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Low-cost renewable electricity as the key driver of the global energy transition towards sustainability

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A B S T R A C T

Climate change threats and the necessity to achieve global Sustainable Development Goals demand unprecedented economic and social shifts around the world, including a fundamental transformation of the global energy system. An energy transition is underway in most regions, predominantly in the power sector. This research highlights the technical feasibility and economic viability of 100% renewable energy systems including the power, heat, transport and desalination sectors. It presents a technology-rich, multi-sectoral, multi-regional and cost-optimal global energy transition pathway for 145 regional energy systems sectionalised into nine major regions of the world. This 1.5 °C target compatible scenario with rapid direct and indirect electrification via Power-to-X processes and massive defossilisation indicates substantial benefits: 50% energy savings, universal access to fresh water and low-cost energy supply. It also provides an energy transition pathway that could lead from the current fossil-based system to an affordable, efficient, sustainable and secure energy future for the world.

1. Introduction

The Sustainable Development Goals (SDGs) report [1] highlights risks posed by the impact of climate change in eroding and reversing decades of progress on inequality, food security and other SDGs. In this context, a transition of the global energy system is of utmost relevance as energy use is responsible for the majority of global greenhouse gas (GHG) emissions [2]. Transition towards higher shares of renewable energy (RE) will simplify achieving universal access to clean and affordable energy, reducing GHG emissions and decreasing water scarcity by eliminating freshwater usage in thermal power plants [3]. This transition has already started with renewables providing more than 27% of the global electricity generation by end of 2019 [4], including about 11% generated by new renewable energy technologies, mainly wind turbines and solar photovoltaics (PV). Driven by cost reductions, renewable electricity is increasingly cost-competitive with conventional thermal power plants: in some regions RE cost is lower than running costs of existing fossil and nuclear power plants [5], and solar PV has emerged as the least costing source of electricity production in the history of mankind [6]. A similar trend is observed in the heat sector: about 10.1% of the heat used worldwide in 2019 was produced from sustainable sources, including renewable electricity [4]. The transport sector is still lagging in adopting sustainable solutions: despite the rapid development of electrification, hybrids and synthetic fuels, oil and petroleum products contribute the vast majority of energy demand.

Many global energy scenarios have tried to project the future transition of energy systems based on a wide ranging set of assumptions, methods and targets from a national as well as global perspective [7]. Most of the global energy transition studies present pathways that result in CO_2 emissions even in 2050, which are not

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compatible with the goals of the Paris Agreement (as is with most IEA global scenarios except the NZE2050 in the recent WEO 2020 [6]) and are dependent on the role of technologies with questionable sustainability (fossil CCS and nuclear) as in the Global Energy Assessment of the International Institute for System Analysis (IIASA) [8], while later studies such as Grubler et al. [9] consider decline of final energy demand by 2050, despite increasing population, income and activity. The Centre for Alternative Technology [10] outlines scenarios on global, regional, national and sub-national scales that illustrate how the Paris Agreement targets could be realised. Most of the studies lay out pathways to phase out non-sustainable technologies, while integrating sustainable renewable energy options to satisfy the increasing energy demands of the future global society. Several studies on the global level with different models and assumptions show that such a transition can be achieved by 2050: Pursiheimo et al. [11] using the TIMES-VTT model, Löffler et al. [12] with GENeSYS-MOD, Jacobson et al. [13] and Teske [14] have different regional structures, technology portfolios, technical and financial assumptions, but all prove that a renewable energy based system is highly cost competitive compared to the conventional system. Jacobson et al. [15] and Teske et al. [14] also show that benefits of a renewable energy system are not limited to radical declines in GHG emissions and low energy system costs, but also lead to lower social costs, and additional jobs. However, limitations in different methods of global energy scenarios lead to some of them failing to acknowledge the role of storage technologies in future energy systems [7] and the impact of sector coupling Power-to-X technologies, namely Power-to-Heat and synthetic fuels production. Hansen et al. [16] provide an overview on 100% renewable energy system studies and highlight the importance of multi-sector analyses, hourly temporal resolution, sector coupling and Power-to-X technologies. In order to reach full sustainability, the use of biofuels should be limited to unavoidable residues and synthetic fuels have to play a more significant role, so that fuel production does not compete with food crops. Emerging issue of water scarcity has to be taken into account, considering the additional energy demand for water desalination, purification and transportation in order to enable universal access to clean water for residential, agricultural and industrial use [17].

While the global energy system and the factors that influence it are far more complex than what any scenario or narrative can capture, this research presents a possible cost-driven energy system transition from the present structure (2015) towards a fully sustainable 100% renewable system in 2050, in high regional and hourly temporal resolution across the power, heat, transport sectors, and seawater desalination. This scenario presents a possible global pathway for the defossilisation of the current energy system to fulfill the IPCC's 1.5 °C scenario requirements in a cost-effective manner.

2. Methods

The LUT Energy System Transition model initially applied across the power sector [18], is further expanded to involve collating all relevant energy data across power, heat, transport and desalination into 145 sub-regions of the world. This novel approach enables a more decentralised, cost-driven energy transition optimisation across 145 sub-regions of the world that can satisfy their energy demands through resources available within the corresponding sub-regions. Lastly, a post-processing of the results involving analyses and visualisation from the 145 sub-regions produces compiled results for nine major regions, Europe, Eurasia, Middle East Northern Africa (MENA), sub-Saharan Africa (SSA), South Asia (SAARC), Northeast Asia, Southeast Asia, North America and South America, which are further aggregated into global results. The high temporal and geospatial resolutions allow to avoid a cooper plate effect by evaluating the impact of VRE integration in greater detail and assesses the role of storage, flexibility options and regional grid interconnections in balancing energy systems with high shares of RE.

2.1. Model description

The energy transition modelling was performed with the LUT Energy System Transition model [18], which optimises an energy system under certain constraints for a comprehensive set of energy, generation, storage, and transformation technologies. Unlike most other models used for global energy systems studies that normally use the time-slices approach (MESSAGE, MARKAL, TIMES, GENeSYS-MOD), the LUT model optimises the energy system in full hourly resolution. This allows for consideration of the variability effects of RE on energy systems in greater detail, thereby ensuring the balance of energy demand and supply for all hours of the year. The model uses myopic foresight, in this study simulation is applied for five-year intervals from 2015 to 2050, comprising the coupled power and heat sectors, transport sector, and energy demand for desalination. A multi-node approach enables the description of any desired configuration of sub-regions and power transmission interconnections. The main constraint for the optimisation is the matching of the energy supply and the energy demand for every hour of the applied year and the optimisation target is the minimum of the total annual cost of the system. Energy supply is modelled for electricity, heat of three temperature levels, and transport fuels: hydrogen (gaseous, liquid), methane (gaseous, liquid), and liquid hydrocarbons, comprised of gasoline, diesel, marine fuel oil and jet fuel. The full hourly resolution of the model significantly increases the computation time. However, it guarantees that for every hour of the year the total supply within a sub-region covers the local demand and enables a more precise system description including synergy effects of different system components. The model is based on linear optimisation and performed on an hourly resolution for an entire year in two stages. First, a prosumers simulation based on annual energy cost in relation to own generation and local retail energy prices is conducted to determine the least cost energy options for prosumers in the sub-regions. The next stage involves an overall energy system simulation across the different sectors to derive cost optimal energy mixes form 2015 to 2050 for the corresponding sub-regions. The model ensures high precision computation and reliable results. The costs of the entire system are calculated as a sum of the annualised capital expenditures including the weighted average cost of capital, operational expenditures (including ramping costs), fuel costs and cost for GHG emissions for all available technologies. The detailed description of the LUT Energy System Transition model is provided in the Supplementary Material in Appendix A (section 1. Model description). Prina et al. [19] compared models for highly renewable energy systems in the main categories: resolution in time, in space, in techno-economic detail, in sector coupling and for transparency. Amongst all long-term energy transition models, the LUT model received the highest scoring, which further validates the efficacy of these findings.

2.2. Applied technologies

To describe the transition of power, heat and transports sectors towards RE-based energy supply the wide list of technologies was considered in the modelling, in total the technologies can be classified into six main categories.

- Electricity generation: RE, fossil and nuclear technologies;
- Heat generation: RE and fossil technologies;
- Transportation: road, rail, marine and aviation;
- Energy storage: electricity, heat and fuels;
- Energy sector coupling technologies;
- Electricity transmission technologies.

Fossil fuels based power generation technologies include condensing coal power plants, oil-based internal combustion engines (ICE), open cycle (OCGT) and combined cycle gas turbines (CCGT), fission based nuclear power plants and coal, gas and oil-based combined heat and power (CHP) plants. Renewable electricity generation includes solar PV technologies (optimally fixed-tilted, single-axis north-south tracking and rooftop PV for residential, commercial and industrial segments), wind turbines (onshore, offshore), hydropower (run-of-river and reservoir), geothermal energy and bioenergy (solid biomass power plants and CHP, biogas and waste-to-energy CHPs).

Heating technologies are subdivided in district heat or utility-scale heating technologies including fossil fuel boilers (coal, gas and oil fuelled), direct electric heating and utility-scale heat pumps, concentrating solar thermal power (CSP) parabolic fields, geothermal and solid biomass district heat plants. Individual heating technologies include small scale fossil fuel boilers (gas and oil fuelled), direct electric heaters and heat pumps, solid biomass and biogas boilers.

