On the History and Future of 100% Renewable Energy Systems Research

Citation for published version (APA):
Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A. S., Aghahosseini, A., Gulagi, A., Solomon, A. A., Keiner, D., Lopez, G., Ostergaard, P. A., Lund, H., Mathiesen, B. V., Jacobson, M. Z., Victoria, M., Teske, S., Pregger, T., Fthenakis, V., Raugei, M., ... Sovacool, B. K. (2022). On the History and Future of 100% Renewable Energy Systems Research. *IEEE Access*, *10*, 78176-78218. Article 9837910. https://doi.org/10.1109/ACCESS.2022.3193402

DOI:
10.1109/ACCESS.2022.3193402

Document status and date:
Published: 01/01/2022

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 21. May. 2025

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 10 June 2022, accepted 19 July 2022, date of publication 25 July 2022, date of current version 29 July 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3193402

TOPICAL REVIEW

On the History and Future of 100% Renewable Energy Systems Research

CHRISTIAN BREYER[1], SIAVASH KHALILI[1], DMITRII BOGDANOV[1], MANISH RAM[1], AYOBAMI SOLOMON OYEWO[1], ARMAN AGHAHOSSEINI[1], ASHISH GULAGI[1], A. A. SOLOMON[1], DOMINIK KEINER[1], GABRIEL LOPEZ[1], POUL ALBERG ØSTERGAARD[2], HENRIK LUND[2], BRIAN V. MATHIESEN[3], MARK Z. JACOBSON[4], MARTA VICTORIA[5], SVEN TESKE[6], THOMAS PREGGER[7], VASILIS FTHENAKIS[8], (Fellow, IEEE), MARCO RAUGEI[8,9], HANNELE HOLTTINEN[10,11], (Senior Member, IEEE), UGO BARDI[12], AUKE HOEKSTRA[13], AND BENJAMIN K. SOVACOOL[14,15,16]

[1]School of Energy Systems, LUT University, 53850 Lappeenranta, Finland
[2]Department of Planning, Aalborg University, 9000 Aalborg, Denmark
[3]Department of Planning, Aalborg University, 2450 Copenhagen, Denmark
[4]Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, USA
[5]Department of Mechanical and Production Engineering, Aarhus University, 8000 Aarhus, Denmark
[6]Institute for Sustainable Futures, University of Technology Sydney (UTS), Sydney, NSW 2007, Australia
[7]German Aerospace Center (DLR), Institute of Networked Energy Systems, 70563 Stuttgart, Germany
[8]Center for Life Cycle Analysis, Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA
[9]School of Engineering, Computing and Mathematics, Oxford Brookes University, Oxford OX3 0BP, U.K.
[10]Recognis Oy, 01530 Vantaa, Finland
[11]School of Electrical & Electronic Engineering, University College Dublin, Dublin 4, D04 V1W8 Ireland
[12]Dipartimento di Chimica, Università di Firenze, Sesto Fiorentino, 50019 Florence, Italy
[13]Deprtment of Mechanical Engineering, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands
[14]Center for Energy Technologies, Department of Business Development and Technology, Aarhus University, 8000 Aarhus, Denmark
[15]Science Policy Research Unit (SPRU), University of Sussex Business School, Brighton BN1 9SN, U.K.
[16]Department of Earth and Environment, Boston University, Boston, MA 02215, USA

Corresponding author: Christian Breyer (christian.breyer@lut.fi)

This work was supported in part by Business Finland through the P2XENABLE Project under Grant 8588/31/2019, in part by the Academy of Finland through the Industrial Emissions and CDR Project under Grant 329313, and in part by the LUT University Research Platform "GreenRenew."

ABSTRACT Research on 100% renewable energy systems is a relatively recent phenomenon. It was initiated in the mid-1970s, catalyzed by skyrocketing oil prices. Since the mid-2000s, it has quickly evolved into a prominent research field encompassing an expansive and growing number of research groups and organizations across the world. The main conclusion of most of these studies is that 100% renewables is feasible worldwide at low cost. Advanced concepts and methods now enable the field to chart realistic as well as cost- or resource-optimized and efficient transition pathways to a future without the use of fossil fuels. Such proposed pathways in turn, have helped spur 100% renewable energy policy targets and actions, leading to more research. In most transition pathways, solar energy and wind power increasingly emerge as the central pillars of a sustainable energy system combined with energy efficiency measures. Cost-optimization modeling and greater resource availability tend to lead to higher solar photovoltaic shares, while emphasis on energy supply diversification tends to point to higher wind power contributions. Recent research has focused on the challenges and opportunities regarding grid congestion, energy storage, sector coupling, electrification of transport and industry implying power-to-X and hydrogen-to-X, and the inclusion of natural and technical carbon dioxide removal (CDR) approaches. The result is a holistic vision of the transition towards a net-negative greenhouse gas emissions economy that can limit global warming to 1.5°C with a clearly defined carbon budget in a sustainable and cost-effective manner based on 100% renewable energy-industry-CDR

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

systems. Initially, the field encountered very strong skepticism. Therefore, this paper also includes a response to major critiques against 100% renewable energy systems, and also discusses the institutional inertia that hampers adoption by the International Energy Agency and the Intergovernmental Panel on Climate Change, as well as possible negative connections to community acceptance and energy justice. We conclude by discussing how this emergent research field can further progress to the benefit of society.

INDEX TERMS Climate safety, energy transition, power-to-X, 100% renewable energy, sector coupling.

I. INTRODUCTION

Looming threats of unabated climate change have propelled societal discussions on the possibility of low-carbon or even carbon-negative sustainable energy systems. The field of 100% renewable energy (RE) systems research proposes this can be fully done using renewable sources not only for the electricity sector, but for all energy and non-energy industry. Over time, the visions and scenarios of science have taken root in politics and society. More and more countries are setting net-zero emission targets, where all greenhouse gas (GHG) emitting and absorbing sectors are combined. These analyses usually result in requiring the energy system to be CO_2-free, and in most countries, this means 100% RE supply. Already, in 2011, Denmark set the target to reach 100% renewables across all energy sectors by 2050 [1]. In 2016, 48 countries pledged at the COP 22 in Marrakesh to reach 100% RE supply in the power sector at a minimum [2]. Additionally, more than 61 countries across the world have set 100% RE targets for at least the power sector [3].

While many policy makers embraced 100% RE, recognition of this field's academic research has been slow. It took until 2018 for the Intergovernmental Panel on Climate Change (IPCC) to acknowledge 100% RE research [4]. The International Renewable Energy Agency (IRENA) has started approaching 100% RE for utilities and countries [5]–[7]; however, its central energy transition scenario [8] does not yet offer a 100% RE pathway. The International Energy Agency (IEA) has developed a global Net Zero by 2050 scenario that only leads to a RE share of 67% (with 11% nuclear and the remaining supply coming from fossil fuels that is partly combined with carbon capture and storage (CCS) [9]. However, in 2021 the IEA also presented a first 100% RE country scenario [10]. By mid-2022, the European Union has not published any 100% RE scenarios but did publish two climate neutral scenarios in 2018 [11].

This review and perspective paper is intended to introduce 100% RE research and its far-reaching potential to a wider audience. First, we will define the field and look at the historic milestones and published literature with the contributions of major research groups in the field. Then, we will describe the present status of the field. Following that, the major criticisms on the results and the resistance against 100% RE scenarios in major organizations are discussed. The discussion also emphasizes how carbon dioxide removal (CDR) may be added to create the net-negative system that is needed to stay below 1.5°C. Finally, we end by describing research gaps and drawing conclusions.

II. DEFINITION OF THE FIELD OF 100% RENEWABLE ENERGY SYSTEMS RESEARCH

To define 100% RE systems research, we first define the different aspects of energy system analysis in general. We then specify what is covered by 100% RE research. Energy system analyses can be structured as follows: energy sources; energy conversion; energy storage; energy transport; and final energy fulfilling energy services demand [12].

Sources of energy covered by 100% RE system research are: solar energy; wind energy; hydropower; bioenergy; geothermal; and ocean energy (tidal, wave, ocean current, ocean thermal). Research indicates that renewable electricity and energy efficiency in combination with an energy system re-design will play a dominant role in the transition due to its low-cost, high efficiency, wide applicability, mature technologies, and vast access to renewable resources [13]–[16]. In the past, bioenergy and hydropower were considered the most important, whereas the strongest growth today is observed in solar and wind energy [17], [18]. While solar and wind energy are also expected to dominate 100% RE system solutions on the global average [19], other renewable resources could play a dominant role in individual countries or regions. Today, ten countries supply near or more than 100% of their electricity from renewables, mostly coming from hydropower [20].

Conversion means the energy sources can be stored, transported and used, independent of the original form. Energy in its original form is called primary energy. Energy in its final form as used at its final destination is called final energy [21]. Electricity from solar photovoltaics (PV), wind power, and hydropower is primary energy [21] only before transmission and distribution grid losses, and electricity after grid losses is final energy for end-use. Modern 100% RE scenarios often make wide use of power-to-X (PtX) technologies, in particular, power-to-heat [22] and power-to-hydrogen [23]–[26]. Where direct hydrogen cannot yet be used, such as in the chemical industry or for long-distance marine and aviation transportation, hydrogen can be further converted to synthetic electricity-based fuels (e-fuels) as chemically bound RE and such as e-methane [27], [28], Fischer-Tropsch fuels [29], [30], e-ammonia [31], [32], and e-methanol [33], [34].

Technologies are available for all required energy conversions, but conversion also leads to losses. For example: burning fossil fuels to produce electricity usually leads to heat losses of over 50%, and in cars even 75% [35]. Another example is transforming electricity into e-fuels (like hydrogen) and then back to electricity which leads to the loss

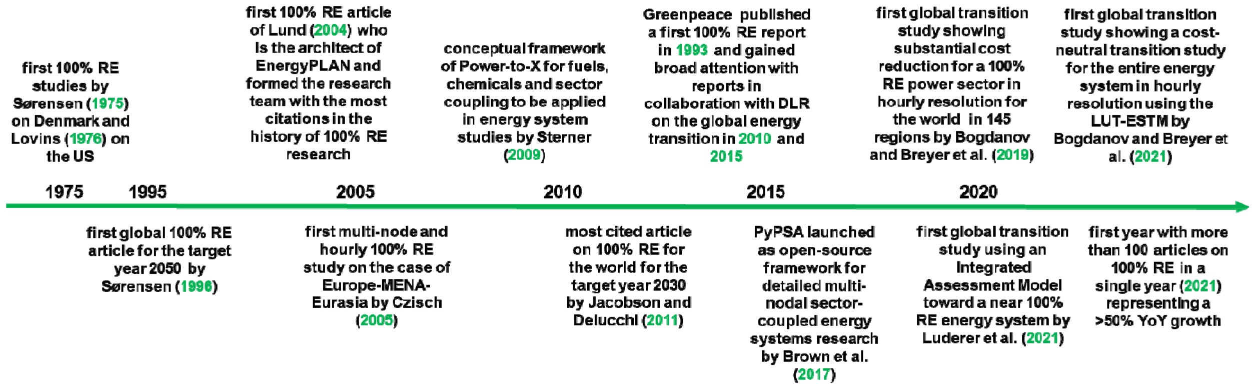


FIGURE 1. Timeline of selected key milestones of 100% RE systems research.

of over half the energy. Thus, conversions should only be used when strictly necessary [13]–[15]. Energy efficiency and waste heat recovery are important in district heating systems [36], e-fuels [37], [38], and sector coupling [39]. Therefore, final energy use should be prioritized as follows: use direct electricity wherever possible, for instance highly efficient heat pumps and battery-electric vehicles, use low temperature heat directly where possible, then add efficient hydrogen solutions where required, and only use hydrogen-to-X conversions for e-fuels and e-chemicals where other solutions are impossible.

Storage of energy is an important element of 100% RE systems, especially when using large shares of variable sources like solar and wind [14], [40]–[42], and it can take various forms [43]–[45]. Batteries can supply efficient short-term storage, while e-fuels can provide long-term storage solutions. Other examples are mechanical storage in pumped hydro energy storage [46], [47] and compressed air energy storage [48], [49], and thermal energy in a range of storage media at various temperature levels [43], [50]. Transport is available for all major forms of energy including electricity, heat and chemical fuels. Electricity is transported by power lines and has losses. Heat is transported using heating/cooling networks. Chemical fuels are moved using pipelines, ships, railways, or vehicles. Renewable electricity integration options have different advantages and disadvantages and a clear focus on the ability to reduce fuel consumptions in the entire supply chain can be recommended [51].

Final energy fulfilling demand will primarily be electricity and heat and cold (used at various temperature levels) when discussing residential, commercial, and industrial applications. Chemically bound fuels will be used in long-distance transportation and steelmaking. Finally, non-energy feedstocks are used by the chemical industry. Electricity will enable electrification of all transport modes, the desalination of water supply [52], [53], and possibly long-term CO_2 storage for net-negative CO_2 solutions enabling climate safety [54].

The 100% RE energy system studies do not cover detailed power system simulations, assessing the dynamics, security and reliability in detail. The assumption has been that system operators will, as time passes, gradually manage future power system operation at times with close to 100% inverter-based, non-synchronous generation. This is still subject to ongoing research, as discussed in Sections VI and IX. However, detailed regional and local grid simulations have been done for more than a decade.

To summarize, 100% RE is a subfield of energy system analysis that assesses solutions without the need for fossil fuels and nuclear energy, while using bioenergy, hydropower, and geothermal energy within sustainable limits.

III. MILESTONES IN THE HISTORY OF 100% RENEWABLE ENERGY SYSTEMS ANALYSES

An overview on selected key milestones of 100% RE systems analyses is presented in this section and briefly summarized in Figure 1. The first 100% renewable energy system analysis was published in 1975 by Sørensen [55] focusing on Denmark as a case study in the prestigious journal Science. Remarkably, Science has published only one article exploring 100% RE scenarios since. In 1976, Lovins [56] published the second article on 100% renewables, but for the United States, calling it ''the soft energy path'', with the prescient sub-title: ''The road not taken?''. Lovins may have been inspired by Sørensen [55], as he was the first scholar citing it [57]. Where Sørensen [55] carried out a quantitative analytic study, Lovins [56] focused more on the framing, relevance and key components. Both applied the approach of a vision-driven energy system transition research, which is still up-to-date [58]. In 1996, Sørensen [59] contributed another major milestone in the research field with the first global academic analysis of a 100% RE system for the target year 2050. In 1993, a report was published by the Stockholm Environment Institute for Greenpeace International [60] on 100% RE for the target year 2100. Although this report aimed to direct the IPCC on 100% RE, it took another 25 years to be acknowledged [4].

An additional 13 years passed until the second global 100% RE system analysis emerged, authored by Jacobson and Delucchi [61] in 2009, prepared for the target year 2030.

More details of that study were published in 2011 [62], [63]. The stark decrease in cost of RE [64], in particular wind power and solar PV, has led to 100% RE being economically feasible and thus an interesting pathway to study in detail. Whereas the Sørensen and Lovins papers included biomass, biofuels, and biogas, Jacobson and Delucchi included no such fuels due to their explicit goal of "consider(ing) only technologies that have near-zero emissions of greenhouse gases and air pollutants over their entire lifecycle" [61]. Ref. [62] is the most cited article in the field, and it has helped to overcome belief systems and barriers across different fields on a global scale, and to catalyze a global breakthrough of 100% RE. Updated research by Jacobson *et al.* [13], [65]–[69] has overcome the previously identified limitations, and has provided more detailed energy system results for almost all countries in the world, as well as grid analyses of 20 or 24 representative regions encompassing the countries. The first study examining specifically 100% renewable transportation was published in 2005 [70]. It examined the air pollution and climate impacts of transitioning all on-road vehicles in the U.S. to hydrogen fuel cell vehicles powered by wind electrolysis.

Unfortunately, Sørensen, as one of the first pioneers in the research field and with the first global 100% RE system analysis for mid-century and various other methodological innovations, did not receive much recognition in the research community at the time. A few reviews and related studies acknowledge his early contributions [19], [41], [71], [72]. An outstanding methodological breakthrough was contributed by Czisch in 2005 [73] with his dissertation describing the first 100% RE multi-node simulation in hourly resolution based on historic weather data for an investigated super-grid for one billion people in Europe, Western Eurasia, North Africa, and the Middle East. A similar study with a global perspective was published in 2004 [74], but appeared to be less noticed. The landmark study of Czisch enabled various super-grid studies and supported the Desertec Vision of those years, as described in more detail by Trieb *et al.* [75], [76] and Breyer *et al.* [72]. In this context in 2005, the German Aerospace Center (DLR) started early research on the development of a spatially and temporally resolved cost-optimizing power system model called REMix. In contrast to the existing models at that time, REMix methodically focused on the expansion and operation of variable RE (VRE) technologies [77].

