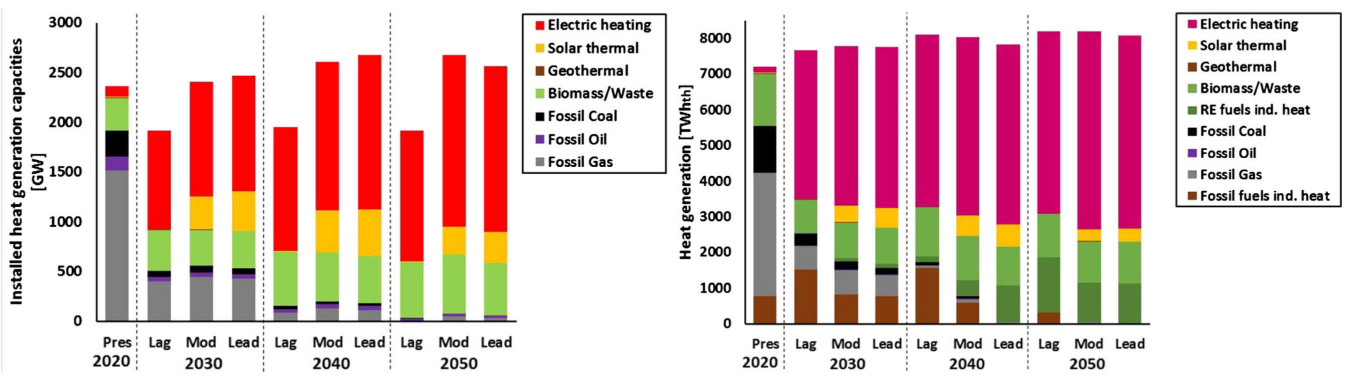

FIGURE 10 Installed heat generation capacities (left) and heat generation (right) from various heat sources across the three scenarios from 2020 to 2050. [Colour figure can be viewed at wileyonlinelibrary.com]

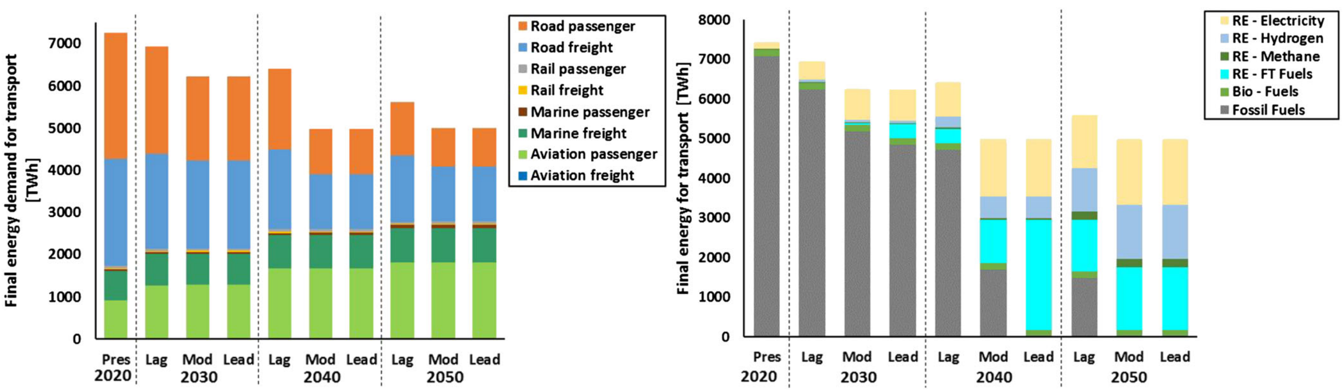

FIGURE 11 Final energy demand for transport modes (left) and energy sources for the transport demand (right) across the three scenarios from 2020 to 2050. FT, Fischer-Tropsch; RE, renewable energy. [Colour figure can be viewed at wileyonlinelibrary.com]

parts of the industry. On the other hand, indirect substitution involves a switch to e-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. The different rates of electrification and corresponding renewable electricity generation across the three scenarios are highlighted in Figure 12.

The current level of electrification across the power, heat and transport sectors in Europe is just about 6%. In the Leadership scenario, rapid electrification leads to 85% by 2040 with 100% electricity from renewables. In the Moderate scenario, a steady increase in electrification occurs up to 85% by 2050 with nearly 100% of the electricity from renewables. In the Laggard scenario, lower levels of electrification lead to about 51% by 2050 with 62% of the electricity coming from renewables and 38% from nuclear and fossil fuels. The drive towards electrification enhances sector coupling, as low-cost renewable electricity emerges as the prime energy carrier in future energy systems.

4.9 | Electricity for heat and transport

Electricity usage in both the heat and transport sectors increases through the transition across the three scenarios, as shown in Figure 13. In the Leadership and Moderate scenarios, e-hydrogen kicks in for heat in 2040, and e-methane delivers some shares of heat in 2050. In the Laggard scenario, renewable electricity and e-hydrogen deliver most of the heat through the transition; however, some fossil fuel-based heat is still in use as shown in Figure 11.

In the transport sector, renewable electricity drives the electrification in the initial periods of the transition, after which e-hydrogen and e-FTL fuels provide the majority of the energy across the three scenarios, as shown in Figure 13. The electricity for transport rises rapidly in the Leadership scenario, more steadily in the Moderate scenario and at slower pace in the Laggard scenario. For transport modes that cannot be directly electrified, e-FTL fuels play an important role in providing a vital source of energy and further enable integration of the power and transport sectors.

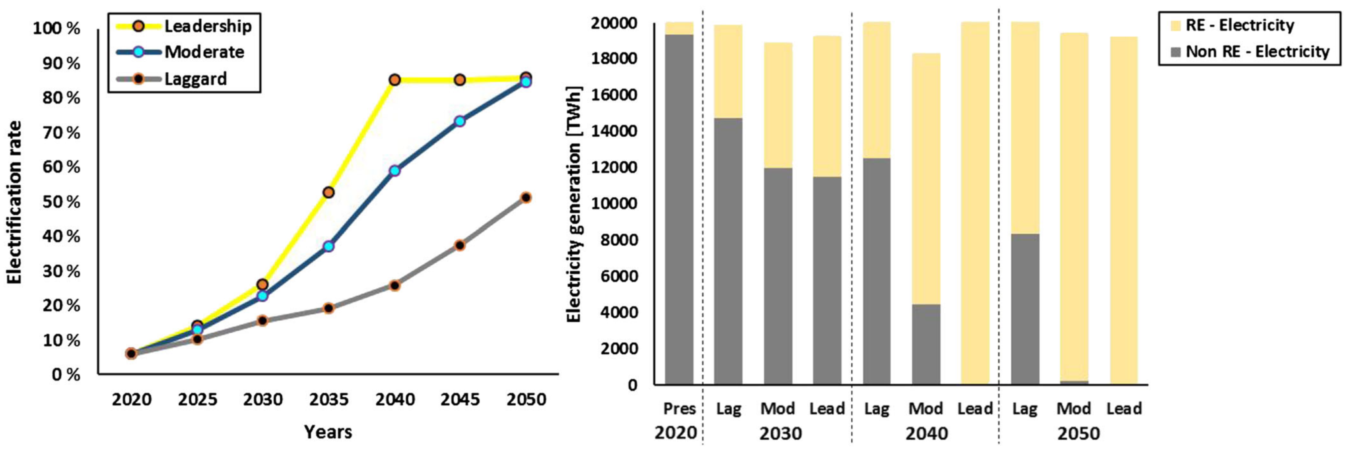

FIGURE 12 Rate of electrification (left) and electricity generation (right) across the three scenarios from 2020 to 2050. RE, renewable energy. [Colour figure can be viewed at wileyonlinelibrary.com]

