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Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness

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HIGHLIGHTS

- 9 global transition pathways are analysed for decarbonisation of electricity sector.
- Input-output data of simulation models are remodelled by a cost-optimisation model.
- The least-cost, highly diversified, and business-as-usual pathways are compared.
- Pace, CO_2 costs and energy diversity are found crucial across the scenarios.
- Ambitious paths show competitive costs, ranging between 45.2 and 59.2 €/MWh by 2050.

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ABSTRACT

This study presents a novel energy system modelling approach for the analysis and comparison of global energy transition pathways for the decarbonisation of the electricity sector. The results of the International Energy Agency (IEA), and the Teske/DLR scenarios are each reproduced. Additionally, five new energy transition trajectories, called LUT, are presented. The research examines the feasibility of each scenario across nine major regions in 5-year intervals, from 2015 to 2050, under a uniform modelling environment with identical technical and financial assumptions. The main differences between the energy transition paths are identified across: (1) the average electricity generation costs; (2) energy diversity; (3) system flexibility; (4) energy security; and, (5) transition dynamics. All LUT and Teske/DLR scenarios are transitioned to zero CO_2 emissions and a 100% renewable energy system by 2050 at the latest. Results reveal that the LUT scenarios are the least-cost pathways, while the Teske/DLR scenarios are centred around energy diversity with slightly higher LCOE of around 10–20%. The IEA shares similarities with the Teske/DLR scenarios in terms of energy diversity yet depends on the continued use of fossil fuels with carbon capture and storage, and nuclear power. The IEA scenario based on current governmental policies presents a worst-case situation regarding CO_2 emissions reduction, climate change and overall system costs.

1. Introduction

Global temperature rise and extreme weather events, such as floods, droughts, wildfires and so on, have unceasingly hit new records [1]. If no serious action is taken, yearly mortality rates caused by climate change will be more than that of the COVID-19 pandemic by mid-century [2], while fatalities due to air pollution caused by fossil fuel and unsustainable biomass combustion are in the same order already today [3,4]. The energy system, as one of the main contributors to the climate crisis, accounted for almost 90% of the total carbon dioxide (CO_2) emissions and around 75% of the total greenhouse gas (GHG) emissions in 2018 [5]. This amount is expected to increase if the current situation in the energy system remains unchanged in the decades to come. An investigation into the historical financial performance of energy

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companies revealed that renewable energy (RE) generated higher and better risk-adjusted returns on investment relative to fossil fuels over the last 10 years and showed higher resilience during severe and volatile situations such as the COVID-19 pandemic [6]. Global new investment in the energy transition totalled 755 bUSD in 2021, most of which was spent in the Asia-Pacific region. RE accounted for 366 bUSD, dominated by wind power and solar photovoltaics (PV) installations, followed by electrification of the transport sector with a total of 273 bUSD [7]. Meanwhile, fossil fuels are subsidised with 5900 bUSD annually, which equals 6.8% of the global gross domestic product, and countries underpaying for their fuel consumption hide the full supply chain and environmental costs of these resources, as pointed out by the International Monetary Fund [8,9]. Analysing energy transition pathways is vital to achieve the climate change mitigation target of the Paris Agreement and to decarbonise the global energy system, in particular the electricity sector.

Energy system scenarios allow us to conceptualise future energy systems and to address the challenges and opportunities of managing decarbonisation. These results and insights further help inform policymakers to take more effective decisions within the context of the energy transition. Several global energy system transition scenarios have been carried out by various research groups, institutions and organisations [10–15], as described in Note S1 of the Supplementary Material (SM). Each of these studies has a set of goals and targets to address certain issues, particularly climate change mitigation, air pollution reduction and security of energy supply, which must be reached at some point in time in the future. However, depending on the scenario's definition and the intention of the research work, the final goal varies drastically from one scenario to another. Analysing and comparing scenarios in a as detailed and transparent as possible manner allows to have a clearer vision of the probable situation of energy systems and helps policymakers interpret the outcome of such analyses. In the current study, energy system transition scenarios based on the three following global energy system models are selected:

- The Stated Policy Scenario (STEPS) and the Sustainable Development Scenario (SDS), modelled originally via the World Energy Model (WEM) and led by the International Energy Agency (IEA) [16,17]. The Net Zero Emissions by 2050 (NZE2050) scenario is not included due to lack of data on a regional basis.
- The 2 °C and 1.5 °C scenarios, modelled originally via the [R]E 24/7 and Energy System Model (EM) and led by Sven Teske from the University of Technology Sydney (UTS) and the German Aerospace Center (DLR) et al. [18,19].
- The Best Policy Scenario (BPS) and its derivations (five scenarios in total), modelled by the LUT Energy System Transition Model (LUT-ESTM) and led by Breyer et al. [20,21].

Each of these scenarios aims to assess future energy systems under different assumptions, constraints, and configurations while addressing the impacts of climate change, the need to shift away from fossil fuels, and the necessity of enabling a healthy planet for current and future generations. In the following, the expression transition is mainly used instead of transformation, as the former is typically used for a more comprehensive change including in particular societal dimensions [22].

Although several energy transition pathways with very high penetration of RE have been created and assessed in the last few years [23], there are not many detailed global analyses for all or individual energy sectors. Some studies have made efforts to establish a quantitative comparison of the results of various energy scenario developers [24,25], review different energy tools [26,27], or run energy system models to identify differences across models [27–29]. A comparison between global scenarios is still missing, where all the scenarios are run under an identical modelling environment with similar economic and technical assumptions. Such a comparison is necessary to identify and consistently quantify differences among energy transition pathways and to help stakeholders to better understand the narratives and conclusions of such scenarios. In this regard, our research aims to address the following research questions:

- How do the input and output data of different scenario models perform in one unique model setup, the LUT-ESTM, which is an hourly resolved optimisation model?
- Can the explored pathways perform successfully without drastic adjustments on the body of the scenarios by, for instance, adding extra capacities or generation, in the new framework as proposed and presented in the original models?
- If not, what additional system flexibilities are required to ensure the feasibility of the pathways in the new model and subsequent system-wide impacts? This includes, for instance, power capacities, energy storage, hydrogen and e-fuels.

No study has yet examined key indicators and functionality of previously developed global energy system pathways derived within the context of specific models and assumptions, and in hourly resolution. This can be because the collection, preparation, and processing of data on such a large scale and volume is complex and time-consuming. In addition, there is often limited transparency in the input data for scenario studies and research gaps are filled with different simplifying assumptions that reduce consistency and comparability. There are a number of reasons why this type of techno-economic analysis should be applied to the electricity sector. On a global scale, the electricity sector can be shifted towards 100% RE sooner, potentially as early as 2030 [30], and is often the first sector to be fully decarbonised in government plans and visions [31]. For these reasons, we aim to assess electricity sector transition pathways for various scenarios as follows:

- Firstly, analyse future trajectories for the electricity sector of nine world regions in 5-year intervals, from 2025 to 2050;
- Secondly, collect the relevant input and output data from the deep decarbonisation scenarios created by the IEA and Teske/DLR;
- Thirdly, apply identical technical and financial assumptions for all scenarios and reproduce the scenarios using a unique energy system model (LUT-ESTM);
- Fourthly, evaluate the feasibility of the scenarios in high temporal resolution and compare the results with five novel scenarios modelled with the LUT-ESTM;
- Finally, contrast and compare the different pathways focussing on the calculated electricity costs.

This paper is focussed on results derived from energy system models (ESMs) designed to analyse the global energy transition towards a sustainable future. The LUT-ESTM and the IEA-WEM are categorised as ESMs. Here, there are also two separate archetypes: endogenous and exogenous investment optimisation models [32]. The former is called a myopic optimisation model like the LUT-ESTM [20,21] and the latter is a simulation model like the IEA model [16,17]. The other global decarbonisation scenarios, discussed in detail by Loftus et al. [25], include back-casting methods, such as Teske et al. [19] and Jacobson et al. [4], and top-down integrated assessment modelling (IAMs) approaches, mainly used for the IPCC studies [33]. The focus of this research is on the transition of the electricity sector using a cost-optimisation model. This makes the scenario comparison more attractive by adding the scenarios of the IEA [16,17] and Teske et al. [18,19], which are modelled by a simulation model and a simulation model based on a heuristic technique, respectively.

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

2. Overview of the selected energy system models and scenarios

The sub-sections that follow provide background on the three ESMs and their scenarios.

2.1. IEA

The IEA publishes annually its flagship report, the World Energy Outlook (WEO) [16,34], representing scenarios for the future energy system. Names and definitions of the scenarios have changed over time, and new scenarios have been introduced recently. A scenario that no longer appears in the WEO report is the Current Policies Scenario. The STEPS is now the Business-As-Usual scenario, which considers current governmental policies and strategies. This scenario is included as a reference scenario in the current research. Also, the 450 Scenario has been replaced by the SDS as one of the most ambitious climate change mitigation scenarios. According to the scenario description, the SDS was designed with the intention to achieve net zero emissions by 2070, given some countries will reach this target sooner. Furthermore, major improvements in air quality and access to energy for all is made possible. At the start of 2021, the IEA published for the first time a long-term energy transition pathway called NZE2050 to achieve net-zero CO_2 emissions for the global energy system by 2050. However, the scenario seems to be in its infancy since the figures in the first publication have been just provided for the world and not by regions as in other regular IEA scenarios. This severe limitation blocked that scenario from consideration in this research. A minimum level of regional detail is required to reproduce it. It is expected that the IEA will publish a more comprehensive version of this scenario in the coming years, as many countries will follow and rely on such a scenario for transitioning their energy system.

2.2. Teske/DLR

Teske et al., Teske/DLR from hereafter, has been active in the field of global energy system analysis and scenario creation for more than a decade, from the earliest Greenpeace reports published in 2008/2009 [35], 2010 [36], 2012 [37] and 2015 [38,39] to the latest book and article released in 2019 [18] and 2021 [19], respectively. The research has outlined the long-term energy pathways from a base year to 2050 that appear feasible for deep decarbonisation while complying with defined constraints such as the phase-out of nuclear power, the avoidance of large hydropower and carbon capture and storage (CCS), and the limited use of biomass according to sustainable potentials. The scenario modelling does not follow system cost optimisation, but applies a heuristic multidimensional and diversity-focused approach that incorporates a wide range of new technologies, accounting for potential uncertainties in implementation due to varying regional to local constraints and interests, energy security requirements, and technology acceptance. In the scenarios, Teske/DLR examine power, heat, and fuel supplies with the main focus on the role of efficiency and RE for each of the 10 regions of the world defined according to the IEA. The study released in 2019 [18] also addresses non-energy and non-CO_2 emissions and uses simplified climate modelling to demonstrate compliance with the climate targets of the Paris Agreement in the two transition pathways (2 °C and 1.5 °C). They also assess economic and infrastructural implications in comparison with a 5.0 °C 'reference' scenario.

2.3. LUT

The LUT-ESTM is a cost-optimising ESM that has been used for developing energy transition pathways from a local to a regional to a global scale, which includes sector coupling, uninterrupted hourly resolution, power-to-X, and grid interconnection. The model has been examined for the 9 world major regions and 145 regions, and the global results are published in three peer-reviewed publications [20,21,23]. The first of its kind was modelling a global interconnected electricity system powered by 100% RE for the year 2030 where the impact of long-distance grid interconnections across 9 major regions and 23 sub-regions have been discussed [23]. The findings reveal that there is a small decline in the LCOE by 4%, especially for close neighbouring regions, whereas the electricity trade and further cost reduction could not be found for long-distance grid interconnections. The second publication [20] modelled the 100% renewables-based electricity sector across 145 regions worldwide in 5-year time steps from 2015 to 2050. Finally, the most recent publication [21] focused on transitioning towards a 100% RE system across all energy sectors, including power, heat and transport sectors, for 145 regions from 2015 to 2050. The study also investigates the possibility of producing fresh water through desalination technologies, in particular seawater reverse osmosis in a scenario variation [40]. Further, the amount of new green jobs created as a consequence of such a transition is estimated for the electricity sector [41] and the entire energy system [42], which is driven by the findings in the global energy transition scenarios [20,21].