The transport sector is divided into four categories: road, rail, marine and aviation. Road passenger transport is divided into light duty vehicles (LDV), buses and 2–3 wheelers (2/3W). Road freight transport is divided into medium-duty vehicles (MDV) and heavy-duty vehicles (HDV). For all road transport vehicles, the model considers four powertrain types: conventional internal combustion engine vehicles (ICE), plug-in hybrid electric vehicles (PHEV), battery-electric vehicles (BEV) and hydrogen-based fuel cell vehicles (FCEV). Rail passenger and freight transport is composed by electrical engine and ICE trains. Marine passenger and freight transport are represented by electrical motor, liquefied methane (LNG) and liquid fuels ICE propelled vessels. Aviation passenger and freight transport are represented by electricity, hydrogen and liquid fuels based aviation.

Storage technologies can be divided in three main categories. Short-term storage: battery and pumped hydro energy storage (PHES). Medium-term storage technologies are adiabatic compressed air energy storage (A-CAES), high and medium temperature thermal energy storage (TES) technologies. Long-term gas storage including power-to-gas (PtG) technology.

Sector coupling technologies include fuel synthesis technologies: electrolysers, and further H_2-to-X synthesis technologies; Power-to-Heat (direct electrical heaters, district and individual scale heat pumps) and Heat-to-Power (steam turbines) technologies; and other: seawater desalination, water storage and pumping technologies. These technologies allow to convert energy or products from one sector into valuable services or energy for another sector increasing the overall efficiency of the system and providing additional flexibility for the system.

Electricity transmission technologies include high voltage AC (HVAC) and DC (HVDC) power lines and AC/DC converters which allow to interconnect AC power grids of regions inside the countries, thought countries power grids are not interconnected. The structure of the regional AC power grids of the regions is not modelled, however regional grids development trends are considered in overall electricity transmission and distribution losses [20].

2.3. Financial and technical assumptions

The financial and technical assumptions are mostly taken from the European Commission [21], but also from various other referenced sources [22–50]. The financial and technical assumptions for all power and heat generation capacities, storage, transmission and sector coupling technologies and fuels with their respective references are presented in Appendix A (Tables A1-A4). Assumptions are made in 5-year time steps for the years 2015–2050. For all scenarios, weighted average cost of capital (WACC) is set to 7%, but for residential PV prosumers WACC is set to 4% due to lower expectation of financial returns. Application of region specific WACC levels would result in more accurate results, however there is limited research with regard to the development of WACC in the long term capturing country-specific variations [51]. Electricity prices for residential, commercial and industrial consumers were derived for every region according to Gerlach et al. [52], and extended to 2050 according to Breyer et al. [53]. Excess electricity generated by prosumers is fed into the national grid and is assumed to be sold for a transfer price of 0.02 €/kWh. The model ensures that prosumers satisfy their own demand for electricity before feeding excess into the grid.

2.4. Demand and resource potential for renewable technologies

Power demand is mostly based on electricity consumption growth data from IEA [45] and local sources, as described in Bogdanov et al. [18], and projections for transmission and distribution grid losses are taken from Sadovskaia et al. [20]. Heat demand is based on a report by Barbosa [54]. Desalination demand is taken from Caldera and Breyer [55]. Transportation demand is taken from Khalili et al. [56]. Power, heat, transport, and desalination demand assumptions for each step of the transition are provided in Appendix A (Table A5).

The capacity factor profiles for optimally fixed tilted PV, CSP and wind energy are calculated according to Bogdanov et al. [57] using global weather data for the year 2005 from NASA [58,59] and reproduced by German Aerospace Centre [60], single-axis tracking PV capacity factors profiles are calculated according to Afanasyeva et al. [61]. The hydropower feed-in profiles are computed based on the monthly resolved river flow data for the year 2005 [62] as a normalised weighed average flow in locations of existing hydropower plants.

The potentials for sustainable biomass and waste resources are based on Bunzel et al. [63] and classified into three main categories: solid wastes (non-recyclable municipal wastes and used wood), solid agriculture and forestry residues and biogas feedstock (municipal biowastes, manure, sludge). The assumptions consider high recycling rates for plastic, cardboard and paper, limiting feedstock for waste incinerators, and high collection rates of biogas feedstock, which increases valuable biogas influx and limits the leakage of landfill gases as emissions. The costs for biomass are calculated using data from the IEA [64] and Intergovernmental Panel on Climate Change (IPCC) data [65]. The gate fee in 2015 is assumed to be in the range 50–100 €/tonne, rising to 100 €/tonne in all regions by 2050. The region specific solid agriculture and forestry residues, biogas and solid wastes, and corresponding cost assumptions are presented in Appendix A (Table A6).

Geothermal energy potential was calculated according to the method described in Aghahosseini et al. [66]. The A-CAES storage potential is based on a global A-CAES resource assessment [67].

3. Results and discussion

3.1. High electrification scenario

The development of the energy sector comprised of power, heat, transport and desalination sectors is characterised by a dynamically growing electricity demand driven by electrification of the energy system and continuous growth in final energy demand across developing and emerging countries. A global compound annual growth rate (CAGR) of final energy demand is about 1%, but the growth rates are much higher for developing countries.

Powertrain assumptions capture the transition from a fossil fuels based transport sector towards one with high levels of direct electrification and adoption of synthetic fuels, based on indirect electrification [56]. Other sectors also face comprehensive electrification due to the overall decline in costs of electricity as well as electricity-based heating and desalination technologies. In the frame of this high electrification scenario, electricity is expected to become the dominant energy carrier with a TPED share of about 89% by 2050, while the utilisation of fossil fuels declines to zero, indicating a fundamental change in terms of energy consumption around the world. Direct and indirect electrification together with the growth of the renewable electricity generation share in the power sector lead to a substantial increase of overall energy efficiency. This defossilisation and electrification induced efficiency gains result in decoupling of final and primary energy growth rates during the transition process, as highlighted in Fig. 1. Despite the growth in energy services and final energy demand, total primary energy demand (TPED) decreases from about 125,000 TWh in 2015 for the mentioned energy sectors to around 105,000 TWh by 2035 and increases to 150,000 TWh by 2050, which results in a CAGR of 0.5%. In comparison, a progression of current practices with low shares of electrification and a majorly fossil fuels based energy system would result in a TPED of nearly 300,000 TWh by 2050, which implies a CAGR of 2.5%. This effect on the energy system is one of the most fundamental results of this research, since it results in efficiency savings of nearly 150,000 TWh (approximately 49%) compared to the continuation of current practices with low shares of electrification, while energy services can be steadily expanded. Moreover, this varies substantially across the different regions of the world, regions with existing high renewable electrification gain less, for instance Norway [68], whereas regions with least efficient energy systems gain most, e.g. oil-rich Libya and Saudi Arabia. Solar-rich Africa, which is yet to develop most of its energy infrastructure, can leapfrog into a highly electrified energy system of the future [69] (see Fig. 1). The TPED is calculated based on IEA's Physical Energy Content Method (PECM), while other methods result in different TPEDs, i.e. the Partial substitution Method (PSM) would lead to higher TPED, while the Direct Equivalent Method would lead to lower TPED [70]. The PECM defines primary energy as the physically obtained energy at the first extraction from nature and equates all fuels and technologies fairly on this fundamental basis of initial human action.

Despite the projected per capita consumption growth of energy services, the average per capita primary energy demand decreases from around 17 MWh/capita in 2015 to around 15 MWh/capita by 2050. Only the projected population growth from 7.2 to 9.7 billion by 2050 [71] leads to absolute TPED growth.

Another metric for renewable energy system efficiency is curtailment of electricity generation. Despite the variability in renewable electricity based generation, the curtailment in the system is rather low at about 3.5% of total electricity generation in 2050. This low curtailment results from the combination of flexibility options, mainly battery storage balancing diurnal PV generation and flexible demand response from synthetic fuel production, particularly electrolysers.

3.2. Evolutionary transition leaps

To support the energy system transition, global electricity generation undergoes a rapidly evolving transition from predominantly fossil fuels in 2015 to 98% renewables in 2040, and entirely zero GHG emissions by 2050. The driving force is the cost of electricity generation technologies, wherein solar PV emerges as the major electricity supply source in a cost optimal energy transition, increasing from a mere 1% in 2015 to around 32% by 2030 and further increases to 76% by 2050 (see Fig. 2). This exponential growth in solar PV electricity supply is also attributed to the excellent resource distribution across the world. Wind energy is the major source of renewables during the early part of the transition, with a share in electricity supply increasing up to 42% by 2030. Thereafter, as solar PV becomes more cost effective the share of wind energy steadily declines to about 20% until 2050, while still growing in absolute terms until 2045. Hydropower, geothermal and bioenergy have some shares in the global electricity mix by 2050, with complementary roles through the transition due to limited resource availability. While, they do contribute substantially in some regions across the world, with major shares in energy supply through the transition. The value of reservoir-based hydropower and bioenergy is high due to their dispatchability. On the other hand, the shares of fossil fuels and nuclear in the electricity generation mix are observed to decline completely through the