This focus also led to new insights into the interaction of VRE and existing plants, resulting infrastructure requirements, and demonstrated that the necessary load balancing in the system is technically and economically feasible [78]. In 2010, Heide *et al.* [79] derived the first optimal balance of solar PV and wind power for a 100% RE system for the case of Europe in hourly and high spatial resolution and concluded that 45% solar PV and 55% wind power would be an optimal mix. By using a stylized approach, known as weather-driven modeling, Greiner and co-workers described the impact of assuming different wind and solar combinations and heterogeneities among the European countries [80], [81] and evaluated the impact of extending transmission links [82] and storage [83], [84].

The most cited research team in the field is the group of Lund, Mathiesen, and Østergaard from Aalborg University, who started in the field of 100% RE systems research in 2004 [85] and contributed to a substantial expansion of the research field with the freeware energy system analysis tool EnergyPLAN [86], [87], which has been optimized for 100% RE system simulations in hourly resolution, sector coupling, and overnight analyses. Several of the most cited articles in the field are authored by this group, which facilitated a broad dissemination of the concept of 100% RE to various research teams around the world. They also helped to look beyond the power sector and electricity grids and started including heat and transport in their model that facilitated insights leading to the smart energy system concept [88]–[92]. This enabled detailed studies on the transition of individual and coupled sectors of the same team [16], but also other teams, such as for the heat sector [93]–[95], transport sector [96]–[98] and seawater desalination [53].

Another building block that the field needed was the conversion of electricity to chemical fuels, aka power-to-X, as previous research required substantial shares of bioenergy (biomass, biofuels, biogas), often based on unsustainable energy crops, or simplified hydrogen economy considerations. This conceptual breakthrough was provided in 2009 by Sterner [27], who described a consistent modern sector coupling view and the link of a 100% renewable electricity-based system with renewable hydrocarbons, in particular e-methane. This required the combination of the known processes of CO_2 reduction using hydrogen [99]–[101], a sustainable CO_2 sourcing from a biomass source, point source, or from air [102], and renewable electricity. In the analyses from the Lund, Mathiesen, and Østergaard group since 2011 power-to-X for transport has been part of the solutions [103], [104], while before the main options were electrification and biofuels [105]. This conceptual innovation, also called power-to-gas, paved the way for the broader power-to-X concept [106], as well as seasonal storage beyond hydrogen, non-bioenergy-based solutions for the chemical industry [107], [108], and drop-in solutions for long-distance aviation with e-kerosene jet fuel [109], and for marine transportation [110], [111], including e-ammonia [31], [32] and e-methanol [33]. This framing allowed the investigation of a cross-sectoral comprehensive electrification, either directly, where possible, or indirectly.

It took another 12 years until the first hourly 100% RE system analysis integrated the five central building blocks for a fully sustainable and scalable energy-industry system for chemical compounds using: hydrogen, Fischer-Tropsch based e-fuels, e-ammonia, e-methanol, and e-methane [39]. Overcoming the limitations of hydrogen by adding CO_2-to-X synthesis in energy system analyses [14], [112] was conceptually initiated by Sterner. CO_2-to-X is typically discussed as carbon capture and utilization (CCU) [113]–[116], with CO_2

sourced from biomass, direct air capture or fossil fuels [108], and used for fuels [109], [117], chemicals [107], [108], [117], and materials [118]. More than 100 academic 100% RE systems analyses are known using renewable electricity-based CCU [117]. CCU is structurally different from CCS [54], [119] and it is a central element of a zero CO_2 emission and 100% RE system that includes hydrocarbon-based fuels and feedstock. Unfortunately, by the end of 2021 not a single Integrated Assessment Model (IAM) used for the IPCC, which include a global representation of energy, economy, land and climate, is known to be able to integrate these five fundamental building blocks of a sustainable energy-industry system. The lack of these core elements might help explain why IAMs struggle to construct 100% RE pathways.

A major milestone in broad societal outreach was contributed by Greenpeace and the DLR with a series of reports and articles [120]–[123] highlighting the merits of a 100% RE system. For the first time, the concept of 100% RE was made accessible for a broad stakeholder basis beyond scientific circles across disciplines and therefore generated more awareness amongst policy makers. These studies also thoroughly explained 100% RE system options as a full transition pathway in incremental time steps. The modeling framework has been further developed [124], [125] and, although Greenpeace has discontinued its activities, the long-term lead author Teske has continued in an academic capacity.

In addition to these research activities, the DLR is broadly investigating 100% RE system analyses with its optimization model REMix [77], [78], [126]. The Open Energy Modelling Initiative [127] was started in 2014 aiming to promote openness and transparency in energy system modeling [128]. Many energy system models (ESM) [129] exchange knowledge and best practices within this network. The modeling framework Python for Power System Analysis (PyPSA) [130], together with the instances for the European power system (PyPSA-Eur) [117], [131] and sector-coupled system (PyPSA-Eur-Sec) [94], [132]–[134], set a new standard in methodological progress in the 100% RE system analysis by combining high modeling capabilities with full open science practices including an open license that extends to the data, model and discussion of results. The PyPSA framework is continuously expanded by Brown and co-workers and a steadily growing basis of research groups use PyPSA for their analyses. PyPSA is currently regarded as among the most advanced models for short-term energy system analyses according to Prina *et al.* [135], and has been expanded in the meantime for long-term pathway [133].

In research during the years 2017 and 2021, Breyer and Bogdanov established a new standard in global-local transition studies toward 100% RE with the LUT Energy System Transition Model (LUT-ESTM). It modelled the world in 145 individual regions in full hourly resolution with multi-node optimization, various regional and country designs, and for an entire energy-industry system. This modeling framework also includes comprehensive power-to-X sector coupling with in total a set of about 120 technologies across all sectors and industries [14], [39]. Earlier versions already contained a coupled power and heat sector transition [136], power sector transition [137], [138] and power sector overnight scenario [139]. The LUT-ESTM links to the first hourly global 0.45° × 0.45° mapping of a cost-optimized solar-wind-battery-e-methane-GT hybrid energy system [140]. It also detailed insights for previously neglected regions in the Global South [141] and identified new effects not observed before, such as a battery-PtX effect [142] and a new pattern to mitigate the challenges of the monsoon in India [143]. The LUT-ESTM is currently regarded as among the most advanced models for long-term energy system transition analyses according to Prina *et al.* [135]. The LUT-ESTM helped to reveal the true potential of solar PV: it emerged as the dominating primary energy supply technology for the global energy-industry-CDR system [54], [144]. In a way, this closes the circle: very high solar PV shares of about 70% in total electricity supply were already shown by Sørensen in the mid-1990s [59] and have since been confirmed by further modeling teams [145], [146].

The evolving models enable the integration of more technologies, energy system coupling, larger study areas with increased spatial and temporal resolution [147], and the transmission grid [148]. Linking energy system models with more detailed power system simulations for each synchronously operated system will be needed to show the feasibility of operating the energy and power systems with future wind and solar dominated resources [149], [150]. However, the history of 100% RE scenarios also has another perspective. For the pioneers, the first step was often to demonstrate convincingly to national stakeholders that renewables can at least partially replace fossil fuels, especially coal and nuclear power plants with their high utilization rates.

In the following, the case of Germany is sketched. First publicly funded studies of the 1980s showed visionary scenarios with RE shares of a maximum of 30% of primary energy consumption in 2030, with nuclear and fossil energy still dominating [23]. Until around 2000, progressive scenarios for Germany defined RE as the possible main power generation source until 2050. However, these shares hardly went beyond 60-65%, even after the phase-out of nuclear energy was decided in 2000 [151]. Then, a series of so called ‘‘lead studies’’ were financed by the German Ministry for the Environment with RE shares in the power sector up to 80%, which, among others, showed the way for the energy concept 2010 of the German government [152]. Even though the defined overall target of 80-95% GHG emissions reduction by 2050 is mentioned there, the concrete targets and subsequent studies have mostly focused on the minimum of 80% GHG emissions reduction and 50% RE share in primary energy until well after 2015 [153].

Although a first national pathway with 100% RE by 2060 had been published in 2012 [154], which was followed by further 100% RE scenarios [155] or close to 100% RE scenarios [156], these studies have not yet played a significant role in the political debate. Controversial discussions took place in

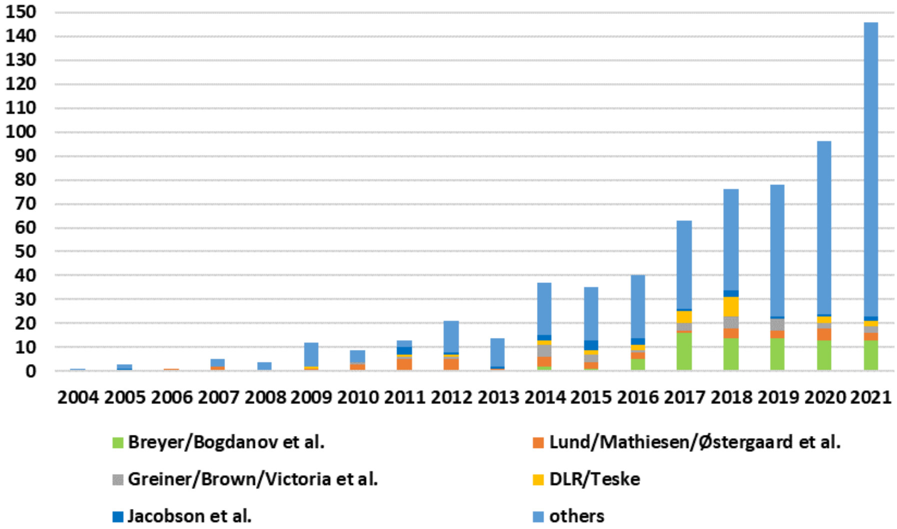


FIGURE 2. Development of peer-reviewed journal articles based on 100% RE system analyses for concrete geographic entities. Only 12 articles are known from pre-2004. Data are taken from Khalili [168].

the public debate at that time especially regarding the costs of transformation and the economic effects. It was not until new political pressure, including from the Fridays for Future movement, supported by Scientists for Future [157], [158], that the consequence of the signed Paris Agreement was more explicitly addressed in the public and placed at the forefront of the political agenda. Since then, there has been a long series of new studies concretely dealing with the design of a 100% RE scenario for Germany such as [97], [159]–[164], linking to earlier studies preparing the ground [71], [155], [165], [166]. Due to the Russian war in the Ukraine, politicians are currently even discussing ways to be largely independent of fossil fuels, at least in terms of electricity supply, by 2035 [167], which is now the 100% RE target for electricity supply in Germany.

IV. BRIEF BIBLIOMETRIC OVERVIEW OF 100% RENEWABLE ENERGY SYSTEMS ANALYSES

The field of 100% RE is very young and growing fast: most papers have been published since 2018, and 2021 alone saw more publications than all the years before 2015. By the end of 2021, 666 known peer-reviewed articles on 100% RE systems, each analyzing a specific geographic scope have been published, plus 44 articles discussing generic questions and 38 articles reviewing the field of 100% RE system analyses, totaling 739 articles known in the field. These articles do not include published reports in the field of 100% RE system analyses focused on non-scientific target audiences such as industry, policy makers and the general public. If these reports were included, the overall number of publications in special interest and mainstream media would increase significantly. The development of the peer-reviewed articles in the research field since the mid-2000s is presented in Figure 2. The compound annual growth rate (CAGR) of annually published articles between the year 2010 and 2020 was 27%, which indicates a strong growth of this research field.

The number of 100% RE system analysis articles published in 2021 forms a new milestone with 146 articles in a single year, and an even accelerated year-on-year growth rate of 52%. Additional analysis on the sectoral resolution and journals that publish research papers, encompassing data up to the year 2018, can be found in Hansen *et al.* [19]. The five leading teams in the world, according to the number of published articles, are Breyer/Bogdanov *et al.*, Lund/Mathiesen/Østergaard *et al.*, DLR/Teske *et al.*, Greiner/Brown/Victoria *et al.*, and Jacobson *et al.*, with 12%, 7%, 4%, 4%, and 4% of all known 100% RE system analysis articles, respectively. Each of the five teams has published at least 20 articles in the field. Their rank according to number of annual citations, as of the year 2020, is Lund/Mathiesen/Østergaard *et al.*, Breyer/Bogdanov *et al.*, Jacobson *et al.*, Greiner/Brown/Victoria *et al.*, and DLR/Teske *et al.* The two most used energy system models for 100% RE system analyses are EnergyPLAN [86], [87] and the LUT-ESTM [169], with 70 and 60, known articles respectively, as of the publication year until 2021. All other models used for national energy systems or higher aggregations were used for less than 20 articles each on 100% RE system analyses. Following these five leading teams with at least 20 articles in the field are six further teams with at least ten articles on 100% RE system analyses, as well as the contribution of Sørensen for whom his last article has been published posthumously in 2020. The six other teams are Duic *et al.* [170]–[172], German Institute for Economic Research (DIW) [163], [173], [174], Reiner Lemoine Institute (RLI) [140], [175], [176], Lenzen *et al.* [177], [178], Johnsson *et al.* [179]–[181], and Blakers *et al.* [46], [182], [183].

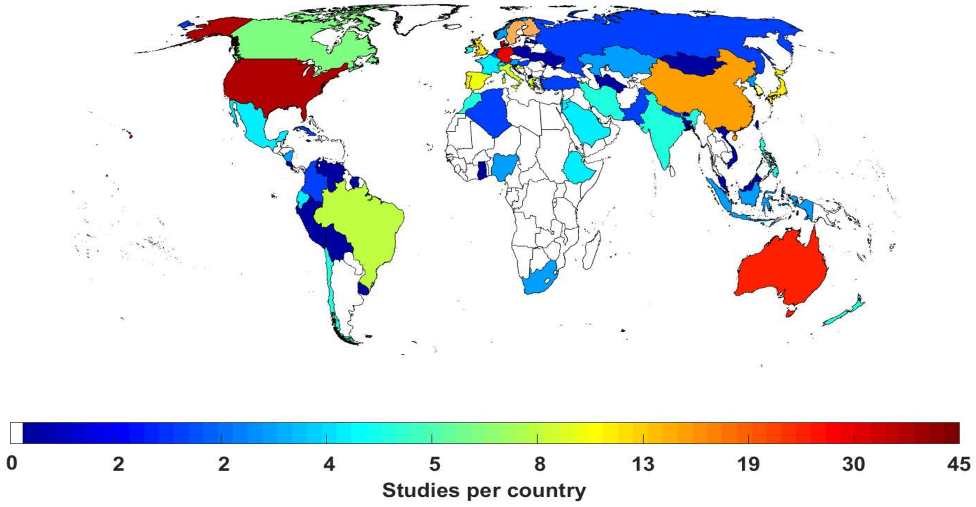


FIGURE 3. 100% RE system analyses per country. Global and regional studies are not included. Data are taken from Khalili [168].

V. OVERVIEW OF GLOBAL 100% RENEWABLE ENERGY SYSTEMS ANALYSES

This section focuses on an overview on global 100% RE system analyses as presented in sections V.A and V.B. Of all 100% RE studies, however, only 8% are global, 18% are regional and continental analyses, and 74% of studies are investigations of national or sub-national 100% RE systems. The total number of known articles underlying Figure 3 is 550 articles as of early July 2021 [168]. The most investigated countries are the United States (45 articles), Denmark (39 articles), Germany (35 articles), Australia (30 articles), China (17 articles), the United Kingdom (14 articles), Finland (13 articles), Sweden (13 articles), Japan (13 articles), Portugal (13 articles), Spain (11 articles), Croatia (11 articles), Italy (10 articles), and Greece (10 articles). These 14 countries belong to the OECD plus China, and represent 63% of all national and sub-national (states, cities, villages, islands) known 100% RE system analyses.