3. Methods, materials and assumptions

The analysis presented in this article employs the data of two global ESMs, as shown in Table 1 and reproduces their results using the LUT-ESTM in an hourly resolution to capture the complex dynamics of input and output for each scenario developed by the models. Therefore, the feasibility of each scenario in high temporal resolution is evaluated and robust conclusions are drawn. Moreover, the findings are compared with five new scenarios developed using the LUT-ESTM and the differences in terms of techno-economic characteristics are discussed.

In the following scenario comparison, the world is clustered into 9 major regions according to the structure of the LUT-ESTM [20]. The main reason for this regional setup is the accessibility to detailed data also required for hourly modelling for 145 regions in the world that collectively form the 9 major regions. Therefore, the data can be easily

Table 1
Overview of the taken input data from the original sources for the scenario comparison.

Main focus	Energy transition pathways			Governmental policy
Scenarios' data	Teske/DLR-2.0°C	Teske/DLR-1.5°C	IEA-SDS	IEA-STEPS
Electricity generation	☑*	☑*	☑	☑
Installed capacity	☑*	☑*	☑	☑
Share of renewables	☑	☑	☑	☑
Use of hydrogen and e-fuels	☑*	☑*	☐	☐
Energy storage technologies	☑	☑	☑	☑
Role of prosumers	☑	☑	☐	☐
Electricity demand	☑	☑	☑	☑
Load profiles	☐**	☐**	☐**	☐**
RE resource profiles	☐**	☐**	☐**	☐**
Technical assumptions	☐***	☐***	☐	☐
Financial assumptions	☐****	☐****	☐****	☐****
CO_2 price	☑	☑	☑	☑

* Data for solar PV and wind power are modified due to the use of hydrogen and e-fuels in other sectors.
** The profiles used in the LUT scenarios are adopted and normalised based on the corresponding data in the Teske/DLR and the IEA scenarios.
*** Only electrolyser efficiency is taken from the original source.
**** Identical financial assumptions are used as listed in Table S2 of the SM. In addition, the financial assumptions from Teske/DLR are adopted and applied to all scenarios for sensitivity analysis.

expanded or compressed for other studies as well and used to restructure data of different studies. This leads to a consistent comparison of the selected scenarios. The scenarios of IEA and Teske/DLR have an almost similar regional structure with only some differences regarding the countries allocated to each region. Both studies consist of 8 major regions, where data for India and China are provided individually forming 10 major regions in total. Since the detailed data is not available for all the countries/ sub-regions within the major regions, proxies are used to distribute the data while restructuring the regions (Note S2). The regional grouping in the LUT-ESTM and the selected models are shown in Fig. 1. The status of the electricity sector in 2015 and 2020 is evaluated from various datasets and set as the starting years of the transition for all the scenarios.

For Teske/DLR and the IEA scenarios, cost calculations have not directly and predominantly driven technology deployment but were executed in the post-processing to illustrate the overall system costs of the pathways and to make comparison among scenarios. However, the LUT scenarios are cost-optimised for given constraints where the main objective function of the model is to minimise the total annual system cost. This feature allows the model to select the most cost-effective set of technologies throughout the transition based on the technical and financial assumptions listed in Table S2 of the SM. Country and regional data have been aggregated or weighted for 9 major regions in all scenarios. Hourly resource profiles for wind, solar PV, concentrating solar thermal power (CSP) and hydropower are extracted from real weather data and applied to the major regions (see also Note S2). The development of electricity consumption and hourly electricity demand profiles is discussed in Note S3.

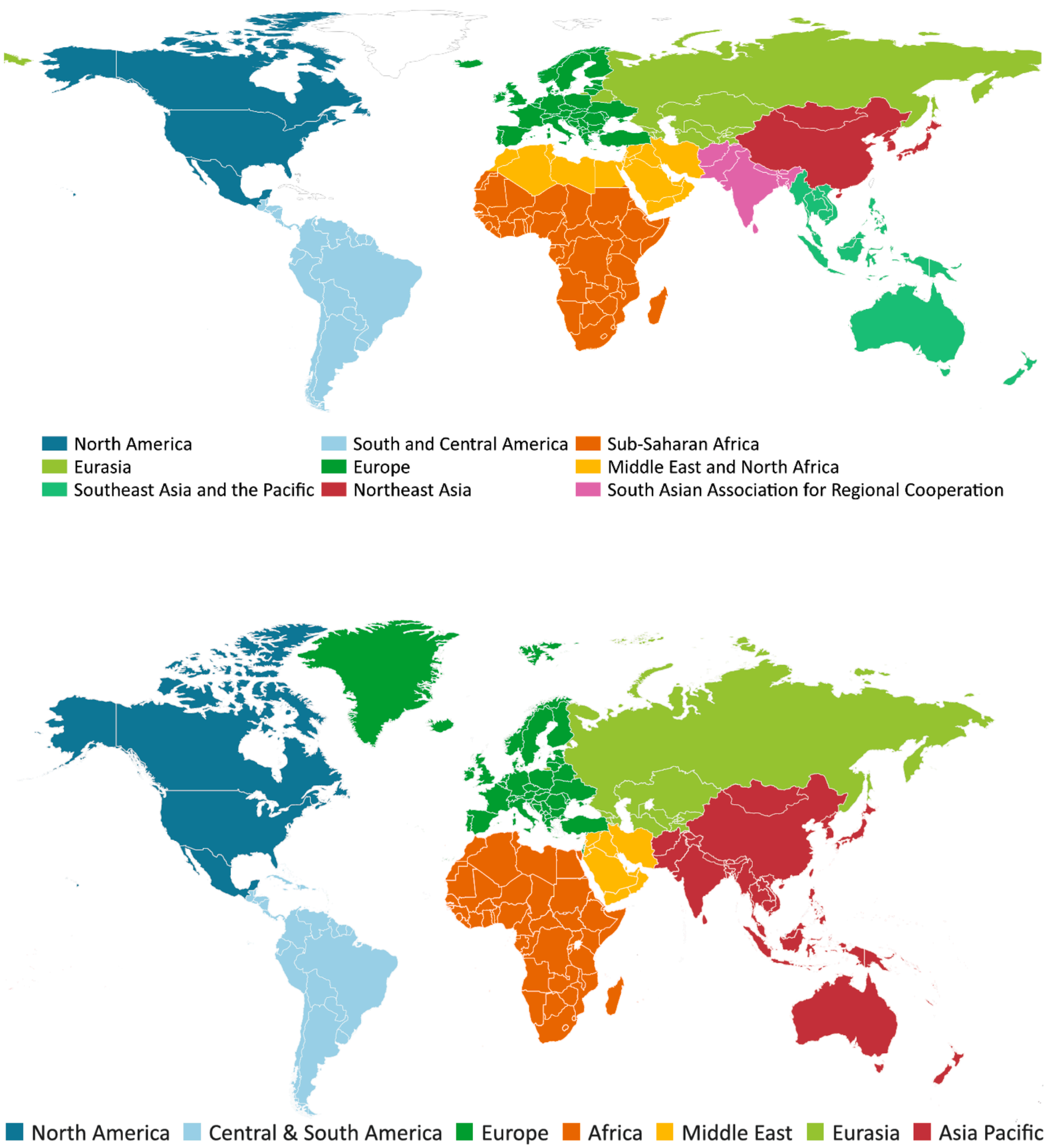

Fig. 1. Regional grouping of the LUT-ESTM (top) and the Teske/DLR and IEA scenarios (bottom) [16]. The countries that are missing in the LUT-ESTM are coloured white.

Both the IEA and the Teske/DLR studies cover all energy demands in buildings, industry, transport and the conversion sectors. Sector coupling, i.e. the interconnection of all energy sectors by achieving a high level of direct and indirect electrification in heating and transportation, allows variable RE to become the new primary energy of the energy system. However, since only the power system is modelled in this research, the potential benefits from sector coupling and high electrification of other sectors are not factored in. In this regard, separating the respective data of other sectors is important to focus on the power system, which required assumptions and modifications as explained in Notes S2-3. Such a separation was more straightforward for the case of IEA as the rate of indirect electrification required for hydrogen and synfuels production is negligible. For the Teske/DLR scenarios, the capacity and generation of solar PV and wind power have been reduced as they are also used for indirect electrification of other sectors, in particular hydrogen and synfuels production. Note S2 provides details for the new electricity generation and capacity estimate after excluding the indirect electricity needed for other sectors.

The fundamental challenge of reproducing other energy system modelling results is access to detailed data, assumptions, constraints, and processes. The selected studies provide sufficient input–output data, as well as a wide range of measures for CO_2 emissions reduction, technological diversity, and transition dynamics that are suitable for comparing long-term energy scenarios for the energy transition. However, further assumptions and modifications are still needed to fulfil the requirements, such as proxies applied to make the regional data comparable. The LUT-ESTM was forced to take the exact capacity and generation provided in the sources to replicate the same results by adding several constraints to control the capacity expansion and retirements as well as the required full load hour (FLH) for electricity generation. This is because, based on the present fast-declining costs of renewable energy [43], the model will not build sufficient additional fossil fuel capacities even when not constrained requiring additional enforcing as applied in [44,45] for scenarios with a lower share of RE. Therefore, the best way to examine the role of slow(er) transition pathways, relying on fossil fuels (with and without CCS) and nuclear power, in an optimisation modelling framework such as the LUT-ESTM was to force the construction of the minimum installed capacities of those technologies. In addition, the cost-optimised model is allowed to provide additional flexibility, if needed, by choosing the least-cost solutions for the IEA and Teske/DLR scenarios. Another challenge is to balance generation and demand, especially in hourly resolved data with high penetration of RE. To ensure the technical feasibility of the Teske/DLR and the IEA scenarios in the LUT-ESTM in hourly resolution, energy storage was not limited to the given capacity and throughput in the respective sources. Instead, the values were set as the minimum constraints with the possibility of further expansion. This might translate to higher numbers than given in the sources. Utility-scale batteries and pumped hydro energy storage (PHES) for all scenarios and hydrogen storage for the Teske/DLR scenarios were part of the solution. The selection of energy storage options is executed via cost optimisation to reduce the burden on the final energy system costs.

Table 2 lists the scenarios chosen for this study and further description regarding the scenarios provided in Note S4. Tables S2-S7 in the SM include detailed technical and cost assumptions considered for this analysis in a harmonised way. Further description of the model setup, including the main equations and system flow chart, is provided in Note S5 of the SM.

4. Results

4.1. Development of electricity generation capacity and supply

Fig. 2 illustrates the transition pathways in terms of global electricity generation capacity and electricity supply in the explored scenarios. Fig. 3 shows the electricity generation mix and RE penetration to the total electricity generation by scenarios throughout the transition. The respective figures on a regional basis are provided in Figures S2 and S3 of the SM.