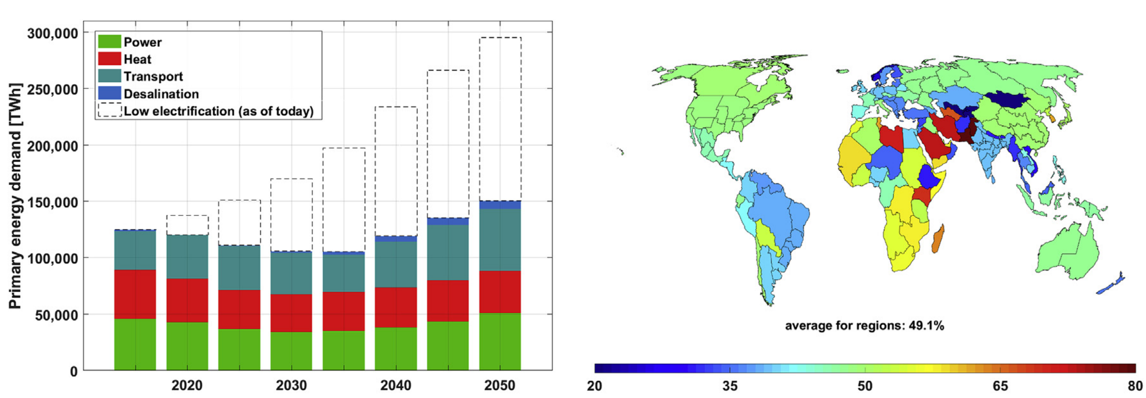

Fig. 1. Global primary energy demand sector-wise (left) including efficiency gains in primary energy demand as indicated by dashed lines for lack of efficiency improvements, and primary energy demand per capita (right) during the energy transition from 2015 to 2050.

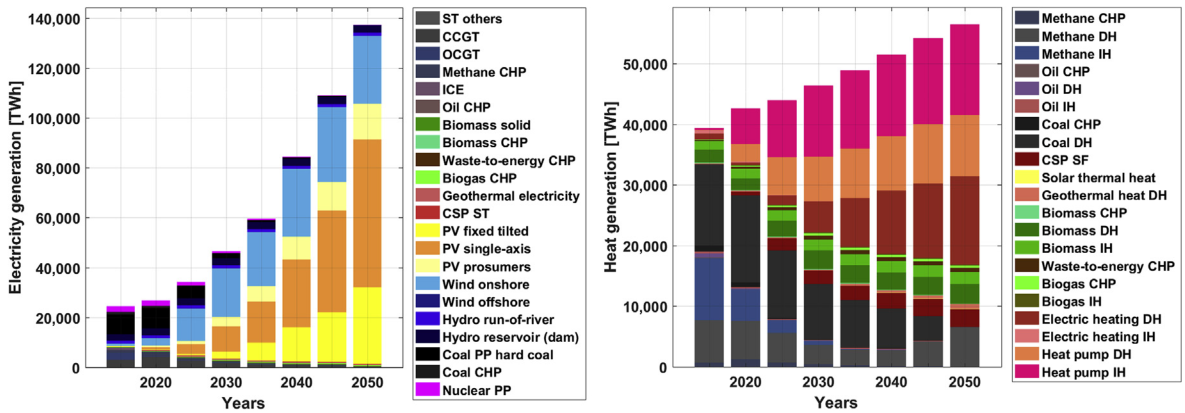

Fig. 2. Global – Technology-wise electricity generation (left) and technology-wise heat generation (right) during the energy transition from 2015 to 2050.

transition period, as they become uneconomical compared to renewables (see Fig. 2). Overall electricity supply increases from nearly 24 PWh in 2015, to 137 PWh in 2050, the main driving force is the fast growth of electricity demand from electrified heat, transport and desalination sectors, while the electricity demand from the power sector (excluding heat, transport and desalination) increase to just around 41 TWh by 2050. In addition, the share of electricity for the power sector declines from over 83% in 2015 to just about 30% in 2050, this highlights the significant rise of electricity demand from the other sectors. The rate of electricity supply growth is even higher in developing regions, where electrification is driven by the overall growth in energy consumption per capita, with efforts to close the gap in energy access between developed and developing countries.

Similarly, global heat generation transitions from high shares of fossil fuels based heat in 2015 to electric and renewable based heat in 2050. Heat pumps and electrical heating in general play a significant role in the heat sector with a share of over 40% of heat generation by 2050 on district heating (DH) and individual heating (IH) levels, as shown in Fig. 2. Additionally, some shares of non-fossil gas and biomass-based heating contribute to satisfying industrial process heat demand. Whereas the shares of coal-based heating along with fossil oil and gas based heating decrease through the transition, from more than 75% in 2015 to zero by 2050.

Electrification of the heat and transport sectors along with the additional electricity demand for desalination, strongly influence the defossilisation of the power and heat sectors. Direct electrification of transportation leads to additional electricity demand of 13,000 TWh_{el} in 2050 compared to 477 TWh_{el} in 2015, whereas indirect electrification results in further additional electricity demand of 39,000 TWh_{el} to produce synthetic fuels in 2050: hydrogen, methane, LH_2, LNG and Fischer-Tropsch (FT) fuels. Projected water desalination demand in most water stressed regions will reach 1100 bm^3 in 2050, which will lead to additional electricity demand of 5900 TWh_{el} to run seawater reverse osmosis units and water transport systems. Rapid growth of electricity demand during the transition increases demand for new power generation capacities and consequently results in diminishing shares of fossil fuels based electricity in the generation mix. Without a high level of sector coupling and additional electricity demand from heat, transport and desalination, electricity generation in 2050 would be approximately 40,000 TWh and fossil generation capacities would play a more significant role through the transition.

3.3. Critical role of solar PV – utility-scale and prosumers

Solar PV is expected to become the prime energy supply technology, similar to the conclusion of Creutzig et al. [72]. The largest share of solar PV in the total generation mix is reached mostly in the Sun Belt and developed countries. In the Sun Belt countries, perfect solar conditions make large-scale solar PV unrivalled, while in developed countries PV prosumers form a significant share of the capacity mix due to high electricity retail prices and respective attractive economics. This can be noticed with the stark difference in the shares of PV prosumer electricity in most European countries with high shares. Whereas, Russia and adjoining countries, which currently have low retail electricity prices (that are heavily subsidised), have much lower shares of electricity from PV prosumers (see Fig. 3).

3.4. Local resource driven energy systems

The regional structure of power and heat supply is strongly dependent on local resource availability and its match with energy consumption profiles. Solar PV capacities are well distributed across the different regions of the world and achieve a total installed capacity base of 63,380 GW in 2050. Whereas wind energy capacities achieve a total installed capacity base of 8130 GW in 2050 and are predominantly from latitudes of 45° N and higher, which show a strong energy consumption and renewable electricity generation seasonality effect, i.e. parts of North America, Europe and Eurasia have higher wind energy capacities (see Fig. 4).

In a system that is massively dependent on variable renewable energy sources, such as solar PV and wind energy electricity, storage plays a vital role in matching supply and demand. Utility-scale and prosumer batteries contribute a major share of electricity storage capacities, with some shares of pumped hydro energy storage (PHES) and compressed air energy storage (A-CAES) by 2050, as shown in Fig. 4. Batteries, both prosumers and utility-scale, deliver the largest shares of output by 2050, as shown in Fig. 4. The share of output from prosumer batteries is relatively higher in the most developed regions with high PV prosumer capacities, especially Europe and North America, whereas utility-scale batteries deliver higher outputs in the southern regions of MENA, SAARC and Northeast Asia. PHES and A-CAES contribute complementary shares of electricity storage output through the transition across the different regions of world. As far as heat is concerned, gas storage is installed across all regions primarily as a buffer storage

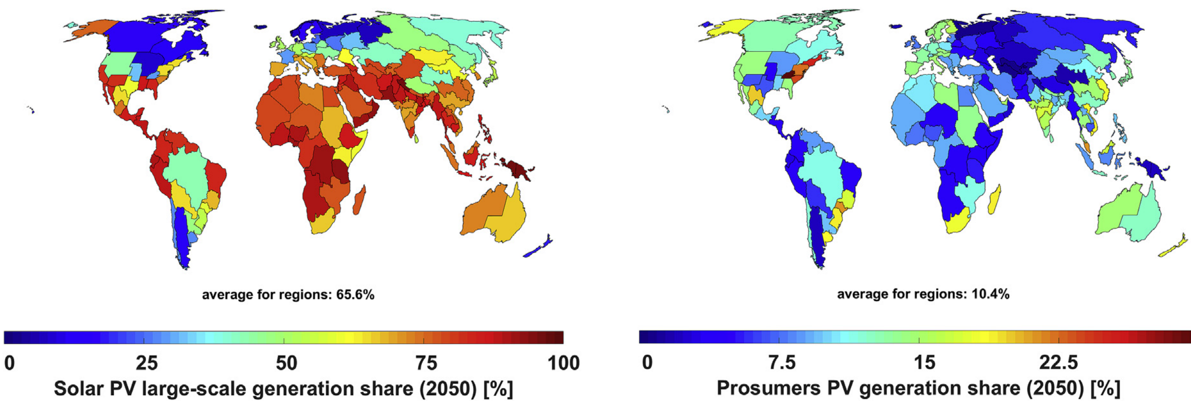

Fig. 3. Regional variation of the share of electricity generation from large-scale solar PV (left) and PV prosumers (right) on a global scale in 2050.