Countries representing about 5 billion people are not yet well studied, especially for Africa, the Middle East, Central Asia, South Asia and Southeast Asia. It will be of highest importance for reaching ambitious climate and sustainable development targets to close this research gap [19], as energy transition agendas and measures are typically set on a national level. Fortunately, 100% RE systems are probably eminently possible for these countries since they often receive large amounts of solar energy and experience less seasonal variations. In the following, insights of global 100% RE system studies are presented and discussed, which allow us to consider trends for the entire world.

A. GLOBAL 100% RENEWABLE ENERGY SYSTEM STUDIES AND MODELS USED

Several research teams have published global 100% RE system analyses as summarized in Table 1. Only studies published in peer-reviewed journals are considered. The studies represent the world from one single geographic entity up to 145 ones. The use of multiple geographic entities in global analysis attempts to draw conclusions for the entire world while reflecting regional differences where applicable. Models and methods used by research teams differ, but they consistently find that a global 100% RE system can be achieved by mid-century.

A core differentiation of model types is according to simulation and optimization [184]. A simulation model can be defined as a representation of a system used to simulate and visualize the behavior of the system under a given set of conditions. An optimization modeling approach uses several decision-variables to minimize or maximize an objective function subject to constraints.

The research results listed in Table 1 typically comprise the entire energy system for the power, heat, and transport sectors, with industrial energy demand typically being included as a component of other sectors. However, a clear deficit and research gap exist, since a detailed description of the industry sector, i.e. separated major industries such as cement, iron and steel, chemicals, aluminum, pulp and paper, etc., is lacking in almost all cases. Therefore, a full defossilization of the non-energy feedstock demand of the industry sector has not been modelled in global 100% RE analysis.

The industry sector is described in detail in Pursiheimo *et al.* [145], though the authors admit that TIMES, the model used, was not capable of applying full power-to-X functionality for the industry sector, thus fossil hydrocarbon inputs to the industry sector were still required by the model. Similarly, Teske *et al.* [125] and Luderer *et al.* [146] mention that the chemical industry is still fully based on fossil fuels. Analysis of a defossilized chemical industry, i.e. phasing out fossil feedstock, though, suggest significant shares of CCU for synthetic hydrocarbon feedstocks to industry, particularly

TABLE 1. Global 100% RE system analyses. A threshold of minimum 95% renewables share in at least the electricity supply was used for inclusion in the table. This criterion was applied to include the near-100% RE system analyses, but also to ensure appearance of fossil energy-free solution structures. Abbreviation: simulation (Sim), optimization (Opt), power sector (P), all sectors (A), transition (T), overnight (O), total primary energy demand (TPED).

							electricity generation		generation share		TPED share			
	Model	Type	Temporal resolution	Sectors	Path	Regions	PV [TWh]	Wind [TWh]	PV	Wind	PV	Wind	RE share	Remark
Luderer et al. (2021) [146]	REMIND-MAgPIE	Opt	annual	A	T	12	57,500	23,890	63%	26%	42%	17%	84.4%	8
Teske et al. (2021) [125]	Mesap/PlaNet (DLR-EM), TRAEM, [R]E 24/7, [R]E-SPACE	Sim	hourly/ annual	A	T	72	19,890	21,550	30%	33%	17%	19%	100%	1
Bogdanov et al. (2021) [14]	LUT-ESTM	Opt	hourly	A	T	145	104,300	27,310	76%	20%	69%	18%	99.8%	9
Jacobson et al. (2019) [13]	LOADMATCH, GATOR-GCMOM	Sim	30-seconds	A	O	24/ 143	33,510	34,280	44%	45%	40%	41%	100%	1
Bogdanov et al. (2019) [138]	LUT-ESTM	Opt	hourly	P	T	145	38,130	10,160	67%	18%	n/a	n/a	99.7%	9
Pursiheimo et al. (2019) [145]	VTT-TIMES	Opt	time slices	A	T	13	92,900	17,000	75%	14%	47%	9%	84.1%	2
Teske et al. (2018) [123]	Mesap/PlaNet (DLR-EM)	Sim	annual	A	T	10	13,610	21,670	34%	54%	16%	25%	100%	3
Jacobson et al. (2018) [66]	LOADMATCH, GATOR-GCMOM	Sim	30-seconds	A	O	20/ 139	45,710	66,190	32%	50%	35%	46%	100%	1
Löffler et al. (2017) [173]	GENeSYS-MOD	Opt	time slices	A	T	10	22,540	35,680	34%	54%	n/a	n/a	100%	
Jacobson et al. (2017) [65]	GATOR-GCMOM	Sim	annual	A	O	139	49,510	38,350	48%	37%	42%	32%	100%	1
Breyer et al. (2017) [192]	LUT-ESM	Opt	hourly	P	O	145	21,670	23,100	41%	44%	n/a	n/a	100%	
Sgouridis et al. (2016) [191]	NETSET	Sim	annual	A	T	1	73,940	51,060	39%	27%	33%	23%	98.3%	4
Plessmann et al. (2014) [140]	MRESOM	Opt	hourly	P	O	- 5	9,400	13,200	33%	46%	n/a	n/a	100%	
Deng et al. (2012) [193]	Ecofys	Sim	annual	A	T	1	10,160	6,390	29%	18%	14%	9%	95%	10
Teske et al. (2011) [122]	Mesap/PlaNet (DLR-EM)	Sim	annual	A	T	10	6,850	10,840	16%	25%	5%	8%	95%	6
Jacobson and Delucchi (2009)[61], (2011) [62], [63]	GATOR-GCMOM	Sim	annual	A	O	1	20,100	50,240	20%	50%	13%	33%	100%	
Sørensen (1996) [59]	unspecified	Sim	annual	A	O	1	29,610	7,010	77%	18%	28%	7%	100%	7

[1] industrial feedstock is missing resulting in remaining fossil fuels material demand
[2] model is unable to defossilize non-energetic industrial demand
[3] non-energy fossil hydrocarbon use of 9620 TWh_{th}
[4] remaining non-renewable energy is nuclear energy
[5] the world is calculated in 0.45° regions
[6] RE share in electricity 95%, for all energy use 92% and including non-energy use 82%
[7] non-energy fossil hydrocarbon use of 21,900 TWh_{th}
[8] RE share in electricity 97.8%, remaining non-renewable energy in industry and long-distance transport
[9] remaining non-renewable energy is nuclear energy of existing reactors prior to their end of technical life
[10] remaining non-renewable energy is coal and fossil methane used in industry

for e-methanol [107], [108], [185]. The latest version of the LUT-ESTM has the full functionality of a 100% renewable energy-industry system [14], but it has not yet been implemented on a global level. The latest version of PyPSA-Eur-Sec also includes a detailed modeling of the energy-industry interaction comprising also industrial feedstock [134].

A new generation of energy system models has enabled the detailed analysis of energy system transition options given specified constraints, e.g. climate targets, societal preferences, energy resources availability, and energy services. Cutting-edge energy system models show a high performance in temporal, spatial, and technological resolution, and include sector coupling. Minimum standards of model documentation are important to ensure transparency of methods and data assumptions [135], [186]. According to Prina *et al.* [135], the leading models meet the highest standards of describing entire transitions at hourly resolution, with sector coupling, interconnected multi-regions, and a technology-rich portfolio of energy system components. PyPSA, as one of the promising open source tools, is best validated for energy transition analyses for Europe [133], but it is not yet available on a global scale [187], and therefore it does not appear in Table 1. The LUT-ESTM framework is "global-local", i.e. it can be implemented for energy system

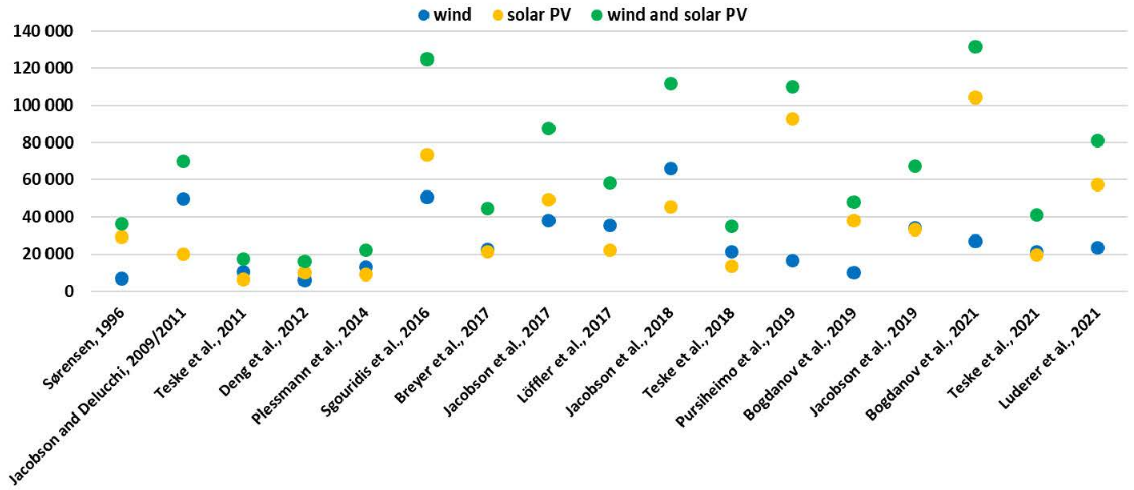


FIGURE 4. Solar PV and wind electricity generation [TWh/yr] in global 100% RE scenarios in the year 2050. References are provided in Table 1.

transition analyses at various scales, from global to regional to local [14], [138]. It is currently capable of analyzing a world divided into 145 individually modelled regions. The modelling of Teske/DLR *et al.* [125] using Mesap/PlaNet (DLR-EM) uses 72 regions and adds more detailed country versions [188]–[190].

Most global models subdivide the world into 12-24 regions as shown in Table 1, which limits their ability to analyze important details. The studies of Jacobson *et al.* [13], [66], [69] performed annual-average 100% RE analyses for 139, 143, or 145 countries, then grouped those countries into 20 or 24 world regions, respectively, for grid analyses at a time resolution of 30 seconds for multiple years. Countries were grouped for grid analyses because currently, many countries are interconnected, and interconnecting reduces costs relative to isolating countries [68]. Sophisticated energy system models reveal that linking least-cost solar PV electricity to low-cost batteries, low-cost electrolyzers, CO_2 direct air capture (DAC) technology, and hydrogen-based synthesis routes can lead to a global average share of VRE of about 90% and 80% of electricity supply and primary energy supply, respectively, as shown by Bogdanov *et al.* [14], and Jacobson *et al.* [13], albeit without H_2-to-X options. Sgouridis *et al.* [191], Pursiheimo *et al.* [145], and Luderer *et al.* [146] reach VRE shares in total primary energy demand (TPED) of 50-60%, i.e. substantially lower than Bogdanov *et al.* [14] and Jacobson *et al.* [13], which is mainly due to both lower levels of power-to-X functionality and higher assumed bioenergy availability in the former models.

B. SOLAR PV AND WIND POWER IN GLOBAL 100% RENEWABLE ENERGY SCENARIOS

The role of solar PV and wind power may be the strongest differentiator among the global 100% RE system analyses, which can be used as a starting point for investigating conceptual differences in such studies. The following discussion focuses on solar PV and wind power as the dominating sources of electricity and energy in total in the investigated studies (Table 1, Figure 5), as 75% of all studies find more than 80% of all electricity from these core pillars. This is not intended to downplay the high value of the other RE sources, and aspects for bioenergy and partly concentrating solar thermal power (CSP) are also discussed in the following. Regionally, every single RE source can play a major role, depending on local conditions.

All known global 100% RE system scenarios published in peer-reviewed articles that provided solar PV and wind electricity generation data were assessed according to the shares of solar PV and wind power they project as a percentage of total electricity supply (Table 1). In total, 17 studies were identified; only the very first, by Sørensen [59], is from the 1990s, while all others were published after the year 2008. The most cited study in the 100% RE research field is the global study by Jacobson and Delucchi [62]. The results for absolute solar PV and wind electricity generation are presented in Figure 4 and the relative solar PV and wind power share in electricity generation and TPED are shown in Figure 5. Most studies describe an energy transition from the present until 2050 and for overall energy demand. Hourly modeling is becoming increasingly standard amongst sophisticated models and is part of the methods used in Jacobson *et al.*, Teske/DLR *et al.*, and Breyer/Bogdanov/Plessmann *et al.*; all other models' analyses suffer from a lack of hourly resolution.

A quarter of all studies show less than 20,000 TWh/yr of solar PV electricity, and only three studies indicate more than 50,000 TWh/yr. The two studies with the highest shares of PV have similar results: Pursiheimo *et al.* [145] arrive at about 93,000 TWh/yr and Bogdanov *et al.* [14] at 104,000 TWh/yr by 2050. These two studies use the lowest solar PV capital

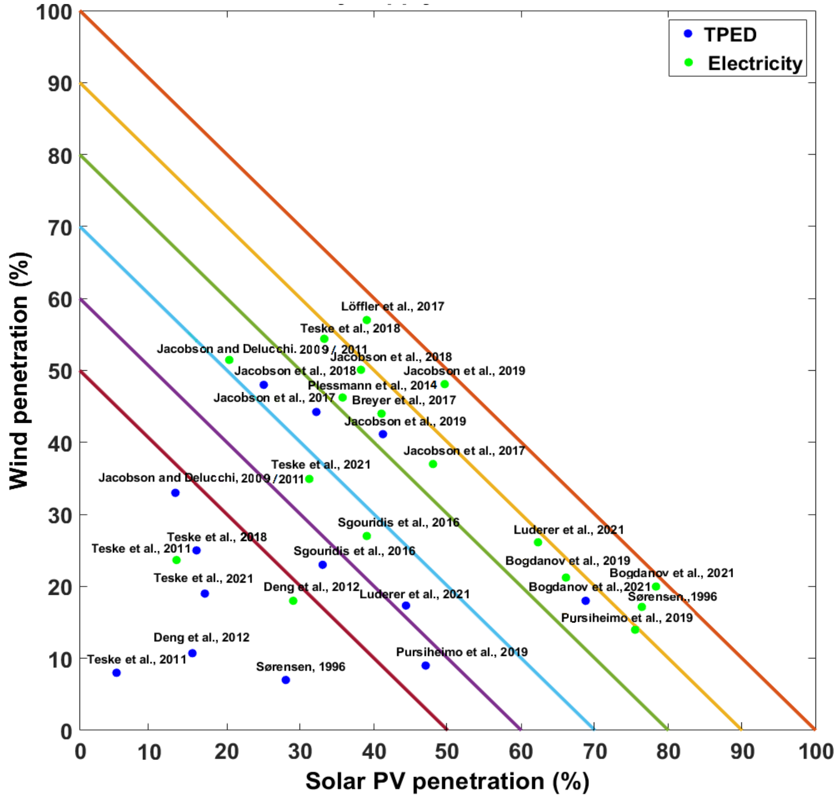


FIGURE 5. Shares of solar PV and wind electricity in global 100% RE scenarios in electricity generation and in total primary energy demand in the year 2050. References are provided in Table 1.

expenditures (capex) in 2050, with 246 €/kWp for fixed-tilted utility-scale power plants and corresponding capex for rooftop PV. In Bogdanov *et al.* [14], [138] related capex for single-axis tracking PV are also applied, as introduced by Afanasyeva *et al.* [194]. Bogdanov *et al.* [14], [138], and Jacobson *et al.* [13], [67]–[69], [195], are the only studies that consider solar PV tracking, leading to higher electricity yields and lower electricity generation cost, which is a major trend in present utility-scale PV power plants [196]. However, even in Bogdanov *et al.* [14], the applied PV capex number does not reflect the latest cost trends, which indicate about 30% lower capex in 2050 for utility-scale PV, i.e. 164 €/kWp as projected by Vartiainen *et al.* [197]. Luderer *et al.* [146], though, have aligned their solar PV capex projection to Vartiainen *et al.* [197].

Modeling with a techno-economic optimization approach will most likely lead to even higher PV electricity supply, higher PV supply shares, and further reductions in projected energy system cost in updated scenarios. The mentioned development in solar PV electricity contribution is also reflected in the wind electricity contribution, as three studies between 2011 and 2018 obtained values of more than 40,000 TWh/yr [62], [66], [191], while, beyond 2018, all studies remained below 40,000 TWh/yr. The cost-optimized studies with recent solar PV cost find consensus values of 14-26% wind shares in electricity supply (Figure 5).

