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More Renewable Energy Leads to a Faster Transition at Lower Cost as Revealed by Comparative Analysis of Global Energy Transition Scenarios

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ABSTRACT

Energy transition scenarios are crucial for policymakers and other stakeholders aiming to develop sustainable energy systems. However, assessing scenario results from different modelling platforms can be challenging, as they can apply wide ranges of input data and assumptions. We develop a new methodology to harmonise global energy transition scenarios among three modelling groups that can address challenges caused by inconsistencies across models. Two scenarios from the International Energy Agency (IEA), two from Teske/DLR, and three from the LUT Energy System Transition Model targeting net-zero emissions by 2035, 2040, and 2050 are compared. Our results indicate that LUT scenarios have the fastest emissions reduction at the lowest cost, whereas Teske/DLR scenarios rely on a diverse energy supply to achieve emissions reductions. The IEA scenarios provide the least ambitious results that are more expensive than LUT scenarios, indicating that widespread use of renewable energy with storage and flexibility leads to both economically and environmentally beneficial outcomes.

1 | Introduction

Energy systems are vital to our common future. We need them for housing, health, food, mobility, and security. However, energy systems face many challenges. We urgently need to decarbonise energy systems in order to limit climate damage, as the current warming caused by greenhouse gas (GHG) and dark particle emissions could bring Earth's temperatures above a possible "tipping point" that could lead to a global disaster [1]. Dark aerosol particle components, black and brown carbon from fossil fuel and biofuel combustion, are major causes of global warming and air pollution mortality. Because of their short lifetimes, though, controlling their emissions can rapidly reduce both problems [2]. At the same time, global energy demand is soaring due to the rapidly growing population and economy [3, 4], and everyone must have access to sustainable, affordable, and reliable energy, as

Abbreviations: A-CAES, Adiabatic compressed air energy storage; CAPEX, Capital expenditures; CCGT, Combined cycle gas turbine; CCS, Carbon capture and sequestration; CHP, Combined heat and power; COP, Coefficient of performance; CSP, Concentrating solar thermal power; DLR, German Aerospace Centre; e-Hydrogen, Electricity-based hydrogen; e-Methane, Electricity-based methane; GHG, Greenhouse gas; IEA, International Energy Agency; LCOE, Levelised cost of electricity; LCOFE, Levelised cost of final energy; LUT-BPS, Best policy scenario; LUT-ESTM, LUT Energy System Transition Model; NGO, Non-governmental organisation; NZE2050, Net zero emissions by 2050; OCGT, Open cycle gas turbine; OPEX, Operational expenditures; PHES, Pumped hydro energy storage; PV, Photovoltaics; RE, Renewable energy; SDS, Sustainable development scenario; STEPS, Stated policy scenario; TES, Thermal energy storage; TFED, Total final energy demand; TPED, Total primary energy demand; WEM, World Energy Model.

TABLE 1 | Scenarios examined in this research.

Source	Scenarios	Model	Years
International Energy Agency (IEA)[a]: World Energy Outlook 2022 (WEO, 2022) [11, 12]	Stated policy (STEPS) sustainable development (SDS)	World Energy Model (WEM) [13]	2015-2050
Sven Teske and the German Aerospace Center (DLR) et al. [14, 15]	2°C 1.5°C	[R]E-SPACE, [R]E 24/7 and Energy system model (EM) [14, 15]	2015-2050
Own scenarios (Best Policy Scenario: LUT-BPS)	BPS2050 BPS2040 BPS2035	LUT-ESTM [16]	2015-2050

[a]The Net Zero Emissions by 2050 (NZE2050) scenario is not included due to a lack of data on a regional basis.

stated in the United Nations Sustainable Development Goals [3]. Additionally, energy systems must deal with shocks such as the COVID-19 pandemic [4] and geopolitical issues such as the war in Ukraine [5]. Fortunately, technological improvements, especially in renewable energy (RE), might still make these goals achievable [6]. But what is the right way forward when faced with such technical and socio-political issues?

1.1 | Energy System Modelling to Anticipate Possible Futures

Energy scenarios simulated by energy system models are an attempt to provide an answer to that question. They address factors, such as energy demand, technological advancements, policy measures, and economic and environmental implications to determine, for example, the most viable and effective path towards achieving net-zero emissions quickly at the lowest cost. Such scenario development also facilitates stakeholder engagement by providing a platform for discussion and informing policymakers to find common ground around energy policies and investments. However, a detailed examination of such scenarios reveals that different models provide different answers. Understanding these differences is crucial to providing a broad and cohesive foundation for sustainable and low-cost energy systems. How should these be handled?

Many tools and approaches for modelling the energy transition [7–9] exist. Some emphasise environmental concerns and the need to transition to RE sources, and others prioritise energy security, cost, diversification, and the importance of maintaining fossil fuel supplies. Table 1 shows the energy scenarios, models, time horizons, and their references included in this comparison. Many other possible scenarios exist, but these scenarios encompass four key scenario archetypes, namely (1) optimised scenarios featuring high electrification and solar PV shares; (2) high RE scenarios with a more diverse RE supply mix at different transition paces; (3) medium and (4) low ambition, both with nuclear power and fossil carbon capture and sequestration (CCS) and maintaining high shares of conventional technology options. In addition these three scenarios approaches have been included in a recent comparison of the International Renewable Energy Agency in featuring 100% RE scenarios [10] and provide regionally resolved data for the full energy system, which is required for scenarios to be harmoniously reproduced in one energy system model.

Thus, this study presents a new methodology to harmonise and compare various energy scenarios. It expands upon previous research on power systems [17] to include all energy sectors and aims to overcome the difficulties posed by inconsistencies among the different methods and assumptions that different researchers use, paired with insufficient data availability. It compares scenarios using the same techno-economic metrics for all scenarios to understand the strengths and limitations of different scenario pathways.

1.2 | Frameworks for Global Energy Transition Simulations

The International Energy Agency (IEA) is the most authoritative organisation providing energy advice to policymakers [18, 19]. Based on their own simulations with their world energy model (WEM), they provide long-term outlooks [20], projecting energy demand and supply forward for the next 20-30 years under various scenarios. Examined here are the IEA's STEPS scenario, often used as a benchmark for what will happen without new fundamental policies towards decarbonisation, as well as their more ambitious Sustainable Development Scenario (SDS).

The second simulation model included here is the Teske/DLR model. It focuses on 100% RE system transitions [21], similar to the LUT Energy System Transition Model (LUT-ESTM). The Teske/DLR model is well considered by non-governmental organisation (NGO) stakeholders with a focus on energy diversity using RE resources. Examined are their moderate 2°C and the more ambitious 1.5°C scenario.

Both the IEA and Teske/DLR models, used to develop the original scenario results but not applied in this research, use the simulation technique rather than optimisation, an approach that extrapolates towards the future from the world as it exists, with all its complexities, nuances, and inefficiencies [22]. In this sense, the model user defines key characteristics of developed scenarios, generally allowing for a wider range of scenario trajectories to be investigated. However, the future energy systems developed by such models can be uncertain due to rapidly decreasing costs of RE technologies, especially solar photovoltaics (PV) and wind power [23–25], as well as energy storage technologies, such as batteries [26, 27], and other relevant technologies, such as electrolysers [28, 29]. As cost reduction becomes the primary factor driving the transition [30], the potential growth of RE, especially solar PV, is often underestimated [31].

Next to simulation, optimisation is a well-established approach for creating bottom-up energy transition models [22, 32]. Optimisation in the context of highly RE system modelling tends to reflect an idealised version of the world in which we would like to live. Historically, optimisation models have produced the most efficient and cost-effective systems with little attention to the socio-technical challenges [33]. However, the modellers often apply several constraints to capture various aspects of the energy system transition in a more realistic way than solely based on unrestricted optimisation [17]. Furthermore, increased attention has been placed on near-cost optimal solutions that incorporate social and political goals [34–36], though this tends to be limited to power sector analysis.

Optimisation is the approach used by LUT-ESTM [16, 37]. All scenarios, including those originally developed by the IEA and Teske/DLR, are run and compared here using this model, allowing for a comparison of the techno-economic and environmental performance of all models using a harmonised and uniform modelling environment.

For this study, three new scenarios simulated in LUT-ESTM are developed. Collectively, they are called the Best Policy Scenario (LUT-BPS) and aim to achieve an energy system that emits global net-zero CO_2 by 2050, 2040, and 2035, respectively. The faster-than-mid-century defossilisation in two of the scenarios is motivated by the fact that the carbon budget for a high probability of attaining a 1.5°C climate target was depleted in the year 2022 [38]. At the same time, data for 2023 indicate an acceleration of the progression of global warming, so it is crucial to investigate faster reductions in GHG emissions.

The publications chosen for the IEA and Teske/DLR scenarios were the most recent at the time this research was conducted.

This research aims to address the following research questions:

- Which pathways result in the best and worst techno-economic performance?
- How might a faster pace transition affect the energy system both economically and environmentally?
- How do the input and output data from different models in different scenarios affect results when used in one unique model setup, LUT-ESTM, an hourly resolved cost-optimisation model?
- What additional system flexibilities are required to ensure the feasibility of the pathways in the new model and subsequent systemwide impacts? For example, the flexibility measures might include the addition of power capacities, energy storage, hydrogen, and non-hydrogen e-fuels. How can the additional adjustments be interpreted and justified when running a sector-coupled energy system fully integrated with hourly resolution?
- What energy system components and technologies are key for a successful energy transition?
- What is the energy system impact on CO_2 avoidance costs?