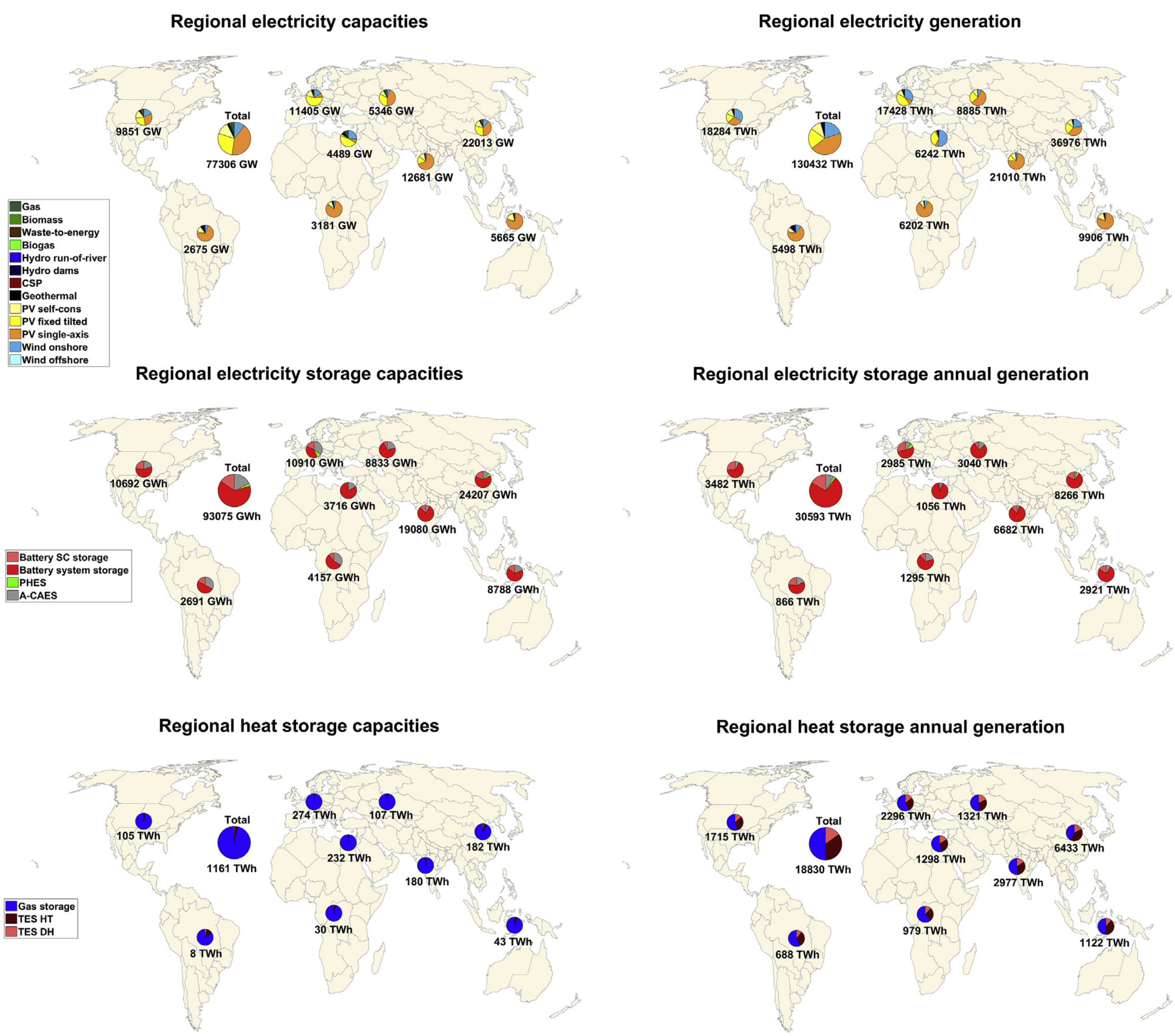

Fig. 4. Regional distribution of electricity generation capacities (top left), electricity generation (top right), electricity storage capacities (centre left), electricity storage output (centre right), heat storage capacities (bottom left) and heat storage output (bottom right) in 2050.

for biomethane and synthetic natural gas production and seasonal storage. On a global level, biomethane and synthetic natural gas contribute 0.29% and 0.14%, respectively, of the total electricity supply, while hydrogen is not considered as a seasonal storage for electricity in this research. However, their role is more significant in high latitude regions where long-term storage is necessary for seasonal balancing. A well-balanced and optimised 100% renewable energy system does not require much seasonal balancing in the form of stored gaseous compounds. High temperature and district heating thermal energy storage (TES) contribute ample shares of output, since they operate to balance short to mid-term heat demand variations.

3.5. Cost optimal energy transition pathway

Renewable energy generation along with electricity and heat storage technologies evolve as the fundamental pillars of the global energy supply system in the first half of the 21st century, changing the system while its levelised cost of energy remains stable through the transition. Levelised cost of energy is defined as the annualised energy system cost per unit of final energy demand. Investments needed to make this transition happen are presented in Fig. 5.

Investments, which are capital expenditures for installed capacities of energy technologies that occur in the 5-year time periods, are well spread across a range of technologies. Majority of the investments are allocated in the power sector, which becomes the backbone of the whole energy system: solar PV, wind energy and batteries are installed to substitute fossil fuels based generation and satisfy the growing electricity demand of all energy sectors. Heat pumps and synthetic fuel production technology capacities are mostly built in the later periods of the transition, when direct and indirect electrification of heat and transport sectors accelerates. Investments increase substantially on an annual basis from over 900 b€ in 2020 to around 2800 b€ by 2050, enabling fossil fuels substitution by RE-based electricity in all energy sectors. Moreover, the cumulative capital expenditures are about 67,200 b€ through the energy transition, with a majority in the later part from 2040 onwards, when a massive defossilisation of the transport sector is projected, in particular for marine and aviation. However, levelised cost of energy remains around 50–57 €/MWh through the transition because increased capital expenditures are well compensated by phasing out fossil fuel costs in the long term, as shown in Fig. 5. However, this does pose a challenge in the short term for developing countries with recent and new investments into fossil fuel assets, which are soon to face economic challenges from declining costs of renewables. Innovative policy and fiscal mechanisms will be needed to effectively plan phase-outs and divestments, at the same time taking on opportunities to leapfrog into a sustainable energy system. Shifting fossil fuel subsidies and additional financial support by development institutions could drive developing and emerging countries towards rapid adoption of sustainable energy. The total system wide levelised cost of energy in 2050 is slightly less than in 2015. This corroborates that an energy transition towards 100% renewable energy is an economically attractive proposition, since the transition in the energy system is projected to be cost-neutral in practical terms.

On a regional level, the levelised cost of energy for a 100% renewable energy system remains in an affordable range of 40–80 €/MWh, with the global average cost of 53.8 €/MWh across the different regions of the world in 2050, as indicated in Fig. 6. Moreover, a vast majority of the regions have levelised cost of energy in the range of 45–55 €/MWh.

Fischer-Tropsch fuels, hydrogen and liquefied gases (methane and hydrogen) are viable alternatives to fossil fuels and are expected to play a vital role in replacing fossil fuels in hard-to-abate applications [73–75]. The regional variation of production costs of these fuels has been factored into the cost optimal energy transition pathway. As indicated in Fig. 6, production costs for FT-fuels vary significantly across the different regions of the world with a global average cost of nearly 86 €/MWh in 2050. FT-fuel costs in Europe and central Asian regions are higher due to a decentralised and localised approach to the production of FT-fuels, whereas an integrated production and trading of FT-fuels will most likely reduce the costs [76]. For most parts of the world the costs range from 75 to 85 €/MWh. In addition, costs are extremely low (60–65 €/MWh) in South America (driven by low-cost wind in Patagonia and low-cost PV in Atacama Desert) and China, which could become future hubs for FT-fuel production (see Fig. 6), if the attractive cost in the Horn of Africa and the very south of the Arabian Peninsula may not be accessible due to political disorder, at least in the short-to mid-term.

3.6. Regionally diverse energy systems

In a highly digitalised future with strong global climate policies, electrification of energy services are expected to be pervasive [77]. Primarily, fossil and nuclear fuels used in the power sector are substituted by technologies directly extracting electricity from the

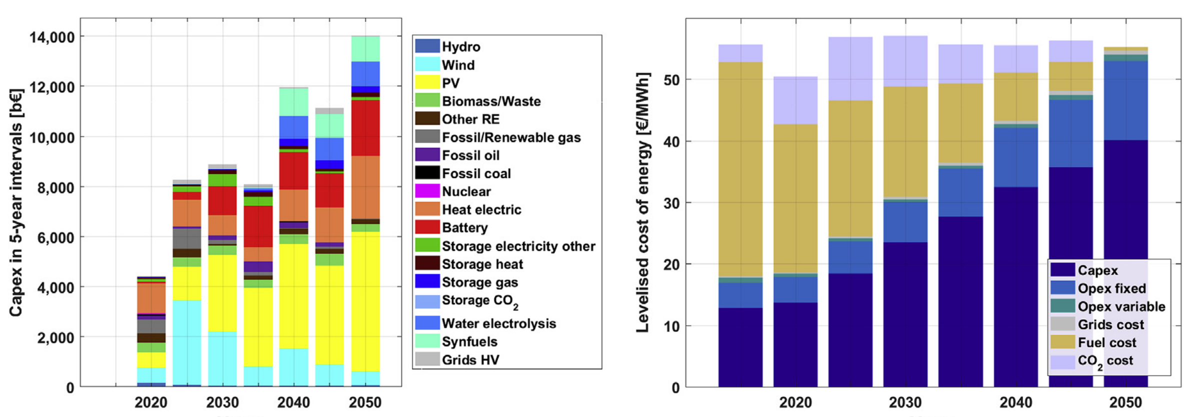

Fig. 5. Capital expenditures for five-year intervals (left) and levelised cost of energy (right) of the entire energy system during the energy transition from 2015 to 2050. Levelised cost of energy is increasingly dominated by capital costs as fuel costs lose importance through the transition period, which implies increased levels of energy security for countries around the world.