As shown, solar PV dominates all the LUT-BPS scenarios by 2050 in terms of both installed capacity and electricity generation, followed by wind power. Regarding the installed capacity, solar PV grows from around 0.6 TW at the beginning of 2020 to 19.7 – 26.3 TW in 2050, depending on the scenarios. This drastic increase accounts for 58 – 79% of the total electricity generation in 2050 and depicts a compound annual growth rate (CAGR) of 13 – 14% over the transition period. Utility-scale fixed-tilted solar PV systems experience a gradual increase from nearly 500 GW in 2020 to about 2170 GW by 2050. Single-axis tracking PV capacities soar rapidly with a CAGR of 14% and reach 11.7 TW by 2050, as the lower cost option. Similarly, PV prosumers surge throughout the transition reaching about 11.2 TW by 2050. Very high shares of solar PV electricity are also found by other researchers in the same range [10,15,48]. Other RE sources, such as hydropower and bioenergy, complement solar and wind energy during the transition but with more restricted expansion due to limited resource potential. Higher installed capacity and electricity generation of the LUT-BPS-Plus2030 scenario in 2030 is due to the requirement to supply the global electricity demand via 100% RE. This leads to a higher capacity addition of solar PV and more utilisation of energy storage in 2030 as compared to the other two BPS-Plus scenarios. Maintaining and repowering installed wind power capacity at the end of the technical lifetime provides further flexibility in the electricity system and decreases the overall system costs. This phenomenon can be understood by comparing the LUT-BPS-NWF and the LUT-BPS-WF scenario. In the LUT-BPS-NWF scenario, the wind power capacity is partially decommissioned and the installed capacity decreases from 4072 GW in 2045 to 1478 GW in 2050, as strict cost optimisation is considered. Whereas, in the LUT-BPS-WF scenario, the wind power capacity is repowered by setting the value of the year 2045 (4663 GW) as a minimum capacity that must be installed in 2050. Consequently, the wind capacity remains unchanged, which partially declines the need for additionally installed capacity of solar PV and battery storage. Further, the capacities of fossil fuel-based power generation plummet mostly in the first half of the transition trajectory and gas turbines switch from fossil methane to e-methane or biomethane towards the end of the transition.

In the Teske/DLR scenarios, the deployment of various RE technologies shows a higher level of diversity compared to other scenarios of fully sustainable energy systems which are mainly based on solar and wind energy. PV and wind power amount to approximately 58% of the electricity generation by 2050 with an almost equal contribution in both the Teske/DLR scenarios, followed by CSP (15%), hydropower (9%), bioenergy and geothermal (6% each), renewable gas (5%) and ocean energy (2%). Biomass- and geothermal-based combined heat and power (CHP) plants additionally provide renewable heat, which indicates the importance of sector coupling and synergies between different sectors in modelling the entire energy systems. Nuclear power capacity is phased out earlier than according to its technical lifetime. This reflects the current situation as many nuclear power plants are being decommissioned earlier than planned [49]. In the Teske/DLR scenarios, hydropower shows a steady growth over the transition period accounting for about 10% of the electricity generation, which is in line with the results of the LUT scenarios. However, the role of CSP, bioenergy and geothermal as dispatchable RE sources that provide further flexibility in the system is more significant. (Figures S6 and S7).

The IEA scenarios are, due to different narratives and lower climate protection targets, the only scenarios with an increase in nuclear power capacity, as well as fossil methane and coal power plants with and without CCS. The contribution of fossil fuels is much higher in the STEPS than the SDS as the former represents the current and future countries-specific policies. From 2040 onwards, all the existing coal-fired power plant capacities in the SDS are either switched to fossil gas power plants or run with CCS units, to support emissions reduction efforts. The SDS as

Table 2
The key features, targets, and assumptions of the modelled scenarios. Abbreviations: BPS: Best Policy Scenario; TES: thermal energy storage; PHES: pumped hydro energy storage; A-CAES: adiabatic compressed air energy storage; PtG: power-to-gas; UN SDGs: United Nations Sustainable Development Goals.

	LUT					Teske/DLR		IEA	
Scenarios	**BPS-NWF**	**BPS-WF**	**BPS-Plus2040**	**BPS-Plus2035**	**BPS-Plus2030**	**2.0°C**	**1.5°C**	**SDS**	**STEPS**
Goals	Aims to reach a zero CO_2 emissions target by **2050**. Main objective function is to minimise the total annual system costs.	Aims to reach a zero CO_2 emissions target by **2050**. Main objective function is to minimise the total annual system costs.	Aims to reach a zero CO_2 emissions target by **2040**. Main objective function is to minimise the total annual system costs.	Aims to reach a zero CO_2 emissions target by **2035**. Main objective function is to minimise the total annual system costs.	Aims to reach a zero CO_2 emissions target by **2030**. Main objective function is to minimise the total annual system costs.	Aims to achieve a zero CO_2 emissions target by **2050** while allowing for some delays due to political, economic, and societal processes and stakeholders.	Aims to achieve a zero CO_2 emissions target by **2050** without considering political or societal barriers. Renewables and efficiency measures need to be deployed faster than 2.0°C.	Focus on necessary actions to achieve UN SDGs (7, 3.9 and 13) [46], Paris Agreement [47] targets and air pollution reduction. Near-term investments in clean energy.	Based on today's policy setup and all governments' targets for the future. Aims to provide a benchmark to assess the potential achievements of the recent development in energy and climate policy.
Simulation/ optimisation periods[1]	2015-2050	2015-2050	2015-2050	2015-2050	2015-2050	2015-2050[2]	2015-2050	2015-2050[3]	2015-2050
Model type	Optimisation	Optimisation	Optimisation	Optimisation	Optimisation	Simulation	Simulation	Simulation	Simulation
Temporal resolution	Hourly	Hourly	Hourly	Hourly	Hourly	Annual/ Hourly (for the electricity sector)	Annual/ Hourly (for the electricity sector)	Annual/ Hourly (partially)	Annual/ Hourly (partially)
Energy sector[4]	Electricity sector	Electricity sector	Electricity sector	Electricity sector	Electricity sector	Electricity sector	Electricity sector	Electricity sector	Electricity sector
Fossil fuels	Historical capacity will be decommissioned based on the technical lifetime. No new fossil fuels capacity addition throughout the transition.	Historical capacity will be decommissioned based on the technical lifetime. No new fossil fuels capacity addition throughout the transition.	Historical capacity will be decommissioned based on the technical lifetime. No new fossil fuels capacity addition throughout the transition.	Historical capacity will be decommissioned based on the technical lifetime. No new fossil fuels capacity addition throughout the transition.	Historical capacity will be decommissioned based on the technical lifetime. No new fossil fuels capacity addition throughout the transition.	No new fossil fuels capacity addition throughout the transition due to the carbon budget limitation.	No new fossil fuels capacity addition throughout the transition due to the carbon budget limitation.	Global coal and oil use decline more significantly compared to the STEPS[5]. Higher utilisation of fossil methane, but less CAGR[6] than STEPS.	Global coal and oil use decline. Higher utilisation of fossil methane.
Fossil fuels + CCS	-	-	-	-	-	-	-	Considerable contribution of gas and coal CCS.	Small contribution of gas and coal CCS.
Nuclear	Historical capacity will be decommissioned based on the technical lifetime. Current capacity, if not retired, will run until the end of the transition.	Historical capacity will be decommissioned based on the technical lifetime. Current capacity, if not retired, will run until the end of the transition.	Historical capacity will be decommissioned based on the technical lifetime. Current capacity, if not retired, will run until the end of the transition.	Historical capacity will be decommissioned based on the technical lifetime. Current capacity, if not retired, will run until the end of the transition.	Historical capacity will be decommissioned based on the technical lifetime. Current capacity, if not retired, will run until the end of the transition.	No new nuclear power capacity addition throughout the transition.	No new nuclear power capacity addition throughout the transition.	Increase in nuclear power capacity throughout the transition (25% more than STEPS in 2040).	Increase in nuclear power capacity throughout the transition.
RE	Optimal installed capacity of RE based on their technical and sustainable potential.	Optimal installed capacity of RE based on their technical and sustainable potential. Wind energy once installed capacity to be repowered.	Optimal installed capacity of RE based on their technical and sustainable potential. Wind energy once installed capacity to be repowered.	Optimal installed capacity of RE based on their technical and sustainable potential. Wind energy once installed capacity to be repowered.	Optimal installed capacity of RE based on their technical and sustainable potential. Wind energy once installed capacity to be repowered.	Solar and wind energy have the highest economic potential and dominate the pathway. They are limited to a maximum of 65%. CSP with TES plays	Solar and wind energy have the highest economic potential and dominate the pathway. They are limited to a maximum of 65%. CSP with TES	Fast deployment of clean energy technologies. Solar PV is leading the change and becomes the new king of electricity supply (capacity grows by about	High levels of solar PV deployment, but there is sufficient potential for more rapid growth due to falling costs and policy support.

(*continued on next page*)

Table 2 (*continued*)

	LUT					Teske/DLR		IEA	
Scenarios	**BPS-NWF**	**BPS-WF**	**BPS-Plus2040**	**BPS-Plus2035**	**BPS-Plus2030**	**2.0°C**	**1.5°C**	**SDS**	**STEPS**
						a role to provide energy security and dispatchable power generation.	plays a role to provide energy security and dispatchable power generation.	12% per year). Solar and wind generation increases from 8% in 2019 to 30% in 2030.	
Energy storage	Optimal installed capacity (utility-scale battery, prosumer battery, PHES, A-CAES, TES, gas, biogas, and hydrogen storage.	Optimal installed capacity (utility-scale battery, prosumer battery, PHES, A-CAES, TES, gas, biogas, and hydrogen storage.	Optimal installed capacity (utility-scale battery, prosumer battery, PHES, A-CAES, TES, gas, biogas, and hydrogen storage.	Optimal installed capacity (utility-scale battery, prosumer battery, PHES, A-CAES, TES, gas, biogas, and hydrogen storage.	Optimal installed capacity (utility-scale battery, prosumer battery, PHES, A-CAES, TES, gas, biogas, and hydrogen storage.	Utility-scale battery, PHES, TES, and hydrogen storage.	Utility-scale battery, PHES, TES, and hydrogen storage.	Utility-scale battery, PHES, and TES.	Utility-scale battery, PHES, and TES.
Hydrogen/ e-fuels for reconversion into electricity	e-methane via PtG and biomethane	e-methane via PtG and biomethane	e-methane via PtG and biomethane	e-methane via PtG and biomethane	e-methane via PtG and biomethane	Hydrogen	Hydrogen	-	-
CO_2 emissions	Zero CO_2 emissions by 2050	Zero CO_2 emissions by 2050	Zero CO_2 emissions by 2040	Zero CO_2 emissions by 2035	Zero CO_2 emissions by 2030	Zero CO_2 emissions by 2050 and carbon budget	Zero CO_2 emissions by 2050 and carbon budget	CO_2 emissions reduction of 90% in the power sector by 2050 in reference to 2020 (estimated)	CO_2 emissions reduction of 15% in the power sector by 2050 in reference to 2020 (estimated)

[1]Data for the years 2015 and 2020 are uniform for all analysed scenarios.
[2]The presented years in the book are 2015, 2025, 2030, 2040 and 2050. Data for missing years were interpolated.
[3]The presented years in the report are 2018, 2025, 2030 and 2040. Data for missing years were interpolated or extrapolated. The target for reaching a net zero emissions world is set to the year 2070 although the data are given up to 2040.
[4]In the original references of the IEA and Teske/DLR, all energy sectors have been included and modelled. For the current study, however, the data are adjusted to focus only on the electricity sector.
[5]Existing coal-fired power plants, for example, are either retrofitted, repurposed or decommissioned in the SDS to halve coal-fired emissions by 2030.
[6]CAGR = Compound Annual Growth Rate.