While model intercomparison and harmonisation research has been conducted for both energy systems [39, 40] and integrated assessment models [41–43], this research is the first to reproduce global transition scenarios for all energy sectors within the same modelling environment and to explore pathways that can lead to carbon neutrality across all energy sectors worldwide by 2035, 2040, and 2050. It also examines key techno-economic indicators and functionalities of global energy system pathways developed within specific models and assumptions with an hourly resolution. The scale of data collection, preparation, and processing required for this study is complex and time-consuming, which explains why previous studies have not fully explored these areas. Moreover, research gaps are often filled with different simplifying assumptions that can reduce consistency and comparability, resulting in limited transparency in scenario studies. This study proposes a novel approach to closely scrutinise energy transition scenarios and their differences.

The following sections discuss the selected energy system models, the methods used to analyse the scenarios, and the key results and comparisons.

2 | Methods

2.1 | Data Sources

The analysis presented in this research uses the data from two global energy system models (Teske/DLR and IEA), each running two scenarios, as shown in Table 2, and reproduces their results using LUT-ESTM with hourly time resolution. More specifically, the results from the Teske/DLR and IEA scenarios are reobtained within LUT-ESTM, harmonising each scenario's input data to LUT-ESTM's data structure. The aim is to capture the complex input and output dynamics of the two models with respect to each scenario. Results from these scenarios are then compared with results obtained from the three LUT-BPSs to identify differences in techno-economic characteristics. Hourly resource profiles for wind power, solar PV, concentrating solar thermal power (CSP), and hydropower are estimated from 2005 hourly weather data and applied to the major regions [17]. Global RE resource potentials are presented in Table S7. The energy systems data in 2015 and 2020 were validated through various datasets [44–50] and set as the starting years for the scenarios.

Comments:

1. Primary energy demand can slightly deviate from the actual numbers in the sources due to differences in efficiency assumptions or additional electricity or heat generation required to avoid infeasibility.
2. Since the data are not always provided by technology (e.g., open cycle gas turbines (OCGT), combined cycle gas turbines (CCGT), gas combined heat and power (CHP)), current shares are used to extrapolate future electricity capacity and generation.

TABLE 2 | Overview of the input data taken from the sources for the scenario comparison.

Focus	Normative energy transition pathways			Governmental policy outlook
Scenarios' data	**Teske/DLR-2.0°C**	**Teske/DLR-1.5°C**	**IEA-SDS**	**IEA-STEPS**
Final energy demand	☑	☑	☑	☑
Primary energy demand[1]	☑	☑	☑	☑
Electricity generation	☑[2]	☑[2]	☑	☑
Installed capacity	☑[2]	☑[2]	☑	☑
Heat generation	☐[3]	☐[3]	☒	☒
Share of renewables	☑	☑	☑	☑
Use of hydrogen and e-fuels	☑	☑	☑	☑
Energy storage technologies	☑	☑	☑	☑
Role of prosumers	☑	☑	☒	☒
Electricity demand	☑	☑	☑	☑
Heat demand[4]	☑	☑	☑	☑
Transportation demand[5]	☑	☑	☑	☑
Load profiles[6]	☐	☐	☒	☒
Heat profiles[6]	☒	☒	☒	☒
RE resource profiles[6]	☐	☐	☒	☒
Technical assumptions[7]	☐	☐	☐	☐
Financial assumptions[8]	☐	☐	☐	☐
CO_2 cost[9]	☑	☑	☑	☑

Note: ☑ *Given* ☒ *Not given* ☐ *See the respective comment.*

3. Heat generation is reported but is mainly considered a share of total heat generation from individual and centralised heating sources, including CHP, required to satisfy demand.
4. Heat demand is estimated based on the final energy demand across different sectors, including residential, commercial, and industrial process heating.
5. For non-LUT scenarios, transportation demands are exogenously set according to the final energy demand by fuel sources.
6. The hourly demand profiles used in the LUT scenarios for space heating, domestic hot water, biomass cooking, and industrial process heat are adopted and normalised based on the corresponding data in the Teske/DLR and the IEA scenarios.
7. Identical technical assumptions are used, except electrolyser efficiency and heat pumps coefficient of performance (COP) are taken from Teske/DLR and battery energy-to-power ratio is taken from the IEA.
8. Identical financial assumptions (see Table S3) are used.
9. The CO_2 emissions costs are taken from the IEA report. The CO_2 costs of the IEA-SDS are applied to the Teske/DLR scenarios.

2.2 | Regional Grouping and Data Structuring

Nine world regions, shown in Figure 1, were simulated for eight periods in an hourly resolution throughout a year. Thus, a total of 72 simulations were run for each transition pathway. Among these simulations, nine each were run for starting years 2015 and 2020, and the remaining 54 were each run for seven scenarios, for a total of 378 iterations.

The detailed data from 145 regions were originally aggregated or weighted to form nine major regions for the three LUT-BPSs. The data from the LUT-ESTM database [16, 37] were used to restructure data from other energy system models. The regional grouping of the IEA and Teske/DLR consisted of eight major regions, with data for India and China provided individually, resulting in a total of ten major regions. The input-output of the IEA and Teske/DLR scenarios were used to reproduce their scenarios, including TFED, TPED, electricity installed capacity, electricity generation, sectoral demand, energy storage installed capacity, energy storage output, and power-to-X conversion, among others. However, since detailed data were unavailable for all countries/sub-regions within the major regions, proxies were used to distribute the data when restructuring the regions [17] and further described in Table S1.

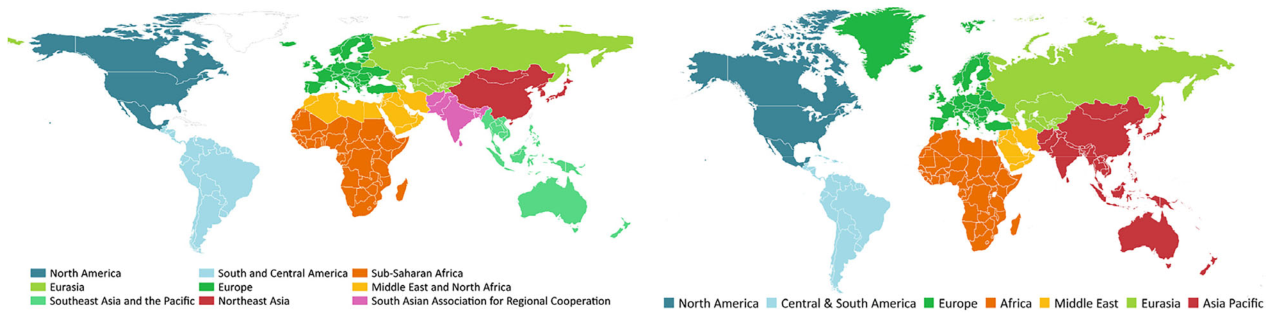

FIGURE 1 | The regional grouping of LUT-ESTM (left) and the Teske/DLR and IEA scenarios (right) [11]. On the map on the right, the Asia Pacific region is further divided into two categories: Non-OECD Asia and OECD Pacific. The countries that are not included in LUT-ESTM are depicted as white.

2.3 | Modelling Environment and Processes

The modelling process used an optimisation model, LUT-ESTM, in 5-year time steps from 2015 to 2050. In the first modelling step, a prosumer model was run to meet the power sector electricity demand via solar rooftop PV and batteries across residential, commercial, and industrial segments [16, 37]. The share of each segment was adapted from the LUT-ESTM database. In addition, individual heat demand was met by the prosumers model. The next step was to model the central energy system at hourly resolution to cover the remaining energy demand across the power, heat, and transport sectors. Finally, the results were collected and evaluated in the post-processing step. For Teske/DLR and the IEA scenarios simulated in LUT-ESTM, cost calculations did not directly or predominantly drive technology deployment, as installed capacities from the original scenario sources by time step were provided as inputs to satisfy hourly energy supply and demand constraints. However, by reproducing the Teske/DLR and IEA scenarios within LUT-ESTM, the levelised cost of electricity (LCOE), levelised cost of final energy (LCOFE), and annualised system costs of the scenarios could be calculated and compared. The LUT scenarios, conversely, are modelled based on cost optimisation for given constraints. The flowchart of the modelling process is presented in Figure 2.

Reproducing results of other energy system models presents a challenge due to limited access to detailed data, assumptions, constraints, and processes. An open-source energy system model facilitates the comparison process, as one can easily access the modelling details. It is planned for LUT-ESTM to publish an open-source version in the foreseeable future. Despite this, selected studies offer adequate input-output data and various measures for reducing CO_2 emissions, promoting technological diversity, and analysing transition dynamics. However, additional assumptions and modifications are necessary to meet requirements, such as proxies applied to make the regional data comparable [17]. To replicate results, LUT-ESTM uses several constraints to control capacity expansion, retirements, and full load hour requirements for electricity generation. Energy system models have constraints that reflect real-world limitations or parameters governing system operation. Constraints ensure that the modelled system behaves realistically and within practical boundaries. Based on current fast-declining costs of RE [23, 24], the model does not build sufficient fossil fuel capacities for scenarios with a lower share of RE, even when unconstrained, necessitating additional enforcement measures as applied in [51, 52]. Therefore, a minimum installed capacity was enforced for fossil fuels with and without CCS, as well as nuclear power in the IEA scenarios.

Balancing generation and demand, particularly with high penetration of RE, is another challenge. Energy storage was not limited to the given capacity and throughput in the respective sources to ensure the technical feasibility of the Teske/DLR and the IEA scenarios in LUT-ESTM. Instead, the values were assigned as the minimum constraints with the possibility of further expansion. Thus, higher storage capacities can be expected than those given in the sources. The selection of energy storage options is executed via cost optimisation, followed by technology preferences of the scenarios, to reduce the burden on the final energy system costs. Other relevant assumptions and considerations for remodelling the scenarios are provided in the Supplementary Material.