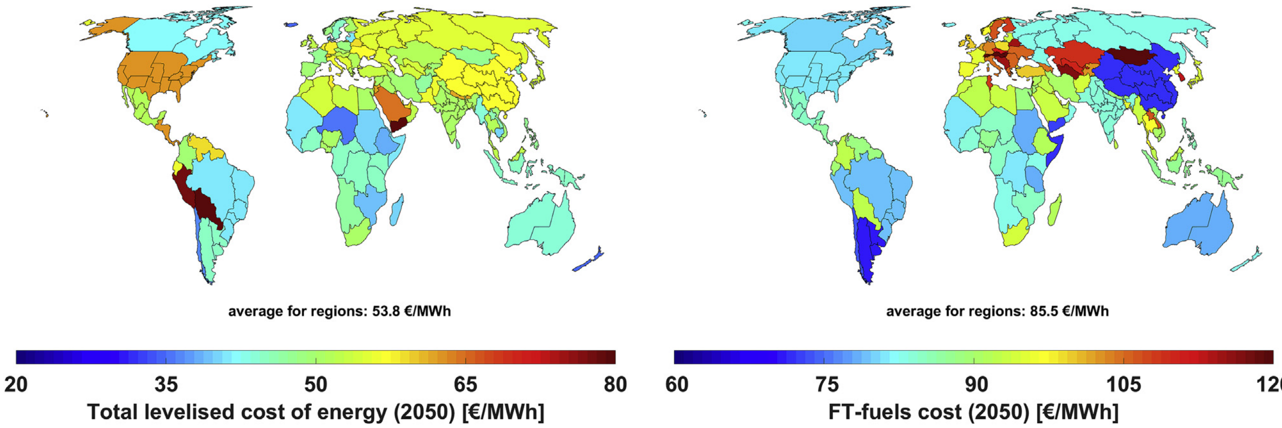

Fig. 6. Regional levelised costs of energy (left) and Fischer-Tropsch (FT) fuels costs (right) in 2050.

environment, in particular solar PV and wind energy. Power-to-X technologies will play a central role in linking low-cost variable renewable electricity and demand across all energy sectors. Electric vehicles will largely replace fossil-fuelled 2-wheelers, 3-wheelers, cars and trucks [56,78]. Meanwhile, heat pumps and electric heating substitute oil and gas furnaces in buildings and industries [79,80]. In addition, renewable electricity is used to produce hydrogen and other synthetic fuels for applications where direct electrification is uneconomical or technically challenging [81,82]. The advantages of widespread electrification are clear and compelling [9].

Another critical aspect of this research is capturing the regional variation in energy systems across the world through the transition period. Renewable energy resources are well distributed around the world, but different resources are available in different proportions, across the different regions. Therefore, the results of this research enable energy transition pathways that maximise utilisation of locally available renewable resources in a cost optimal manner, as indicated in Fig. 7.

The results provide regional insights into energy systems from a global perspective. Likewise, the high latitude countries utilise relatively higher shares of wind energy as compared to Sun Belt and moderate climate countries, where solar PV is rather predominant. Eurasia along with some regions in Europe and North America utilise higher shares of onshore wind energy across the northern regions. Hence, regions in Eurasia are wind dominated (see Fig. 7). Additionally, Canada and some parts of the USA are dominated by wind energy. Meanwhile, just the Patagonian region of Argentina is dominated by wind energy in the Southern hemisphere. In most regions and countries around the world, low-cost solar PV, as highlighted in Fig. 7, will dominate energy systems. By 2050, the highest generation share of solar PV among regions is in SAARC [83] with more than 95% in its cost optimal generation mix, whereas sub-Saharan Africa [69] utilises 82% of all electricity generation from single-axis tracking solar PV in its cost optimal generation mix. Meanwhile, only Iceland is dominated by hydropower in 2050 due to limited hydropower potential in other regions [84]. Notably, some regions, such as New Zealand, Chile, Northeast China, Nordic

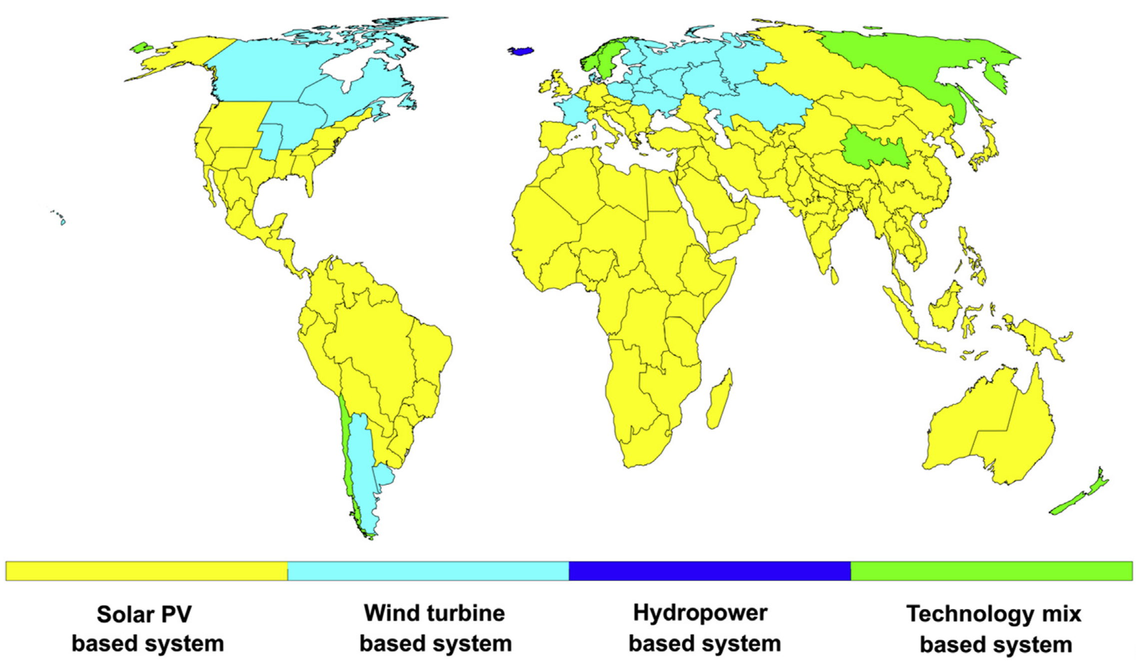

Fig. 7. Regional energy mix for power, heat, transport and desalination sectors in 2050.

region and Russian Far East have an energy system based on an even mix of renewable energy technologies with solar PV, wind energy and hydropower playing substantial roles (see Fig. 7). Similarly, from a heat supply perspective Eurasia has the most attractive techno-economic conditions for the application of heat pumps in the heat sector, providing about 60% of heating demand by this technology from 2030 through 2050. Other regions that cover a large part of the heating demand with heat pumps by 2050 are Europe with 51%, North America with 50%, Northeast Asia and sub-Saharan Africa both with 45%, respectively.

3.7. Climate compliant energy transition pathway

The results of the global transition towards a 100% renewable energy system indicate a steady decline in global GHG emissions to zero until 2050, as shown in Fig. 8. Global Tank-to-Wheel (TTW) GHG emissions from the power sector decline through the transition from over 11,000 $MtCO_{2eq}$/a in 2015 to zero by 2050. Similarly, GHG emissions from the heat sector decline through the transition from over 9300 $MtCO_{2eq}$/a in 2015 to zero by 2050. Global GHG emissions from the transport sector decline through the transition from over 9000 $MtCO_{2eq}$/a in 2015 to zero by 2050. During the initial periods, GHG emissions of the transport sector increases, whereas a rapid electrification of the road transport mode and parallel rise in renewable electricity leads to a massive GHG emissions reduction from the 2020s onwards. The power sector undergoes a deep defossilisation by 2030, whereas for the heat and transport sectors this occurs mostly between 2030 and 2050. The remaining cumulative energy related GHG emissions taken into account in this study comprise around 422 $GtCO_{2eq}$ from 2018 to 2050 as shown in Fig. 8.