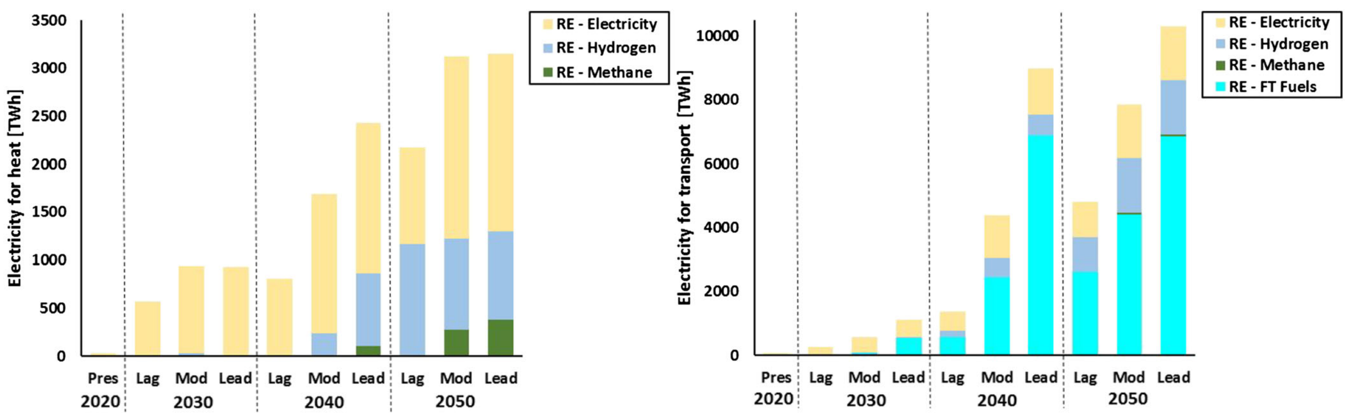

FIGURE 13 Electricity for heat (left) and electricity for transport (right) across the three scenarios from 2020 to 2050. RE, renewable energy. [Colour figure can be viewed at wileyonlinelibrary.com]

4.10 | Energy costs

The levelised cost of energy, defined as the total annualised energy system cost divided by the total final energy demand, declines across the three scenarios through the transition up to 2050, after an initial increase, as shown in Figure 14. The total system-wide levelised cost of energy is the lowest in the Moderate scenario by 2050 at 47.0 €/MWh, followed by the Leadership scenario with a slightly higher levelised cost of energy of 47.5 €/MWh. In the Laggard scenario, comparatively, the levelised cost of energy is higher at 49.9 €/MWh in 2050. This corroborates the claim that an accelerated energy transition towards 100% RE is an economically attractive proposition. In addition, levelised cost of energy is increasingly dominated by capital costs as input fuel costs lose importance through the transition period, which could mean increased levels of energy security across Europe by 2050.

The levelised cost of electricity (LCOE) of the power sector decreases substantially across the three scenarios through the transition until 2050, as shown in Figure 14. In the Laggard scenario, the LCOE declines from around 71 €/MWh in 2020 to around 48 €/MWh by 2050; in the Moderate scenario, the LCOE declines to nearly 39.1 €/MWh; and in the Leadership scenario, it declines to about 39.4 €/MWh. The share of fuel costs declines through the transition, as the shift towards electrification results in capital expenditure driven energy system costs.

4.11 | Greenhouse gas emissions

The results of the energy transition indicate a sharp decline in GHG emissions until 2050, across the power, heat and transport sectors for the three scenarios as shown in Figure 15. The GHG emissions across Europe are over 4500 $MtCO_{2eq}$ in 2020; it undergoes a rapid decline to zero by 2040 in the Leadership scenario and a steady decline to zero by 2050 in the Moderate scenario. Whereas, in the Laggard scenario, GHG emissions decline to around 800 $MtCO_{2eq}$ by 2050. Moreover, the remaining cumulative GHG emissions comprise of around 53 $GtCO_{2eq}$ in the Leadership scenario, about 64 $GtCO_{2eq}$ in the Moderate scenario and around 89 $GtCO_{2eq}$ in the Laggard scenario, from 2020 to 2050 as shown in Figure 15. The additional cumulative GHG emissions resulting from the Laggard scenario in comparison to the Leadership scenario are around 36 $GtCO_{2eq}$ by 2050.

Higher CO_2 pricing leads in several segments of the energy system to a phase-out of fossil fuel usage at a faster rate, whereas hard-to-abate segments, for example, marine, aviation and industrial applications, may be better directly regulated for having the right solutions at scale when required, or to avoid stranded assets and continued investments in fossil applications, such as for space heating.

This study shows for the first time a fully sector coupled energy system transition for entire Europe including Ukraine and Turkey leading to zero CO_2 emissions by 2040 (Figure 15) without shrinking final energy demand. Scenarios for Europe with zero CO_2 emissions target by 2040 are rarely known (Table 1) and differ in pathway emissions. The total energy supply is dominantly based on electricity, utilising various power-to-X options and sector coupling (Figures 2 and 16–18), enabling cost-effective solutions (Figure 14). It is the first known scenario with PV contributing more than 50% of total electricity supply (Figures 6 and 17), as benchmarked to known scientific papers on energy systems for Europe with high shares of RE. Europe is described in 20 regions and hourly resolution. It is the only known study describing a pathway for 100% RE in Europe for the entire energy system in multi-node and hourly resolution, independently optimising PV rooftop and utility-scale, with breakdowns in rooftop residential, commercial and industrial and fixed-tilted and single-axis tracking utility-scale plants.

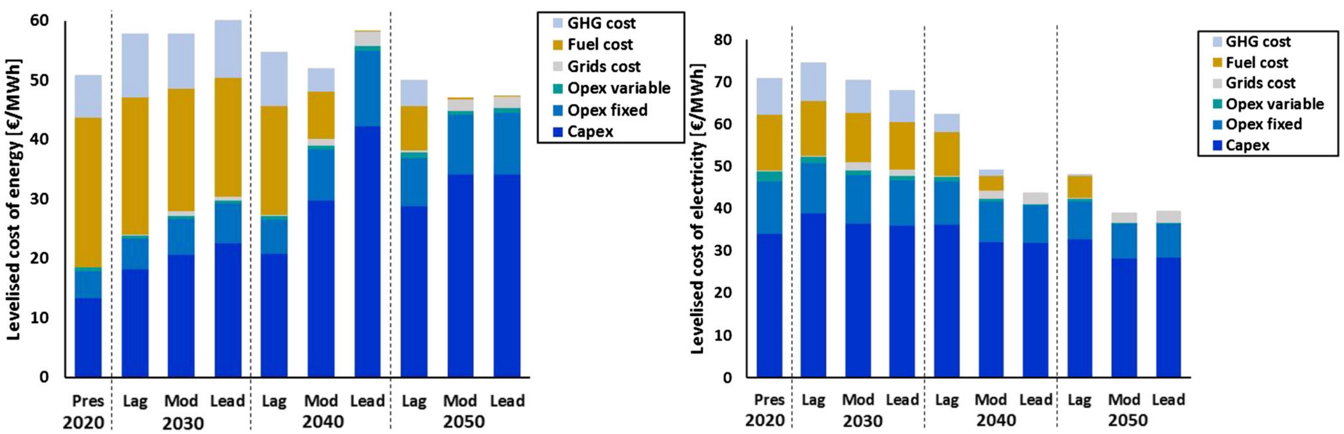

FIGURE 14 Different aspects of the levelised cost of energy (left) and the levelised cost of electricity (right) across the three scenarios from 2020 to 2050. Levelised cost of energy is defined by total annualised system cost divided by all final energy demand. [Colour figure can be viewed at wileyonlinelibrary.com]