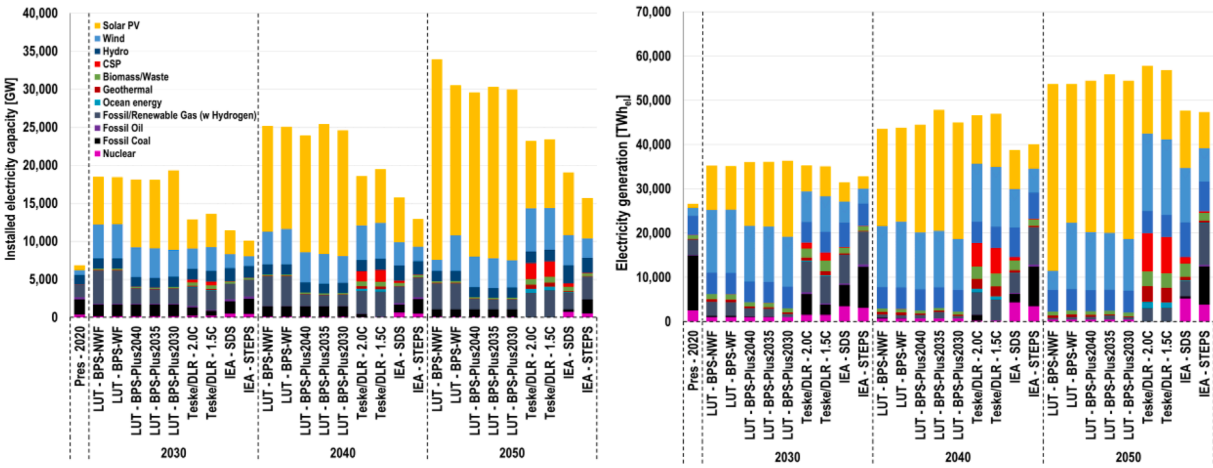

Fig. 2. Development of installed power capacity (left) and electricity generation (right) throughout the transition trajectory, for the selected years 2020 (present), 2030, 2040 and 2050.

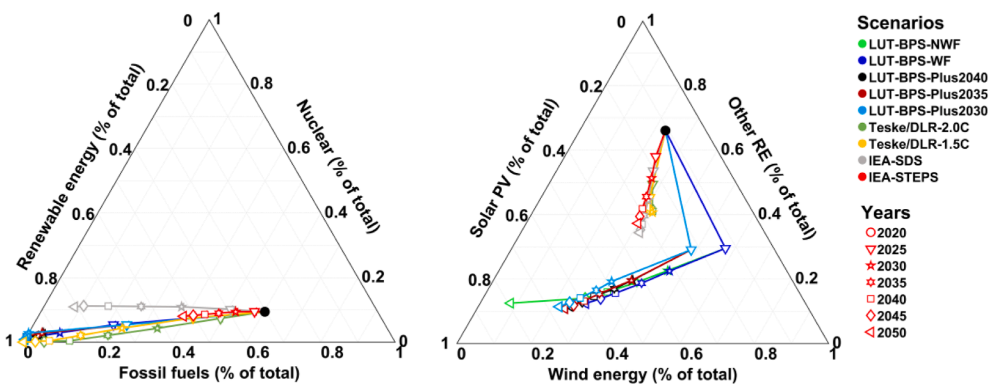

Fig. 3. Ternary plots for the electricity generation mix (left) and RE generation mix (right) per transition pathways. The total relative numbers add up to 1, meaning 100% of the total electricity generation (left) and 100% of the total RE generation (right). Fossil fuels include electricity generation with and without CCS. Other RE consists of hydropower, bioenergy, CSP, ocean power, geothermal energy and renewable gas including hydrogen. Black circles indicate the starting points in 2020. Markers are placed in every 5-year intervals from 2020 to 2050 to illustrate transition paths and their dynamics. See also Figures S2 and S3 in the SM.

the climate-friendly scenario of the IEA pushes for higher installation of solar PV and wind energy towards the end of the transition, accounting for a slightly more than half of the electricity generation in 2050. RE installed capacity increases from around 36% in 2020 to 81% by 2050. Nuclear power generation lifts from about 2500 TWh in 2020 to 5200 TWh by 2050, and the contribution to total electricity generation remains almost constant throughout the transition (11%). It is worthwhile to note that this scenario aims to be fully carbon–neutral by 2070, thus relying on some fossil fuels, roughly 9%, for the electricity supply in 2050 from which 70% is without CCS technology. A sample of hourly time series for the LUT-BPS-Plus2040 representing all the components contributing to the electricity generation and demand for the year 2050 is provided in the SM 2.

4.2. Economics of energy transition pathways

Owing to the fundamental shift in the energy system structure and technological improvement in the CO_2 emissions mitigation scenarios, the global average levelised cost of electricity (LCOE) decreases from 70.9 €/MWh in 2015 to 45.2 – 49.7 €/MWh for the LUT-BPS scenarios, to 53.9 – 54.1 €/MWh for the Teske/DLR scenarios, and to 59.2 – 69.5 €/MWh for the IEA scenarios in 2050. As shown in Fig. 4 (top left), the LCOE experiences a temporary fluctuation at the beginning of the transition with a drop in 2020 due to a moderate increase in RE and stabilising fossil fuel-based electricity generation compared to 2015, followed by a quick jump in 2025 because of new investments required for the structural and systematic change as well as higher CO_2 costs. The difference between scenarios' LCOE is more profound in 2030, especially for the LUT scenarios, due to a faster pace of the transition. Thanks to the RE development and deployment as well as relatively low carbon prices assumed in the IEA-STEPS scenario, even the most pessimistic scenario shows a gradual cost reduction despite holding a high share of fossil fuels by 2050. However, it is quite clear that a 100% RE-based scenario is the least-cost energy transition pathway to bring CO_2 emissions down to zero by 2050 or even earlier.

The LCOE for the LUT-BPS-Plus2040 and the LUT-BPS-Plus2030 declines neck-and-neck throughout the transition representing the lowest LCOE at 45 €/MWh by 2050 compared with the other scenarios. Regarding the cumulative pathway costs, the LUT-BPS-Plus2030 indicates that even a rapid and radical transition to a 100% RE-based power system is technically and economically feasible. This scenario setup shows the least-cost solution with regards to the cumulative annual cost among all scenarios although it requires immediate and effective actions by policymakers to make it possible. Additionally, repowering wind capacity in the BPS-WF compared to the BPS-NWF reduced the total annual system cost and the LCOE by 141b€ (6%) and 2.9 €/MWh (6%), respectively. All the LUT scenarios depict almost the same downward trend in cost despite different assumptions, dynamics, and constraints.

The IEA-STEPS scenario requires the least investments compared to any other scenario since there is no drastic change in the electricity system by continuing the current policy of the countries with some modest modifications (Figure S9). The impact of slow transition and continued dependency on fossil fuels can be observed in the total annual system costs, particularly as it gets closer to the mid-century (Fig. 4). The impact of a higher CO_2 pricing on the IEA-SDS scenario results in much higher LCOE at the beginning of the transition than for the IEA-STEPS, and it becomes cheaper towards the end of the trajectory as the share

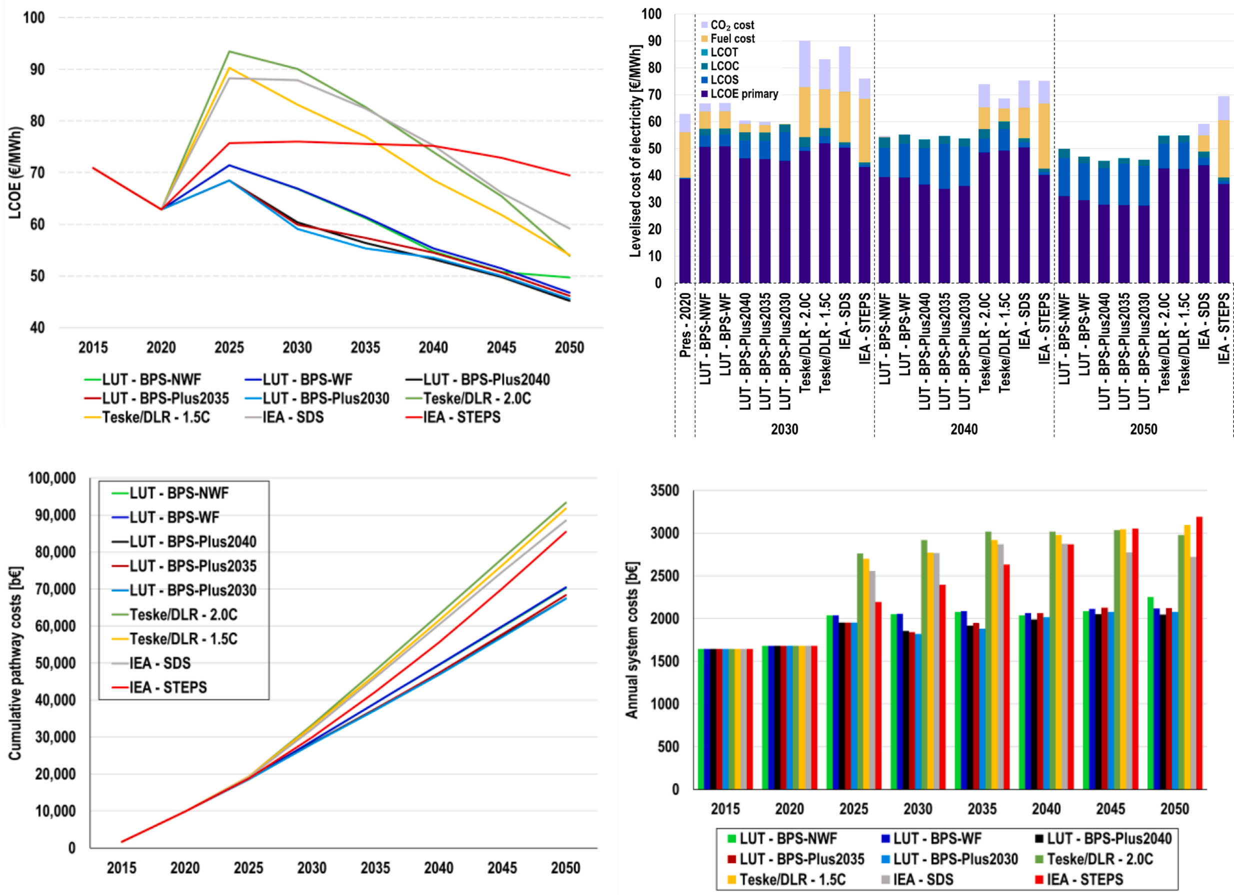

Fig. 4. Evolution of the electricity system cost in the studied scenarios, LCOE throughout the transition pathways from 2015 to 2050 (top left), LCOE with the key components for the present and future years (top right), cumulative pathway cost during the transition (bottom left) and annual system cost (bottom right). The respective values for the annual cost and the cumulative annual cost are normalised based on the electricity consumption of the IEA-SDS across all the scenarios for comparability of absolute values.

of renewables soars.