The IPCC SR1.5 report [2] recommends that cumulative CO_2 emissions should be kept within a budget by reducing global annual GHG emissions to net-zero and further suggests a remaining budget for limiting warming to 1.5 °C with a 66% chance of about 550 $GtCO_2$, and of about 750 $GtCO_2$ for a 50% chance, accounting GHG emissions from 2018 onwards. In this context, this research shows that cumulative GHG emissions can be limited to 422 $GtCO_2$ from 2018 to 2050 across the power, heat, transport and desalination sectors globally. CO_2 emissions from remaining sectors have not been factored, in particular from non-energetic industrial feedstock and processes, land use, agriculture and waste. The non-energetic industrial feedstock demand is mainly represented by the chemical industry, which can be also transitioned to zero GHG emissions with renewable electricity based bulk chemicals, in particular ammonia and methanol [85,86]. Comparing the GHG emissions of this research to the second half of the previous decade with global anthropogenic CO_2 emissions of about 40 $GtCO_2$ per year [87] shows that this research covers about 75% of all CO_2 emissions, while about 85% of all CO_2 emissions originating from fossil fuels use and the remaining 15% are land use related. Assuming that all anthropogenic CO_2 emissions would be reduced in the same pace as the traced emissions in this research, then the total remaining CO_2 emissions would equate to about 567 $GtCO_2$. Consequently, the ambitious energy transition pathway described in this research could be categorised as limiting peak warming to about 1.5 °C with 66% probability by mid-21st century, as the total pathway emissions are quite close to the 550 $GtCO_2$ limit. Even more aggressive actions could be needed for a more safer temperature level [88], including a rapid transition and carbon dioxide removal (CDR) [89], which may be realised mainly by the highly scalable direct air captured carbon and storage (DACCS) [90], as indicated by Realmonte et al. [91]. Grubler et al. [9] demonstrated a 1.5 °C scenario without CDR, but with the compromise of 40% less final energy demand in 2050 compared to the present level. Whereas, this research shows a 1.5 °C scenario without CDR, along with a final energy demand growth of 43% from 2015 to 2050, and in a cost-optimal manner, which is enabled by massive direct and indirect electrification of the entire energy system and the consequent use of low-cost renewable electricity.

4. Conclusions

The fundamental structure of the global energy system can shift from conventional, low-efficient burning of extracted fuels towards almost pure exergy, which is electricity, generated from low-cost solar, wind and other natural energy resources. This transition will result in substantial growth of the system efficiency and enable rapid reduction of GHG emissions to fulfil a 1.5 °C scenario without CDR utilisation or limitations on final energy consumption. The broad electrification of end-use sectors like transport and heat makes electricity the growing backbone of the world's energy supply [92].

A 1.5 °C compatible transition scenario requires rapid defossilisation coupled with accelerated electrification of the different energy sectors, starting with the power sector already in the 2020s. Global levelised cost of energy of the whole system stays rather constant through the transition, even with the levelised cost of electricity declining significantly, as this new sustainable energy system includes storage technologies, increased flexibility and production of synthetic fuels. This in turn, demands massive capital investments, which not only enable a sustainable energy system but also increase socio economic welfare [93]. From an investment perspective, reduced fuel costs in the long term could benefit

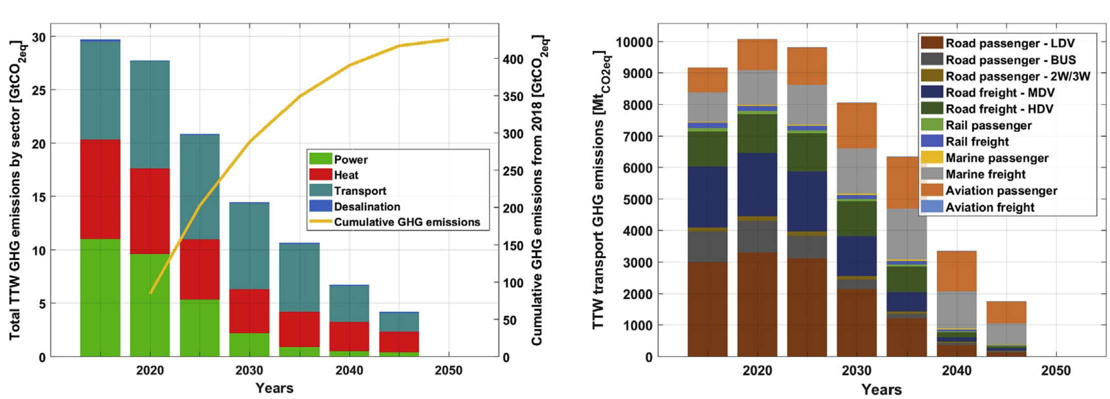

Fig. 8. Global sector-wise and cumulative GHG emissions (left) and GHG emissions in the transport sector from different categories (right) during the energy transition from 2015 to 2050. Tank-to-Wheel (TTW) considers GHG emissions from readily available fuels and does not consider GHG emissions from the upstream production and delivery of fuels.

various countries, but significant capital investments in the short term can pose a challenge for economies around the world. However, findings from BNP Paribas [94] indicate that the net energetic yield per invested unit of capital in renewable electricity solutions far exceeds the one in upstream fossil fuels, which are neglected in most energy system analyses. As energy policy has been evolving around the world to drive growth in renewable electricity uptake, these efforts must be scaled up and diversified across the other sectors.

Economics and markets continue to shape energy choices around the world, but policymakers will play the central role in transforming the global energy sector, as highlighted by Daszkiewicz [95]. Various energy strategies, targets and policies aiming at decreasing capital investment costs can be used to trigger the deployment of renewables across the sectors of power, heat, and transport. Moreover, from a developing countries perspective, as Relva et al. [96] point out, in addition to higher shares of renewable energy resources, this process also requires complementary innovations such as energy storage, smart grids, demand response, network expansion, new business models and market arrangements. Moving forward, energy policies will continue to shape the energy transition, continuously evolving and adapting to individual country requirements and dynamic market conditions.

Solar PV transpires to become the main energy source in the system, similar to the findings of Creutzig et al. [72] and Haegel et al. [97] with installed capacities in the range of dozens of TW. The solar PV industry is capable of providing all required capacities, as shown by Verlinden [98], since 70 TW of PV capacities can be ramped up by 2050, which is about 10% more than 63.38 TW found in this research. At the same time, increasing adoption of variable renewable energy and drastic reduction of the supply of inflexible baseload generation, is made possible by promoting of Power-to-X, dispatchable renewables, grids, storage technologies and overall sector coupling [99] forming a flexible energy system [4]. The combination of high shares of variable renewable energy and Power-to-X has been identified as a major gap in Integrated Assessment Models, mainly used by the IPCC [100], which is a consequence of unreasonably high solar PV cost assumptions, as documented in Krey et al. [101] and concluded in Jaxa-Rozen and Trutnevyte [102]. This is further amplified by methodological short comings in Power-to-X modelling and lack of hourly resolution [100]. The results of this research indicate that RE resources are sufficient to satisfy the growing global energy demand even with high rates of electrification and moreover, increase in energy access across developing countries, thereby bridging the gap between developing and developed countries in terms of energy supply per capita.

A global energy transition towards 100% renewable energy has the potential to lift the standards of living for people all around the world due to phasing out emissions and giving equal access to energy and water, especially in the Global South, which has excellent solar conditions throughout the year and tremendous potential for adopting solar PV as indicated by the results of this research and others [72]. Introduction of desalination will resolve the water scarcity issue providing 3 billion m^3 of clean water per day. As most of the development across the regions is yet to take shape, shifting them towards sustainable energy infrastructure development presents the opportunity to leapfrog developed countries into a sustainable future. In consequence, global energy resource based conflicts can be mitigated and a pathway towards peace and increased welfare can be attained.

Such a transition will directly accomplish four major Sustainable Development Goals. First, it decreases the probability of significant climate change threatening civilisation, by reducing GHG emissions without limiting growth of energy consumption in the future. Second, it provides equal access to low-cost energy supply in all regions across the world. Third, it enables sustainable growth in standards of living across developing countries of the Global South. Fourth, it enables universal access to clean water and decreases water stress. Indirectly, it will also help accomplish several other Sustainable Development Goals leading to an overall sustainable future.

Credit author statement

Dmitrii Bogdanov: Conceptualisation, Methodology, Investigation, Software, Visualisation, Writing- Original draft preparation.Manish Ram: Investigation, Writing- Original draft preparation. Arman Aghahosseini: Investigation, Visualisation. Ashish Gulagi:Investigation. Ayobami Solomon Oyewo: Investigation. Michael Child: Investigation. Upeksha Caldera: Investigation. Kristina Sadovskaia: Investigation. Javier Farfan: Investigation. Larissa De Souza Noel Simas Barbosa: Investigation. Mahdi Fasihi: Investigation. Siavash Khalili: Investigation. Thure Traber: Investigation. Christian Breyer: Investigation, Supervision, Writing-Reviewing and 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.120467.

References

[1] Independent Group of Scientists appointed by the Secretary-General. Global sustainable development report 2019: the future is now – Science for Achieving Sustainable Development. New York. 2019. https://doi.org/10.1016/S0262-4079(12).60125–0.
[2] [IPCC] - International Panel on Climate Change. IPCC - special report on 1.5 degrees. Geneva. 2018.
[3] Lohrmann A, Farfan J, Caldera U, Lohrmann C, Breyer C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. Nat Energy 2019;4:1040–8. https://doi.org/10.1038/s41560-019-0501-4.
[4] REN21. Renewables 2020 global status report. Paris. 2020.
[5] Ram M, Child M, Aghahosseini A, Bogdanov D, Lohrmann A, Breyer C. A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015–2030. J Clean Prod 2018;199:687–704. https://doi.org/10.1016/j.jclepro.2018.07.159.
[6] [IEA] - International Energy Agency. World energy outlook. 2020. p. 2020. Paris.
[7] Koskinen O, Breyer C. Energy storage in global and transcontinental energy scenarios: a critical review. Energy Procedia n.d. 2016;99:53–63. https://doi.org/10.1016/j.egypro.2016.10.097.
[8] Global Energy Assessment (GEA). https://doi.org/10.1017/cbo9780511793677; 2012.
[9] Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, McCollum DL, et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy 2018;3:515–27. https://doi.org/10.1038/s41560-018-0172-6.