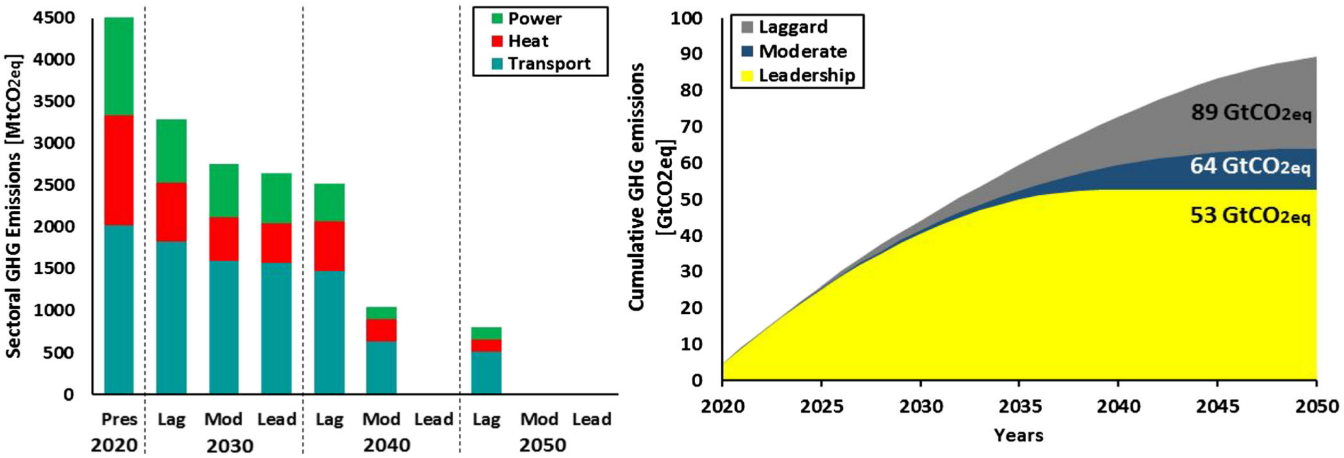

FIGURE 15 Sectoral annual greenhouse gas emissions (left) and cumulative greenhouse gas emissions (right) across the three scenarios from 2020 to 2050. [Colour figure can be viewed at wileyonlinelibrary.com]

5 | DISCUSSION

5.1 | Hourly operation and seasonal balancing

It is regularly questioned whether an energy system largely based on solar and wind resources would be stable on both the hourly and seasonal scales, and if stable, then with considerable extra costs or with overcapacities leading to high curtailment.[82–84] These are regularly responded with the fact that 100% RE systems can operate with higher stability and flexibility with stable costs and minimal curtailment.[2,85] In the following, it is discussed how a 100% RE system would be operated from an hourly and seasonal perspective. For this discussion, the hourly operation is depicted in Figure 16 for the integrated European energy system in the Moderate scenario in 2050, during the week of highest RE generation in spring and the week of least RE generation in winter for the whole of Europe.

There is substantially more electricity generation in the range of 4750–6000 GW during the spring week, in comparison to the winter week wherein the electricity generation is in the range of 3000–3500 GW. Solar PV is the dominant energy generation source in the spring week, whereas in the winter week, there is more wind power and hydropower generation. There is much more power-to-fuels in the spring week and more power-to-heat in the winter week. Battery charging and discharging are prominent in both the weeks, while there is some excess electricity in the spring week. The curtailment found for the Moderate scenario is 4.5% of the total VRE generation potential.

On regional level, grid integration plays a key role to balance supply and demand during low RE supply periods. One can see how balancing regions like France can import electricity during some hours and export electricity later on the same day. During the RE supply deficit, the system also maximises the use of storage and grids (see Figure 16): It is possible to see that batteries are charged with imported electricity in Germany and France during some hours (e.g. hours 8500–8510) to be used during demand peak within the region, or as in case of France to be exported later (e.g. hours 8510–8520). Grids for regional balancing, battery storage for temporal balancing and power-to-X technologies for demand balancing provide the necessary flexibility to the energy system, while the role of flexible generation like biomass power plants or hydropower dams is very low.

On the case of Germany, a more detailed investigation on longer periods of 'dark lulls' was carried out. The 8760 h of the 100% RE case in the year 2050 was analysed not only for the total number of hours below a certain threshold of the maximum generation within the year but also for the total hours in a row below that threshold for solar PV, for wind power and both in the same hour. The findings are summarised in Table 2. The results are quite remarkable, as no longer periods in a row of 'dark lulls' could be found at all, independently of the season. The threshold values are 1%, 5%, 10%, 20%, 30%, 40% and 50% of the maximum generation of the best hour of the year. There are periods of up to 5 days of wind power below 20% of the maximum annual generation, but this happens in periods of good solar PV availability, as for the 20% threshold for wind power and solar PV in the same hours, the longest period is 17 h, which is a typical winter afternoon to next morning period. The high capacities of solar PV and wind power always enable the direct inelastic electricity demand utilising battery storage and grid exchange, whereas the flexible demand of power-to-X technologies is lowest during such periods. Böttger *et al.*[86] found that longer periods of 'dark lulls' cannot be detected for critical system constellations investigating the years 2006 to 2021 on the case of Germany, which leads to their conclusion that the public debate on 'dark lulls' may be exaggerated.

For entire Europe, modelled in 20 interconnected regions whereof Germany is one, the same analysis was repeated. Not a single hour was detected in which both wind power and solar PV would be below 10% of the maximum generation in the year. Below 20% of the maximum annual generation, there is one period up to 40 h in a row and only 216 h in total, while both generators together are only limited for 9 h in a row and 83 h in total for that limit. This is an