The Teske/DLR scenarios show similar trends regarding the development of the LCOE and cumulative pathway costs to the IEA-SDS scenario. This translates to a sustainable energy system with zero CO_2 emissions with LCOE just slightly lower than a system relying on fossil fuels (with or without CCS) and nuclear power. Further, using the untapped potential of other RE sources than solar PV and wind, where available, can contribute to the security of the energy supply in the long term. In addition, the Teske/DLR scenarios depict that shifting away from fossil fuels at faster or slower pace would cost approximately the same, provided that energy consumption in the coming years can be reduced somewhat more on the 1.5 °C path. This makes the rapid shift towards a 100% RE system more attractive due to less CO_2 emissions, less air pollution and reduced nuclear accident risk. Both scenarios have lower LCOE by 2050 than the current energy system. Similar findings have been identified for the LUT-BPS scenarios and to a lower degree for the IEA-SDS.

The cumulative pathway cost is normalised to the electricity consumption of the IEA-SDS across all the scenarios due to different assumptions regarding the development of annual electricity consumption. Table S8 compares the cumulative pathway cost across all the scenarios. In this regard, the LUT scenarios are approximately 18 – 28% lower in cost than other scenarios. With respect to the LCOE, The LUT-BPS-Plus2030 is the least-cost pathway with a lower cost of about 21 – 28% than the IEA and the Teske/DLR scenarios and around 0.1 – 4% than the other LUT-BPS scenarios by 2050. This is mainly due to the faster pace of RE growth rate and the phase-out of fossil fuels by 2030. In terms of the total annual cost, capital expenditures (CAPEX) and LCOE, the LUT-BPS-Plus2040 is even a bit lower in cost as the LUT-BPS-Plus2030 scenario requires more investment in RE, energy storage and electrolysis capacity in 2030 to be carbon–neutral. Thus, the CAPEX of this scenario is higher than that in the BPS-Plus2040, while the LCOE is lower due to less CO_2 and fuel costs. Moreover, the curtailment is more efficiently managed thanks to the extra battery storage capacity to support the massive solar PV penetration in the BPS-Plus 2030 scenario (see Section 4.3). The results, therefore, confirm that RE penetration, curtailment, and storage flexibility are interdependent and also a function of relative cost [50].

By the end of the transition, the IEA-STEPS has the highest cost per MWh of electricity generated, as can be seen in Table 3. It should be noted that the lowest CO_2 pricing is applied for the IEA-STEPS (Table S6), yet the scenario is around 10.3 – 24.3 €/MWh (17 – 54%) more expensive than the other pathways mainly due to noticeable fossil fuels remained in 2050. The Teske/DLR-2.0 °C scenario costs the most in terms of the cumulative pathway cost, accounting for 38% higher cost than the BPS-Plus2030. The main reasons are higher technology costs due to diversification and higher CO_2 emissions and its associated costs. Besides, the IEA-SDS scenario, having a lower electricity generation due to less integration of variable RE and energy storage, thus less curtailment, results in 3 – 5% lower costs than the Teske/DLR scenarios with identical CO_2 costs. This is despite the negative social and environmental impacts as well as air pollution associated with fossil CCS and nuclear power in the IEA-SDS [51–55]. Consequently, the Teske/DLR scenarios have the LCOE of about 5.1 – 5.3 €/MWh lower than the IEA-SDS in 2050. A very low CO_2 pricing assumption can make an energy system relying on fossil fuels, IEA-STEPS, cost competitive over a long-

Table 3
Comparison of LCOE by scenario for the year 2050 in percent; The '+' sign shows higher cost, and the '-' sign stands for a lower cost. Every scenario in each row is compared with the corresponding scenarios in the columns.

		LUT-BPS					Teske/DLR		IEA	
		NWF	WF	Plus2040	Plus2035	Plus2030	2.0°C	1.5°C	SDS	STEPS
LUT-BPS	NWF		−5.9%	−9.1%	−7.1%	−8.3%	8.5%	8.8%	19.0%	39.9%
	WF			−3.4%	−1.3%	−2.6%	15.2%	15.6%	26.5%	48.6%
	Plus2040				2.2%	0.9%	19.3%	19.7%	31.0%	53.9%
	Plus2035					−1.3%	16.7%	17.1%	28.1%	50.5%
	Plus2030						18.3%	18.7%	29.8%	52.5%
Teske/DLR	2.0°C							0.3%	9.8%	29.0%
	1.5°C								9.4%	28.5%
IEA	SDS									17.5%
	STEPS									

run compared to a system with significantly higher penetration of RE and CO_2 pricing, Teske/DLR. However, the former contains many socio-environmental side effects and the respective costs of externalities, such as air pollution morbidity and mortality, water pollution, and other non-health environmental impacts, that remain until the end of the transition horizon. These effects are not fully factored in for this research.

4.3. System flexibility in hourly modelling of electricity systems

Energy storage is found crucial in carbon–neutral scenarios for the hours when variable RE sources are not sufficiently available to meet demand (Fig. 5). Another option to ensure the viability of a highly RE-based electricity system is the complementarity between RE sources, especially related to a large geographical region with seasonal variation such as Europe. Employing various RE options in the final electricity generation mix can significantly reduce the need for storage, curtailment, and electrolysis capacity for hydrogen generation. Different combinations of technologies can provide high reliability of supply in this context, especially given favourable local boundary conditions. For example, CSP together with thermal energy storage (TES) can provide high security of supply, but also PV and wind power plants together with short-term battery storage can achieve comparably high flexibility. Using a wide range of RE sources to support the energy security aspect might increase the overall system cost, as observed in Fig. 4. On the other hand, diversity may reduce possible societal, structural and economic risks of the energy transition. Some argue that coupling nuclear power and fossil CCS in the transition pathways with high penetration of RE can be another viable option for controllability and flexibility in the electricity supply due to the dispatchability of these technologies [33,56]. However, one of the main disadvantages of such a combination

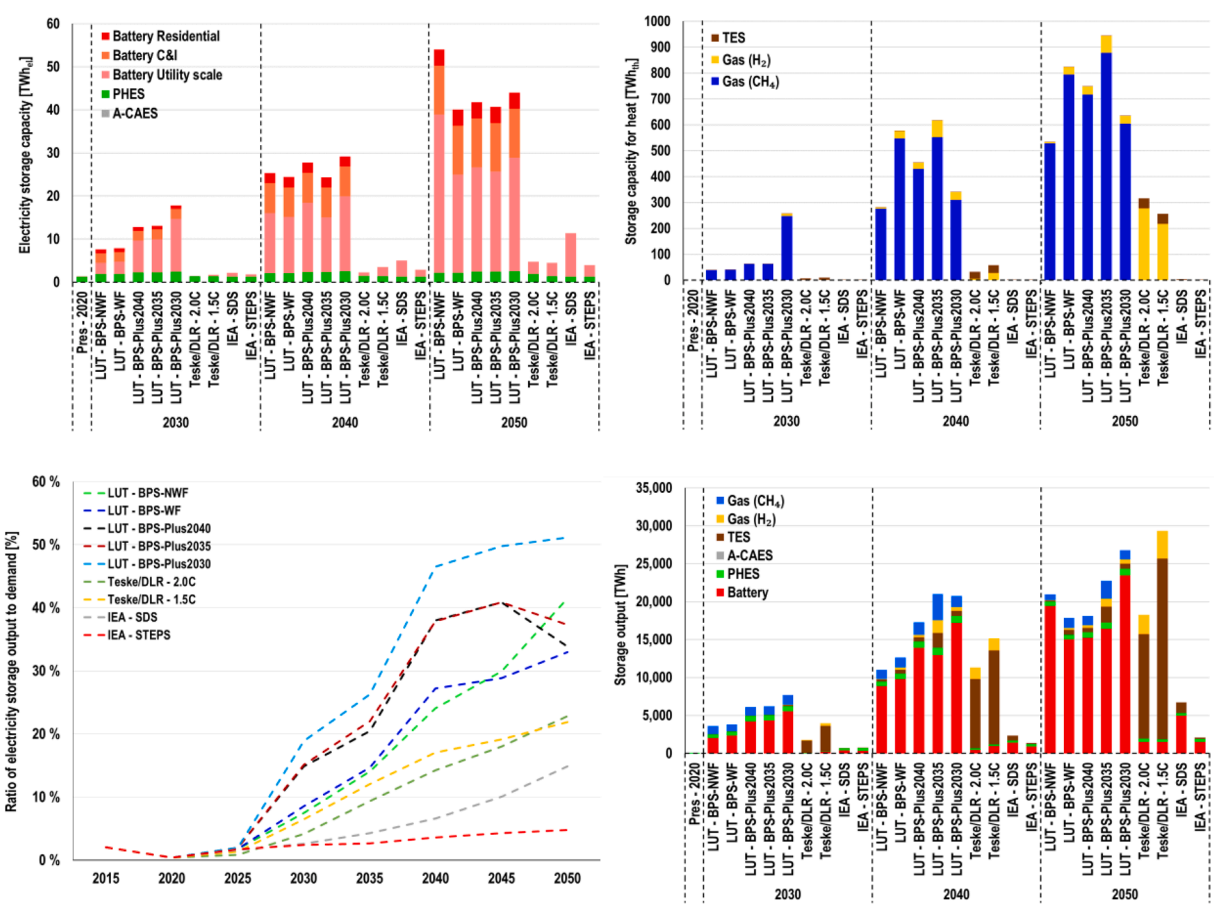

Fig. 5. Development of electricity storage capacity by scenarios and years (top left), storage capacity for heat (top right), ratio of electrical energy storage throughput to electricity demand (bottom left), and energy storage throughput including electricity, gas, and heat storage (bottom right).

is higher cost as opposed to the considered 100% RE systems. Older research is often based on outdated cost assumptions or lack of proper methods [57–59], thus distorted results are obtained if the true and full costs of the supply chain of fossil CCS and nuclear power are not accounted for.

As the pace of transition increases, the need for energy storage capacity and throughput becomes pivotal earlier, as can be seen in the LUT-BPS-Plus scenarios. This means the system requires more flexibility to meet the hourly demand, which can be provided by energy storage in this configuration. This can be observed for the case of BPS-Plus2030, which by far has the largest battery capacity addition in 2030, covering 20% of the electricity demand, and tops the list until the end of the transition. In 2050, because of not repowering the already installed wind power capacity at earlier stages in the LUT-BPS-NWF, a big jump for battery storage capacity, by a factor of 1.6, relative to 2040 has occurred to supplement solar PV. On the other hand, solar-wind resource complementarity in the LUT-BPS-WF reduces the need for energy storage and solar PV capacity. The LUT-BPS-Plus2030 holds the highest electrical energy storage throughput by about 24,310 TWh, mainly via utility-scale batteries (95%). The Teske/DLR-1.5 °C accounts for the highest energy storage throughput for heat, including TES, gas, and hydrogen, with 27,525 TWh from which 87% comes from TES in 2050. The ratio of energy storage output to the total electricity demand is significant for both studies, estimated to be around 22% in the Teske/DLR and between 33% and 51% in the LUT scenarios in 2050. However, the IEA scenarios run with less energy storage in 2050 (15% storage output compared to the annual demand in the SDS and 5% in the STEPS) as large amounts of fossil fuels and nuclear power are added or remained until the end of the transition. In some cases, the model opts to run one technology in higher FLH or more cycles during a year, making the energy system more efficient and cost-competitive. The IEA-STEPS could run in the hourly model with no need for additional storage capacity due to a high share of fossil fuels and nuclear power. Other scenarios with high shares of renewables rely on extra storage, especially towards the end of the transition. Fig. 5 shows the energy storage capacity and throughput as well as the ratio of electrical storage output to demand during the transition across all the scenarios.

The results of the remodelling of the IEA and Teske/DLR scenarios can be compared with the storage capacities mentioned in the studies (Fig. 6). Among all the IEA and Teske/DLR scenarios, Teske/DLR-1.5 °C needs the most flexibility provided by energy storage due to a rapid transition and phasing out of fossil fuels and nuclear capacities by approximately 1042 GW capacity and 2842 TWh throughput of all storage technologies collectively in 2050.