[10] Centre for Alternative Technology (CAT). Raising ambition - zero carbon scenarios from across the globe. Wales, UK. 2018.
[11] Pursiheimo E, Holttinen H, Koljonen T. Inter-sectoral effects of high renewable energy share in global energy system. Renew Energy 2019;136: 1119–29. https://doi.org/10.1016/j.renene.2018.09.082.
[12] Löffler K, Hainsch K, Burandt T, Oei P-Y, Kemfert C, von Hirschhausen C, et al. Designing a model for the global energy system—GENeSYS-MOD: an application of the open-source energy modeling system (OSeMOSYS). Energies 2017;1468:10. https://doi.org/10.3390/en10101468.
[13] Jacobson MZ, Delucchi MA, Cameron MA, Mathiesen BV. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renew Energy 2018;123:236–48. https://doi.org/10.1016/j.renene.2018.02.009.
[14] Teske S. Achieving the paris climate agreement goals: global and regional 100% renewable energy scenarios with non-energy GHG pathways for +1.5°C and +2°C. Cham: Springer International Publishing; 2019. https://doi.org/10.1007/978-3-030-05843-2.
[15] Jacobson MZ, Delucchi MA, Cameron MA, Coughlin SJ, Hay CA, Manogaran IP, et al. Impacts of green new deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. One Earth 2019;1:449–63. https://doi.org/10.1016/j.oneear.2019.12.003.
[16] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. https://doi.org/10.1016/j.energy.2019.03.092.
[17] Wada Y, Gleeson T, Esnault L. Wedge approach to water stress. Nat Geosci 2014;7:615–7. https://doi.org/10.1038/ngeo2241.
[18] Bogdanov D, Farfan J, Sadovskaia K, Aghahosseini A, Child M, Gulagi A, et al. Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat Commun 2019;1077:10. https://doi.org/10.1038/s41467-019-08855-1.
[19] Prina MG, Manzolini G, Moser D, Nastasi B, Sparber W. Classification and challenges of bottom-up energy system models - a review. Renew Sustain Energy Rev 2020. https://doi.org/10.1016/j.rser.2020.109917.
[20] Sadovskaia K, Bogdanov D, Honkapuro S, Breyer C. Power transmission and distribution losses – a model based on available empirical data and future trends for all countries globally. Int J Electr Power Energy Syst 2019;107: 98–109. https://doi.org/10.1016/j.ijepes.2018.11.012.
[21] European Commission. Joint research centre. Institute for energy and transport., SERTIS. Energy technology reference indicator (ETRI) projections for 2010-2050. Petten. 2014.
[22] [ETIP-PV] - European Technology and Innovation Platform Photovoltaics. The true competitiveness of solar PV. A European case study. Munich. 2017.
[23] Bolinger M, Seel J, Hamachi LaCommare K. Utility-scale solar 2016: an empirical analysis of project cost, performance, and pricing trends in the United States. Berkley: Lawrence Berkeley National Laboratory; 2017.
[24] Kutscher C, Mehos M, Turchi C, Glatzmaier G, Moss T. Line-focus solar power plant cost reduction plan. National Renewable Energy Laboratory (NREL); 2010. vol. NREL/TP-55. Golden.
[25] Danish Energy Agency. Energinet. Technology data for individual heating plants and energy transport. Copenhagen. 2016.
[26] [IEA] - International Energy Agency. Technology roadmap: solar heating and cooling. Paris. 2012.
[27] Connolly D. EnergyPLAN cost database. Copenhagen. 2015.
[28] Danish Energy Agency. Energinet. Technology data - energy plants for electricity and district heating generation. Copenhagen 2016.
[29] Fraunhofer ISE. Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems bis 2050. Freiburg. 2015.
[30] Energiewende Agora. Stromspeicher in der Energiewende. Berlin. 2014.
[31] Breyer C, Tsupari E, Tikka V, Vainikka P. Power-to-gas as an emerging profitable business through creating an integrated value chain. Energy Procedia 2015;73:182–9. https://doi.org/10.1016/j.egypro.2015.07.668.
[32] Fasihi M, Bogdanov D, Breyer C. Long-term hydrocarbon trade options for the Maghreb region and Europe-renewable energy based synthetic fuels for a net zero emissions world. Sustain 2017;9:306. https://doi.org/10.3390/su9020306.
[33] Hoffmann W. Importance and evidence for cost effective electricity storage. 29th EU PVSEC, Amsterdam, September 22–26. 2014.
[34] Neij L. Cost development of future technologies for power generation — a study based on experience curves and complementary bottom-up assessments. Energy Pol 2008;36:2200–11. https://doi.org/10.1016/j.enpol.2008.02.029.
[35] Bundesministerium für Wirtschaft und Energie. Thermvolt: systemvergleich vonsolarthermischen und photovoltaischen Kraftwerken für die Versorgungssicherheit. Berlin. 2016.
[36] Connolly DA. Review of energy storage technologies: for the integration of fluctuating renewableenergy. Aalborg. 2010.
[37] Svensson R, Odenberger M, Johnsson F, Ströömberg L. Transportation systems for CO2––application to carbon capture and storage. Energy Convers Manag 2004;45:2343–53.
[38] Michalski J, Bunger U, Crotogino F, Donadei S, Schneider G, Pregger T. Hydrogen generation by electrolysis and storage in salt caverns: potentials, economics and systems aspects with regard to the German energy transition. Int J Hydrogen Energy 2017;42:13427–43.
[39] Caldera U, Bogdanov D, Afanasyeva S, Breyer C. Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia. Water 2018;10(1):3. https://doi.org/10.3390/w10010003.
[40] Deutsches Institut für Wirtschaftsforschung. Data documnetation: current and prospective costs of electricity generation until 2050. Berlin. 2013.
[41] [BNEF]. Bloomberg new energy finance. New energy outlook 2015-Long-term projections of the global energy sector. London. 2015. https://doi.org/10.1017/CBO9781107415324.004.
[42] CSIRO division of atmospheric research. Lifecycle emissions and energy analysis of LNG, oil and coal. 1996. Aspendale.
[43] Environmental Protection Agency. Annexes to the inventory of U.S. GHG emissions and sinks. Washington, D.C. 2013.
[44] Sigfusson B, Uihlein A. 2015 JRC geothermal energy status report. European Commission - Joint Research Centre. Petten; 2015. https://doi.org/10.2790/959587.
[45] [IEA] - International Energy Agency. World energy outlook. Paris. 2015.
[46] McDonald A, Schrattenholzer L. Learning rates for energy technologies. Energy Pol 2001;29:255–61. https://doi.org/10.1016/S0301-4215(00)00122-1.
[47] Koomey J, Hultman NE. A reactor-level analysis of busbar costs for US nuclear plants, 1970-2005. Energy Pol 2007;35:5630–42. https://doi.org/10.1016/j.enpol.2007.06.005.
[48] [IEA] - International Energy Agency and [NEA]-Nuclear Energy Agency. Projected costs of generating electricity. Paris. 2015. https://doi.org/10.1787/cost_electricity-2015-en.
[49] Urban W, Lohmann H, Girod K. Abschlussbericht für das BMBF-Verbundprojekt Biogaseinspeisung. Fraunhofer UMSICHT. 2009.
[50] Haysom JE, Jafarieh O, Anis H, Hinzer K, Wright D. Learning curve analysis of concentrated photovoltaic systems. Prog Photovoltaics Res Appl 2015;23: 1678–86. https://doi.org/10.1002/pip.2567.
[51] Bogdanov D, Child M, Breyer C. Reply to 'Bias in energy system models with uniform cost of capital assumption'. Nat Commun 2019;10:4587. https://doi.org/10.1038/s41467-019-12469-y.
[52] Gerlach A, Breyer C, Werner C. Impact of financing cost on global gridparity dynamics till 2030. In: 29th Eur. Photovolt. Sol. Energy Conf; 2014 [Amsterdam., n.d].
[53] Breyer C, Gerlach A. Global overview on grid-parity. Prog Photovoltaics Res Appl 2013;21:121–36. https://doi.org/10.1002/pip.1254.
[54] Barbosa LSN, Bogdanov D, Breyer C. Heat demand for space heating, domestic hot water, industrial heat and biomass-based cooking – worldwide assessment on national level. LUT report. Lappeenranta: Lappeenranta University of Technology; 2016.
[55] Caldera U, Breyer C. Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems. Energy 2020;117507:200. https://doi.org/10.1016/j.energy.2020.117507.
[56] Khalili S, Rantanen E, Bogdanov D, Breyer C. Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world. Energies 2019;12:3870. https://doi.org/10.3390/en12203870.
[57] Bogdanov D, Breyer C. North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manag 2016;112:176–90. https://doi.org/10.1016/j.enconman.2016.01.019.
[58] Stackhouse P, Whitlock C. Surface meteorology and solar energy (SSE) release 6.0 methodology. National aeronautic and space administration (NASA). Langley, VA, USA. 2008.
[59] Stackhouse P, Whitlock C. Surface meteorology and solar energy (SSE) release 6.0 methodology. National aeronautic and space administration (NASA). Langley, VA, USA. 2009.
[60] Stetter D. Enhancement of the REMix energy system model: global renewable energy potentials, optimized power plant siting and scenario validation. PhD thesis. Faculty of energy-, process- and bio-engineering, University of Stuttgart; 2012.
[61] Afanasyeva S, Bogdanov D, Breyer C. Relevance of PV with single-Axis tracking for energy scenarios. Sol Energy 2018;173:173–91.
[62] Verzano K. Climate change impacts on flood related hydrological processes: further development and application of a global scale hydrological model. University of Kassel; 2009. https://doi.org/10.17617/2.993926.
[63] Bunzel K, Zeller V, Buchhorn M, Griem F, Thrän D. Regionale und globale räumliche Verteilung von Biomassepotenzialen. Leipzig. 2009.
[64] Eisentraut A, Brown A. Technology roadmap bioenergy for heat and power. [IEA] - Int Energy Agency 2012:1–41. https://doi.org/10.1108/meq.2013.08324aaa.005.
[65] IPCC. Renewable energy sources and climate change mitigation. Geneva: IPCC; 2011.
[66] Aghahosseini A, Bogdanov D, Breyer C. A techno-economic study of an entirely renewable energy-based power supply for north America for 2030 conditions. Energies 2017;10:1171. https://doi.org/10.3390/en10081171.
[67] Aghahosseini A, Breyer C. Assessment of geological resource potential for compressed air energy storage in global electricity supply. Energy Convers Manag 2018;169:161–73. https://doi.org/10.1016/j.enconman.2018.05.058.
[68] Sweco. Race to electrification – Norway in Pole position - urban insight. Stockholm. 2019.
[69] Barasa M, Bogdanov D, Oyewo AS, Breyer C. A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030. Renew Sustain Energy Rev 2018;92:440–57. https://doi.org/10.1016/j.rser.2018.04.110.
[70] Kraan O, Chappin E, Kramer GJ, Nikolic I. The influence of the energy