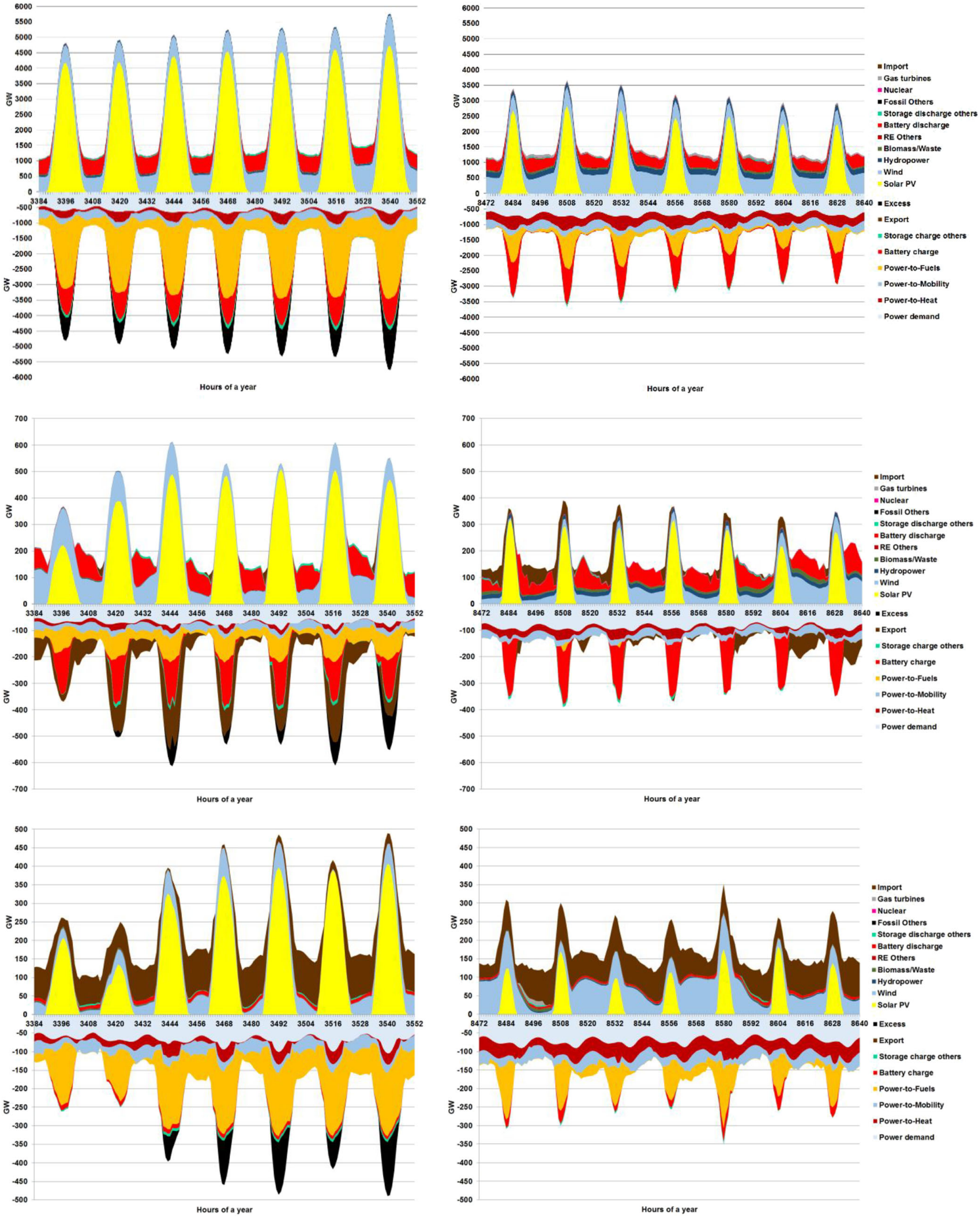

FIGURE 16 Hourly operation of the European energy system (top), France (centre), and Germany (bottom) in the Moderate scenario in 2050 for the spring week (left) of best resource availability and the winter week (right) with the least resources. Supply (generation and storage discharge) is on the positive axis, and demand (including storage charge) on the negative. PV, photovoltaic; RE, renewable energy. [Colour figure can be viewed at wileyonlinelibrary.com]

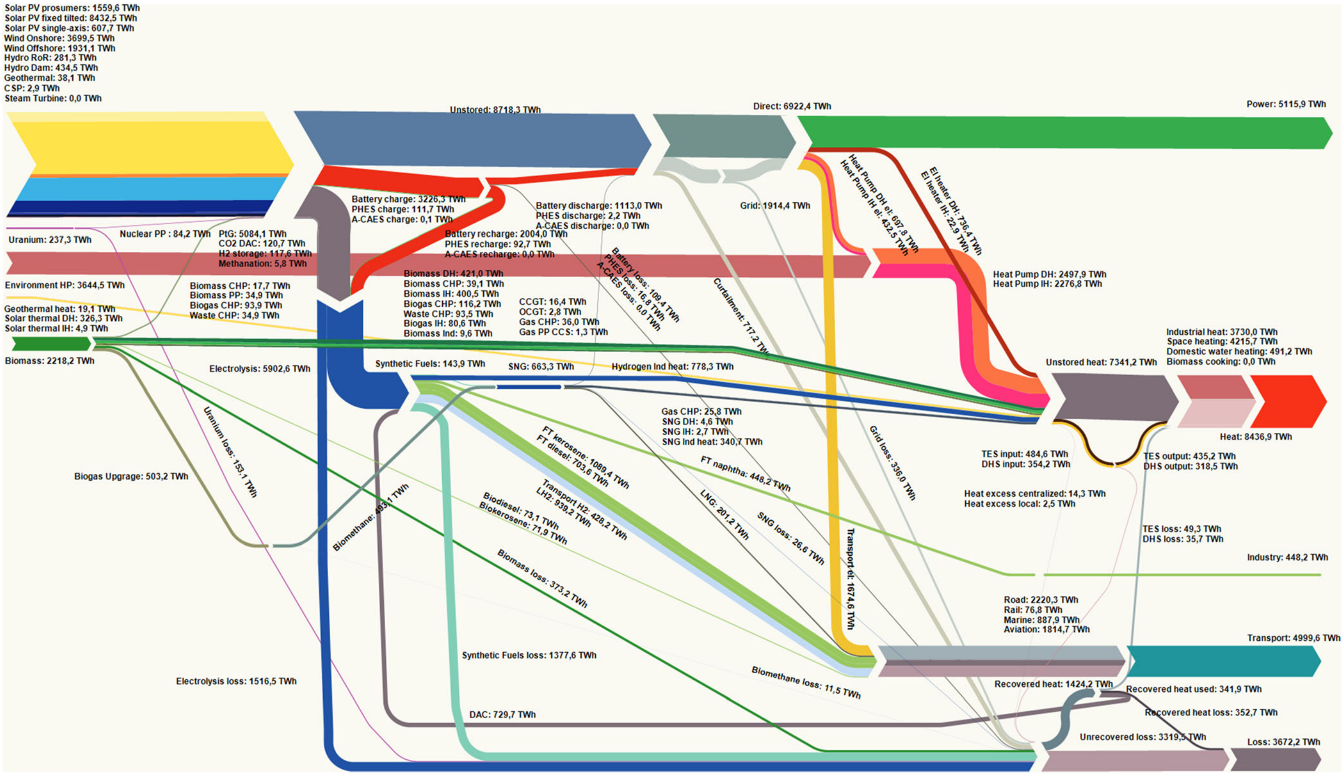

FIGURE 17 Energy flows for the European energy system in the Moderate scenario in 2050. CCGT, combined cycle gas turbine; DAC, direct air capture; DH, district heating; DHS, district heating system; HP, heat pump; IH, individual heating; OCGT, open-cycle gas turbine; PHES, pumped hydro energy storage; PV, photovoltaic; SNG, synthetic natural gas (e-methane). [Colour figure can be viewed at wileyonlinelibrary.com]