2.4 | Scenarios Description and Assumptions

Table S2 lists the scenarios chosen for this study and their characteristics. Fundamentally, these scenarios can be categorised into two main groups. The LUT-BPSs represent technology-neutral cost optimisation aiming for net-zero emission energy supply by 2035, 2040, and 2050, respectively. The Teske/DLR scenarios represent simulated transition pathways with predefined technology shares aiming for 2.0 and 1.5°C warming by 2050. The IEA STEPS and SDS represent policy scenarios representing moderate policy ambition (SDS) and current policies (STEPS). Tables S3–S8 include detailed technical and financial assumptions considered for this analysis in a harmonised way. The sectoral demands for major global regions for the LUT scenarios are presented in Table S9. To compare the results of different scenarios, the TFED of each scenario is normalised using the TFED of the IEA-SDS as a benchmark. After that, all cost metrics and CO_2 emission values are recalculated during post-processing to present and visualise the data in the same way.

3 | Results

This study uses a consistent labelling system, colour code, and legend to differentiate the various scenarios presented in the

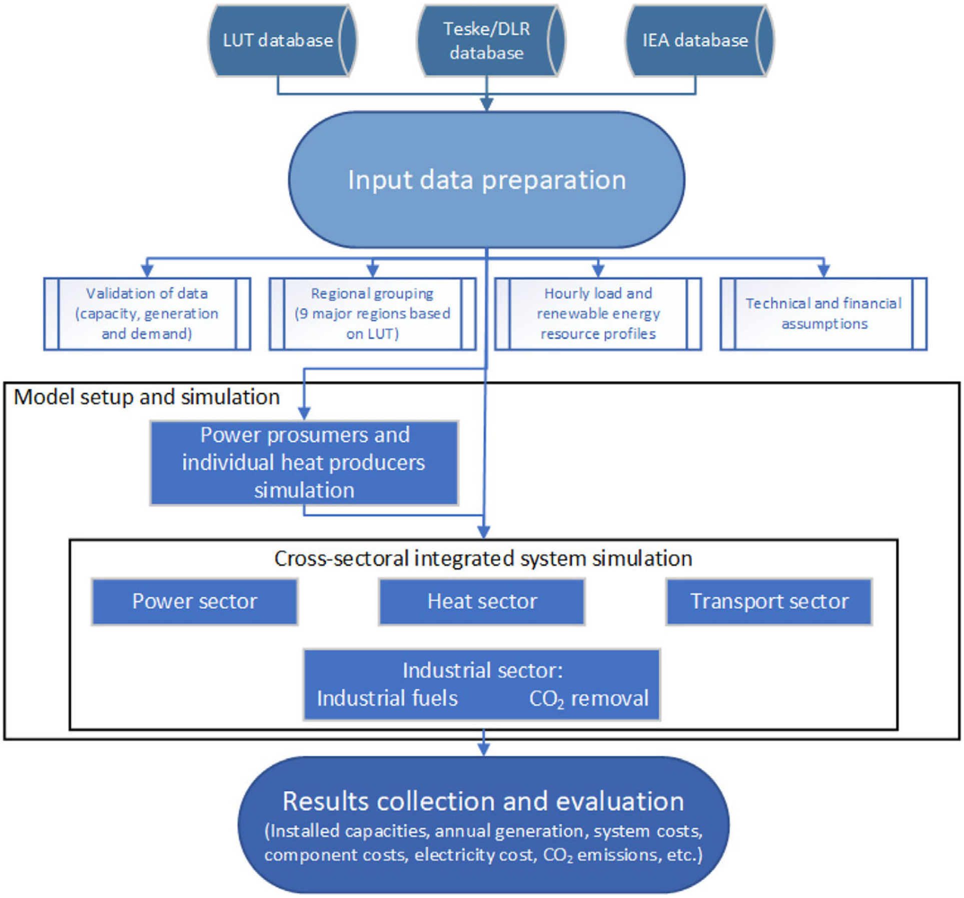

FIGURE 2 | The overall structure of LUT-ESTM as used in this research.

figures. The years 2015 and 2020 are both used as the current year, interchangeably depending on the context. The primary modelling results are shown in Figures 3–10, and additional insights and regional findings are available in the Supplementary Material 1 and 2 Figures S2–S13. This study introduces three new scenarios with varying levels of ambition to achieve carbon neutrality. The two modelling group scenarios are reproduced and compared with the three developed scenarios in this study to identify the critical differences in assumptions and modelling. As a result, there may be some disparities in energy demand and supply, but certain indicators in the energy transition, such as electrification and techno-economic drivers, can still be distinguished. Additionally, an economic harmonisation approach is implemented to improve the comparability of the scenarios. Numerical results for all scenarios are presented in Supplementary Material 2.

3.1 | Long-Term Energy Demand and Electrification

The projections for global energy demand vary depending on the assumptions made by each modelling group regarding socioeconomic metrics, government policies, and technological development, as shown in Figure 3 (top left and right). In the LUT scenarios, the total final energy demand (TFED) grows annually at 0.7% globally, reaching 123,000 TWh in 2050. Total primary energy demand (TPED) decreases from 155,000 TWh in 2020 to 108,000 TWh by 2035, then increases to 135,000 TWh by 2050 in the LUT-BPS2050. The TPED in the earlier LUT global energy transition study for 145 regions [16] was significantly higher, at 150,000 TWh by 2050 (Figure 3 top left), reflecting differences in assumptions and system configuration, including efficiency gains in the heat sector [53], coupling of the power, heat, and transport sectors, and regional resolution applied. The TPED trend differs in the other two LUT scenarios, which assume different target years for achieving a net-zero emissions system. This impact is more pronounced in the BPS2035, which would require high investment in RE and flexibility services from 2025-2035. Meanwhile, current practices (IEA-STEPS) would result in a TPED of nearly 187,000 TWh by 2050 (Figure 3 top right), highlighting the low efficiency performance of energy systems in a business-as-usual case. The Teske/DLR scenarios and the IEA-SDS project a decrease in TFED, leading to a lower ratio of final energy to primary energy by 2050 than the IEA-STEPS (Figure 3, bottom left). At the same time, the lower electrification rate in these scenarios than the LUT-BPSs is due to the integration of more solar thermal and geothermal energy in the Teske/DLR scenarios and nuclear and fossil fuels with CCS in the IEA-SDS. Primary energy is accounted for according to the Physical Energy Content Method, as discussed in [54, 55]. It is also important to note that through the harmonisation process, the TFED and TPEDs in the reproduced IEA and Teske/DLR scenarios match the original values.

A higher electrification rate can lead to a more efficient energy system with reduced losses, as depicted in Figure 3 (bottom right).

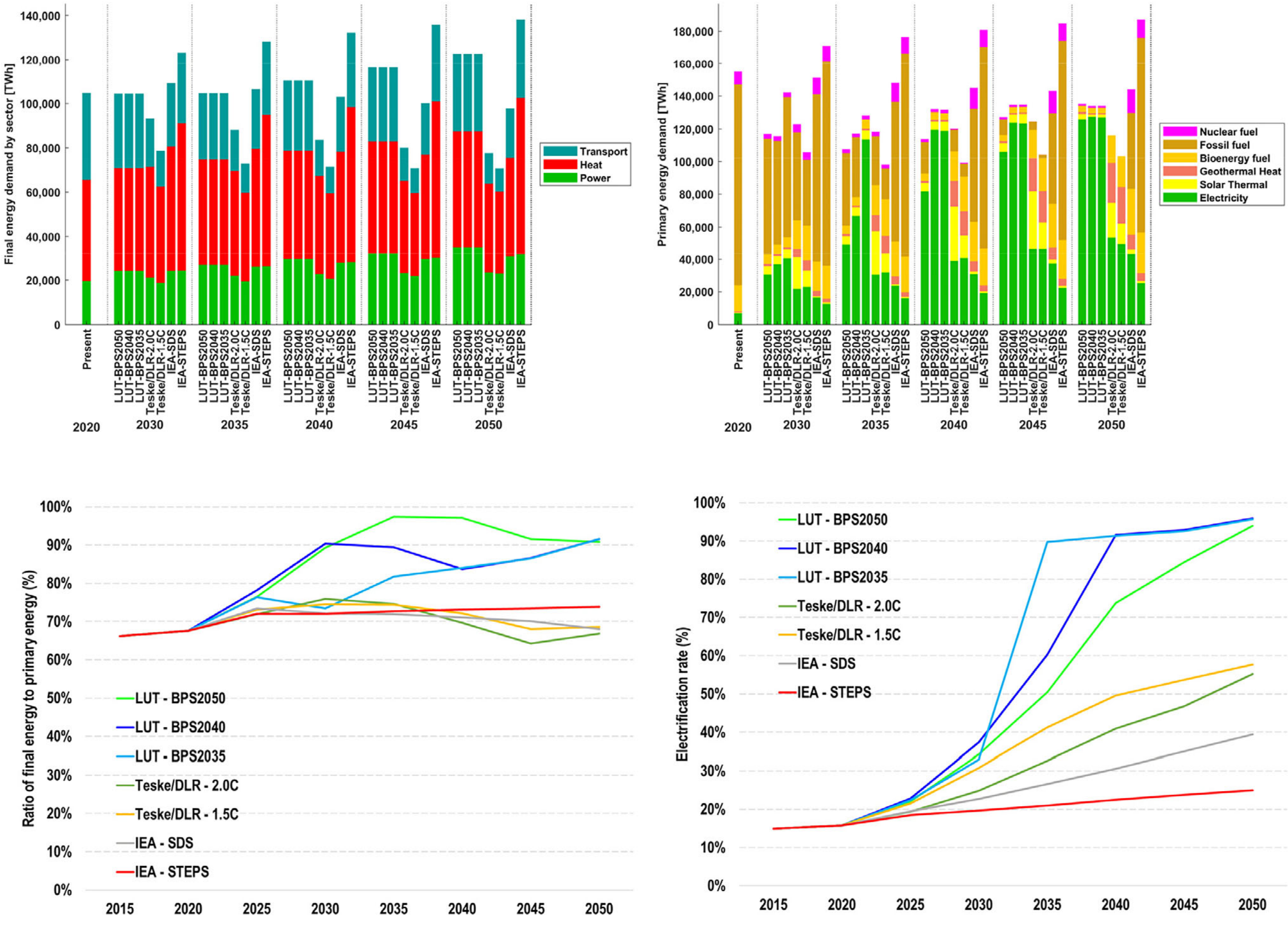

FIGURE 3 | Global final energy demand by sector (top left), global primary energy demand by source (top right), the ratio of final energy demand to primary energy demand (bottom left), and electrification rate (bottom right) across all scenarios.