Interestingly, Sørensen [59] in 1996 had estimated a TPED share of 28% for solar PV, while only three studies derived shares higher than 40%: Luderer *et al.* [146] in 2021 with 42%, Pursiheimo *et al.* [145] in 2019 with 44% and Bogdanov *et al.* [14] in 2021 with 69%. The main difference between the two former and the latter studies is the stronger sector coupling in Bogdanov *et al.* and the fossil hydrocarbons energy supply for industrial demand in Pursiheimo *et al.* and Luderer *et al.* Further, the lower temporal resolution of TIMES used in Pursiheimo *et al.* and REMIND-MAgPIE in Luderer *et al.* may have some impact on power-to-X applications and sector coupling. There are several reasons for low PV supply shares, and typically higher wind supply shares, in other scenarios. The following discussion reflects reasons for higher or lower shares of main RE technologies.

First, unreasonably high cost assumptions for solar PV automatically block higher PV supply shares in cost-optimizing modeling. This is a major issue in almost all scenarios created during the first half of the 2010s, when solar PV capex projection were still very high in most cases. With the exceptions of Pursiheimo *et al.* [145], Bogdanov *et al.* [14], and Luderer *et al.* [146], there was a failure to anticipate the steep PV cost decline of the mid to late 2010s. Relative cost differences can also impact the relative shares of solar PV and wind power, which seems to be less a challenge with wind capex. Conversely, financial assumptions for batteries have a strong impact as solar PV benefits more from low-cost batteries compared to wind power. The three studies with the highest solar PV shares consider low-cost batteries or respective system integration costs.

Second, some scenarios assume relatively high bioenergy shares, such as in Deng *et al.* [193]. High bioenergy use may be in serious conflict with sustainability criteria, given that the global arable land is shrinking [198], ecosystems are under massive pressure [199], the world population is growing [200], and more food supply is required, while ongoing climate change impacts threaten even current food production [201]–[203]. Creutzig *et al.* [204] conclude that no more than 100 EJ/yr (about 27,800 TWh/yr) of bioenergy can be supplied sustainably.

Thus, overly large and possibly unsustainable bioenergy supply assumptions in some models block indirect electrification opportunities that, absent bioenergy, will otherwise be covered by solar PV. Teske/DLR *et al.* [122], [123], [125] and Luderer *et al.* [146] have a substantial bioenergy share, but respect the 100 EJ/yr limit. However, scenarios without any bioenergy supply, as assumed in the Jacobson *et al.* [13], [61]–[63], [65], [66], [69] studies do not lead to least private cost solutions as recently shown in a comparison of model scenarios with and without bioenergy [205], [206]. Even though Jacobson *et al.* do not find least-cost solutions, they perform social cost analyses and find that both annual private and social costs are consistently much lower than in business-as-usual scenarios. However, cost optimization models have limits and optimization for the use of resources such as metals and land-use that provide a more holistic approach than the narrow focus on costs without considering external costs. Such considerations are typically considered with applied constraints. A model driven by cost inputs, which are estimated for the calculated scenario period and the development that occurs within this time period, e.g. between 2020 and 2050 rely on respective cost projections, is subject to considerable uncertainties, especially for energy resources, such as fossil fuels that do not play a role in 100% RE systems. In addition, the projection of technology costs over decades implies uncertainties.

Third, some scenarios favor resource diversity over cost optimization for reasons of political and societal robustness and broader considerations of security of supply, though this may lead to higher costs. This is more often applied in simulation type scenarios [184], in which specific shares for each of the technologies included in the model can be defined. After the model scenario is run, results are then checked for stable energy supply and costs within applied constraints. Resource diversity is strongly emphasized in the various Teske/DLR *et al.* scenarios as well as the Jacobson *et al.* scenarios, as high shares of CSP plants are assumed. CSP in combination with thermal energy storage (TES) is a technically feasible solution and enables a broader technological diversity, but at a higher system cost compared to solar PV. Full year optimization of CSP-TES compared to PV-battery systems based on latest cost projections may lead to results adjustments in future studies. However, in the case of coupled CSP-TES systems, advantages such as a high capacity factor of over 90%, as well as lower life cycle emissions, the ability to provide process heat for industry and water desalination, and the option of hybridization for complementary use of biofuels or geothermal energy may be beneficial. Applying outdated cost assumptions for solar PV and battery storage as in Kennedy *et al.* [207] delivers conclusions on a TES-related value of CSP-TES that require further investigation with latest cost assumptions. The CSP related factors can play a major role locally in energy systems but are often not considered in cost-optimizing models.

Fourth, distorted renewable energy resources assumptions can also lead to lower PV supply shares, as in Löffler *et al.* [173]. This case is quite interesting, since their PV capex are identical to Pursiheimo *et al.* [145] and Bogdanov *et al.* [14], but the role of PV seems to be strongly underestimated due to an artificially limited solar PV potential. This limitation strongly constrains the PV capacity increase from 2035 onwards and thus leads to high additional wind capacity installations. In almost all other scenarios for the years beyond 2035, solar PV increasingly appropriates market share from wind power because the rate of solar PV cost degression is greater, and solar PV electricity eventually becomes cheaper than wind electricity.

Fifth, many scenarios suffer from incomplete power-to-X routes, a lack of comprehensive sector coupling, and excessively high costs assumed for key flexibility-providing technologies: batteries and electrolyzers. These are the two most important VRE supporting technologies that strongly increase the VRE supply share in scenarios by overcoming the day-night limitation of solar PV, supporting strong electrification of practically all on-road transportation, squeezing out biofuels for road vehicles, and enabling highly cost-attractive power-to-hydrogen-to-X routes for almost all remaining energy segments that cannot be directly electrified, including long-distance transportation, high temperature industrial energy demand that may remain despite comprehensive direct electrification, and hydrogen-based chemicals demand in industry. Thus, low-cost batteries, low-cost electrolyzers, and established power-to-X routes strongly increase the VRE share in covering the total primary energy demand. Solar PV benefits more from low-cost electrolyzers than wind power, since low-cost electricity is most efficiently matched with relatively inflexible energy demand categories through the intermediaries of hydrogen storage and electrolyzer-based power-to-X routes. More research on global 100% RE system scenarios is required to further investigate a societally optimized balance of resources and technologies, including power system studies with resource adequacy.

Sixth, aside from the shares of solar PV and wind power, the absolute contribution of the two most important VRE technologies differs, and their sum differs substantially across the studies as displayed in Figure 4. This is driven by three main factors within the respective studies. Different assumptions on the development of energy services demand and thus final energy demand have a strong impact on the overall VRE generation demand. This is further pronounced by assumptions on energy efficiency development, which differ across the studies. The assumed bioenergy utilization directly affects the need for VRE generation as the degree of power-to-X is related to the supply share of bioenergy. If strict sustainability limits for bioenergy are applied, or if bioenergy supply is even blocked, the demand for VRE generation increases significantly. Energy demand for the transport sector is discussed by Khalili *et al.* [98] and for the heat sector by Keiner *et al.* [95], who highlight structural differences of several of the studies also used for Figure 4 and in addition compared to studies aiming for lower RE shares.

Resource-driven differences of technology shares are documented for higher solar energy shares in the sunbelt, higher wind energy shares in the northern hemisphere, higher hydropower shares in regions with excellent hydropower resources, similarly for geothermal energy, and higher bioenergy shares in regions of excellent bioenergy availability, typically related to a low population density [13], [14], [65], [66], [124], [125], [138]. The remaining ecological hydropower potential is estimated to 3290 TWh for costs at or below 100 USD/MWh [208], which indicates an increase potential of about 75% compared to the hydropower generation of about 4350 TWh in 2020 [209]. Since the data year of the ecological hydropower potential estimate, more than 400 TWh of higher hydropower generation has been added. Given the enormous demand increase for electricity generation, the remaining ecological hydropower potential can be regarded as very limited and not substantially scalable. In addition, hydropower generation has a substantially higher risk of negative climate change impacts compared to wind power and in particular solar PV [210].

Finally, two strong arguments are in contradiction: full cost optimization that leads to higher PV-battery shares versus broader resource diversity that would lead to higher wind power and CSP shares, or trigger higher shares of geothermal and ocean energy, resulting in higher energy costs in the system. The strong system impact of the PV-battery-electrolyzer nexus is increasingly found in energy system analyses on a global level [13], [14] and even more on a national level, as for China [211], [212], India [213], and Africa [214], [215]. Depending on cost development, materials availability and local acceptance, battery storage may compete with pumped hydro energy storage [169], [216] as the pumped hydro energy storage potential could be much larger than most studies considered so far [46]. As the cost and the operation profile of battery and pumped hydro energy storage are very close, no relevant impact on system cost or system structure may be expected. However, lower shares of battery storage and higher shares of pumped hydro energy storage may be possible.

A major step ahead for the 100% RE system research may be achievable by means of model intercomparisons, such as the one carried out for EnergyPLAN and the LUT-ESTM [169]. Model intercomparisons could reveal undetected limitations and thus further improve standards, as well as investigate the challenges already identified here. In addition, cost comparisons of different transition pathways generated using different input assumptions and constraints or technology cost degression assumptions within the same model will allow researchers to further clarify the cost impacts of given scenario constraints and options. A more detailed analysis of the regional results generated with global models should also consider any power system operational issues, long term resource adequacy issues, sociotechnical, environmental and overall political and economic aspects. These analyses should also examine the feasibility of the demonstrated pathways in direct comparison with national studies. In recent years, more and more co-benefits of 100% RE systems have been highlighted, such as reduced air pollution [13], [217], a substantial reduction in energy-induced water stress [218], a strong increase in jobs in the energy system [13], [219], higher levels of energy security [220], first estimates of material requirements [221], and stabilization and improvement in net energy [191], [222].

More efforts will be required for a solid description of the co-benefits and a more comprehensive inclusion of the societal constraints framing and limiting the energy transition [223] as well as the economy-wide impacts of RE [224]. It will also be quite important to have the leading ESMs available as full open science tools for a faster and broader uptake by newly joining research groups and a more comprehensive stakeholder discourse.

High geographically-resolved global 100% RE system analyses can also help overcome the strong imbalance of 100% RE studies for Europe, the United States, and Australia and a dramatic lack of such studies for the Global South, as already pointed out by Hansen *et al.* [19]. This also requires more openness of scientific journals, as first of its kind studies should be favored by journals, while marginal progress of intensively researched countries is regularly published. Such imbalance requires critical reflection.

VI. CRITICISM OF 100% RENEWABLE ENERGY SYSTEMS RESEARCH

Scientific progress implies challenging existing dogmas. 100% RE scenarios challenge the dogma that fossil fuels and/or nuclear are unavoidable for a stable energy system. This has triggered strong reactions with a crescendo in 2017 by Clack *et al.* [225], Trainer [226], and Heard *et al.* [227]. These, and others like Jenkins *et al.* [228], have cast doubts on the technical feasibility of 100% RE systems, their cost-competitivity, or, if affordable, the lack of resources that they would require. However, in 2017, the field consisted of just a few pioneers. Since then, the field has quickly grown with hundreds of published papers by many different research groups across the world [168] (see Figure 2 and Table 1 for an overview), and a consensus is starting to emerge that many of those early criticisms do not hold when examined in detail. In particular, Jacobson *et al.*

[195], [229], [230], Aghahosseini *et al.* [231], [232], and Sgouridis *et al.* [58] explicitly addressed Clack *et al.* [225]. In response to Heard *et al.* [227], it was Brown *et al.* [233] who in 2018 provided the first broad overview of 100% RE research and highlighted the technical feasibility in detail, complemented by the response by Diesendorf and Elliston [234]. Also, overall economic feasibility has been shown by several researchers in various studies on the global level by Teske/DLR *et al.* [125], Jacobson *et al.* [13], [65], [66], [69], Bogdanov *et al.* [14], [138], and comparable results have been found for the leading 20 economies [235].

In 2021, Seibert and Rees [236] voiced new concerns on the feasibility of 100% RE scenarios, and even claimed that "the pat notion of affordable clean energy views the world through a narrow keyhole that is blind to innumerable economic, ecological and social costs" and that the only way forward would be a drastic curtailment of the global population to "one billion or so people". Detailed responses to these claims were provided by Diesendorf [237] and Fthenakis *et al.* [238] as comprehensive reviews of the RE techno-economic evolution and history of overcoming challenges in a fast growing field. We will now discuss the different aspects of the various criticisms of 100% RE systems in more detail.

A. ENERGY RETURN ON INVESTMENT

A persistent stream of literature claims that a switch from fossil fuels to renewables would be problematic or even impossible due to limitations in fundamental energy economics [236], [239]–[241], based on metrics such as energy return on investment (EROI). Authors making such claims often refer to Georgescu-Roegen and his widely cited book from 1971 on entropy [242], which is still prominent in economics. However, from a physics point of view, it should be noted that Georgescu-Roegen's attempt to apply the laws of thermodynamics was fundamentally flawed [243]–[245], since he incorrectly characterized the earth as a "closed" system, leading to predictions of economic collapse due to lack of energy that ignored the constant influx of solar energy [246], [247]. The concept of EROI was first proposed by Hall *et al.* [248] EROI = R/I is defined as the ratio of R = the energy "returned" (i.e., delivered to the user) by a chain of processes designed to exploit a primary energy resource flow (PE), to I = the sum of the energy "investments" required to operate all such processes, including manufacturing, maintenance and end-of-life disposal of all the infrastructure. It is a concept embedded in biophysical economics and it gives a fundamental insight into the practical viability of energy technologies from the point of view of the end user. It should be noted, however, that EROI is not an indicator of overall thermodynamic efficiency, which would instead be expressed by the ratio $\eta = R/(PE + I)$. In other words, a process, or chain of processes, may still be characterized by a high EROI even if it entails large thermodynamic losses, provided that such losses are at the expense of the primary energy resource being exploited, and do not entail a large increase in the energy investments that are required per unit of output (i.e., R may even be $\ll$ PE, as long as I $\ll$ R). It has been often claimed that the EROI of RE technologies would be too small in comparison to that of fossil fuels, thus creating a fundamental limitation [236], [239]–[241]. This claim, though, is unsubstantiated for several reasons.

Firstly, the realistic EROI of fossil fuels has been often overestimated by only focusing on EROI values calculated at point of extraction. For instance, while the EROI of crude oil at the well head may, in some cases, have been as high as 100 during its initial "golden age" [249], [250], detailed analyses have shown that this value has been steadily declining over time as a consequence of depletion [251]–[254]. Even more importantly, the many subsequent energy investments required along the crude oil supply chain to process and deliver it in the form of readily usable energy carriers have always reduced the resulting EROI values at point of use to well below 10, irrespective of the initial EROI at point of extraction [250], [255]. Similar, albeit perhaps not as drastic, EROI reductions from point of extraction to point of use also affect all other fossil fuels such as coal and gas. Furthermore, a substantial decline of fossil oil and gas EROI is projected [252], [253], [255] for the decades to come [251], [252]. The decline of the EROI of non-renewable resources is an unavoidable effect of depletion, a phenomenon that has been dynamically modeled [254].

Secondly, many literature comparisons between the EROI of fossil fuels and those of RE suffer from methodological inconsistencies that make their results doubtful, as discussed by Raugei *et al.* [256], Diesendorf and Wiedmann [124], [257], White and Kramer [222], Fthenakis *et al.* [238], and Diesendorf [237]. In fact, in order to meaningfully compare the EROIs of fossil fuels to those of RE technologies, the comparison must be framed using consistent system boundaries [258]–[260]. This may be done either by calculating EROI as the ratio of electricity output to energy investment, in which case the EROI of fossil fuels at point of use is further reduced by a factor of $1/\eta_{\text{th}}$ (where η_{th} is the heat rate of the thermal power plant), or by back-calculating the EROI "primary energy equivalent" of RE technologies, by adopting a substitution logic whereby each unit of electricity delivered is deemed equivalent to $1/\eta_{\text{LC}}$ units of primary energy, where η_{LC} is the life-cycle energy conversion efficiency of the grid mix into which the RE technology is embedded. The choice of the system composition as optimally-designed may lead to different results depending on the resource mix and corresponding location-dependent yields. Additionally, common issues in EROI debates are the use of outdated data, neglect of the energy learning [261], or even fundamental misconceptions [222], [257].