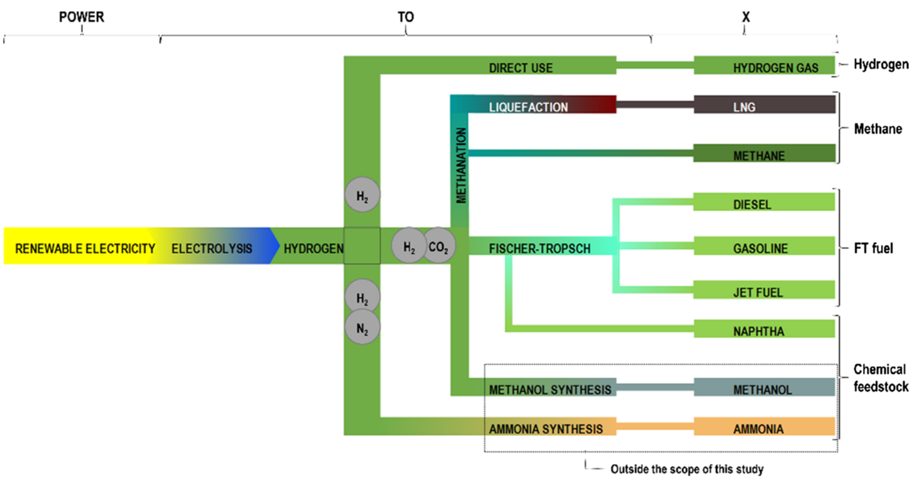

FIGURE 18 Electrons-to-molecules as a centrepiece of sector coupling. All major routes start with hydrogen. [Colour figure can be viewed at wileyonlinelibrary.com]

enormous improvement to the higher limitation for Germany. The combination of solar PV and wind power for entire Europe in an inter-connected and sector-coupled energy system is the best mitigation for managing ‘dark lulls’.

The used weather year for this research is 2005, and for more general conclusions for single regions and Europe as a whole, longer periods of weather years have to be investigated for a fully sector-coupled energy system, not only on inter-annual variation but also for inter-annual storage requirements, which was beyond of the scope of this study.

The most characteristic elements of the energy system in Figure 16 are the generators solar PV and wind power, battery storage and electric vehicles, electrolysers for e-fuel production and heat pumps as the main part of power-to-heat. Every core component of this energy system has a substantial contribution for the high overall efficiency and low-cost of the European energy system: Solar PV and wind power provide least cost electricity in scalable volumes, batteries enable the diurnal balancing of the solar resource and support wind power balancing, and electrolysers indirectly balance the power sector and finally convert electrons of renewable electricity into hydrogen

TABLE 2 Hours of wind power, solar PV and both technologies at the same time below a threshold capacity as percentage of the annual maximum capacity of the respective generator in a row, and hours in total fulfilling that criterion, on the case of Germany (left) and entire Europe (right). The case on entire Europe indicates the value of grids for interconnected regions.

	Germany						Europe					
	Wind power		Solar PV		Wind power and solar PV		Wind power		Solar PV		Wind power and solar PV	
Threshold	In a row	In total	In a row	In total	In a row	In total	In a row	In total	In a row	In total	In a row	In total
1%	7	32	15	4355	4	13	0	0	11	3318	0	0
5%	37	699	16	4563	15	295	0	0	12	3654	0	0
10%	68	1473	17	4712	15	653	0	0	13	3870	0	0
20%	116	2765	17	4890	17	1425	40	216	14	4173	9	83
30%	156	3809	18	5054	17	2063	107	1258	15	4410	11	582
40%	246	4773	19	5228	18	2761	277	3300	16	4631	16	1617
50%	386	5584	41	5381	19	3330	1002	4962	16	4810	16	2538

Abbreviation: PV, photovoltaic.

whenever electricity of PV and wind power is not directly needed. Meanwhile, electric vehicles use low-cost electricity, and heat pumps convert low-cost electricity in heat and provide some flexibility in combination with thermal energy storage. Battery-electric vehicles can further contribute to an optimised energy system operation via smart charging and vehicle-to-grid applications,[87–90] while this was not considered in this study. The very high overall system flexibility is provided by electrolysers for the power-to-hydrogen conversion, which finally converts VRE to hydrogen buffered in underground hydrogen storage. This in turn enables the near baseload operation of synthesis units for e-fuel production and smaller shares of seasonal storage. The dominant seasonal balancing is contributed by the hydrogen buffer storage for hydrogen-to-X conversion routes and hydrogen usage as final energy, but only in minor shares for reconversion into electricity, as only 0.8% of final energy demand is covered by seasonal storage, but thereof almost all is contributed by seasonal biomethane storage.

Ramping rates for different energy system components can be very high, in particular for solar PV, as shown in Figure 16. The key enabling technologies to manage the high ramping rates are batteries and electrolysers that can adapt very fast to changing system conditions, including frequency containment regulation[91–93] and system inertia.[2,94,95] In addition, smart charging and vehicle-to-grid applications can further contribute to manage high gradients in electricity generation.

5.2 | Characteristics of a Power-to-X Economy

The energy flows of the Moderate scenario in 2050 are shown in Figure 17. The final energy demand is comprised of the power sector, heat demand for space heating, domestic hot water and industrial process heat and transportation services. The primary energy demand is comprised by renewable electricity from solar PV, wind power and hydropower and some bioenergy. Environmental heat extracted from heat pumps is in most definitions of primary energy not accounted. Renewable electricity contributes 86% of primary energy, 37% of final energy and 3.3 times more renewable electricity is generated as demanded in the power sector.

The central element is power-to-X in this future energy system. Electricity is used for heat supply,[49,51] in heat pumps and direct power-to-heat conversion in electric boilers, for mobility in battery-electric road vehicles, trains, ferries and first short-haul flights[96,97] and for e-fuels[50,98] and e-chemicals,[50,79,99–101] in e-hydrogen,[102,103] e-methane/LNG[104,105] and e-liquids.[80,106] Similar usage would be electricity-based seawater reverse osmosis desalination,[107] which is not required in Europe. The most important energy carrier is electricity from renewable sources, and the second most important energy carrier is hydrogen, but less for final energy supply, and mainly for conversion in e-fuels and e-chemicals, which are needed for long-distance marine and aviation transportation and chemicals. High-temperature industrial process heat may be largely provided by direct electricity use,[49] but also some fuel combustion, in future mainly e-hydrogen or renewable methane. Seasonal electricity storage is required in the amount of 56.5 TWh, entirely provided by bio-methane, which represents 0.8% of the direct electricity demand. This further emphasises the high flexibility and efficiency of this power-to-X economy because battery storage and electrolyser operation effectively balance the VRE generation.

Hydrogen has a most important function to buffer the VRE generation in an effective way for near baseload synthesis to e-fuels and e-chemicals. About 36% of the total hydrogen production is used as final energy, thereof 7% for road transportation, which may be taken over by battery-electric vehicles due to higher efficiency and lower cost, and about 6% for marine transportation, which may be easier to be realised by e-ammonia and e-methanol.[108–110] Thus, less than a quarter of the hydrogen production may be finally used directly, and more than three quarters further converted in hydrogen-based final energy carriers such as e-ammonia, e-methanol, e-liquids and e-methane.