4.4. CO_2 emissions perspective

Fig. 7 compares the annual and cumulative CO_2 emissions, normalised to the electricity consumption of the IEA-SDS, across all the scenarios. The LUT scenarios experience the deepest and fastest CO_2 emissions reduction. Over 10 years, CO_2 emissions for both the LUT-BPS-NWF and the LUT-BPS-WF are reduced from around 13 Gt CO_2 in 2020 to about 2 Gt CO_2 in 2030 and further decreased to zero by 2050. As Fig. 7 shows, the Teske/DLR-1.5 °C scenario has a consistent downward trend from 2020 to 2050. In contrast, CO_2 emissions in the IEA-STEPS scenario decline slightly throughout the transition by 14%, which does not limit CO_2 emissions fast enough to ensure controlling global temperature rise. Cumulative CO_2 emissions of the IEA-STEPS are estimated to be slightly more than 350 Gt CO_2 in 2050 for the electricity sector alone, which is about 287 Gt CO_2 (+436%) higher than that in the LUT-BPS-Plus2030. Among all the studied scenarios, the LUT-BPS-Plus2030 stands out as the best pathway to keep the global temperature rise below 1.5 °C with the minimum cumulative CO_2 emissions of 66 Gt CO_2 by 2050. However, a comparable pattern of emission reduction must be followed by all energy sectors across the world to reach the target of the Paris Agreement and thus to limit the global average temperature rise.

The Teske/DLR-2 °C and the IEA-SDS scenarios decline quite similarly throughout the transition, falling to just below 2 Gt CO_2 in 2045. The Teske/DLR-2 °C reaches zero CO_2 emissions by 2050 and it is expected to decrease further due to the negative emission technologies (NETs) employed, while the IEA-SDS still includes fossil fuels and emits CO_2 by 2050. The emissions reduction is swifter in the Teske/DLR-1.5 °C, placing it right in the middle of the fastest and slowest carbon–neutral pathways. An earlier retirement of fossil fuels power plants is assumed in this scenario as in Teske/DLR-2 °C and the IEA-SDS

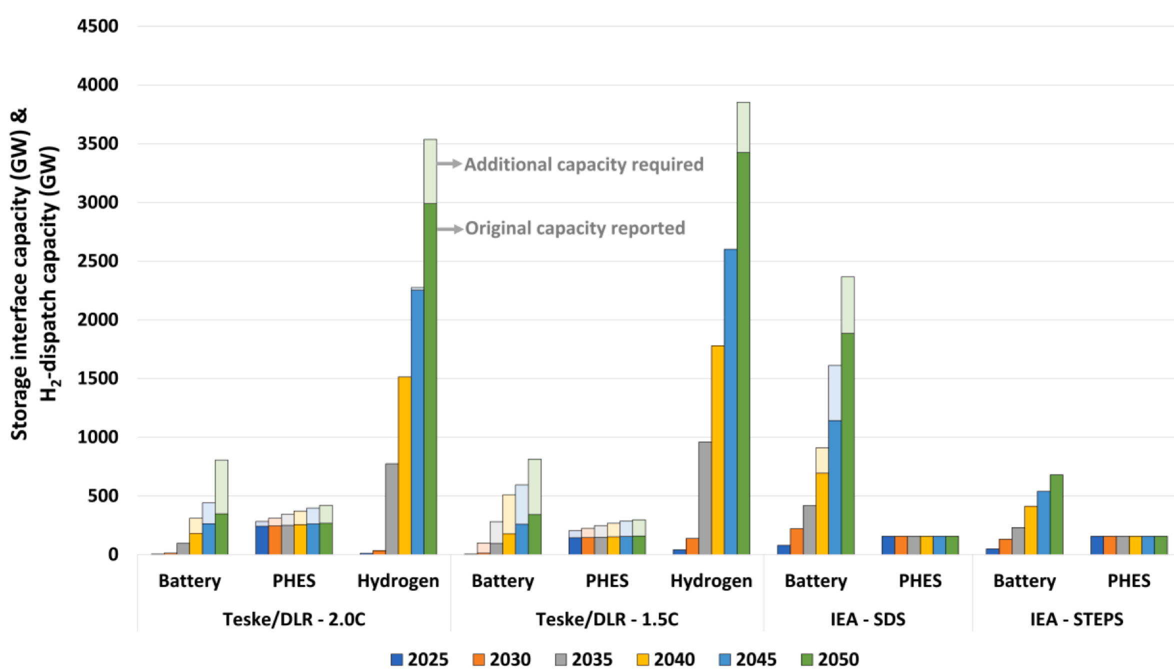

Fig. 6. The reported in comparison to the remodelled energy storage interface capacity for batteries and PHES plus hydrogen dispatch capacity in the IEA and Teske/DLR scenarios throughout the transition. See also Figure S10 for storage throughput comparison.

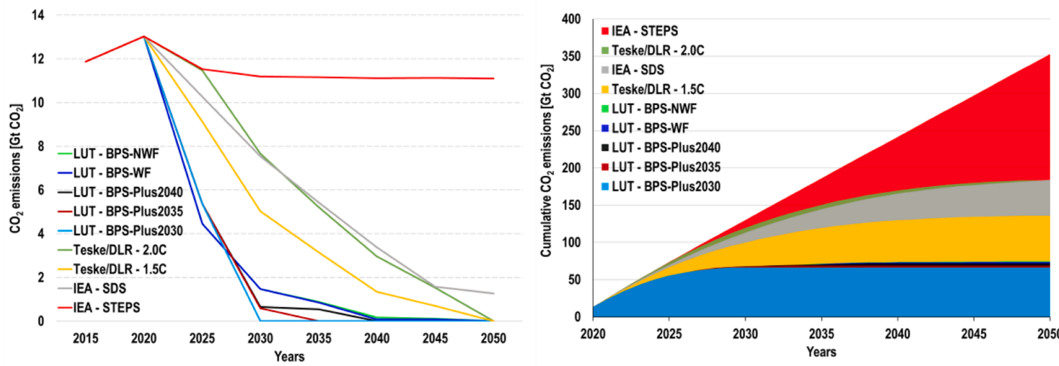

Fig. 7. Total annual (left) and cumulative (right) CO_2 emissions estimated globally throughout the transition pathways.

scenarios, although the remaining conventional gas-fired power plants are assumed to run on synthetic fuel such as hydrogen by 2050.

Further details about the regional findings such as the development of RE to the total electricity generation, regional LCOE, CO_2 emissions reduction, emissions intensity and examples of hourly resolved data for balancing supply and demand throughout the transition can be found in Note S6.

5. Discussion

5.1. *Diversity versus optimised cost and transition dynamics in deep decarbonisation*

It is worth noting that the scenarios considered in this research differ in their narratives and approaches for modelling the global energy systems. As a result, the remodelling carried out could only be partially harmonised and compared. The LUT-BPS scenarios represent a faster pace of defossilisation based on a techno-economic optimisation while pushing forward the societal aspects of the energy transition, such as the role of prosumers, the use of waste incineration but not landfills, and limiting the RE potential due to not only technical but also sustainability reasons. The Teske/DLR scenarios represent ambitious paths following an emission budget approach. Taking into account different preferences and barriers of the world regions, the aim is to create a basis for discussion that reduces possible risks and barriers through parallel technology development, and that gains broad industrial support and momentum. Both the LUT and Teske/DLR scenarios have a clear focus on RE and reduction of specific energy consumption. In contrast, the IEA-SDS scenario takes a further step towards technology accessibility and diversity by using nuclear power and fossil fuels with CCS in the long term. This can increase the acceptance of the scenario among political stakeholders, despite the associated socio-environmental impacts and the lower CO_2 emissions reduction target. The IEA-STEPS scenario demonstrates to these stakeholders what a world following today's policies and without an ambitious transition would look like in terms of the final electricity generation mix and the respective costs and emissions. If the CO_2 costs had been assumed to be at a similar level as the other scenarios considered, as a need to internalise external effects due to climate change, for example, the IEA-STEPS would have the highest cumulative pathway costs. In terms of the LCOE, however, it is the most expensive scenario by the end of the transition as it would continue to depend on fossil fuels with additional fuel prices and CO_2 costs. The results show that the LUT scenarios with more ambitious targets, i.e. 100% RE and zero CO_2 emissions prior to or by 2050, cost less than the IEA-STEPS with only 14% CO_2 emissions reduction over 30 years (Fig. 8).

However, the final cost of future energy systems comes down to the system design, assumptions, and integration of various RE sources and energy storage into the power system, while considering the importance of energy security and system reliability throughout a year. Of course, other flexibility options such as grid interconnections [60,61] and demand-side management [62] can facilitate a massive penetration of

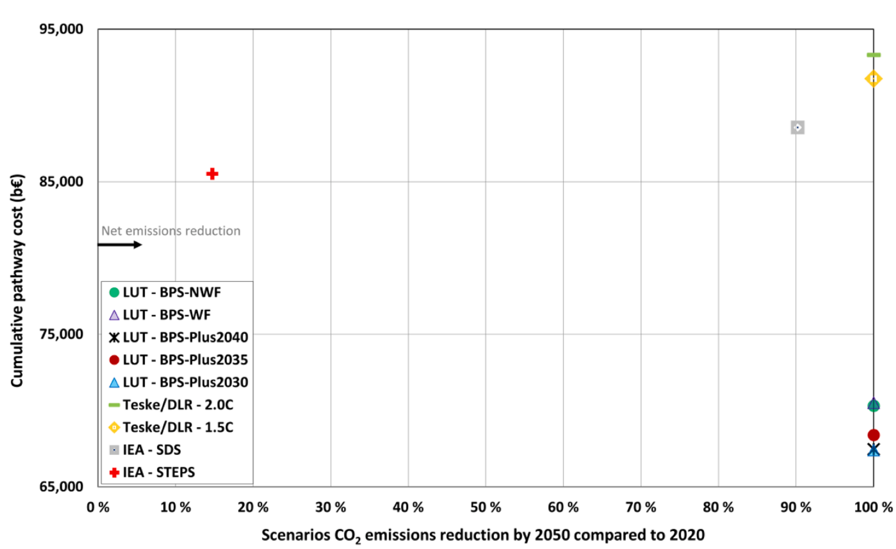

Fig. 8. CO_2 emissions reduction by 2050 compared to 2020 relative to the cumulative pathway cost for the analysed scenarios. Results are normalised to the electricity consumption of the IEA-SDS.

variable RE sources into the electricity system, but this requires a highly detailed multi-nodal analysis, which is out of the scope of the present study.

The contribution of various RE technologies in the Teske/DLR scenarios ensures energy security and system flexibility, whereas it costs more than other considered scenarios over the transition time horizon. In fact, the diversity of energy carriers, sources and technologies provides security of supply in the energy system [63]. It can be argued that the energy diversity is even more noticeable for the IEA scenarios, where the contribution of fossil CCS and nuclear power together with a mixture of RE sources promises a stable electricity system. While this argument is valid for the sake of diversity, it fails to address other critical dimensions of energy security [63]. Undoubtedly, the improvement of energy security is a crucial aspect of any sustainable energy strategy since this guarantees meeting basic human needs [64]. This can prevent potential energy crises such as the 2012 shortage of imported natural gas by European countries from Russia [65] and the recent similar shortage that expanded beyond Europe [66] and became a global energy crisis [67]. In contrast, the situation would be much easier and more secure if RE sources of countries have been harnessed and utilised, which in turn reduce the energy dependency and reliance on energy imports. However, this is not in contradiction with electricity trade among countries that brings numerous benefits for nations [68], such as green jobs creation [41,42], massive reductions in air pollution [4,69] and overall cost reduction [60,70], but it addresses the need for diversification and security of energy supply at a national level. It should be noted that mutual dependency might be an asset which can foster cooperation among nations, whereas one-sided and concentrated import dependency, such as huge reliance on Russian natural gas, increases the risk of energy crises that can lead to many other issues such as food insecurity and humanitarian needs [71]. Meanwhile, RE sources are cheap and environmentally friendly, create more jobs, improve health conditions etc., which is undeniably excellent value added to energy systems. In this regard, the IAMs have been critiqued by Jaxa-Rozen and Trutnevyte [57], Xiao et al. [58] and Victoria et al. [59] for underestimating the role of RE due to outdated cost assumptions but also methodological issues which may lead to misinformation.