Thirdly, the EROIs of modern RE technologies, especially for solar PV and wind electricity, have improved significantly in recent years, thanks to fast technological improvements. Much discussion has been focused specially on solar PV, and some recent studies have investigated the main reasons for the wide range of EROI values reported in the literature for these technologies [262], [263]. Recent studies have shown that the energy payback time (EPBT) of solar PV has now reached values in the range of 0.5-2 years, depending on solar irradiation levels and type of PV systems [261], [264]–[266]. This implies EROIs in the range of 15-60 for a technical lifetime of 30 years, if the electricity output is converted to primary energy equivalents, as explained above. The ongoing PV system energy learning curve [261], showing efficiency and longevity improvements, suggests additional EROI improvements in the future. For example, insights by Peters *et al.* [267] indicate that PV modules could be operated for 50 years. Furthermore, recently enacted research funding from the US DoE is focused on extending the lifetime of existing PV through improved encapsulation and lower degradation [268]. A large meta-analysis of the published estimates for the EROI of wind electricity up to the year 2010 [269] indicated an average EROI of 20, if the electricity output is converted to primary energy equivalents. Since then, more recent studies have pointed to even better net energy performance, with average primary energy weighted EROIs ranging from 28 [270] to 34 [271], with maximum values up to 58 [271].

Other studies that evaluated global energy system transition options reported a globally decreasing overall EROI trend, which supposedly risks falling below a threshold that would be required to maintain a sustainable industrial economy [241], [272]. However, the quantification of such a minimum EROI threshold is problematic since it always implicitly rests on an assumed average efficiency for the downstream processes where the various energy carriers are used throughout the economy. However, one of the key benefits of a transition to a 100% RE system is precisely a shift away from inefficient thermal processes across multiple sectors, thereby inherently reducing the requirement for high EROIs at the point of use. Despite these methodological difficulties, correctly-framed EROI studies are still useful in allowing for the development of energy transition scenarios that are not based simply on the technical feasibility of a 100% RE-based society, but which also question the specific path that society needs to follow to carry out the transition before it is too late.

A point that is often misunderstood in this latter debate is the one called "energy cannibalism" [273]. This is an improper term, but it is sometimes used to indicate the fact that the transition from a given resource of energy, e.g., fossil fuels, to another, e.g., renewables, requires the use of a certain quantity of energy from the first resource to create the infrastructure for the second one. Since, currently, the largest share of energy in the world's mix is sourced from fossil fuels, this gives rise to the incorrect claim that "renewables cannot replace fossil fuels, since RE plants require fossil fuels to be manufactured". This issue has been framed as the concept of the "Sower's way" by Sgouridis *et al.* [191], because ancient farmers were faced with a similar dilemma when they had to save part of each year's harvest as seed for the following year's crops. In the present context, it means that a fraction of the energy supply from fossil fuels needs to be used for the construction of the RE infrastructure that will replace fossil fuels.

Studies that are based on the concept of EROI [191], [274], and the results depend on various assumptions on how the EROI of different technologies will increase with time as the result of technological progress or will decline as the result of reduced site availability or the depletion of the mineral resources needed for plants, including fossil fuels as energy sources. Evidently, if the results were that the fraction of fossil energy invested is larger than the energy currently supplied, the transition would not be feasible. Instead, some initial studies [191], [274] indicate that the transition is indeed possible, and that it can be fast enough to reduce the impact on climate change below the limits set by the Paris Agreement, although doing so would require larger investments than currently dedicated to RE. More research is required to understand the link between various energy transition pathways and the dominance of VRE in the energy system on the EROI. Such studies may be one way of enabling the identification of the transition path that could conform to diverse societal need as discussed above. The lack of more detailed EROI analyses for the entire energy system transition constitutes a research gap that needs to be closed soon.

B. DEALING WITH VARIABILITY AND STABILITY

Much of the resistance towards 100% RE systems in the literature seems to come from the a-priori assumption that an energy system based on solar and wind is impossible since these energy sources are variable. Critics of 100% RE systems like to contrast solar and wind with 'firm' energy sources like nuclear and fossil fuels (often combined with CCS) that bring their own storage. This is the key point made in some already mentioned reactions, such as those by Clack *et al.* [225], Trainer [226], Heard *et al.* [227] Jenkins *et al.* [228], and Caldeira *et al.* [275], [276]. However, while it is true that keeping a system with variable sources stable is more complex, a range of strategies can be employed that are often ignored or underutilized in critical studies: oversizing solar and wind capacities; strengthening interconnections [68], [82], [132], [143], [277], [278]; demand response [279], [172], e.g. smart electric vehicles charging using delayed charging or delivering energy back to the electricity grid via vehicle-to-grid [181], [280]–[282]; storage [40]–[43], [46], [83], [140], [142], such as stationary batteries; sector coupling [16], [39], [90]–[92], [97], [132], [216], e.g. optimizing the interaction between electricity, heat, transport, and industry; power-to-X [39], [106], [134], [176], e.g. producing hydrogen at moments when there is abundant energy; et cetera. Using all these strategies effectively to mitigate variability is where much of the cutting-edge development of 100% RE scenarios takes place.

With every iteration in the research and with every technological breakthrough in these areas, 100% RE systems become increasingly viable. Even former critics must admit that adding e-fuels through PtX makes 100% RE possible at costs similar to fossil fuels. These critics are still questioning whether 100% RE is the cheapest solution but no longer claim it would be unfeasible or prohibitively expensive. Variability, especially short term, has many mitigation options, and energy system studies are increasingly capturing these in their 100% RE scenarios. However, power system stability is usually overlooked as part of energy-balancing studies, where the focus is on consumption-generation matching on an hourly time scale. Wind and solar PV power plants are connected to the grid by inverters, thus making them different from conventional, synchronously connected power plants. The growing importance of electricity-based systems has led system operators to analyze the challenges of maintaining the reliability and stability of power systems dominated by non-synchronous sources for generation in greater detail [149], [283]–[285]. Ongoing research is targeting ways to manage 100% inverter-based system operations [286].

A 100% wind and solar PV inverter-based system operation has so far only been seen on a smaller part of a larger synchronous system, or at small islands [287]. As VRE will reach a 100% share of consumption at certain times (even if their share is still much less on average), close-to-100% VRE operation should be enabled as these events become more frequent. Currently, excess and not otherwise usable wind power and solar PV is curtailed, not allowing non-synchronous sources to exceed a given percentage at any instant. For example, in the synchronous system of the island of Ireland, the so-called non-synchronous system penetration was originally set at 50%, then raised to 60%, and is currently at 75% [288]. This enables a wind share of 40% without extensive curtailment; however, to reach a higher renewable goal mostly contributed by wind, the non-synchronous system penetration will need to be increased to 90%. 100% inverter-based resources (IBRs) can be highly flexible and controllable, with independent control over real and reactive current, and they have an ability to shape the equipment's response to various grid conditions. New types of inverters, called grid-forming inverters, have demonstrated the capability to provide the backbone for stable system operation when no synchronous generators are online [289], [290].

This promising technology development together with evolving power system modeling tools show possibilities to overcome the foreseen challenges [291]–[293]. There could be opportunities to make IBRs behave in an even more supportive manner than synchronous machines in some respects. However, the changes are so profound that a fundamental rethinking of power systems is required, including the definition of needed system services. One challenge is that the control algorithms that dictate the response of IBRs to grid conditions are not heterogeneous across various inverter designs and manufacturers, and these can interact at both a local and system-wide level as well as with other elements in the power system, such as high-voltage direct current transmission terminals. This dramatically complicates the analysis of IBRs in the power system and could lead to stability challenges [284], [286]. For 100% RE systems, where solar PV and wind power dominate, more studies are needed to prove the feasibility and assess the cost impact for grid-supporting resources, both at wind and solar PV power plants and elsewhere. This and the challenge for resource adequacy for weather-dominated, energy-constrained resources are further discussed in section IX.E.

C. THE COSTS OF SOLAR PV AND WIND POWER

Some models and studies find that solar PV and wind would be too expensive, especially if one adds measures that increase system flexibility to deal with variability. Most often, though, this is because some of the model assumptions result in an overestimation of the cost of wind power, solar PV and related flexibility measures [294]. First, models that obtain high RE costs generally lack the existing flexibility strategies described previously, including dispatchable renewables, demand flexibility, sector coupling, transmission grid expansion, and storage. Moreover, some models that lack detailed spatial and temporal granularity include additional 'integration cost' for wind power and solar PV that might overestimate the real integration cost and hamper the penetration of VRE sources in the optimal solutions. When flexibility options are properly included, large solar PV and wind power penetration are part of the solutions [14], [145], [146], [277].

Second, some models overestimate the current cost of new technologies and underestimate cost decreases. This limitation has been particularly severe for solar PV as discussed by several authors [277], [294]–[296]. Additionally, most energy models assume exogenous cost evolution for new technologies. In reality, the cost of a technology depends on the cumulative installed capacity, through the learning curve. Modelling endogenous learning in technologies is computationally more difficult because the learning curve makes the model non-linear, and some simplifications might be added. Moreover, it requires estimating the learning rate based on historical data, which is particularly challenging for immature technologies. When endogenous learning is included, the penetration of wind power and solar PV typically increases and the cumulative system cost decreases. Grubb *et al.* [297] even demonstrated that integrating endogenous learning curves into the standard DICE model, which usually finds that slow RE growth would be best, leads to remarkably fast and cheap transition pathways because quickly adopting RE would rapidly reduce system cost and avoid lock-in and sunk cost in fossil technologies. A similar observation was achieved with the REMIND model, which has produced quite slow RE uptake [298], [299]. However, if realistic solar PV and VRE integration costs are applied, the model switches to VRE-dominated solutions [146], [295].

D. RAW MATERIAL DEMAND FOR 100% RENEWABLE ENERGY SYSTEMS

As the previous criticisms are starting to become less and less tenable, increasing attention is now shifting towards the more salient point of raw materials needed for the transition towards a sustainable energy system. Practically all research in this field finds critical limits for material availability. This may be a major concern and should be addressed with more consideration and analyses to truly test the material limits. Highly ambitious energy system transition scenarios towards 100% RE systems have been used as a basis for investigating material availability limits. Junne *et al.* [221] used the scenarios of Jacobson *et al.* [13], Teske/DLR *et al.* [125] and Bogdanov *et al.* [14] and identified criticalities for the four focused materials: lithium, cobalt, neodymium, and dysprosium. A comprehensive overview on materials criticality for the energy transition is provided by Lundaev *et al.* [300]. That analysis identifies antimony, chromium, indium, manganese, molybdenum, nickel, silver, zinc, and zirconium as minerals that can cause severe limitations to energy transition without proper interventions, material substitutions, or significant discovery of new resources. Their severity is because of the limited number of known reserves/resources of these minerals compared to the expected demand increase. For example, the nickel demand by 2040 could be more than 200% of its 2020 demand due to its need in battery application for EVs and utility services [301], [302]; however, the present reserve/resource could be depleted in about four decades even at the rate of 2020 production [300].

Lithium extraction could reach material limits in the second half of this century according to Greim *et al.* [303]. However, scenario combinations have been identified by the same authors that enable transition scenarios without conflicting with the lithium resource base, according to Bogdanov *et al.* [14] and Khalili [168]. One option relies on extremely high collection and recycling rates, close to 100%, eventually becoming mandatory, leading to an almost circular economy for lithium batteries comparable to the present status for lead acid batteries. A second option would be for the cost of lithium extraction from ocean water to decline significantly. It is estimated that the oceans contain 6,000 times more lithium than on land, as it is the sixth most abundant dissolved metal ion in the oceans [304], and new research by Li *et al.* [305], Zhang *et al.* [306], Liu *et al.* [307], and Tang *et al.* [308] conclude that ocean extraction could become relatively cheap. Another source of ocean-related lithium extraction could be via brines of seawater desalination [309]. Finally, lithium could be substituted, e.g., by Na-ion batteries that are gradually getting closer to commercialization [310].

Cobalt demand may be managed by transitioning to cobalt-free lithium batteries [311], [312]. Neodymium and dysprosium are primarily needed for permanent magnets used in the motors and generators of vehicles and wind turbines. Their availability requires further study, though these materials can be substituted by ferrite-type magnets in wind turbines when their availability becomes problematic [310]. For the case of electric vehicles, induction motors and synchronous reluctance motors are well known alternative options [313].

Additional potentially critical materials are required for solar PV technologies. For instance, silver is needed for the current generation of silicon-based PV cells, and tellurium is used in CdTe PV cells. While it is widely recognized that individual PV technologies would experience material challenges for reaching very high levels of production, such sustainability challenges do not appear before any technology reaches multi-GW annual production and multi-TW cumulative production. For example, CdTe PV is constrained by tellurium availability, but there is enough tellurium available from copper anode slimes to support at least 4-5 times current production capacity [314], which equals around 25-30 GW/yr, and cumulative TW-scale production by 2050 [315]. Similar constraints apply to indium and gallium for CIGS PV [316], [317]. The tellurium, indium, and gallium criticality may not be dramatic, since more than 95% of the annual PV market consists of crystalline silicon (c-Si) solar cells that do not use those materials [318].

If multi-TW annual manufacturing is achieved, silver supply will be not sufficient for continuing to apply current c-Si PV metallization techniques [319], [320]. The silver supply challenge may not be critical, though, as a substitution with copper has already been investigated [319], [321] and PV cells with the substitute technology are expected to be commercially introduced during the 2020s [196]. Copper may be another material that requires more detailed analyses, as a comprehensive electrification of the energy system will inevitably lead to a surge in copper demand. So far, researchers analyzing copper criticality have not yet identified copper limitations; however, most have considered copper demand growth according to economic development and population growth and collection-recycling rates of about 70% [322], [323]. If additional demand from a more equitable energy supply development is included, significant copper supply limitations are found, according to Elshkaki *et al.* [324]. If copper constraints exist, aluminum, which is typically regarded as a natural and practically unlimited substitute, could be used.

While comprehensive electrification of the global energy system has not yet been considered in full, research by Kleijn *et al.* [325] strongly indicates that the challenges will increase, with regard to both the long-term availability and the potential impact of materials. Such challenges could become a short-term bottleneck to the energy transition as mining projects have longer lead times, often in the order of 10-20 years [326]. It is also noteworthy, though, that in most cases, the scarce materials used in RE technology are in bulk form and can be recycled with relative ease in comparison to materials used in dispersed form. For instance, rare earth magnets can be easily separated from waste using their strong magnetic field. Comprehensive analysis tools are necessary to properly tackle potential challenges and more material criticalities may be identified in the years to come. Nevertheless, it is clear that aiming for a circular economy is indispensable [221], [327], [328]. All in all, there appears to be reason for moderate optimism that material criticalities will not represent an unsurmountable roadblock towards the transition to 100% RE systems. However, it is also clear that it will be a formidable challenge to ensure the timely availability of resources while simultaneously minimizing the negative impacts of extraction on humans and the environment. This needs to be a focus of upcoming research.

E. COMMUNITY DISRUPTION AND ENERGY INJUSTICE

A final critique sometimes levelled at RE systems is that they do not always bring community co-benefits or promote equity or energy justice, and that they may have their own negative externalities [329]. These can include toxic materials used during manufacturing and installation, required integration with other systems, land use and the loss of biodiversity, water use or consumption, and dependence on rare earth mineral extraction that do have global whole-systems geopolitical impacts [330], [331]. For example, hydropower dams can provide clean baseload electricity but may require the relocation of indigenous communities or the deforestation of tropical areas [332]. Wind power plants rely on carbon intensive components such as concrete, fiberglass, and steel with many manufacturing externalities spread across the supply chain [333], especially in Asia. Patterns of solar PV adoption are not uniform, and face demographic and social equity concerns given that those with solar PV tend to live in higher-value homes, have higher credit scores, be more educated, live in white neighborhoods, be older, and have steady jobs working in business and finance-related occupations compared to the general population [334]. One study examining diffusion patterns in the United Kingdom warned that increased solar adoption risked transferring wealth between lower income and higher income consumers, given that feed-in tariffs for solar PV are paid for by a levy on energy bills by all consumers [335]. The access of low-income households to solar PV rooftop systems can be ensured with the adequate design of policy support mechanisms [336].