The term hydrogen economy is widely used[111–115] and was introduced independently by Bockris[116] and Justi[117] tracing back to fundamental insights on hydrogen transport in the 1930s.[111,117] Additional framing of the hydrogen economy in the 2000s[118–120] focussed on the end-use applicability of hydrogen as a fuel, especially as a replacement for fossil fuels in the transport sector, suggesting that the fuel cell would be the energy converting technology to catalyse the widespread use of hydrogen. Synthetic fuel production through the Fischer-Tropsch process had been mentioned in the framing of the hydrogen economy[121,122]; however, the assumption was that either fossil methane or coal would be inputs rather than green e-hydrogen and sustainable or air-captured CO_2, which is a more recent view.[73,80,106,123,124] Abe *et al.*[125] define hydrogen economy for an energy system characteristic of having hydrogen as the principal energy carrier; however, as shown in Figure 17, hydrogen is very important for this energy system, but not the principal energy carrier nor the characteristic. The core characteristic of this energy system is primary energy supplied dominantly by renewable electricity from solar PV and wind power, high direct electrification of multiple end-use segments and indirect electricity use via power-to-hydrogen-to-X processes, using hydrogen as an energy carrier to enable the electron-to-molecule conversion for the end-use energy carriers, as visualised in Figure 18. Interestingly, this is analogous to the primary uses of hydrogen today, especially in the chemical industry, where fossil feedstocks are reduced to a synthetic gas that is a mixture of CO and H_2 and then converted to high value chemicals such as methanol. These fossil-to-X routes fundamentally use hydrogen as an intermediate energy carrier to produce end-use energy carriers.[126,127] The power-to-X concept expands on this model to all energy sectors, with renewable electricity being the key input.

The concept of the hydrogen economy typically follows the assumption of substituting fossil fuels in applications with hydrogen solutions, essentially transitioning from a 'hydrocarbon society' to a 'hydrogen society',[120] while usually ignoring the energy system impact of low-cost batteries and high efficiency applications of direct electricity solutions. This largely substitutes not only hydrogen solutions for road transportation, which had been suggested in Bell and Weitschel,[121] but also heat applications and due to efficient sector coupling, the need for seasonal power storage is around 1.0% of electricity demand, thus of limited relevance. The historic roots of the hydrogen economy are nuclear power,[116] solar PV[117] and wind power,[128,129] while the idea of a fossil energy-based hydrogen economy has been popular during the 2000s,[122,130–134] 2010s[129] and still in 2020s.[112,135,136] Whereas Bockris clearly pointed out in 1999[137] that nuclear power is too costly for hydrogen supply and finally solar PV will emerge as the core electricity source for hydrogen, with increased level of confidence due to the cost progress of PV.[137,138] The steep cost decline of solar PV and electrolysers leads to least cost hydrogen production costs for the PV route in the 2020s.[139] The impact of projected low-cost PV led to the early conclusion of an arising solar-hydrogen energy system already in 1999,[137] confirmed by Kleijn and van der Voet[140] and with more wind power by Jacobson and Delucchi,[141] which would be in a more recent interpretation a solar PV-battery-electrolyser-DAC energy system.[5,142] The challenges of hydrogen handling further developed the concept of a hydrogen economy to a methanol economy, as supported by Bockris[111,138] and Olah *et al.*,[143] an ammonia economy, as supported by Lan *et al.*,[144] or a hydrogen economy significantly dependent on liquid organic hydrogen carriers.[145] More discussion is required for the defossilisation of industry within a hydrogen-to-X perspective,[112,146] in particular for chemicals[99–101] and steelmaking,[147–149] which needs to be integrated into a more holistic power-to-X economy approach.

The presented insights of this section also reflecting the historic development of the term hydrogen economy indicate that the term power-to-X economy covers more facets of the identified energy system. Direct electric solutions are typically more efficient and lower in cost than hydrogen-based solutions, shrinking the demand for hydrogen as energy carrier, and the challenges of hydrogen as final energy carrier leads to hydrogen-to-X routes, which in particular limits the role of hydrogen for final energy demand. Boretti[150] shares a similar view in pointing out that a hydrogen economy is complementary and synergetic to an electric economy. Furthermore, given the wide range of alternatives for electrification and limited areas for direct use of hydrogen, Ball and Weeda[151] claim that the term 'hydrogen economy' may be misleading. Similarly, Andrews and Shabani[152] suggest that the time for an exclusive hydrogen economy has passed and hydrogen would serve a more complementary role to the use of electricity as the major energy vector. Because Figure 17 documents a much higher relevance of electricity as energy carrier and hydrogen rather as an intermediate energy carrier for hydrogen-based final energy carriers, the term power-to-X economy seems to be more appropriate. On a global scale, the role of solar PV is even more prominent as for the case of Europe (see Section 5.4) so that the term solar-to-X economy may characterise the energy system more concretely, especially across the sunbelt.

5.3 | Results in comparison to literature for Europe

The central results of the Moderate and Leadership scenarios are pathways towards 100% RE in Europe by 2050 and 2040 based on the core technologies solar PV, wind power, batteries, electrolysers and heat pumps for comprehensive direct and indirect electrification of a power-to-X economy. The share of VRE reaches 94%–95% in electricity and 83%–84% in TPED supply. The share of solar PV reaches 61%–63% in electricity generation and 54%–56% in TPED being equivalent to 7740–8820 GW installed PV capacity and 10,600–12,345 TWh of generated PV electricity, thereof about 12.6%–14.7% by PV prosumers. The regional scope of these results includes entire Europe including Ukraine and Turkey with projected 666 million people by 2050.

5.3.1 | Scientific studies published in journals

The absolute numbers for PV capacity and generation cannot be well compared to existing literature due to a different number of included countries, and partly due to the included energy sectors and level of direct and indirect electrification. However, several studies reach VRE shares in electricity supply higher than 80% (see Table 1, Figure 2), which is close to results in this research. The VRE share in TPED is available only for two other studies that reach 65%[65] and 75%,[63] and these studies reach 28%–31% PV share in TPED, substantially below the findings of this research. The PV share in electricity supply shows substantial differences, as explicitly disclosed numbers in other studies not using LUT-ESTM reach consistently values below 40%, whereas previous LUT-ESTM studies considering the power sector reach about 41% for well-balanced power sector studies. The PV share in electricity supply of Victoria *et al.*[61] find 56%, which is close to the results of this research.

One of the reasons for the different PV shares across studies is largely driven by capex assumptions for PV and its most important supporting technologies batteries and electrolysers. In addition, factors such as the extent of sector coupling, the level of PV prosumers, consideration of diversified PV system technologies in particular single-axis tracking PV and whether rooftop and ground-mounted PV systems are individually optimised within energy system models have a bearing on the final energy mix. Most studies assume higher PV capex but comparable wind power capex as this study, which consequently leads to lower PV and higher wind power shares. Important for PV are low-capex batteries for diurnal balancing, thus a higher cost assumption for batteries is another impacting factor for deviating shares. A very strong factor for differences is cost assumptions for electrolysers, as low-capex electrolysers show the characteristic of least hydrogen production cost for very low input electricity cost, whereas the utilisation of electrolysers can be lower, because somewhat higher specific electrolyser cost due to lower utilisation is overcompensated by lower electricity input cost. Interestingly, the PV share of 56% in electricity generation in Victoria *et al.*[61] is very close to this research, which seems to be a consequence of the similar fundamental capex assumptions for rooftop and ground-mounted PV, prosumer and utility-scale batteries and electrolysers. The remaining differences in the PV share of this research and Victoria *et al.*[61] may be driven by the decoupled ratio of PV prosumers and utility-scale PV in this research. In this research, the PV prosumers are closely linked to the actual power sector demand, and PV power plants are scalable to deliver low-cost electricity for power-to-X applications in particular e-fuel production, whereas the ratio of PV prosumers and utility-scale PV is fixed to 50% each in Victoria *et al.*[61] In addition, this research enabled single-axis tracking PV,[153] which leads to higher specific yield of PV power plants due to the tracking and slightly lower LCOE of these PV plants, both are most attractive for power-to-X applications, especially for e-hydrogen production as electrolysers can produce hydrogen for lower cost if the input electricity is lower in LCOE and higher utilisation of the electrolysers is enabled. It is also observed that less battery capacity is required for diurnal balancing due to improved PV generation profiles due to tracking.[153]