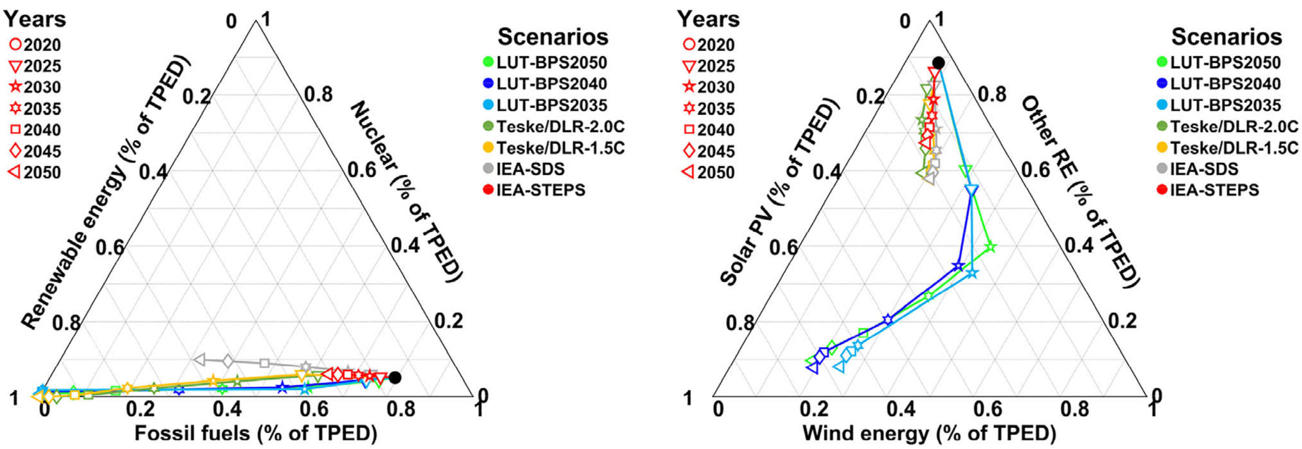

FIGURE 4 | Ternary plots for the primary energy sources (left) and primary RE sources (right) per transition pathway. The total relative numbers add up to 1, meaning 100% of the TPED (left) and 100% of the whole RE-based generation (right). Fossil fuels encompass electricity generation with and without CCS. Other RE sources include hydropower, bioenergy, CSP, ocean power, and geothermal energy. Starting points in 2020 are marked by black circles, and markers are placed in 5-year intervals from 2020 to 2050 to illustrate transition paths and their dynamics.

The electrification rate in this context measures the proportion of electricity generation in relation to the TPED. Despite an increase in TFED, the TPED values are lower than the 2020 benchmark and projected to reach a 91%–92% electrification rate by 2050 in the LUT pathways. These values document a Power-to-X Economy [56] since renewable electricity, primarily that from solar PV, wind power, and hydropower, is the dominant primary energy and then converted to all required forms of final energy

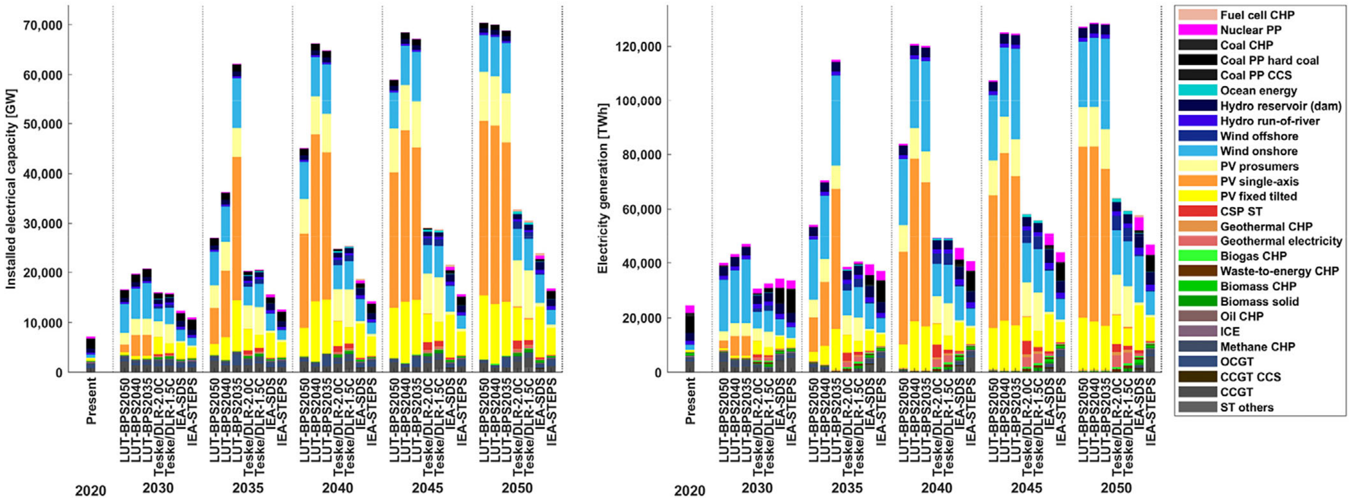

FIGURE 5 | The progression of installed power capacity (left) and electricity generation (right) throughout the transition for the selected years 2020 (present) and from 2030 to 2050 in 5-year increments.

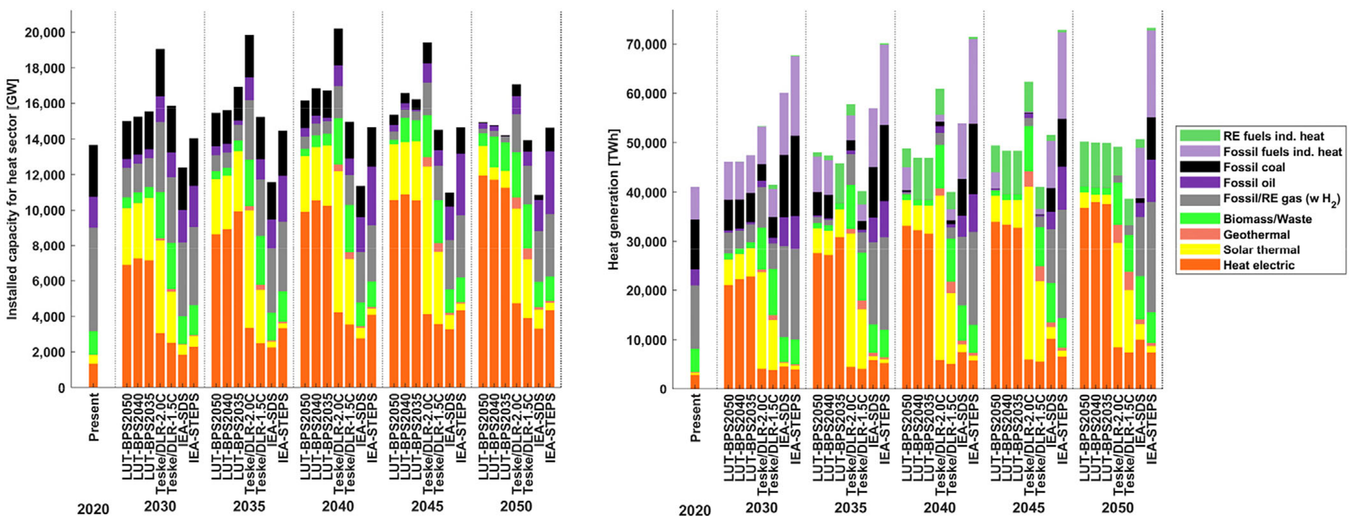

FIGURE 6 | Development of installed heat capacity (**left**) and heat generation (**right**) throughout the transition for the selected years 2020 (present) and from 2030 to 2050 in 5-year time steps.

as part of an efficient and low-cost energy system. The IEA-STEPS shows a slight growth in the electrification rate, rising by approximately 10% over the next 30 years. Throughout the transition, fossil fuels remain the dominant source of TPED. The IEA-SDS outperforms the STEPS by increasing the contribution of electricity (40%) to cover TFED across all sectors, while fossil fuels with and without CCS endure until the end of the transition time horizon. The 2022 IEA-NZE2050, not modelled in this research due to lack of disclosed data on a regional basis, shows the highest electrification of TFED in IEA scenarios at 52% [57].

Modern bioenergy, geothermal energy, and solar thermal, combined with electricity, help replace fossil fuels throughout the energy transition. The Teske/DLR-2.0°C shows a more gradual increase in electrification during the transition, reaching 55% by 2050. In contrast, the 1.5°C pathway aims for a higher electrification rate and faster pace. The Teske/DLR scenarios are not considered classical degrowth scenarios that project decreases in population and energy demand [58–60]. However, both TFED and TPED decline towards 2050 while world population increases. This reflects a further differentiation of the selected scenarios as requested by Raugei [61] for a more differentiated discourse. Figure 4 illustrates the transitioning trend of TPED by sources and scenarios. Figure S1 represents the energy flow involved in the system transition for the LUT-BPSs in 2050. Furthermore, Figure S2 displays the TPED for nine major regions and potential scenarios in the year 2050.