The IEA and the Teske/DLR scenarios are relatively similar in the costs of the pathways, while they both used the same cost assumptions, except for solar PV and wind power, and the Teske/DLR scenarios have a net-zero CO_2 emissions target by 2050 that outperform the IEA scenarios. Furthermore, it is expected that NETs, i.e. land-use sequestration as applied in Teske et al. [18,19], help reduce the emissions further for the energy system transition including all sectors. The Teske/DLR and the LUT scenarios all lead to net-zero CO_2 emissions in 2050, while the LUT scenarios are substantially lower in cost because of strict cost optimisation. The cost-optimised system leads to less diversity of technologies, while all scenarios ensure full energy system stability in hourly resolution. The IEA scenarios show lower performance in different dimensions: low CO_2 emissions reduction, high cost and low transition dynamic with a high risk of additionally accumulated stranded assets due to sub-prime investment trajectories.

The ambitious LUT scenarios demonstrate the CO_2 emissions reduction benefits for the electricity sector, as earlier documented for solar PV investments [72], which is in stark contrast to the perceived high costs of reaching zero CO_2 emissions. Lack of cost optimisation and investment in unproven technologies, as documented in the IEA scenarios, may cause a delay in or even take away seizing the great opportunities of the energy transition ahead. Similarly, this had been also concluded by Xiao et al. [58] on invalidated cost assumptions for energy scenarios that lead to underestimation of RE economic potential, overestimation of the transition pathway costs, and delayed energy transition towards RE in the falsely belied that they are too costly. In short, the wide difference between these scenarios results in calls for better approaches that can address the dilemma of path choice to narrow the gap in policy-making and scenario development. Furthermore, the relatively close technology-related system costs calculated for the explored scenarios show that decisions about the future mix of renewables can be made based on important factors such as security of supply, technology acceptance, availability of rare materials, and economic implications.

5.2. Are the existing technologies sufficient and scalable for such transitions?

Some specific RE technologies stand out among the available options that could technically be scaled up in a large volume and quite fast, such as solar PV and wind power plants. As found in the LUT-BPS cost-optimised energy transition pathways, a substantially low-cost solar PV can meet the projected electricity demand globally, which is further complemented by battery storage, wind power, other RE and storage options. More importantly, it is expected that solar PV plays a vital role in the entire energy system transition [21,59,73–75]. In this regard, it is necessary to shift away from combustion processes to renewable electricity-based alternatives, such as direct electric heating, heat pumps and electric vehicles, or indirect renewable electricity-relevant solutions for water desalination [76,77] or electrification via power-to-X applications [60,78–81], especially for tackling the hard-to-abate sectors [73]. The massive industrialisation of global solar PV manufacturing with a factor of 17 to reach 10.4 TW by 2030 from 0.6 TW at the beginning of 2020 would remain the main hurdle to overcome in the LUT-BPS-Plus2030. Achieving such a target is very ambitious but is possible under conducive political and social circumstances and some technological innovation and materials recycling, according to Breyer [73]. The CAGR in the cumulative installed capacities need to be around 33%, which would lead to annual PV capacity installations of about 2.6 TW in 2030. This is exactly in line with Verlinden [82] who analyses the scalability of the PV industry for a cumulative 70 TW PV capacity around mid-century for serving energy demand across all energy sectors [21,74]. Based on a historical learning rate of nearly 24% since 1976 and 40% from 2007 to 2020, solar PV can be categorised as a dynamic, multi-purpose, fast-evolving, low land coverage and least-cost energy technology as of today [59,83]. A very fast transition towards 100% RE in the electricity sector may be the decisive trigger for a low-cost energy system directly and indirectly based on electricity serving all energy demands [4,21,84,85]. It can be noted that unlike the LUT and the Teske/DLR scenarios, the role of solar PV and its expansion potential over the transition time horizon is rather underestimated in the IEA scenarios, as also discussed by Creutzig et al. [86].

The variability of RE can be balanced through resource complementarity as well. This case is noticed for the LUT-BPS-WF scenario in which repowering wind capacity was complemented by solar PV to meet the hourly demand while reducing the additional need for energy storage and solar PV capacity in 2050. Consequently, more optimal results are obtained, and the annual system cost dropped by 6% in 2050 compared to the LUT-BPS-NWF scenario. This warrants further investigation in future research. The role of solar-wind complementarity and its significant benefits, such as less storage and conventional backup requirements for less than 100% RE systems, have been discussed in length in the literature [87,88].

Integration of other renewable energy technologies is mostly restricted by sustainable and economic limitations that hinder their development at a scale needed for the energy transition. Hydropower is mainly restricted by scalability to meet the growing energy demand and it is associated with negative climate change impacts. Hydropower plants may experience a shortfall due to low precipitation rate or an increase in electricity generation because of glacier melt in some locations such as in Europe and other parts of the world [89]. The latter can also cause flooding which might not translate to a rise in electricity generation. Environmental concerns negatively affect large-scale hydropower projects [90], which may even lack clear economic attractiveness compared to solar PV and wind power alternatives [91]. Bioenergy is limited due to sustainable issues. High bioenergy utilisation can conflict with sustainability criteria as global arable land is decreasing [92], ecosystems are under pressure [93], the global population is rising [94], and more food production is needed. Meanwhile, ongoing climate change impacts threaten the current food supply [95–97], further worsened by geopolitical disruptions, such as the ongoing Russian war in Ukraine, involving two of the biggest food suppliers, happening today. Further, bioenergy can be used in the heat and transport sectors as well, but its total estimated potential that can be sustainably produced is restricted to 100 EJ/yr (~27,800 TWh/yr) [98]. Untapped geothermal resources can be extracted and utilised through enhanced geothermal systems [99]. More research is needed to better understand the cost-competitiveness of geothermal energy with solar PV and wind power. A study for Central America [100] concluded that geothermal energy can be a complementary renewable resource to be combined with solar PV for covering the energy demand. This is particularly the case for the regions with excellent geothermal resource potential. However, the deployment rate is currently very low [101], and the scalability of geothermal energy has not been proven yet. Similarly, wave power has an attractive potential [102], but it is still in its infancy. Therefore, it can take much longer to be technically and economically feasible to compete with solar PV and wind power at the time needed to stop climate change. At the same time, this technology is limited to coastal locations.

It is of utmost importance to pay careful attention to technological readiness, scalability, industry maturity and cost-competitiveness while designing an energy transition pathway. Victoria et al. [59] suggested that when modelling energy scenarios, up-to-date and accurate cost assumptions, materials and land availability constraints, high temporal resolution, and the impact of sector coupling should be considered and applied. Nevertheless, the feasibility and scalability of some of the technologies included in the scenarios have not been verified yet, as there are rarely any commercial plants currently available. To begin with, carbon capture is the first nominee that is supposed to capture CO_2 through various applications, such as capturing CO_2 from the point sources like coal- and gas-fired power plants, industrial processes, or directly from the air via direct air capture (DAC) unit. The captured CO_2 can be used as a by-product in industry or alternatively transported and stored underground in geological formations. Despite the demonstration of a few components commercially, this technology is still in its infancy and there are several issues associated with it that put it on hold for further expansion, as discussed in the literature [61]. Fossil CCS is only considered for the case of the IEA scenarios, which increases the system cost due to high capital costs. The utilisation of DAC was very limited for the LUT-BPSs, as not much e-methane is required for seasonal balancing. DAC as a sustainable CO_2 sourcing option may be more favourable while assessing all energy sectors and as a NETs option to further decrease the CO_2 emissions and to enable net-negative emissions [78,103]. Secondly, the viability of nuclear power is highly questionable due to various reasons, i.e. economics, waste disposal, terrorism risk, nuclear-weapons-proliferation, public acceptance, safety and decommissioning [54,61,104]. Several countries have already shut down multiple nuclear power plants mainly due to economic reasons [105]. The share of nuclear power in electricity generation declined from 17.5% of the global electricity generation in 1995 to slightly less than 10% in 2021 [106,107]. Budget overruns of nuclear power plants in recent years, but also decades-long substantial negative learning rates [108,109] have made investors sceptical, making it challenging to augment capital [110]. The share of newly added nuclear power capacity in total added power capacity in the world has become very low for the last ten years [111]. Jacobson et al. [112] studied a 100% RE-based system for the case of the US and concluded that the combination of solar, wind and water sources can lead the country to a full energy transition by 2035 while it takes longer between planning and commissioning of a nuclear power plant. In addition, small modular and advanced nuclear reactors are unlikely to rescue nuclear power due to the very high cost associated with these technologies [105]. It is also evaluated that investment in the new nuclear power plant of the type Gen III/III + is not profitable mainly due to very high construction costs [54]. The role of nuclear power in the future energy system becomes quite limited as renewables coupled with other flexibility measures, such as energy storage and power-to-X, become cheaper faster. On top of that, there is the issue of nuclear waste storage and particular concern of using plutonium and uranium enrichment technologies as weapons for military purposes that causes a great risk to security worldwide [113].

Technological progress and massive implementation in battery storage applications are the fundamental enablers for expanding the battery installed capacities together with solar PV and wind power. There is a considerable potential to exploit and expand lithium-ion battery storage capacity [114,115] as the price falls off a cliff [116–118] although well-established recycling systems are required [119]. Aside from battery storage, PHES [120], hydrogen production and storage through conversion of electricity to hydrogen via electrolysis [121,122] with the possibility of methanation [81,123], and CSP coupled with TES are found to be the other crucial flexibility providers in 100% RE systems. However, using fuel cell CHP plants for hydrogen could result in a cost increase in comparison with using hydrogen-based CHP plants. The cost-competitiveness of this option should be more closely measured for the case of an all-energy sectors analysis because the heat sector can also benefit from the CHP plants, while gas CHP plants may be the lower cost option [124]. Analysing hourly energy demand reveals that a great contribution of flexibility is needed in a climate-neutral scenario, which can be modelled with energy storage as a solid technical solution. This aspect might be simply ignored if the annual demand is only supposed to be met rather than hourly demand in modelling energy systems. It should be noted that any time horizon less than 1 h is not relevant for large-scale geographical area analysis since the variations of load and RE resource aggregated profiles at large spatial resolution are typically smoothed out and the final results would not change dramatically [61]. Furthermore, the used energy system components can deliver all energy services required for system stability in a sub-hourly consideration, in particular batteries [91,125]. In addition, curtailment can play a vital role to balance an electricity system with high penetration of solar PV and wind power that can save cost and decrease the need for energy storage [50].