The absolute findings for PV capacity and generation are not comparable to other studies in literature due to different regional scopes and included countries, different final energy demand requirements and import and export relations. Interestingly, this research aims for full self-sufficient energy supply in Europe for high standards of energy security. This automatically leads to a higher electricity generation in Europe as e-fuels have to be produced in Europe. Thus, substantial shares of e-fuel and e-chemical imports automatically reduce the electricity generation in Europe. Another effect had been very strong in the Leadership scenario, which is the speed of transition and required fuels for stock-driven fuel demand. Delays in transitioning of road vehicles lead to a longer lock-in of liquid fuel requirements for the transport sector, which can lead to substantial electricity demand for e-liquids of not yet decommissioned road vehicles, as long as stranded assets for those vehicles shall be avoided. In addition, aviation fuel transition to e-hydrogen instead of e-kerosene jet fuel may lead to not fully required synthesis units for e-liquid synthesis. This partial mismatch of demand for e-fuels due to lock-in effects of stocks leads to about 450 TWh_{th} of not directly needed e-fuels and respective production capacities in the PtX value chain in the Moderate scenario, but 2950 TWh_{th} in the Leadership scenario. The excess electricity cannot be used for other purposes due to ongoing efficiency improvements in the energy system and stable or stagnating final energy demand due to stable or slightly declining population. However, this challenge can be mitigated either by exports of these e-fuels, as assumed in this research, or by earlier balancing with e-fuel imports as an alternative approach.

5.3.2 | Reports for stakeholder discourse

The results of the Moderate and Leadership scenario are compared to relevant reports that are used for stakeholder discourse on the energy transition in Europe. The selected reports are listed in Table 3 for the same structure as Table 1 for scientific journal papers.

Similar to the scientific papers as discussed in Sections 2 and 5.3.1, electricity generation differs strongly across studies, in total, and for solar PV in particular, for similar reasons as discussed previously. Interestingly, the results for Europe in the Advanced E [R] scenario from Greenpeace[160] reached 100% RE in 2015 in a transition pathway, earlier than the first scientific transition paper by Pleßmann and Blechinger[67] in 2017. Only one report finds PV shares higher than 20%: The CAN Europe PAC[157] scenario reaches a solar PV share of 38%. The IRENA World Energy Transitions Outlook[161] could not be used due to lack of reported regional data, similarly to the Net Zero Emissions by 2050 scenario of the IEA.[162] Therefore, the Sustainable Development Scenario of the IEA in the latest full data reporting was used for Europe[160] and reports the lowest values for solar PV relevance across all investigated reports, both in absolute and relative terms. The Eurelectric scenario[154] finds a PV share of 20% by 2045, which may indicate substantial discourse requirements, given not only the findings of the investigated scenarios in this research but also the structural findings of Victoria *et al.*,[61] because the PV shares of 20% versus 50%–60% lead to fundamentally different energy system designs. The EC 1.5 TECH scenario[156] shows comparable issues. Summing up, all except one report present very low

TABLE 3 Overview on relevant reports used for stakeholder discussion for the energy transition in Europe. Values of this study are added for comparison. Energy sectors comprise power, heat, transport and industry.

Authors	Year	Model	Temporal resolution	Sectors	Regions	Electricity generation		Electricity generation share		TPED share		RE share[a]	Target year[b]
						PV [TWh]	Wind [TWh]	PV	Wind	PV	Wind		
This study—Moderate	2022	LUT-ESTM	Hourly	All	20	10,600	5630	61%	33%	54%	29%	99.5%	2050
This study—Leadership[a]	2022	LUT-ESTM	Hourly	All	20	12,345	6400	63%	32%	56%	29%	100%	2040
Eurelectric Scenario 3[154]	2018	McKinsey	n/a	All	8	1200	4000	20%	67%	n/a	n/a	82%	2045
WindEurope Paris Compatible[155]	2018	DNV ETO	Annual	All	1	900	2223	15%	36%	n/a	n/a	78%	2050
EC 1.5 TECH[156]	2018	PRIMES	Time slices	All	1	1232	4252	16%	53%	n/a	n/a	83%	2050
CAN Europe PAC[157]	2021	Unspecified	n/a	All[c]	1	2500	3600	38%	55%	32%	46%	100%	2050
Navigant Optimised gas[158]	2019	Navigant Energy System Model	Hourly	All	1	1000	4000	14%	56%	n/a	n/a	88%	2050
IEA WEO SDS[169]	2020	IEA World Energy Model	Annual	All	1	747	2131	13%	38%	4%	13%	76%	2040
Greenpeace Adv E[R][160]	2015	Mesap/PlaNet (DLR-EM)	Annual	All	1	1080	2351	19%	41%	9%	21%	100%	2050

Abbreviations: LUT-ESTM, LUT Energy System Transition Model; PV, photovoltaic; RE, renewable energy; TPED, total primary energy demand.

[a]RE share in electricity generation.

[b]Target year of displayed numbers.

[c]Electric vehicles and power-to-heat are excluded.

solar PV shares compared with the findings of not only this study but also Victoria *et al.*[61] and several other scientific studies (Table 1), which indicates a lagging of major European stakeholders and their consultants carrying out respective studies to real market trends. Furthermore, the applied methods seem to be not anymore state-of-the-art, given the low spatial resolution, as well as deficits in temporal resolution in a majority of the reports, whereas multi-node and hourly resolution is the norm in leading scientific studies.

5.4 | Results for European energy transition in the global context

Europe faces a strong seasonality and benefits from very strong wind resources, leading to an energy system based on these two fundamental sources in a rather balanced structure. Most people in the word live in sunbelt regions, where solar resources are better and wind resources typically less favourable than in Europe. This leads to higher solar PV and lower wind electricity shares in studies of comparable assumptions as for Europe.

The structural results obtained in this research can be also found in global studies as recently summarised.[2] This research found 61%–63% PV share in electricity generation. Such a level and more has been found by five studies as presented in Figure 19, thereof three independent of the LUT team: Sørensen[3] found 77%, Pursiheimo *et al.*[4] found 75% and Luderer *et al.*[163] found 63%, whereas Bogdanov *et al.*[5,164] found 67% and 76% for power sector and all-sector scenarios, respectively. The results of these five studies have been obtained with four different models, which indicate a broader methodological agreement on the potential for higher shares of PV electricity in energy supply. The solar PV share in TPED of 54%–56%, however, is not yet achieved by other teams than the LUT team, as in Bogdanov *et al.*[5] 69% PV share in TPED was shown, whereas highest PV shares in other studies are in the range of 40%–50%, as achieved by Pursiheimo *et al.*[4] with 47%, Jacobson *et al.*[96,165] with 40%–42% and Luderer *et al.*[163] with 42%.