transition on the significance of key energy metrics. Renew Sustain Energy Rev 2019. https://doi.org/10.1016/j.rser.2019.04.032.
[71] United Nations - DESA/Population division. World population prospects 2019. Geneva. 2019.
[72] Creutzig F, Agoston P, Goldschmidt JC, Luderer G, Nemet G, Pietzcker RC. The underestimated potential of solar energy to mitigate climate change. Nat Energy 2017;2:17140.
[73] Fasihi M, Bogdanov D, Breyer C. Techno-economic assessment of power-to-liquids (PtL) fuels production and global trading based on hybrid PV-wind power plants. Energy Procedia 2016;99:243−68. https://doi.org/10.1016/j.egypro.2016.10.115.
[74] Tremel A, Wasserscheid P, Baldauf M, Hammer T. Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis. Int J Hydrogen Energy 2015;40:11457−64. https://doi.org/10.1016/j.ijhydene.2015.01.097.
[75] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, et al. Renewable Power-to-Gas: a technological and economic review. Renew Energy 2016;85:1371−90. https://doi.org/10.1016/j.renene.2015.07.066.
[76] Breyer C, Bogdanov D, Aghahosseini A, Gulagi A, Fasihi M. On the techno-economic benefits of a global energy interconnection. Econ Energy Environ Policy 2020;9:83−102. https://doi.org/10.5547/2160-5890.9.1.cbre.
[77] [IRENA] - International Renewble Energy Agency. Global energy transformation: a roadmap to 2050. Abu dhabi. 2018.
[78] Breyer C, Khalili S, Bogdanov D. Solar photovoltaic capacity demand for a sustainable transport sector to fulfil the Paris Agreement by 2050. Prog Photovoltaics Res Appl 2019;27:978−89. https://doi.org/10.1002/pip.3114.
[79] Averfalk H, Ingvarsson P, Persson U, Gong M, Werner S. Large heat pumps in Swedish district heating systems. Renew Sustain Energy Rev 2017;79:1275−84. https://doi.org/10.1016/j.rser.2017.05.135.
[80] Blarke M. Towards an intermittency-friendly energy system: comparing electric boilers and heat pumps in distributed cogeneration. Appl Energy 2012;91:349−65.
[81] Varone A, Ferrari M. Power to liquid and power to gas: an option for the German Energiewende. Renew Sustain Energy Rev 2015;45:207−18. https://doi.org/10.1016/j.rser.2015.01.049.
[82] Schmidt P, Weindorf W. Potentials and - perspectives for the -future supply of -Renewable-Aviation fuel. Munich. 2016.
[83] Gulagi A, Choudhary P, Bogdanov D, Breyer C. Electricity system based on 100% renewable energy for India and SAARC. PloS One 2017;12:e0180611. https://doi.org/10.1371/journal.pone.0180611.
[84] Gernaat DEHJ, Bogaart PW, Vuuren DPV, Biemans H, Niessink R. High-resolution assessment of global technical and economic hydropower potential. Nat Energy 2017;2:821−8. https://doi.org/10.1038/s41560-017-0006-y.
[85] Kätelhön A, Meys R, Deutz S, Suh S, Bardow A. Climate change mitigation potential of carbon capture and utilization in the chemical industry. Proc Natl Acad Sci U S A 2019;166:11187−94. https://doi.org/10.1073/pnas.1821029116.
[86] Fasihi M, Weiss R, Savolainen J, Breyer C. Global potential of green ammonia based on hybrid PV-wind power plants. Appl Energy 2021. https://doi.org/10.1016/j.apenergy.2020.116170. in press.
[87] Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, Olsen A, et al. Global carbon budget 2020. Earth Syst Sci Data 2020;12:3269−340. https://doi.org/10.5194/essd-12-3269-2020.
[88] Hansen J, Sato M, Kharecha P, Von Schuckmann K, Beerling DJ, Cao J, et al. Young people's burden: requirement of negative CO2 emissions. Earth Syst Dyn 2017;8:577−616. https://doi.org/10.5194/esd-8-577-2017.
[89] Fuss S, Canadell JG, Ciais P, Jackson RB, Jones CD, Lyngfelt A, et al. Moving toward net-zero emissions requires new alliances for carbon dioxide removal. One Earth 2020;3:145−9. https://doi.org/10.1016/j.oneear.2020.08.002.
[90] Breyer C, Fasihi M, Bajamundi C, Creutzig F. Direct air capture of CO2: a key technology for ambitious climate change mitigation. Joule 2019;3:2053−7. https://doi.org/10.1016/j.joule.2019.08.010.
[91] Realmonte G, Drouet L, Gambhir A, Glynn J, Hawkes A, Köberle AC, et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 2019;3277:10. https://doi.org/10.1038/s41467-019-10842-5.
[92] Davis Lisa. Electrifying the developing world will help us all. Here's how | World Economic Forum. World Econ Forum, https://www.weforum.org/agenda/2019/01/energizing-the-world-how-electrification-will-drive-inclusion/. [Accessed 4 October 2019].
[93] Garcia-Casals X, Ferroukhi R, Parajuli B. Measuring the socio-economic footprint of the energy transition. Energy Transitions 2019. https://doi.org/10.1007/s41825-019-00018-6.
[94] BNP Paribas Asset Management. Wells, Wires, and Wheels. - EROCI and the tough road ahead for oil. 2019.
[95] Daszkiewicz K. Policy and regulation of energy transition. In: Hafner M, Tagliapietra S, editors. Geopolit. Glob. Energy transition. Lect. Notes energy, Cham. Springer; 2020. https://doi.org/10.1007/978-3-030-39066-2_9.
[96] Relva SG, Silva VO da, Gimenes ALV, Udaeta MEM, Ashworth P, Peyerl D. Enhancing developing countries' transition to a low-carbon electricity sector. Energy 2021;220:119659. https://doi.org/10.1016/j.energy.2020.119659.
[97] Haegel NM, Atwater H, Barnes T, Breyer C, Burrell A, Chiang Y-M, et al. Terawatt-scale photovoltaics: transform global energy. Science (80-) 2019;364:836−8. https://doi.org/10.1126/science.aaw1845.
[98] Verlinden PJ. Future challenges for photovoltaic manufacturing at the terawatt level. J Renew Sustain Energy 2020;12:053505. https://doi.org/10.1063/5.0020380.
[99] Child M, Koskinen O, Linnanen L, Breyer C. Sustainability guardrails for energy scenarios of the global energy transition. Renew Sustain Energy Rev 2018;91:321−34. https://doi.org/10.1016/j.rser.2018.03.079.
[100] Victoria M, Haegel N, Peters IM, Sinton R, Jäger-Waldau A, Cañizo C, et al. Solar photovoltaics is ready to power a sustainable future. Joule 2021. https://doi.org/10.1016/j.joule.2021.03.005.
[101] Krey V, Guo F, Kolp P, Zhou W, Schaeffer R, Awasthy A, et al. Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models. Energy 2019;172:1254−67. https://doi.org/10.1016/j.energy.2018.12.131.
[102] Jaxa-Rozen M, Trutnevyte E. Sources of uncertainty in long-term global scenarios of solar photovoltaic technology. Nat Clim Change 2021;11:266−73. https://doi.org/10.1038/s41558-021-00998-8.