One meta-analysis of hundreds of academic studies published on the sustainability of solar PV noted that many heavy metals embedded within solar PV systems are hazardous for workers or the environment, especially lead, lithium, tin, and cadmium, which can pose toxic risks during their manufacturing or disposal [337]. Another noted the rising contribution of solar modules to global stockpiles of electronic waste [338]. Atasu *et al.* [339] add that an additional problem contributing to future stockpiles of waste is that rapid advances in technology cause homeowners to sometimes switch or replace their solar systems before the end of their useful lifetime to capitalize on better performing systems. The authors refer to this as the "early retirement" problem with solar involving the mass disposal of "no failure" panels. If one accounts for these future waste streams, the levelized cost of energy for solar PV increases by a factor of four, i.e., solar is four times more expensive than expected if one includes the expected costs (and volumes) of waste. Similar problems with waste, and solar "rebounds" where adopters increase energy consumption after installing solar PV, have also been confirmed for Germany [340] and the UK [341]. Finally, Ramirez-Tejeda *et al.* [342] critique unsustainable turbine blade disposal practices, including landfilling in the United States. These aspects are increasingly tackled by circular economy approaches.

Land use and community wellbeing emerge as a final concern connected to mass-installations of RE systems. Looking at the siting and land politics of solar PV power plants in India, injustices of process, planning, and misrecognition in how such facilities are sited regardless of community concerns are widespread [343]–[345]. Argenti and Knight [346] reveal how the development of wind farms enabled enclosure via the appropriation and grabbing of farming land, exclusion of local concerns from the planning process, encroachment of environmentally sensitive sites with endangered fauna and flora, and the entrenchment of inequality with no project benefits distributed to local communities. Calzadilla and Mauger [347] show how global wind projects have resulted in substantial increases in alcoholism and prostitution among both the host communities and the camps full of job seekers. While this finding may be more related to large construction projects than to a specific wind power context, Shoeib *et al.* [348] find temporary increases in local rents and a boom town feel as a result of US wind power development. Gorayeb *et al.* [349] also catalogued how wind farms brought increases in child sex trafficking. Although siting often focuses on impacts to "communities," there are challenges in defining what is meant by community and thus who "counts" in terms of distributional justice, as wind power projects can have regional effects, effects on Indigenous communities [350], and on communities of practice [351]. Nevertheless, many of these issues around justice, community acceptance, and land use also occur with fossil fuels.

To be clear, in a comparative sense, RE is still less harmful than fossil fuels in almost all contexts. Oil and gas systems in particular are known to pose more serious and longer-lasting negative externalities including pollution, climate change, and severe threats to some local communities [331], [352]–[355]. Moreover, while the characteristics of fossil fuel supply chains may have unavoidable justice issues, especially related to their carbon content or pollution flows, plentiful policy options and governance tools exist to make wind, solar, and other low-carbon systems more just and equitable. In other words, while fossil fuel injustices may be inevitable and unavoidable, those facing 100% RE systems can be planned for, minimized, and at times even eliminated. Figure 6 showcases policy mechanisms or measures cutting across raw materials (e.g., better supply chain management), planning and policy (adherence to proper informed consent), use (shared ownership models), and waste (extended producer responsibility). Each of these measures would make RE technologies more equitable, accountable, and just, helping to both contextualize and manage this potential barrier. Unlike fossil fuels, the equity and justice issues facing RE systems are avoidable and solvable, rather than inevitable.

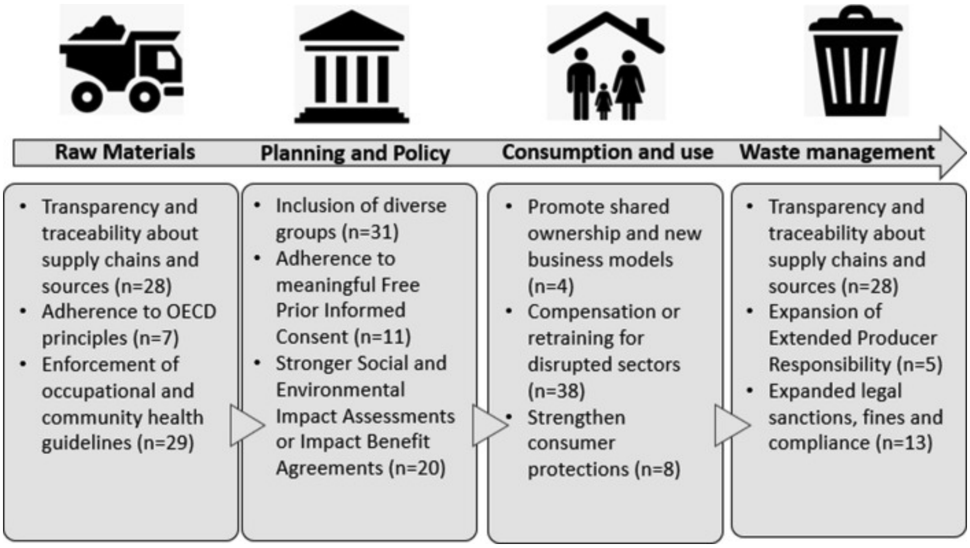


FIGURE 6. Policy mechanisms for more just RE transitions at multiple scales. Source: Sovacool *et al.* [356] Note: N = frequency within an expert interview and elicitation exercise.

VII. DEFICITS IN 100% RENEWABLE ENERGY SYSTEMS DISCUSSION IN MAJOR ORGANIZATIONS

Large institutions are prone to 'institutional inertia' and this is no different in the energy transition [357], [358]. Similar to parts of the academic community at large, they resist the challenge of 100% RE scenarios based on the dogma that the world cannot do without fossil fuels and nuclear energy. Over the years, two influential organizations have attracted especially heavy criticism for underestimating VRE in general and solar PV specifically: the International Energy Agency, and the Intergovernmental Panel on Climate Change, as pointed out for instance by Philipps *et al.* [359], Breyer *et al.* [192], Creutzig *et al.* [295], and Breyer and Jefferson [360].

A. INTERNATIONAL ENERGY AGENCY

The IEA is tasked with advising governments on their energy systems. While it is probably the most important advisory body in the energy field, the IEA has consistently failed to realistically project VRE in their flagship publication, the World Energy Outlook (WEO). One example is that for twenty years it projected that the yearly growth of solar PV installations would level off and essentially come to a halt. At the same time, though, it also reported that solar PV kept increasing by, on average, 43% per year. This was first put in stark relief by Hoekstra [361] and can also be found in Breyer and Jefferson [360].

Unfortunately, sustained criticism from various stakeholders seemed to have no impact for many years. In 2019, this changed, helped by a massive critique endorsed by dozens of stakeholders, including global financial giants such as Allianz [362]. In the WEO 2020 [363], the IEA acknowledged that solar PV has emerged as the world's least-cost source of electricity and that it will remain so for the foreseeable future in all major regions of the world. Notwithstanding that verbal acknowledgement, solar PV shares in IEA scenarios remain low, compared to various global scenarios [364]. Only the new Net Zero Emissions by 2050 (NZE) scenario seems somewhat realistic regarding solar PV. But even this NZE scenario does not project the annual installation of solar PV and wind turbines to grow after 2030, despite growing global energy demand [9], [209]. In the NZE scenario, solar PV installations do not go beyond 630 GW/yr. For the 100% RE scenarios of Bogdanov *et al.* [14], about 2,000 GW/yr is needed in 2030 and 3,300 GW/yr in 2040. Similarly, Verlinden [319], based on Haegel *et al.* [365], expects about 3,000 GW/yr from the early 2030s onwards. So even in the most ambitious IEA scenario, solar PV is artificially capped. This indirectly means more fossil CCS and unprecedented nuclear demand, while the system costs increase dramatically [209]. Further societal discourse is apparently needed to bring IEA scenarios closer to societal requirements. This can be eased by making the data used in the IEA scenarios openly available, as called for by various stakeholders [366], [367].

B. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The IPCC is the world's central advisory institution on the climate emergency. Its reports are meant to summarize existing scientific insights on climate change, and the mitigation options that are available to humanity. Therefore, the IPCC might be expected to welcome the opportunities for rapid climate change mitigation that 100% RE systems research offers. Yet, the first IPCC report that mentioned the existence of 100% RE system scenarios at all was that on "Global Warming of 1.5°C" in 2018 [4]. In that report, 100% RE system scenarios were not discussed broadly; rather, their existence was only briefly mentioned. This was 43 years after the first 100% RE system article [55], 25 years after a dedicated 100% RE report of two leading international organizations [60], and 22 years after the first global 100% RE system article [59]. By the end of 2017, at least 290 research articles discussing 100% RE systems were available, but they were not included in the IPCC report. As Jaxa-Rozen and Trutnevyte [296] have convincingly argued, more diversity is probably required, not just in terms of scenarios, but also when it comes to the authors that are tasked with writing these IPCC reports. The latter could potentially decrease institutional inertia and enable new developments allowing 100% RE scenarios to reach stakeholders and decision-makers faster and more comprehensively.

In early 2021, three studies using different methods [277], [294], [296] concluded that the IPCC severely underestimated PV in practically all their developed scenarios, and especially in the important IAM scenarios. This was partly caused by the fact that very few scenarios used plausible assumptions for the cost reductions of solar PV. The solar PV capex used in IAMs, documented in Krey *et al.* [298], leads to 4-5 times higher cost in 2050 compared to up-to-date projections of Vartiainen *et al.* [197]. Moreover, the IAM cost assumptions for 2050 are higher than reality in 2020. Strongly distorted scenario results are the consequence, for instance presented in Eom *et al.* [299], confirmed by Victoria *et al.* [277], Xiao *et al.* [294], and indicated in Jaxa-Rozen and Trutnevyte [296]. Xiao *et al.* concluded: "In the worst case, transformation efforts towards clean energy are delayed, in the false belief that they are too expensive that may lead to misadjusted incentive systems." Jaxa-Rozen and Trutnevyte [296] wrote: "We [. . .] recommend increasing the diversity of models and scenario methods included in IPCC assessments to represent the multiple perspectives present in the PV scenario literature." Victoria *et al.* [277] found that "the contribution of solar electricity to primary energy in 2050 averages to 3.1%/6.8% in the IPCC 5thAR/SR1.5." In other words, the first global 100% RE system article in 1996 [59] indicated four times the TPED contribution of solar PV than the average of IAMs used for the most recent IPCC report published over 20 years later. Victoria *et al.* [277] also reported some progress in some publications using IAMs, though a major turn towards correcting PV cost data has not yet been observed in IAM publications except for the recent Luderer *et al.* [146] (as discussed below).

Victoria *et al.* [277] also point out that sector coupling and comprehensive electrification for all energy demand is still missing from almost all IAMs and their respective scenarios. An important example of such a lack of electrification of demand is the IAMs treatment of electric vehicles. Research into the ten leading IAMs for the IPCC found that they all assumed that electric vehicles will remain more expensive until 2100 [368]. However, industry experts expect total cost of ownership parity between 2020 and 2025 and retail price parity between 2025 and 2030 [369]. Based on this, politicians in many countries are starting to phase out all combustion vehicles with the EU currently drafting a plan to ban new internal combustion cars by 2035 and combustion trucks by 2040 [370]. Furthermore, the UK, Netherlands, Sweden, Singapore, and Iceland are planning a ban by 2030, and Norway even by 2025 [371], [372]. Nevertheless, IAMs still assume EVs will be more expensive until 2100 and they compound the problem with equally outdated assumptions on user acceptance.

At the end of 2021, Luderer *et al.* [146] sought to initiate a turning point. They published a scenario based on the IAM REMIND-MAgPIE in which they applied realistic costs for solar PV, fossil CCS, and nuclear energy using the PV projections by Vartiainen *et al.* [197]. It led to the first known IAM scenario which fulfils the criterion for inclusion in Table 1 as a 100% RE system analysis. When these realistic assumptions where used, low-cost solar PV disrupted nuclear energy and fossil CCS and led to a renewable electricity share of 98% in 2050. Updated VRE integration cost functions led to VRE integration cost of 10-20 USD/MWh in 2050, which is comparable to findings by Bogdanov *et al.* [14] and Pursiheimo *et al.* [145]. Additionally, this scenario overcame the previous overestimation of VRE integration cost, and led to realistic values for very high shares of VRE, as pointed out by Brown and Reichenberg [373]. VRE integration cost strongly varies across models, as not all transmission and grid operations constraints are considered, resulting in respective uncertainties [374].

Despite the application of realistic cost assumptions, Luderer *et al.* [375] still neglected all H_2-to-X routes, which unfortunately limits the VRE share in TPED to less than 60%. Inclusion of these routes as done by Bogdanov *et al.* [14] and partly Pursiheimo *et al.* [145], can lead to a VRE share in TPED of more than 80%. This might be rectified in future publications by the team of Luderer *et al.*, as their other research shows they are well aware of the value of e-fuels and e-chemicals [376]. Ideally, they would integrate a 100% renewables-based energy-industry transition with the five major e-fuels and e-chemicals (hydrogen, e-kerosene/diesel/gasoline Fischer-Tropsch liquids, e-ammonia, e-methanol, e-methane) as in Bogdanov *et al.* [39]. Such advances in Luderer *et al.* [146] and Ueckerdt *et al.* [376] could trigger a structural advancement in the entire IPCC. In parallel to this improvement, the IPCC could also consider that its exclusive reliance on IAMs constitutes a potential risk. For that reason, it could include 100% RE research directly, as recommended by Jaxa-Rozen and Trutnevyte [296], Victoria *et al.* [277] and Xiao *et al.* [294].

VIII. PROGRESSING 100% RENEWABLE ENERGY SYSTEMS RESEARCH TOWARDS NET-NEGATIVE CO_2 EMISSIONS SYSTEMS

Carbon dioxide removal options are not yet consistently considered in 100% RE systems research. The necessity to study net-negative CO_2 emission scenarios and a broader CDR portfolio that is integrated in long-term 100% RE scenarios is outlined in section IX.A. Teske/DLR *et al.* [125] integrated natural climate solutions (NCS) comprehensively, but their model lacked other CDR options such as direct air captured carbon and storage (DACCS) and bioenergy carbon capture and storage (BECCS) [377]. So far, only the LUT-ESTM has presented insights on DACCS [54], [378] among the models used for 100% RE systems research, while lacking the most important NCS. DACCS has been investigated with solar PV [54], CSP [379], and geothermal energy [380], among others. Research exists projecting CDR demand provided by DACCS in the order of 20-30 $GtCO_2$/yr in the second half of this century for ambitious climate targets [144], [381]. DACCS and BECCS are not the only CDR technologies available, though, with other promising technologies including more NCS, i.e. natural- and land-based solutions, such as soil carbon sequestration, ecosystem restoration, afforestation and reforestation, blue carbon and seagrass, and biochar [382].

Rigorous models connecting these CDR systems to 100% RE models are incredibly rare, though. All 100% RE system research teams focus on true-zero CO_2 emission solutions for the energy system, a consequence of 100% RE system scenarios, but they do not yet encompass technologies and pathways that could enable net-negative CO_2 emissions. Results by Sgouridis *et al.* [383] indicate that, at present, focusing on expanding RE supply rather than on carbon capture is more profitable in terms of advancing toward the energy transition but, in the long run, active control of the atmospheric CO_2 concentration may become a necessity. Remarkably, Luderer *et al.* [146] present the first scenario created with a model belonging to the IAMs that fulfills the minimum criterion of a 95% RE share by the year 2050 and covers the entire energy system. This closed a research gap within the climate energy research community that was addressed by Hansen *et al.* [19] and Victoria *et al.* [277].

The next major development step in 100% RE research may be highly resolved energy system models capable of incorporating a broader collection of CDR options, and describing transition scenarios that trace all fossil fuels-based industrial feedstock flows. This should include non-energy feedstock use, such as fossil hydrocarbon demand in today's chemical industry, and should consider the full range of energy-industry-CDR options. It is becoming increasingly important to describe 1.5°C climate target scenarios that fulfill the latest insights of climate system science. Such insights indicate that the formerly assumed remaining carbon budgets [4] must be corrected to lower values due to negative climate feedback loops not yet correctly considered [384]. Recent climate science research indicates that climate tipping points [385] may already have been activated at present temperature levels, including dynamics in several Earth systems that are likely irreversible at temperatures in the range of ca. 1.0°C to 1.5°C above the pre-industrial global average surface air temperature level. These include progressive thawing of permafrost soils [386], melting of Greenland ice [387], Western Antarctic Ice Shield instability [388], and coral reef dieback [4]. This would mean that for a higher level of climate security, substantially more ambitious climate targets must be the target. Such climate security temperature target levels may be around 1.0°C, or even below, and in a range of 280-350 ppm atmospheric CO_2 concentration [389], [390], compared with 420 ppm CO_2 concentration reached in the year 2021.