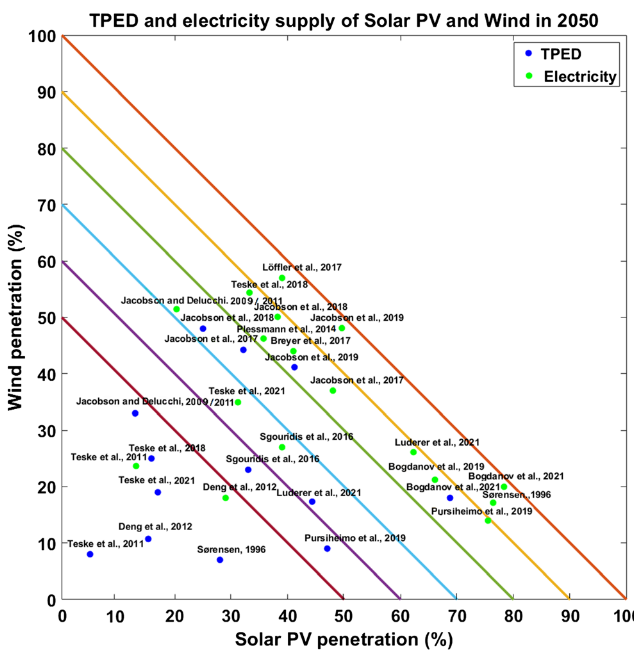

FIGURE 19 Shares of solar photovoltaic (PV) and wind power in global 100% renewable energy (RE) scenarios in electricity generation and in total primary energy demand (TPED) in the year 2050.[2] The parameters for this study on Europe are: Moderate: PV (61% and 54%) and wind power (33% and 29%) for electricity and TPED, respectively. Leadership: PV (63% and 56%) and wind power (32% and 29%) for electricity and TPED, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

The reasons for lower PV shares in global studies are more or less the same as identified in Europe.[2] In addition, some studies assume substantial shares of bioenergy for fuels, heat and even power supply, while the sustainable bioenergy limit of 100 EJ (27,800 TWh)[166] is typically respected. Moreover, some studies assume substantial shares of concentrating solar thermal power (CSP) plants, which directly reduce the share of PV; however, optimisation models continuously reduce the share of CSP due to relative higher cost competitiveness of PV-battery solutions, whereas simulation models may have higher CSP shares, which may be also justified for diversity benefits but at higher costs.[167]

Recent announcements of PV industry indicate that by 2025, annual solar silicon manufacturing capacities of 940 GW are online,[168] which can be then processed to PV systems of comparable capacity. This is in great agreement with the highest PV share scenario among the global studies,[5] which leads by 2050 to 63,400 GW installed capacity, which requires by 2025 about 500 GW per year installations and about 1350 GW per year by 2030, about 2500 GW per year by 2040 and 3000–4000 GW per year by 2050.[5,169] The scenario of Bogdanov *et al.*[5] leading to 63,400 GW installed capacity by 2050 was taken up by international PV experts in Haegel *et al.*,[170] Verlinden[171] and ITRPV.[169] Breyer *et al.*[17] have revised their assumptions to about 80,000 GW installed capacity by 2050, as demand for fully transitioning the chemical industry towards sustainable feedstock, mainly based on e-methanol and e-ammonia,[99–101] and rising demand for CO_2 removal (CDR) based on PV-based direct air carbon capture and storage[172,173] require more electricity supply in a comprehensive energy-industry-CDR system.[2] The 80,000 GW capacity by 2050 is the upper limit of the projected range in Haegel *et al.*[170]

6 | CONCLUSIONS

Accelerating climate change response requires transitioning towards zero CO_2 emission energy systems as soon as possible, while most countries target around 2050. Two scenarios were investigated in this research targeting zero CO_2 emissions by 2050 and by 2040 as 100% renewable energy systems. The structural findings of these two scenarios are compared to a less ambitious reference scenario, and the identified literature for Europe and discussion in the global context.

The two scenarios show that pre-pandemic level energy system costs can be reached by 2050 with both the scenarios, but with 8.5% lower pathway costs in the scenario reaching zero CO_2 emissions by 2050 compared with the one by 2040. Both scenarios reach very high levels of electrification across the entire energy system in strongly sector-coupled system solutions, which enable substantial system flexibility and thus low curtailment of less than 5%. The largest source of energy is solar PV with 54%–56% of total primary energy demand and 61%–63% of total electricity generation in 2050. Total final energy demand remains roughly stable across the energy transition, whereas the primary energy demand declines by 11% due to realised efficiency gains, despite of increasing demand for energy services. Energy services demand that is not directly electrified is covered by renewable electricity-based e-fuels, in particular for long-distance marine and aviation transport and high-temperature heat for industrial applications. The decade faster energy transition results in about 17% lower pathway emissions, which are vital in the context of climate mitigation.

Comparison of the two investigated scenarios with scientific literature of energy transition scenarios for Europe revealed that all other scenarios find lower solar PV shares, due to a variety of reasons including particularly higher solar PV cost assumptions and for important supporting technologies, in particular battery storage and electrolysers. One identified study has a close solar PV share, mainly due to comparable cost assumptions for all three core technologies. The remaining identified differences are the importance of freely scalable utility-scale PV power plants and the beneficial system impact of single-axis tracking PV systems. Comparison to reports used for stakeholder discourse in Europe shows low shares of solar PV for almost all cases, indicating substantial demand for stakeholder discussions in the years to come.

Global energy system transition studies have partly higher solar PV shares in electricity supply, which can be explained by higher overall PV supply shares in the global sunbelt where the majority of world population lives. Only one study achieved a similar PV share in total primary energy supply; however, with partly identical authors to this research, all other studies reach lower values. The same reasons as identified for Europe can be found for global studies as well, however, two further differentiators are noticed, namely relevant shares for concentrating solar thermal power plants, in particular in simulation models paying more attention to energy supply diversity than to cost optimisation, and bioenergy supply, often including energy crops, which may be in conflict to land-use for food production and biodiversity.

Hourly operation of the two investigated scenarios reveals the interplay between the core technologies of solar PV, wind power, battery storage, electrolysers and heat pumps. Battery storage enables the diurnal use of PV electricity and supports wind power balancing. Heat pumps contribute some flexibility in combination with thermal energy storage. Electrolysers contribute the major flexibility in the energy system in transferring not directly used electrons into molecules in a first step in the form of hydrogen, which is buffered in hydrogen storage for subsequent near baseload conversion to the target e-fuels.

The nature of the arising future energy system can be best termed as a power-to-X economy, as the dominating majority of primary energy is electricity that is used across the energy system in direct applications, such as power-to-heat, power-to-mobility or power-to-water in dry regions, whereas indirect electricity use mainly follows the route of power-to-hydrogen-to-X, with final energy carriers in the form of liquids, methane, ammonia and methanol. The power-to-X economy is further characterised by a high systemic efficiency due to high direct electrification levels, comprehensive sector coupling and avoidance of less efficient combustion processes where possible. Solar PV can emerge as the largest source of energy mainly driven by its least cost nature and ubiquitous resource availability.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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