3.2 | Development of Electricity Installed Capacity and Generation

Figure 5 shows the global installed electrical capacity and electricity generation in the explored scenarios. For regional breakdown, refer to Figures S3 and S4. By 2050, solar PV dominates the LUT scenarios in terms of installed capacity (Figure 5, left)

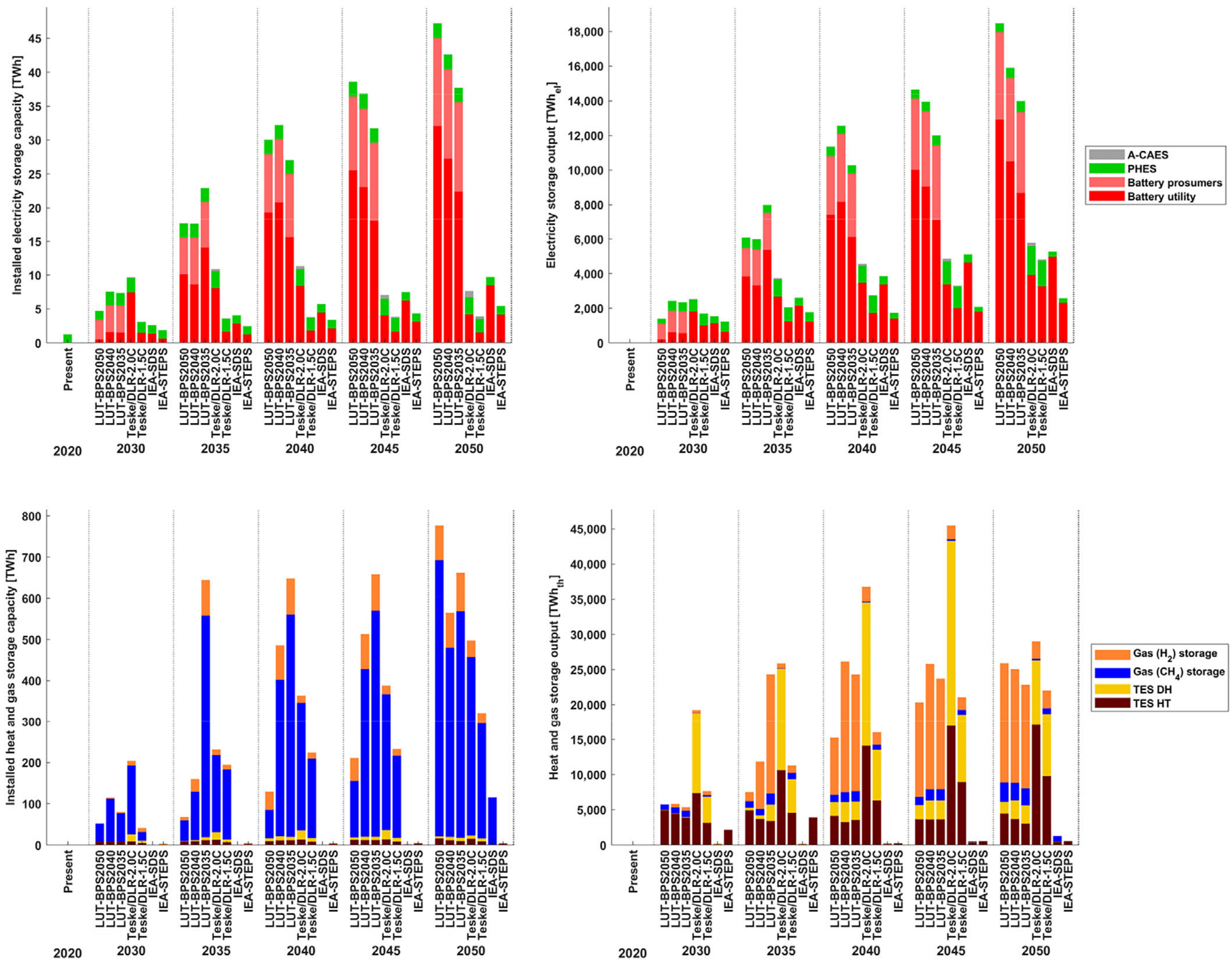

FIGURE 7 | The evolution of installed electricity storage capacity (top left) and output (top right) and installed heat storage capacity (bottom left) and output (bottom right) throughout the transition trajectory for the selected years 2020 (present) and from 2030 to 2050 in 5-year intervals.

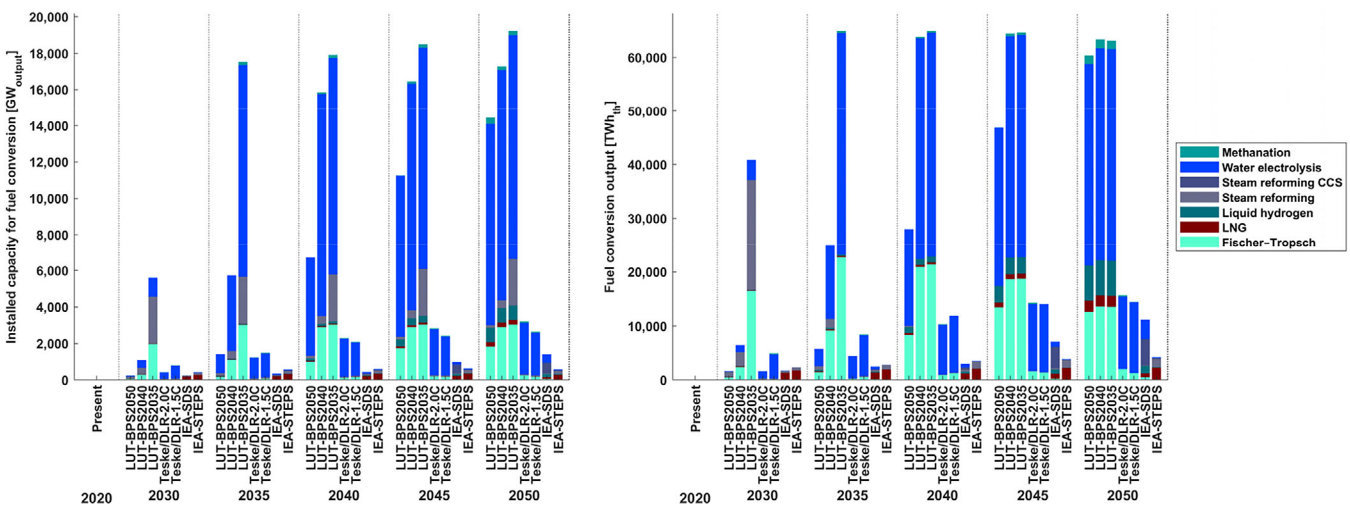

FIGURE 8 | Installed capacity (left) and output (right) for e-fuel production throughout the transition trajectory for the selected years 2020 (present) and from 2030 to 2050 in 5-year time steps.

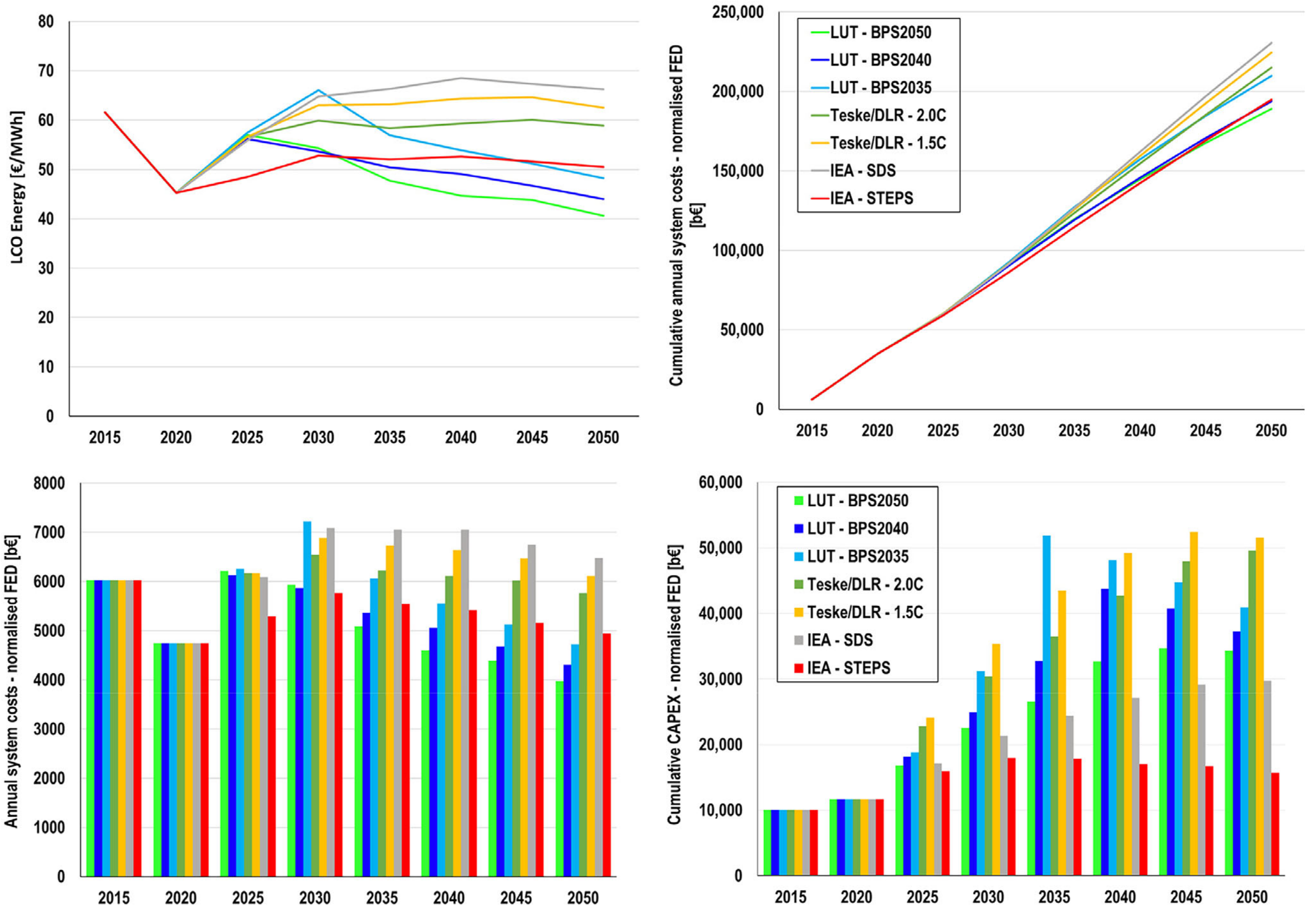

FIGURE 9 | Levelised cost of final energy (LCOFE) (top left), cumulative annual system costs (top right), annual system costs (bottom left), and cumulative capital expenditures (CAPEX; bottom right) normalised based on the total final energy demand of the IEA-SDS.