5.3. Uncertainties and limitations

One crucial topic that should be noted is the importance of data availability at different levels, such as detailed cost reporting, for input and output metrics, in terms of absolute, specific, and cumulative data for proper comparison and analyses. Global scenarios are typically non-transparent in their cost presentation, input cost assumptions (partly) and output system cost. For instance, the IEA does not report on system LCOE, annualised system cost, or cumulative pathway cost, as these should be a central metric for scenario comparison. The only cost reporting was the required investments, but this could be a misleading metric as the findings show that the IEA-STEPS is performing best in investments, but worst in all other cost metrics. That said, reporting on investments is critically needed and is a relevant metric, but more attention should be given to additional details, well-documented and traceable outcomes of energy system modelling. The calculated cost data are intrinsically dependent on the technology-specific CAPEX and OPEX assumed for the future, and the optimisation approach in energy system modelling can have large sensitivities to cost assumptions. This crucial factor is evaluated by applying the Teske/DLR cost assumptions for sensitivity analysis of key cost metrics. The biggest changes are observed in both Teske/DLR scenarios and the IEA-SDS in terms of the LCOE and the annual system costs. The Teske-1.5 °C shows the highest increase by 23% for the LCOE in 2050. In addition, the annual system cost of the IEA-SDS is mostly affected by a 26% increase in 2050. Meanwhile, the LCOE and the annual system costs of the LUT scenarios are raised by around 10–11% each in 2050. Note S7 provides further details and the respective figures for the sensitivity analysis.

Modelling global energy transition pathways for the 9 major regions and under 9 scenarios in a large geographical area is a quite simplified approach for energy system analysis. The main reasons for such simplification are the lack of access to the detailed sub-regions' or countries' data in the explored scenarios from other research groups, as well as reducing the data volume and thus the computation time. For instance, RE resource profiles are adopted from Bogdanov et al. [20,21] and calculated as the weighted average for the major regions. The same profiles have been applied to the IEA and the Teske/DLR scenarios, while they are normalised with the given yield data for each resource. The same approach was implemented for load profiles. Although extra care is given to avoid the exaggeration of resource utilisation in the considered major regions, it should be noted that the impact of seasonal variation and resource distribution might be different on a smaller scale, such as the analysis of smaller regions, as shown e.g. with the LUT-ESTM for Chile [45,126] and with the PyPSA-Eur-Sec-30 for Europe with a large variation of regional structuring [127]. Ignoring the impact of seasonal variation of RE sources, in particular solar PV and wind energy, on different hemispheres and especially high latitude locations for solar PV [59], might lead to different outcomes. However, most of the global population lives close to the equator where solar resources are widely and evenly distributed across the Sunbelt region and the impact of seasonal variation is low [59,74].

Grid interconnections between countries or regions within a world region are expected to bring further benefits to the energy system by enabling system flexibility and cost reduction. In the case of high variable RE shares, combinations of battery storage and the expansion of grid transfer capacities are important elements of load balancing in the system [128,129]. However, it has been argued that very long-distance power transmission networks beyond the dimensions of major regions can transfer only a smaller fraction of electricity and contribute very limited to the overall cost reduction as discussed for various cases around the world [23], and in detail for the Americas [60], East Asia [130], Europe-China [131] and Europe-Eurasia-MENA [132]. Therefore, it is expected to gain marginal cost benefits over interconnecting the major regions globally, but individual countries and clusters can take substantial advantage of grid interconnections to balance hourly energy supply and demand while minimising the cost. Additionally, some studies investigated the potential and techno-economic feasibility of exporting electricity from North Africa to Europe using CSP plus TES plants and point-to-point high voltage direct current lines for load balancing [133,134].

In the adopted scenarios from the peer research groups, the full energy system including all sectors has been modelled. However, only electricity-related data have been extracted and replicated to the designated format of the current study. In a sector coupling approach that goes beyond electricity to contain all energy sectors' demand, it is plausible to expect a far higher demand for renewable generation capacity, but also better balancing of the electricity sector via integration of flexibility options and synergy between sectors. Hydrogen and e-fuels can be used in the transport sector for international shipping and aviation demand plus thermal and gas storage can be the backbone of the heat sector [18,21,45,135]. The most valuable technologies that are also linked to storage options are flexible and low-cost electrolysers coupled to hydrogen storage which can indirectly balance the electricity system, smart charging of electric vehicles, vehicle-to-grid balancing and heat pumps using TES.

In the normative, goal-oriented scenarios considered in this study, it is assumed that joint cooperation and international agreements among nations would take place making a radical energy transition feasible and economically viable for all countries worldwide. This needs to be powered by the support of non-governmental organisations (NGOs), governments and policymakers, especially those from developed countries, in order to de-risk the projects through a range of guarantee mechanisms for developing countries [136]. This includes, for example, commitment to the planned framework, increased transparency around bid solicitation, and enhanced communication with utility planners and developers [137]. More concrete targets for shaping the energy transition equitably by leaders of the countries during the climate conferences can accelerate achieving sustainable, affordable, and reliable energy for all globally. Despite the difficulties and challenges ahead of such an ideal hypothesis, the presumed ideology is in line with the UN SDGs [46] aiming to make a better and brighter future for the entire humankind, not to mention other species, living beings and ecosystems.

6. Conclusion

This research aims to explore and analyse various energy transition pathways through a uniform modelling environment. This is a research gap that has not yet been investigated, although it significantly enhances comparability and offers new insights into underlying narratives and systemic effects of energy models and scenarios. Data for countries or sub-regions were aggregated or weighted for 9 world regions. In total, 9 scenarios have been developed or remodelled using the LUT-ESTM with identical technical and financial assumptions:

- Two scenarios from the IEA: the SDS as a deep decarbonisation scenario aiming to decrease CO_2 emissions significantly by 2050 and reach a net zero emissions in 2070, and the STEPS as a business-as-usual pathway for comparison. The NZE2050 scenario is excluded due to lack of sufficient data availability on a regional basis.
- Two scenarios from the Teske/DLR: the 2.0 °C and the 1.5 °C pathways following the target of the Paris Agreement with a budget approach and 100% RE until 2050.
- Five scenarios from the LUT: BPS-NWF, BPS-WF, BPS-Plus2040, BPS-Plus2035, and BPS-Plus2030 in line with the Paris Agreement target and representing the least cost and the most ambitious transition pathways for also investigating zero CO_2 emission targets earlier than 2050.

The LUT scenarios are built on the LUT-ESTM, which is a linear optimisation model with hourly temporal resolution and an objective function of minimising the total annual system costs. The Teske/DLR and the IEA scenarios are based on simulation models in the source publications, which have been remodelled using the LUT-ESTM in hourly resolution over the time horizon from 2015 to 2050 in 5-year intervals. The results of the (re)modelling indicate that scenarios with lower shares of renewable energy can meet hourly demand with minimum storage requirements, whereas variability of solar PV and wind power in deep decarbonisation pathways must be balanced via additional storage capacity and throughput. Other flexibility options such as grid interconnections, demand-side management, sector coupling, and NETs were not considered for the analysed scenarios.

The findings reveal that renewable energy technologies, particularly solar PV, and wind power, coupled with energy storage are the least-cost energy solutions and will emerge as the central pillars of the electricity sector despite the scenario configuration. Other renewable energy technologies that could complement the future electricity system include hydropower, geothermal, CSP, biomass and ocean energy. The LCOE of the electricity sector decreases substantially for all goal-oriented scenarios, for instance in the LUT-BPS-Plus2040 scenario from around 70.9 €/MWh in 2015 to around 45.2 €/MWh by 2050. Considering the cumulative pathway cost, normalised to the electricity consumption of the IEA-SDS, the least cost scenario is found to be the LUT-BPS-Plus2030 with around 67.5 t€ globally, which is 21% lower in cost than the IEA-STEPS that is based on current government policies and targets. The LUT scenarios show that a faster pace of the energy transition, i.e. reaching zero CO_2 emissions by 2030, would cost slightly less than a more delayed transition pathway by 2040. It may be one of the most relevant results of this study that a zero CO_2 emission system reached by 2030 or 2040 costs substantially less than a low-performing current policy scenario, i.e. CO_2 reduction benefits are to be expected not costs while transitioning to zero emissions. Solar PV emerges as the most prominent electricity supply source in the LUT scenarios with around 58–79% of the total electricity supply on the global average by 2050. Batteries are found as the key storage technology for the LUT scenarios complemented by pumped hydro energy storage, synthetic gas generation, and storage for seasonal balancing. This leads to PV-battery systems as the inner core of future cost-optimised power systems in most parts of the world.

The Teske/DLR scenarios show a more diverse and therefore more costly technology mix in the electricity sector, resulting from the attempt to deal with uncertainties regarding regional or local societal, economic and political developments and their risks for the transition pathways. CSP plays a significant role in the Teske/DLR scenarios due to its vast potential globally, assumed co-benefits, and being aligned with thermal energy storage that ensures large-scale dispatchable and secured electricity supply. The role of hydrogen production is also significant with high electrolyser capacities and high-volume hydrogen storage to ensure flexibility in the power system with interlinkages to the other energy sectors not assessed in this study. However, although the technology mix in 2050 is different from the LUT scenarios, the LCOE are only around 10% to 20% higher. This shows that the transition of the energy system to 100% renewable energy can be achieved via several different expansion paths with similar costs.

The IEA-SDS consists of a mix of renewable energy, nuclear power, and fossil fuels with and without carbon capture and storage throughout the transition. This also results in a scenario with strong transition dynamics worldwide, albeit with remaining specific CO_2 emissions of about 27 g/kWh in 2050. The LCOE of the technology mix in 2050 is also lower than today's electricity generation costs, but higher than in the other scenarios. The IEA-STEPS scenario reflects all of today's announced policy plans, targets, and strategies. Such a scenario presents a worst-case situation in terms of CO_2 emissions reduction, climate change and even the overall system costs. The STEPS is identified as the most expensive scenario with an LCOE of 69.5 €/MWh in 2050, even though conservative CO_2 costs have been applied.

According to the scenario modelling, deep decarbonisation of the electricity sector is possible under conducive political and social circumstances from around 13 Gt CO_2 in 2020 to 0–8 Gt CO_2 in 2030 and further to zero by 2050, depending on the scenario variant. It is explicitly observed from the findings of all the analysed scenarios that a 100% renewable energy system is more efficient and cost competitive than a today's policy scenario relying on fossil and nuclear fuels even by 2050. Entirely renewable scenarios are compatible with the Paris Agreement and the United Nations Sustainable Development Goals. Thanks to low-cost electricity from solar PV and wind power, which can be complemented by other RE sources, the electricity sector can run on 100% renewable energy sources and energy storage 24/7, all year round, without relying on fossil fuels (with or without carbon capture and storage) and nuclear power. Such a transition can pave the way for shifting away from fossil fuels in all energy sectors towards a climate-neutral and sustainable energy system for all by the latest around the mid-century.

Disclaimer

The views expressed are based on the current information available to the authors and may not in any circumstances be regarded as stating an official or policy position of the European Commission.

CRediT authorship contribution statement

Arman Aghahosseini: Conceptualization, Data curation, Resources, Methodology, Software, Formal analysis, Investigation, Validation, Visualization, Writing – original draft. **A.A. Solomon:** Conceptualization, Supervision, Methodology, Formal analysis, Investigation, Validation, Writing – review & editing, Funding acquisition. **Christian Breyer:** Conceptualization, Supervision, Methodology, Formal analysis, Investigation, Validation, Writing – review & editing, Funding acquisition. **Thomas Pregger:** Formal analysis, Validation, Writing – review & editing. **Sonja Simon:** Formal analysis, Validation, Writing – review & editing. **Peter Strachan:** Validation, Writing – review & editing. **Arnulf Jäger-Waldau:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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