Thus, sophisticated energy system models must be upgraded so that they advance the scope of analysis beyond zero emission energy systems. Generating scenarios for a world with lower atmospheric CO_2 levels than today will mean modeling net-negative emission energy-industry-CDR systems, based on 100% RE supply.

IX. DEVELOPMENT PERSPECTIVES FOR 100% RENEWABLE ENERGY SYSTEMS ANALYSES

Many methodological advances have been implemented in recent years in the research on 100% RE system analyses. However, various gaps in methods, data and research remain, which must be bridged to enable a comprehensive societal discourse on the energy transition that lies ahead. Several of these major gaps and aspects are discussed in the following sections.

A. ENERGY-INDUSTRY-CDR SYSTEMS SPANNING THE ENTIRE CENTURY

It is becoming increasingly apparent that 100% RE systems will emerge as the new standard, since fossil CCS and nuclear energy represent more costly options, as documented by the IEA [209] and recently in the IAM environment [146]. Fossil hydrogen with CCS does not seem to be a silver bullet on the horizon either [26], [391]. These trends highlight the need for 100% RE system analyses to fully cover the energy-industry-CDR system. While ESMs are well developed for the energy system, they still show substantial gaps for the industry description, as only the LUT-ESTM is known to be capable to describe a full 100% RE-based industry transition [39], while the latest version of PyPSA-Eur-Sec also includes a detailed modeling of the transformation in the industry and feedstock supply [134] and can be used for 100% renewable energy-industry systems if fossil inputs are not allowed. Most ESMs, though, are not yet able to fully describe the transition of energy-intensive industry, including green steel [392]–[394], and a chemical industry without fossil feedstock [108], [185], [395], [396].

Not a single ESM used for 100% RE system studies is able to take directly into account the main CDR options of afforestation, reforestation, BECCS and DACCS. Natural climate solutions for negative CO_2 emissions are part of the scenarios of Teske/DLR [124], [125], while the other ESMs used for 100% RE systems have not yet implemented these attractive options. NCS and CDR options must be part of any net-negative CO_2 emission pathway discussion, which is an obligatory discussion for any development beyond 2050 if the ambitious target of the Paris Agreement of 1.5°C is to be taken seriously. Climate safety cannot stop at 1.5°C, given the severe distortion of the planetary climate system already underway [397]; thus, more ambitious targets of substantially less than 1.5°C require consideration, such as 1.0°C or 350 ppm of atmospheric CO_2 levels [389], [390] or less [144], for dedicated scientific advice on the option space and respective societal discourse. This, in turn, leads to an expansion of 100% RE system research beyond the often-adopted target year 2050, as net-negative CO_2 emissions may be a major societal effort in the second half of the century. The necessity of including CDR as a new energy sector using negative emission technologies (NETs) is motivated by a rising availability of research addressing the possibility that NETs will become urgently necessary for rebalancing the Earth's climate [398]. Especially for low-lying islands and coastal areas, this topic is significantly pressing for the survival of whole nations considering the long-term repercussions of climate change such as rising sea levels, even after the year 2100 [399].

To represent this new energy sector in appropriate detail, comprehensive CDR/NET technology portfolios must be developed. For such technology portfolios, an assessment of technological and environmental limitations is indispensable [377], [398], [400], [401]. The second half of this century will also be very important for scaling the energy-industry-CDR system toward a truly sustainable system [144], [212], since about 10 billion people will expect standards of living comparable with the most developed countries as of today. This will trigger a formidable additional energy demand that may lead to a doubling of TPED at the end of the century compared to mid-century [402], leading to about 170 TW PV demand as the dominating source of energy as indicated by Goldschmidt *et al.* [403] and Breyer *et al.* [212]. The consequences of an ''energy for all'' strategy on the required energy resources, land-use and material demand for a 100% RE system for a truly sustainable civilization are still poorly understood and not yet discussed.

B. SOFT COUPLING OF ENERGY SYSTEM MODELS AND INTEGRATED ASSESSMENT MODELS

The requirement to describe proper energy-industry-CDR systems leads to a stronger coupling of ESMs to the insights of IAMs, especially those for emission pathways and constraints, as well as land-use limitations. IAMs are inherently unable to describe energy systems in the required high temporal and geo-spatial resolution. The obvious solution is a stronger interaction and collaboration of research teams specialized in ESMs with those with expertise in IAMs, as also suggested in Hansen *et al.* [19] and Victoria *et al.* [277]. Such co-working could integrate the best of both disciplines for the benefit of substantially advancing the state-of-the-art in comprehensive transition pathway descriptions and pathway comparisons.

C. MATERIAL CRITICALITY OF TRANSITION PATHWAYS

The transition from the present fossil fuels-based energy-industry system to a solar-wind-based energy-industry-CDR system leads to new potential challenges. Materials are essential to manufacture all the required components, and the expansion of energy supply for reaching a sustainable energy system for high standards of living for about 10 billion people is not yet well understood [221], [403]. The discourse on critical materials tends to confuse the economics of commodity cycles with geological scarcity and overlooks the vital aspect that, unlike fossil fuels, most critical materials for renewable energy technologies can be recycled [404]. Thus, circular economy will be a central pillar for 100% RE systems, as clearly found for the case of lithium [303] and indicated for solar PV [277], [403], [405]. However, a holistic analysis of material criticality for 100% RE systems until 2050 and beyond represents a substantial research gap. This also requires a feasible and meaningful concept of criticality in terms of the likelihood and potential impact of shortages in raw material supply [406].

D. IMPACT OF INTER-ANNUAL RESOURCE VARIATIONS ON 100% RENEWABLE ENERGY SYSTEMS SOLUTIONS

The 100% RE system analyses use a variety of methods and datasets. The impact of inter-annual resource variations and respective inter-annual storage demand is not yet studied adequately, but will be important for ensuring energy system security of supply for the known and foreseeable variations of the key renewable resources, in particular solar, wind and hydro.

Resource variability can be grouped into two main categories: firstly, the natural variability of resources as observed in recent decades; secondly, new types of resource variations induced by climate change [210], [407]. Present knowledge indicates a stronger variability for hydropower [408] and wind resources and a rather marginal variation for solar resources. This correlates well with an energy system mainly based on solar energy, as indicated by Bogdanov *et al.* [14], Pursiheimo *et al.* [145], and Luderer *et al.* [146]. A strategic energy reserve in the form of long-term and low-cost storage in chemical compounds may be the prime solution for balancing inter-annual resource variations, and detailed analyses should be able to deliver a quantification. Re-visiting the resource adequacy paradigm, building balancing generation or long-term storage in different forms should be complemented by opportunities in new kinds of demand flexibility arising from defossilization, and the main economic criteria for costs and risks [284]. International trade of e-fuels [409] and an accompanying infrastructure to be built may ease a dispatch and support in case of regionally limited inter-annual resource deficits. Detailed global-local 100% RE systems analyses will be required for inter-annual resource balancing investigations.

E. IMPACT OF VARIABLE RENEWABLES ON POWER SYSTEM RELIABILITY AND SECURITY

As the underlying nature of the power system is changing from one based largely on a synchronous paradigm to one based on a non-synchronous paradigm, analytic tools that help evaluate the operation of a power system with a large number of IBRs are still to be developed [286]. Planning models increasingly need to take the operational constraints into account [147]. IBR-dominated systems are fundamentally different to current power systems in many ways, and the differences need to be reflected in the design, analysis, operations, and planning of power systems. There is a vast difference between a 75% penetration of VRE supported by some synchronous generators and synchronous compensators and a 100% VRE all-IBR system. The changes are so profound that a fundamental rethinking of power systems is required.

One solution is to use a portion of wind and solar PV power plants as grid forming, providing the capabilities needed for stable system operation. More research and development and demonstrations are still needed regarding use of new grid-forming technology in the power system. Where and when will the grid-forming services need to be available? If installed as deeply embedded, at medium and low voltages, would grid forming be effective for all the challenges? Will a mix of synchronous condensers (SCs) and IBRs prove an economic solution to adding system strength? Should these be large central units or smaller decentralized units? How economic and practical is the use of large decommissioned generators as SCs? [283] One of the challenges is how to manage the power system when it is at times dominated by IBRs like wind power and solar PV and batteries and, at other times (only hours apart), dominated by synchronous machines, and all other possible combinations in between, both spatially and temporarily.

IBRs can be highly flexible and controllable, with independent control over real and reactive current, and they can shape the equipment's response to various grid conditions. Because of this, there could be opportunities to improve the behavior of IBRs compared to synchronous generators in some respects. Incremental tweaking and artificially forcing IBRs to function similarly to synchronous machines is a short-term strategy that is limited and does not leverage the true potential of IBRs. However, the control algorithms that dictate the response of IBRs to grid conditions can interact at both a local and system-wide level and with other elements in the power system, such as high-voltage direct current transmission terminals. This dramatically complicates the analysis of IBRs in the power system and could lead to stability challenges [284], [286].

The experience of operating and planning systems with large amounts of variable generation is accumulating, and research to tackle challenges of inverter-based, non-synchronous generation is on the way. Energy transitions and digitalization also bring new flexibility opportunities, both short and long term. However, no study comprehensively addresses both the long-term and short-term challenges so far. Linking the models to capture all constraints and potential cost impacts of 100% RE systems from power system operation will be needed. Some key issues and recommendations can be identified across the challenges for planning, operation, and system stability [150]:

- Modeling complexity: There will be an increased computational burden because more variable IBRs details need to be captured, and more data are needed to capture higher resolutions, both time resolution and distributed resources, and larger areas, with extended time series to capture weather-dependent events.
- Larger areas: The entire synchronous system is relevant for stability studies. Sharing resources for balancing and adequacy purposes with neighboring regions will be more beneficial.
- New technologies: All tools need to be modified to enable new types of (flexible) demand and storage while facilitating further links through energy system coupling.
- Modeling integration: There will be increased importance in integrated planning and operation methodologies, tools, and data. Due to operational and planning timescales, models need greater overlap. Flexibility needs and plant capabilities must be incorporated into adequacy methods, and stability concerns must be considered for network expansion planning and operating future grids.
- Cost versus risk: The reliability interface needs to be revisited with the evolution of flexibility and price-responsive loads to ensure that high-cost increases are not imposed when modified reliability targets could yield acceptable results.
- Looking forward, new paradigms for 100% IBR-dominated, asynchronous power system operation can be found. This would profoundly impact the tools and methods used, especially for stability.

F. DISTRICT HEATING AND COOLING IN TRANSITION SCENARIOS

Sector coupling, also referred to as smart energy systems, as argued by e.g. Lund *et al.* [91] and Mathiesen *et al.* [16] offers the possibility of exploiting synergies across energy sectors also using power-to-X. It has been developed a combination of temporal and spatial modelling which enables a deeper understanding of the possibilities in the heating sector, e.g. applied in the Heat Roadmap Europe studies [410], [411]. Coupling with district heating, for instance, holds more potential benefits in a 100% RE system context as it enables using the vast amounts of waste heat present even in a future with extensive electrification. Also, it offers to utilize waste heat from data centers, power-to-X, solar thermal and geothermal energy [412]. Through the exploitation of power-to-heat technologies and low-cost thermal energy storage [40], coupling offers flexibility that can assist in the integration of VRE. In future systems with further decarbonization and finally defossilization of the transport and industry sectors partly using hydrogen or other e-fuels [14], [39], [376], [409], [413], district heating systems may also serve as waste heat sinks. Substantial sector coupling benefits have been identified for hydrocarbon-based e-fuels with CO_2 DAC, as the low-temperature heat demand of DAC [102] can be mainly provided by recovered waste heat of e-fuels and synthesis plants, such as from electrolyzers [37] and Fischer-Tropsch plants [30]. Volumes, potential waste heat supply and heat demand may be huge, as the global electrolyzer, CO_2 DAC, and Fischer-Tropsch capacity is projected to about 11,000 GWel, 2300 $MtCO_2$/yr, and 1700 GWFT, respectively, for a zero-emission energy system by 2050 [14]. Including the e-chemicals feedstock demand, both waste heat from electrolyzers and demand for CO_2 DAC increases substantially [39], [112].

In addition, heat losses from data centers [414], [415] and other activities may provide a large quantity of thermal energy for district heating systems that alternatively would be wasted, or which could even constitute local environmental hazards. Presently, there is limited district heating outside the EU, China, and the former Soviet Union [416], though US data is assumed to be underestimated. Analyses have shown district heating prospects in China [417], [418], Chile [419], and across Europe [410], [420]. For Denmark, two different teams have investigated the optimal level and both, Münster *et al.* [421] using Balmorel [422] and analyses based on EnergyPLAN [87], have found appropriate shares in the 55-65 % range.

District heating is facing competition from individual solutions in certain areas; however, while individual solutions in cases may be economically attractive for users, the solutions are not necessarily optimal from a wider systems perspective as indicated by e.g. the work on Europe [423]. Low-temperature district heating of the 4th or 5th generation [36], [424] expands the utility of district heating as it improves the efficiency of heat generation while lowering grid losses. Nevertheless, analyses have also stressed the importance of local conditions as specific point sources of waste heat. Additionally, issues regarding the raising of the temperature to appropriate district heating levels need to be addressed [425]. The temporal and spatial interaction of industrial waste heat and industrial and residential heat demand requires more detailed consideration in 100% RE system analyses, also reflecting overall system efficiency provided by synergies of sector coupling. Several analyses of different solutions with extremely low temperature district heating with local booster heat pumps do not seem to create a more energy efficient or cost effective system, hence the limit tends to be temperatures where individual installations can be avoided in the buildings [426]. While small building level individual heat pumps are much more efficient than individual boilers, they are not very efficient in integrating VRE [427]. District cooling may provide some of the same sector coupling benefits to the energy system, and while district heating is most relevant in temperate or cold climates, district cooling has prospects from tropics to temperate climates. In areas where both are relevant, synergies are even better [428].

G. RAISING GEO-SPATIAL RESOLUTION OF INTERCONNECTED ENERGY SYSTEM ANALYSES

The standards in geo-spatial resolution of global 100% RE system analyses are insufficient for proper societal discourse. Most models used for global energy system analyses aggregate the world into 10 to 24 individually modelled regions. This is done strategically because grids are interconnected across political boundaries. Europe, for example, is well-interconnected. LOADMATCH/GATOR-GCMOM uses 24/143 regions, [R]E 24/7 uses 72, and the LUT-ESTM uses 145 regions (Table 1), which is still insufficient for connecting the global perspective to local systems and to consistently address the interdependency between global paths and local developments. Regular practices are national energy transition analyses on a national level (Figure 3) with all relevant stakeholders in a bottom-up approach. However, global-local interactions may be beyond that scope, and regional and global scenarios require an improved understanding of limitations caused by local restrictions.

A technical solution may be to substantially increase the number of regions. The nomenclature of territorial units for statistics (NUTS) as developed for the European Union [429], may be the right guidance to estimate what such a resolution may mean on a global level. The NUTS1 level structures the EU-27 rim into 87 well shaped regions, with the definition that all regions shall cover not less than 3 million inhabitants, but also not more than 7 million, with an average of 5.15 million per region for the present 448 million inhabitants. For the current world population of about 7.9 billion this would translate to about 1530 regions.

Considering the NUTS2 structuring of EU-27, the 241 regions within the limits of 0.8 to 3 million inhabitants per region with an average of 1.86 million would translate to about 4250 regions globally for the present. It may not be possible to scale the existing models with 10 to 24 global regions in one step on a NUTS1 or even NUTS2 equivalent level; however, intermediate steps may enable that.

Experience for Europe clearly shows that a NUTS1 level can be managed, as shown by Sassa and Trutnevyete [430], in demonstrating even a NUTS3 resolution for six Central European countries in power sector overnight simulations applying a soft-linked EXPANSE-PyPSA model. A similar experience with the LUT-ESTM for countries such as Chile [216], Ghana [205], Cameroon [431], and Nepal and Bhutan [432] clearly indicates that a NUTS1 equivalent level may be achievable globally, as the average size per sub-region is about 2.9, 5.5, 3.8, 3.9 million inhabitants for Chile, Ghana, Cameroon, and Nepal and Bhutan, respectively. Even the NUTS2 level may be possible in the long-term, as indicated in the case of Finland, which has been modelled into five NUTS2 regions as well as in seven regions with the LUT-ESTM [433]. An intermediate step for models may be about 100 to 200 global regions, which has been demonstrated to be doable with the LUT-ESTM using 145 regions. A next expansion step, then, may be the about 1500 regions in the NUTS1 equivalent resolution, or an intermediate step, with about 800 regions globally. A global resolution of about 800 regions would allow for the first time to have the global megacities [434] individually modelled in global-local context, and thus demonstrate how regions can be supplied despite the lack of local energy resources. This has been shown for the first time on the case of Delhi, the largest megacity mid-century in an interconnected energy system analysis for the entire north Indian grid [435].