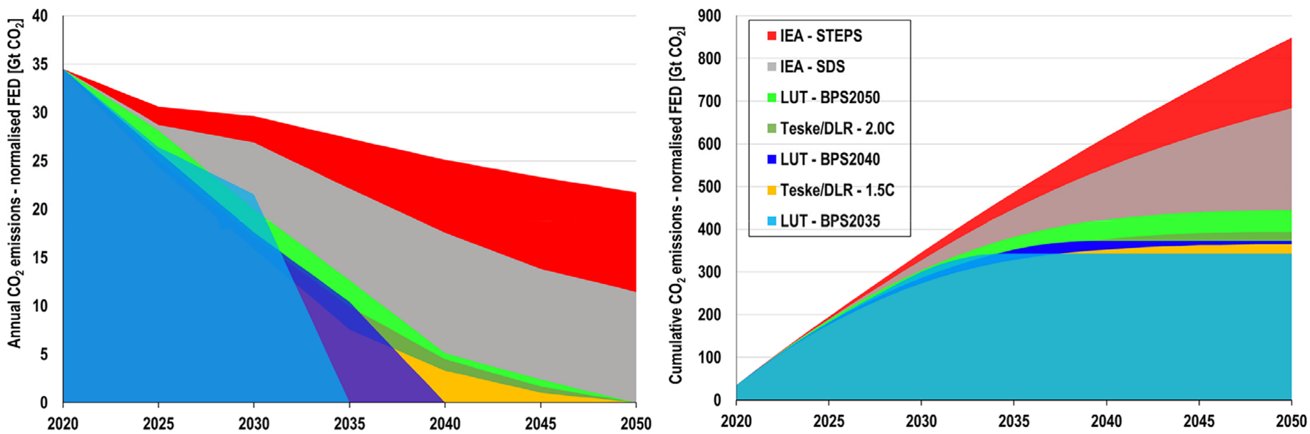

FIGURE 10 | Total annual (left) and cumulative (right) CO_2 emissions estimated globally throughout the transition.

and electricity generation (Figure 5, right), accounting for 77%–83% and 69%–76%, respectively. Wind power follows with a capacity range of 11%–15% and electricity generation of 19%–26%. A cost-optimisation model highlights the importance of technology variation, with single-axis tracking PV being the primary electricity generator and fixed-tilted PV as a complement. The LUT-BPS2035 scenario has a higher installed capacity and electricity generation in 2035 due to RE supplying 100% of global electricity demand. This leads to a higher capacity addition of solar PV and wind power in 2035 compared with the other two BPS scenarios, with wind power contributing more in 2050 due to earlier investments. The reasons for the increased electricity generation in the BPSs are due to greater TFED and a higher rate of electrification across all energy sectors. The use of various RE technologies in the Teske/DLR scenarios may lead to a potentially higher energy diversity and security level [17]. Rooftop solar PV plays a significant role in the electricity generation mix. The IEA scenarios show increased power capacities for nuclear, gas, and coal (with or without CCS). The contribution of fossil fuels is higher in the STEPS than in the SDS, as the former represents the current and future country-specific policies. By 2050, all existing coal power plant capacities in the SDS are either switched to gas power plants or run with CCS units to support emissions reduction efforts. In the NZE-2050, this trend is extended, as unabated fossil electricity generation reaches near-zero levels and renewables reach 88% of all electricity generation in 2050.

3.3 | Development of Heat Installed Capacity and Generation

In the LUT pathways, direct electrification accounts for 73%–76% of heat generation through direct electric heating and heat pumps (Figure 6, right), followed by RE-based fuels including e-hydrogen and e-methane at 18%, solar thermal at 3%–6%, and bioenergy at 2%–3%. The share provided by e-fuels largely covers industrial process heat, which is often required at high temperature levels, while lock-in effects can imply a longer transition phase for direct electricity use. Space heating does not require e-fuels at relevant levels [62]. The CO_2 as raw material needed for e-methane is assumed to be provided by CO_2 direct air capture units. The total installed heat capacity increases from nearly 13.6 TW in 2020 to 14.5-15.1 TW in 2050. Similarly, heat generation rises from about 40 PWh in 2020 to around 50 PWh in 2050 (Figure 6, right). A part of heat generation covers heat demand in the other sectors, such as heat demand for e-fuels in the transport sector. In the Teske/DLR pathways, a higher level of diversification is observed. More investment occurs in direct electrification and solar thermal, accounting for 52%–60% of the total heat generation. The IEA scenarios prioritise diversification but still rely on fossil fuels. The SDS presents a more sustainable mix with higher electrification and RE penetration compared with the STEPS. The NZE-2050 scenario shows the maximum heat pump penetration of IEA scenarios, as 50% of building heating demand is supplied by heat pumps, corresponding to 6.1 TW_{th} of capacity (Figure 6, left). Figure 6 shows the heat installed capacity and generation by scenario throughout the transition. Regional heat capacity and generation in 2050 are provided in Figures S5 and S6, respectively.

3.4 | Energy Storage Capacity and Output

Integration of variable RE leads to increased energy storage capacity and throughput, as demonstrated in Figure 7, particularly for the LUT-BPS pathways. This configuration requires more flexibility to meet hourly electricity demand, which can be fulfilled through energy storage. In the LUT scenarios, battery storage is the primary technology due to the high electrification rate and variable RE penetration, whereas thermal energy storage (TES), hydrogen, and gas storage are essential solutions for flexibility in the Teske/DLR scenarios. Gas storage is mainly used for seasonal variations, while hydrogen storage acts as a buffer. In the Teske/DLR and IEA scenarios, energy storage capacity and throughput were not restricted to the given sources to ensure the LUT-ESTM runs in hourly resolution. For instance, even though adiabatic compressed air energy storage (A-CAES) is not present in the Teske/DLR scenarios, a limited capacity was constructed to guarantee the viability of the simulation.

Batteries dominate the significant ratio of electricity storage output to the total electricity demand, while pumped hydro energy storage (PHES) and A-CAES contribute more noticeably in the Teske/DLR scenarios than in other pathways. PHES works similarly to battery storage in the Teske scenario to cover the hourly demand. However, the LUT-BPS2050 indicates both daily and hourly coverage via PHES. A-CAES operates daily and hourly in the Teske/DLR with a dynamic range throughout the year, while storing excess solar PV generation during the day and discharging it at night in the LUT-BPSs. Heat and gas storage output in the LUT scenarios covers around 23-26 PWh_{th} (Figure 7, bottom right) of total heat demand in 2050. The heat and gas storage output ratio to the total heat demand is mainly dominated by hydrogen storage, with around 23%–27% in 2050 for the LUT scenarios, where the BPS2050 has the largest share. TES is the central storage technology in the Teske/DLR scenarios, followed by hydrogen and gas storage. For the IEA scenarios, no heat or gas storage is reported. However, the model allows building the required capacity and output to match the hourly demand. Consequently, the IEA pathways show a slight heat and gas storage contribution. A breakdown of the regional electricity and heat storage capacities and output is given in Figures S8–S11.

3.5 | Power-to-X Economy

Power-to-X technologies play a vital role in connecting low-cost variable RE and demand across all energy sectors. This is particularly evident in the LUT scenarios depicted in Figure 8. The power-to-X concept has been expanded from gases (e-hydrogen, e-methane) to liquid fuels, chemicals (ammonia, methanol), heat, desalination, and materials (steel, carbon fibres, silicon carbide, etc.) [21, 63, 64]. In the Power-to-X Economy [56] framework, electricity is the dominant primary energy (see Section 3.1), used directly as much as possible and as an energy carrier for heating purposes (power-to-heat as shown in Section 3.3) and mobility in battery-electric road vehicles, trains, ferries, and short-distance air travel, as well as for producing e-fuels and e-chemicals, such as e-hydrogen, e-methane/LNG, and e-liquids, including e-kerosene jet fuel, e-methanol, and e-ammonia. e-Hydrogen is the main component used to transform electricity into the final product required across various sectors (power-to-hydrogen-to-X). From the modelling perspective, such power-to-X routes should be allowed to use excess renewable electricity and allow flexible electrolysis and semi-flexibility of hydrogen-to-X processes, with a notable exception being FT production, which requires high capacity factors.

In the BPS2035, a substantial amount of hydrogen for the Fischer-Tropsch (FT) production comes from steam methane reforming in 2030 (Figure 8, right). This is largely due to a limit on the RE capacity share increase of 20% in every 5-year time step and the earlier integration of FT in comparison with the other LUT scenarios.

In all scenarios, gas storage is needed for seasonal balancing, and hydrogen storage is used as buffer storage for subsequent fuel conversion to the targeted e-fuels. A regional breakdown of hydrogen flows in the year 2050 is presented in Figure S11. In the LUT scenarios, more than half of hydrogen converts into

FT fuels for the transport sector. Meanwhile, in the Teske/DLR pathways, hydrogen is primarily used for heat production. The IEA-SDS shows a diverse range of applications for hydrogen across various sectors, but its contribution is relatively small compared to the more ambitious pathways. In the IEA-NZE2050, hydrogen plays a more pronounced role compared with the modelled IEA scenarios, reaching 19,361 $TWh_{H2,LHV}$ (Figure 8, right), with 50% being used directly, which appears consistent with the trend observed in the IEA-SDS.

3.6 | Economics of Energy Transition Pathways

The LCOFE, shown in Figure 9 (top left) and defined as the total annualised system cost divided by TFED, decreased in 2020 due to a moderate increase in RE and stabilisation of fossil fuel supply compared with 2015. However, if the energy system continues to rely on carbon-intensive solutions and does not introduce structured carbon emissions costs by market mechanisms or policy, investing in RE and selecting the right technologies for the energy transition will eventually come at a higher cost. The LUT scenarios find that least-cost solutions are those with high electrification rates driven mainly by solar PV, wind power, batteries, and renewable power-to-X technologies. On the other hand, the Teske/DLR pathways indicate that achieving a completely sustainable and diversified energy system comes at a higher cost. However, it is still more cost-effective than investing in less proven technologies, such as fossil fuels with CCS and nuclear power, as stated in the IEA-SDS. Notably, however, the IEA-NZE2050 seems to indicate that fossil fuels with CCS will not play a significant role in energy systems aiming for safe climate conditions, though nuclear power's relatively high share may lead this scenario to be less cost-effective.

The costs of each scenario are harmonised by normalising their TFED in reference to the IEA-SDS and applying the calculated ratio to their costs, as shown in Figure 9 (bottom). In terms of investment requirements, the IEA-STEPS has the lowest among the trajectories studied, as it assumes a continuation of current policies without significant changes to the energy system, while upstream investments are not considered in detail despite potentially high investment requirements for continued fossil fuel use [57]. However, the total annual system costs (Figure 9, bottom left) are higher than those of the LUT pathways, despite the lower assumed carbon costs. New nuclear power plants are at risk of cost overruns and long delays [65] and low overall economic attractiveness [66] and are not considered to be an effective measure for climate change mitigation [67], among further issues [68], while thermal power plants, particularly those using coal and gas, may face scheduling issues and could end up as stranded assets [69], also pushed by increasing challenges in providing cooling water [70].

Regarding the cumulative annual system costs (Figure 9, top right), the LUT-BPS2050 shows the least-cost solution. The BPS2040 depicts that an even faster pace of the energy transition would be economically feasible. The BPS2035 is the mid-range scenario cost-wise due to the rapid and radical shift to a 100% RE-based system in a short time horizon. Such a transition would require global coordination for an unprecedented scaling of solar PV and electrolysers, among other power-to-X technologies. Nevertheless, more rapid transition speeds would lead to faster defossilisation, which would lead to more environmentally beneficial outcomes, which may be worth the higher system costs. Both Teske/DLR scenarios show lower cumulative annual costs than the IEA-SDS, but with no nuclear power plants and no fossil fuels (with or without CCS). These pathways suggest that greener energy systems would be more cost-effective than alternatives. Remarkably, the most radical pathway towards 100% renewables for the entire energy system (LUT-BPS2035) is substantially lower in total cost than scenarios lacking respective ambition (IEA-SDS, IEA-STEPS). Figure 9 presents more information on the cost metrics for the explored scenarios. Further details on the regional breakdown of the total annual system cost and LCOFE are shown in Figures S12 and S13, respectively.

3.7 | CO_2 Emissions Perspective

The power sector will likely be the first to fully decarbonise, as illustrated by all pathways, regardless of system configuration or ultimate target. Among all scenarios, the LUT-BPS2035 stands out as the least cost way to keep the global temperature within 1.5°C limits (Figure 10). Despite a higher increase in CO_2 up to 2030 compared with the Teske/DLR-1.5°C (Figure 10, left), its consistent trend towards the end of the transition makes it the most environmentally friendly. The IEA-STEPS shows a marginal decline in CO_2 emissions throughout the transition, highlighting the dire situation humankind may face in the future if governments, policymakers, and large organisations do not take serious action today. Cumulative CO_2 emissions in the STEPS (Figure 9, right) will be around 850 $GtCO_2$ by 2050, which is 2.9 times higher than the BPS2035 (295 $GtCO_2$). Meanwhile, the IEA-SDS performs poorly in reducing annual CO_2 emissions, reaching 11 $GtCO_2$ by 2050. However, it is documented that bioenergy with CCS and direct air carbon capture and sequestration could potentially reduce a portion of CO_2 emissions, reaching 8.2 $GtCO_2$ by 2050. The IEA-NZE2050 scenario, which aims for climate targets similar to the LUT and Teske/DLR-1.5°C scenarios, requires 1.5 $GtCO_2$ of carbon dioxide removal to offset remaining positive emissions. Comparing the cost and CO_2 emission trajectories reveals that the most polluting scenarios are also the highest cost ones, a worst-case combination, while the scenarios following the fastest RE ramping show both the lowest CO_2 emissions and the lowest cost. The changes in CO_2 emissions across all sectors are illustrated in Figure S15.

4 | Discussion

RE is becoming so low cost that even the most progressive energy transition pathway in the presented comparison costs less than a low-ambition fossil-fuelled pathway. The least-cost pathway we identified reaches carbon neutrality by 2050, using low-cost solar PV complemented by continued electrification using efficient power-to-X solutions. It is acknowledged that ramping up all required capacities and infrastructure may face substantial bottlenecks and limitations in industrial capacities, construction, and installation. However, the comparison makes clear that RE is the way forward, and the faster the transition is managed, the lower in cost the energy system will be.

4.1 | Comparison of Global Energy Scenario Trajectories

The low-cost 100% RE system that has been identified has other advantages as well. It can lead to a nearly 92% reduction in air pollution by 2050, preventing tens of millions of lives from being cut short and reducing financial damages by 88.5% [71, 72]. It could decrease global power plant water consumption and water withdrawal by more than 95% by 2050 [70], freeing up water for aquatic ecosystems and food production. Finally, it could provide more energy security [73, 74] and jobs [75].

Solar PV is becoming very low-cost [24], and large amounts of solar PV and wind power have become the new normal [76], even leading to economic CO_2 reduction benefits [77]. A more recent insight is that this can also be the basis for an entire low-cost electricity system [37] and that electricity will play an increasingly dominant role, whether through electrification of demand or e-fuel production [10, 16, 21]. This will impact the electricity system design, both in terms of generation and regarding grid stability and system flexibility.

Creating a scenario with high solar PV penetration that is low cost requires sector coupling and an optimal combination with wind power, batteries, electrolysers, and power-to-X routes in order to reduce storage costs. This makes the LUT scenarios low cost [17]; see also Figure S15. The LUT-BPS2050 scenario has the lowest system LCOFE at 40.6€/MWh in 2050, followed by the BPS2040 at 44.0€/MWh and the BPS2035 at 48.2€/MWh. The main reason the less accelerated scenarios are cheaper is the decreasing cost of RE technologies between 2035 and 2050.

The IEA-SDS is the most expensive scenario with an LCOFE of 66.2€/MWh. The fossil-intensive IEA-STEPS would be even costlier if the same CO_2 emission pricing as for the IEA-SDS had been assumed, indicating that CO_2 pricing should be harmonised across models in the future. An issue in the IEA model pricing is the value-adjusted LCOE as used in its Global Energy and Climate Model [78]. This is supposed to account for inflexibility and low full load hours or variable RE technologies, but when reprocessed in LUT-ESTM it not only leads to lower RE penetration but also higher energy system cost, mainly due to suboptimal use of flexibility options and sector coupling, indicating limitations within the value-adjusted LCOE method. Furthermore, limited power-to-X penetration in the IEA scenarios appears to artificially constrain the growth of variable RE [20], while more bioenergy is required to reach climate targets defined in the IEA normative scenarios [20, 79].

Comparing the CO_2 emissions and total cumulated cost for the pathways of the scenarios reveals massive CO_2 reduction benefits of all 100% RE scenarios compared with the IEA-SDS. The LUT scenarios are 170, 112, and 52€ lower in cost per avoided tonne of CO_2 for the BPS2050, BPS2040, and BPS2035, respectively. Similarly, the Teske/DLR scenarios, which place a higher focus on RE supply diversity, are 155 and 177€ lower. All five 100% RE scenarios phase out CO_2 faster than the IEA scenarios, and all cost less. This amplifies the key finding of an overview study that demonstrated that most climate scenarios fail to reflect sharply decreasing costs in RE, which in turn enables lower-cost climate change mitigation than previously envisaged [80]. Accelerating the energy transition towards high shares of RE reduces both costs and societal risks and, thus, improves social welfare.

4.2 | Role of Power-to-X in Reaching Highly Renewable Energy Systems

According to the LUT scenarios, solar PV is expected to become the primary source of electricity worldwide, comprising around 69%–76% of the total electricity supply by 2050. In comparison with the cost of electricity generation in a power system alone [17], the LUT scenarios show that a highly electrified and RE-based system may be 37%–42% lower in cost. This cost reduction is due to the efficiency of such a system, where excess electricity is converted into e-fuels, stored, or curtailed, and used to meet other demands in various sectors. In the IEA-SDS, solar PV only reaches 30% of total electricity supply in 2050 and has been found to have a maximum share of 37% in the IEA-NZE2050. In these normative IEA scenarios [20], it is identified that for solar PV and wind power, the peak annual additions occur in 2040, which seems to reflect a lack of electrification routes compared to the LUT scenarios. Additionally, there are various untapped applications for solar PV, which potentially can increase the applicability of solar PV in the future. These applications include building-integrated PV, such as rooftops and facades; dual-use infrastructure; for example, parking lot canopies; PV on brownfield sites, including solar farming on unused land; and novel applications, including floating PV systems and agrivoltaics [81–86].

Batteries are the integral electricity storage technology with 95%–97% of total electricity storage output for the LUT scenarios, followed by 89%–94% for the IEA scenarios (but with much less storage capacity and output) and 67% for the Teske/DLR scenarios. In all scenarios, gas storage is needed for seasonal balancing, and hydrogen storage is used as buffer storage for subsequent e-fuel conversion. Power-to-X technologies play a crucial role in connecting low-cost variable RE and demand across all energy sectors, especially in the LUT scenarios. This includes using electricity for heat supply, mobility, e-fuels, and e-chemicals. Costs may be further reduced with international e-fuel trading [87], which was not assumed in this research. Integrating more solar thermal and geothermal energy into TPED reduces the electrification rate in the Teske/DLR scenarios by 36%–41% compared with the LUT scenarios in 2050 and increases the energy system cost. In the STEPS scenario, the electrification rate is even lower at 25%.

As RE becomes a more significant source of electricity generation, curtailment also increases. This can happen whether RE is the primary source of electricity (LUT and Teske/DLR) or just a part of the generation mix (IEA). However, curtailed electricity can provide system flexibility and decrease costs as variable RE sources offer the least-cost solution and are not required to be stored all the time [88]. The range of global average curtailment to electricity generation for the scenarios is between 3%–9% in 2050, as depicted in Figure S16. Differences in assumptions and regional configurations could lead to a higher curtailment in some regions. To reduce curtailment even further, higher spatial resolution can be used to study the regions and transfer excess electricity to where it is needed. Higher curtailment can happen due to existing dispatchable electricity generation, lower electrification rate of the entire energy system, and lack of sufficient energy storage and power-to-X facilities. In the LUT scenarios, excess electricity and heat are recovered, reused, and repurposed for power-to-X processes.

4.3 | Limitations

The first and foremost challenge in replicating scenarios created by fellow researchers is access to detailed data and modelling processes. Requests for increased access to open data, particularly with regard to IEA scenarios, have been growing among researchers [89, 90]. In this study, two scenarios of Teske/DLR were selected that provided extensive data and aimed to reduce CO_2 emissions and transition to a sustainable energy system. However, some assumptions, including some regional restructuring to fit the major region structure used in the LUT-BPSs and allowing for the installation of additional energy storage in reproduced scenarios, had to be made during the data preparation and modelling exercises. Another significant obstacle is balancing supply and demand, especially in a system with massive penetration of variable RE and high temporal resolution. To address this, LUT-ESTM was allowed to build more storage capacity and throughput as needed to ensure the feasibility of the results in hourly resolution.

The input-output data of the Teske/DLR and the IEA scenarios were assigned to LUT-ESTM to examine their hourly performance under the given assumptions and constraints. The IEA scenarios, particularly the STEPS, ran smoothly in the model due to sufficient support of the dispatchable power and heat generation technologies with a minimal need for flexibility options such as energy storage. The Teske/DLR scenarios required much more flexibility due to the high penetration of variable RE, and more simulation iterations were needed to run the scenarios for all nine of the world's major regions successfully in LUT-ESTM.

The model limitations have been discussed in [17]. Meanwhile, this study uses weather data from 2005. Weather year selection and inter-annual variability of RE sources are crucial for integrating large-scale variable RE sources [91, 92]. Inter-annual variability and meteorological conditions should be considered in energy system models to account for potential consequences on variable RE sources. As mentioned earlier, access to detailed input-output data, techno-economic assumptions, and an open access model is also crucial.

Despite the attempt to make models as complete as possible, they cannot include all the elements that may affect the development of the system in the real world. In this specific case, there are several elements that might improve the perspectives of the renewables-based energy transition which have not been included in this study. Among these are flexibility options [93] such as grid interconnections [94], demand-side management [95], smart charging of electric vehicles, and vehicle-to-grid technologies [96]. Integration of chemical feedstock such as e-ammonia [97, 98] and e-methanol [99, 100] can further decrease the direct use of e-hydrogen, which is outside the scope of this study. The IEA scenarios, which have these electricity-based feedstocks enabled [78], tend to maintain usage of fossil oil feedstocks, even in the IEA-NZE2050 scenario.

Other technologies that were not considered are carbon dioxide removal technologies [101, 102] as well as that of solar radiation management [103], which often goes under the general name of "geoengineering" [104]. These technologies are still very much in the development stage, but they might influence the energy transition since they are perceived as able to extend the life of fossil fuels as a significant component of the world's energy mix. At the same time, such technologies, in particular carbon dioxide removal, make sense only if powered by RE; otherwise, their effects would be extremely inefficient if not self-defeating. In any case, modelling the introduction of these technologies in the world is out of scope in the present study.

In this research uniform cost metrics were used, such as weighted average cost of capital, CAPEX and operational expenditures (OPEX). Ideally these are examined at a regional and national level [105, 106], though this should not significantly impact the structural findings since the metrics affect all technologies across a region.

Finally, an important element that was not explicitly modelled in this study is the effect of depletion on the supply of minerals needed for the energy transition. The subject is evidently complex, and it has been the object of several studies [107–110]. The results can be summarised as follows: first, apart from some limited exceptions, there is no evidence that the supply of mineral commodities for RE technologies is constrained by the available resources according to the current estimates [111]. The exceptions are tellurium for CdTe solar PV systems and platinum and other noble metals as catalysts for fuel cells [112]. Neither one is a crucial technology for the transition: fuel cells are mainly thought for road vehicles, but a more efficient and lower-cost technology is that of batteries which do not need noble metals. CdTe PV systems are not needed, as silicon-based PV systems provide an equivalent performance without depletion problems.

In general, it is clear that the energy transition will enormously reduce the burden of extraction costs in comparison to the present situation. Nevertheless, the problem is more subtle than it may appear by comparing the estimated mineral resources to the projected demand for RE infrastructure. The cost of extraction of all minerals varies as a function of gradual depletion, and it tends to increase as the less expensive sources are exploited [113]. In addition, the ramping up of production of some minerals may require large investments which lead to price increases. Even in the case of silicon, an abundant element in Earth's crust, a "bottleneck" developed in 2004 as the result of the need for the industry to invest in new silicon plants. The price for polysilicon reached above 400 USD/kg before it crashed down to 55 USD/kg within 15 months (today, it is around 10 USD/kg). Such bottlenecks are short-lived but may have a disruptive effect on the market. Overall, depletion-related problems can be solved by a combination of flexibility, technology improvements, and careful planning; however, the growth of the RE infrastructure must be done within the limits of what the Earth's ecosystem can sustainably tolerate [114].

5 | Conclusion

This study compares seven different global energy transition scenarios originally developed in three different models:

- LUT: three scenarios (BPS2050, BPS2040, BPS2035).
- Teske/DLR: two scenarios (2.0°C and 1.5°C).
- IEA: two scenarios (STEPS and SDS); excluding the NZE scenario due to insufficient regional data.

All scenarios have been recreated using the LUT Energy System Transition Model (LUT-ESTM) to make comparison possible. The three "native" LUT scenarios use hourly resolved data and an objective function that minimises the annual system costs. For the Teske/DLR and IEA models, the objective function of the original model environment is not used. Instead, the scenarios are recreated in LUT-ESTM, applying the same objective function in a way that matches what is known of the original scenarios as closely as possible, while still matching electricity demand and supply in yearly and hourly intervals.

Dramatic cost declines in renewable electricity and storage and flexibility options throughout the energy system lead the LUT-Best Policy Scenarios to result in the lowest-cost scenarios achieving net-zero emissions as early as 2035. Notably, achieving global net-zero emissions is found to lead to a lower levelised cost of final energy than the fossil fuel-intensive IEA-STEPS, indicating the economic viability of a transition to high shares of renewable energy. Indeed, in terms of levelised system costs, the LUT-Best Policy Scenario reaching net-zero emissions by 2050 leads to the lowest levelised cost of final energy at 40.6€/MWh in 2050, compared to the IEA-SDS, which has the highest levelised costs at 66.2€/MWh. Additionally, the highly renewable energy scenarios shown in this research would lead to significant co-benefits, including reduced air pollution and decreased water required to operate global power systems.

These outcomes highlight the value of scenario intercomparison and reprocessing of various model results under identical financial assumptions. Although the Teske/DLR scenarios lead to higher costs for similar emissions reductions as the LUT-BPSs, the increased costs may be justified in increased system resiliency through diversity of investments. Such scenarios represent a near-cost optimal solution space that, while higher in cost, may have increased societal acceptance. Conversely, limited action towards sustainable energy systems and inaction, as shown in the IEA scenarios, lead to higher system costs than fully renewable energy systems along with the poorest environmental outcomes, with 11-22 $GtCO_2$ of CO_2 emissions in 2050. Thus, a rapid transition to a 100% renewable energy for the entire sector-coupled energy system can be understood to lead to economically optimal and environmentally beneficial futures.

Author Contributions

Arman Aghahosseini: conceptualisation, methodology, investigation, data curation, writing – original draft. **Abebe Asfaw Solomon:** methodology, investigation, data curation, writing – review and editing, resources. **Ugo Bardi:** validation, writing – review and editing. **Felix Creutzig:** validation, writing – review and editing. **Auke Hoekstra:** validation, writing – review and editing. **Mark Z. Jacobson:** validation, writing – review and editing. **Arnulf Jäger-Waldau:** validation, writing – review and editing. **Gabriel Lopez:** writing – review and editing. **Christian Breyer:** conceptualisation, data curation, validation, writing – review and editing, resources, funding acquisition.

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Conflicts of Interest

The authors declare no competing interests.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Document S1: Extended methodology, Tables S1–S9, Figures S1–S16.

Document S2: Extended numerical results by scenario.

Supporting File 1: rpg270225-sup-0001-SuppMat1.pdf.

Supporting File 2: rpg270225-sup-0002-SuppMat2.xlsx.