A true global-local energy system analysis framework would directly link the global, continental, national and state-level and local energy transition discourses in a single context, enabling various new insights.

H. OVERCOMING THE LACK OF 100% RENEWABLE ENERGY SYSTEMS ANALYSES FOR THE GLOBAL SOUTH

The large majority of the known 100% RE system analyses are for the Global North (and Australia and New Zealand), with 79% of all national and regional analyses as documented in Hansen *et al.* [19] for the status of about 180 known articles at the end of 2018 and visualized for 550 articles known by July 2021 [168] in Figure 3. This has improved only marginally with 72% of about 666 known 100% RE system analysis articles at the end of 2021. Many of the known 100% RE system analyses for the Global South cover off-grid analyses of individual villages or smaller regions or smaller islands [436], such as the very well investigated La Réunion [437], Galapagos [438] or Canary Islands [126], so that the relative share of country-level analyses are substantially smaller. We apply the definition of the Global South according to Dados and Connell [439]. The known studies for Global South countries, including countries from the northern hemisphere if they are not yet on a high development level comparable to the USA, Canada, EU, Japan, Korea and China, but excluding high-income countries from the southern hemisphere, namely Australia, New Zealand, and Singapore, reveal a substantial lack of used models, as tabulated for all ESMs with at least ten known 100% RE system articles in Table 2, differentiated into global, regional and countries, off-grid and small islands.

The eight most used ESMs for 100% RE system analyses are summarized in Table 2, with at least ten known 100% RE system analysis articles per ESM. The two leading ESMs according to published articles are EnergyPLAN and the LUT-ESTM. About 9% of these studies are for global considerations, while 28% are for smaller geographic entities, in particular off-grid islands and city regions. The remaining 64% of all articles cover the regional and national level of countries, thereof 70% are for countries of the Global North, and only 30% for countries of the Global South, where the majority of people live and where the highest additional energy demand in the decades to come will arise. Interestingly, the dominating share of all national studies for countries of the Global South are carried out with the LUT-ESTM, with 84% of all 45 studies for the Global South on national level. GENeSYS-MOD follows, covering 7% of the national studies on regional and national level for the Global South, and all other models are below 3%. A successful global transition toward 100% renewables does require a detailed societal discourse all around the world, especially in countries of the Global South, so that an effective leapfrogging can be enabled that avoids stranded assets in a fossil infrastructure that is no longer needed and establishes a low-cost energy supply, which is nowadays based on low-cost wind and in particular solar energy.

I. OFF-GRID RENEWABLE ENERGY SUPPLY IMPLEMENTED IN COMPREHENSIVE ENERGY SYSTEM ANALYSES

About 760 million people do not have access to electricity, and 2.6 billion do not have access to sustainable cooking solutions [440]. Energy systems based on 100% RE and respecting sustainability criteria will lead to a massive electrification across energy sectors, and will lead to a massive decline in the role of bioenergy for energy services, especially for cooking in developing countries [95], [215]. Even solar PV electricity-based cooking solutions are thinkable [441], following the trend of electricity-based cooking [442]. However, not a single ESM is able to coherently model the energy transition including off-grid solutions or a transition of off-grid and on-grid solutions in a comprehensive energy system transition pathway with the interactions and gradual phase-in and phase-out of existing solutions [443].

The integration of off-grid mini- and micro-grids is essential as they are expected to play a vital role from transitioning as an energy access tool to meeting aspirational energy growth [444]. HOMER is an ESM optimized for off-grid electrification in a local micro-grid environment and used widely for respective analyses [445], [446]; however, it is practically limited to electricity and not used for national energy systems and interconnected multi-node analyses. Further, solar home systems, which represent a major part of fast off-grid electrification [447], are missing. ESMs addressing the off-grid aspects across the energy sectors with interaction to the on-grid system are required to close this methodological gap and thus enable a more coherent discourse with stakeholders and policy makers for optimized electrification, sustainable energy supply, and energy transition solutions.

J. SOCIETAL CONSTRAINTS FOR 100% RENEWABLE ENERGY SYSTEMS ANALYSES

As already underscored in section VI.E linking RE transitions to community wellbeing and acceptance, it is increasingly understood that techno-economic energy system transition analyses lack critical elements [223], [448]–[450] and may fail the intended targets. ESMs try to implement various societal aspects and constraints, such as air pollution [13], [217], water stress [218], jobs [13], [219], critical materials [221], EROI [191], resource potential limitations [451], and phase-in inertia in transition studies [14], while other aspects remain untouched despite being of highest importance. Such aspects include maximum area availability in societies, acceptance

TABLE 2. Regional scope of the most used energy system models with differentiation on geographic levels. ESMs are considered, if at least ten articles on 100% RE system analyses are known. The geographic categories are global, regional and countries, and off-grid and small islands. The total number of known articles underlying this table is 550 articles as of early July 2021 [168]. The total per ESM is the sum of articles for the categories "global," "smaller geography," and "regions and countries." Definition of the Global South according to Dados and Connell [439]. The LUT-ESTM also includes earlier overnight studies.

Model	articles	global	smaller geography	regions and countries			Global South share	
				total	Global North	Global South	model	total
EnergyPLAN	73	0	36	37	36	1	3%	2%
LUT-ESTM	63	13	0	50	12	38	76%	84%
HOMER	22	0	21	1	1	0	0%	0%
TIMES	19	2	6	11	10	1	9%	2%
AU model	16	0	0	16	16	0	0%	0%
PyPSA	16	0	0	16	16	0	0%	0%
GENeSYS-MOD	10	1	0	9	6	3	33%	7%
LOADMATCH	10	5	2	3	3	0	0%	0%

of specific technologies such as wind power or power transmission lines, and critical behavioral aspects that are still unknown, as for smart electric vehicles charging and vehicle-to-grid operation, among many others.

It is also very likely that such aspects and associated societal risks for the energy transition will differ from country to country. More research on economy-wide impacts [224] and geopolitical consequences [452] of transitioning toward 100% RE systems is required, which should then be linked to ESMs. New methods must be developed to expand the features of ESMs to better cover societal constraints and implement insights from social sciences. The techno-economic models are powerful, but the right constraints must be set and expanded. Otherwise, novel methods will be required to adequately integrate more societal dimensions, especially concerning vulnerable groups, tradeoffs concerning equity, or issues of policy, planning, and governance.

Furthermore, RE and sustainable technologies, and in particular solar energy, wind power and the various storage and conversion technologies, have a higher peace potential [453]. Energy security has various dimensions [454], which can be engaged in many ways [220]. It had been found that energy security is improved with storage technology [455], and an energy transition towards 100% RE may improve key energy security dimensions [456], which strongly impacts an overall resilience [457]. RE has already displayed many advantages over fossil fuels in terms of international security and peace, mostly because renewable resources are abundant, well distributed, and continuously replenished [404]. However, for concentrated forms of RE, in particular for hydropower, potential conflicts require attention for beneficial solutions [458]. In terms of critical materials and cybersecurity, renewable energy is thought to pose greater security risks. However, technological developments and circular economy approaches have the potential to address these needs and lead to more decentralized resource availability compared to geocentric fossil fuels exploitation. Moreover, there is an expectation that increased RE use may lead to a variety of small-scale conflicts but will reduce the risk of large geopolitical conflicts [452]. Further improved research is required linking 100% RE system transition to energy security and consequences for peace and stability.

K. OPEN SCIENCE AS THE NEW NORMAL FOR 100% RENEWABLE ENERGY SYSTEMS ANALYSES

All leading ESMs have been enabled with public funding, which leads to the justified claim that the public shall have full access to the investment in an open science environment. Open science comprises an open source of used modeling tools, open data of inputs and results, and open access to publications, among others. The ten most used ESMs for 100% RE system analyses fulfill such requirements to various degrees, such as PyPSA and GENeSYS-MOD in full, and TIMES partly, while all others are not yet available as an open-source tool. There are plans to transfer the LUT-ESTM into an open-source environment. Scientific and societal discourse is substantially facilitated by comprehensive open science practices, while the transfer of knowledge to researchers of the Global South can be substantially improved.

L. MODEL INTERCOMPARISION STUDIES OF 100% RENEWABLE ENERGY SYSTEMS ANALYSES

The critical aspect of model intercomparison in the field of 100% RE system analyses is almost non-existent. Various reviews do exist which compare ESMs [135], [459], [460], so that a minimum level of model overview is accessible. However, real model intercomparison studies among ESMs are required for further improving the models and closing model-specific gaps, limitations, and maybe existing failures. ESMs can be validated using existing data on real systems, but 100% RE systems in sector-coupled features do not yet exist, which may lead to gaps and failures in their description. Such limitations could best be identified and removed in direct model intercomparisons, which would serve the purpose of model cross-validation. Such a cross-validation was done with the two most used models for 100% RE system studies, and it helped to reveal limitations [169], which could then be removed, at least in part.

Full ex-post model intercomparison will only be achievable if all research is publicly available. This includes input data, more specific socio-economic data and macroeconomic scenario assumptions. With fully transparent input data, it will be possible to compare different ESMs with similar or equal input data. In return, the results of the ESMs for such simulation or optimization runs will enable an easier identification of differences and similarities between the ESMs. An alternative are joint projects of different modeling teams with the explicit goal of an in-depth model comparison, but these are associated with a large effort regarding the harmonization of the model parameterization and the synthesis of results [461]–[464].

The global ESMs could learn from respective model intercomparison efforts within the IAMs [465]–[468], which helped substantially in standardizing specific features and reporting structures and thus created higher relevance for policy makers. In this case, IAMs used for the IPCC are one step ahead, by publishing all assumptions and scenario variations for the used shared socio-economic pathways (SSPs) [469]–[473] and providing a broad scientific literature collection for transparency. Furthermore, a comprehensive database for all numeric input data is available online [474].

M. PROVIDING PATHWAYS FOR REBALANCING THE EARTH'S CLIMATE WITHIN THE PLANET'S LIMITS

Finally, all points raised in this section will have to be addressed cumulatively. By doing so, ESMs will be able to provide valuable pathways including NETs enabling net-negative CO_2 emission energy-industry-CDR systems. To this end, there are several challenges ahead. First, it is most important to achieve a global 100% renewable energy-industry system by 2050 at the latest, and ideally by 2035, in order to slow down the biggest threat to civilization and most living beings on planet Earth: climate change. Second, pathways must be investigated to ramp up CDR, especially in the second half of the century. This is important to compensate unavoidable and remaining GHG emissions not related to the energy system. However, this also opens the door for taking one step further and using the options for net-negative CO_2 emissions to rebalance the global temperature below a 1.5°C increase. As estimated [144], about 1480 $GtCO_2$ will have to be removed for rebalancing the CO_2 concentration in Earth's atmosphere to 350 ppm, which may comply with a 1.0°C target. Such ambitious goals will only be possible if the ESM and IAM research community act together hand in hand, pushing each other to advancements via constructive criticism and highest research standards.

X. CONCLUSION

The research field of 100% renewable energy systems analyses was initiated in the 1970s, started to attract attention in the mid-2000s, and has experienced strong growth since circa 2009. Some methodological milestones have been the ability to differentiate between local, national, and global perspectives to address various stakeholders; the use of hourly temporal resolution; describing not only the power sector but entire energy systems; and integral pathways that deal with the variability of solar and wind through conversion and storage combined with demand response and sector coupling.

Global 100% renewable energy systems analyses have been increasingly discussed since 2009 and three main groups of studies can be identified: i) optimization studies with low-cost solar PV leading to high shares of solar PV in electricity supply of 70-80%; ii) higher solar PV cost assumptions partly in optimization and often in simulation studies preferring substantial wind resource utilization; iii) simulation studies implying a broader resource diversity often assuming a higher bioenergy resource potential and less solar PV but more CSP shares utilizing the solar resource potential. Several teams find more than 90% of all electricity supply from solar PV and wind power in 100% renewable energy systems analyses. However, only two teams find a solar PV and wind power supply of at least 80% of the total primary energy demand, which is strongly driven by a comprehensive power-to-X consideration in both teams and either a strict sustainability limitation for bioenergy or even a full bioenergy ban. A further finding is that a strict cost optimization with latest solar PV costs and respective future projections leads to very high solar PV shares. Conversely, a more diversified energy system, utilizing a broader variety of resources, may also have value on its own, as the political, social, and economic risks of the energy transition might be lower, however on the price of higher absolute cost. After implementing the latest solar PV cost assumptions, reacting on continued respective critiques, improving grid integration methods, and applying latest insights on battery and electrolyzer cost, a first scenario using an integrated assessment model joined the field of 100% renewable energy systems analyses.

The field of 100% renewable energy systems analyses has successfully emerged from power sector analyses to describe the entire energy system, but the industry sector is not yet well described by most energy system models. The increasingly important new sector of carbon dioxide removal is also not yet addressed by any of the leading energy system models. Moreover, potential connections with injustice, social exclusion, community disagreement, and the degradation of the environment are possible when RE systems are installed without due consideration for equity, social acceptance, or good governance. These issues need to be managed by strong industry practices supplemented with robust policy enforcement.

As any new scientific field, 100% renewable energy systems research receives continued critiques based on justified as well as unjustified claims, which is part of a productive scientific discourse that has led to improved scientific standards that help to expand the field and gain impact on a growing stakeholder basis. Many studies have been carried out for energy return on investment on a component basis, but there are not yet many on an entire energy system level. Similarly, investigations on materials criticality will be most important for an early reaction in addressing mitigation strategies on a component level. Major international organizations, namely the IPCC, the IEA, and even the IRENA are late followers for highly renewable energy systems solutions with a considerable institutional inertia, while the time for adequate policy recommendations is more pressing than ever. The latest progress for the IPCC and the IEA indicates a shift in the right direction, although there is still a long way to go.

Within the field of 100% renewable energy systems analyses, various areas of study require more attention and improvement in the years to come. This especially includes full coverage of a coupled description of energy, industry and carbon dioxide removal systems in an integrated framework spanning the entire century. This shall lead to a stronger interaction of energy system models and integrated assessment models. The consequences of 100% renewable energy systems on materials criticality require substantially more attention so that potential limitations can be identified early, and mitigation strategies can be developed. Methodological improvements are required for inter-annual energy resource variations as well as the geo-spatial resolution of interconnected regions modelled on a global-local resolution. More detailed power system studies are needed to prove the feasibility of an operation with 100% inverter-based resources at a non-synchronous mode of operation as well as how to transfer those potential constraints to energy system models. The strong imbalance of 100% renewable energy systems studies for the Global North vs. for the Global South must be overcome so that a successful response to the climate emergency can be enabled. Energy system models still ignore off-grid solutions while hundreds of millions of people lack access to electrification and even more to clean cooking solutions. Thus, comprehensive energy transition pathways for developing countries must address off-grid and on-grid solutions within a better framework. More emphasis must be put on societal constraints for transition pathways toward 100% renewable energy solutions, especially issues of justice as noted above, which also includes a consequent open science approach in the field for improved societal discourse and faster diffusion of tools, data and knowledge. Last but not least, diffusion of insights within the field must be facilitated by initiating comprehensive model intercomparison studies of 100% renewable energy systems analyses.

The main conclusion of the vast majority of 100% renewable energy systems studies is that such systems can power all energy in all regions of the world at low cost. As such, we do not need to rely on fossil fuels in the future. In the early 2020s, the consensus has increasingly become that solar PV and wind power will dominate the future energy system and new research increasingly shows that 100% renewable energy systems are not only feasible but also cost effective. This gives us the key to a sustainable civilization and the long-lasting prosperity of humankind.

ABBREVIATIONS

BECCS	bioenergy carbon capture and storage
CAGR	compound annual growth rate
CAPEX	capital expenditures
CCS	carbon capture and storage
CCU	carbon capture and utilization
CDR	carbon dioxide removal
c-Si	crystalline silicon
CSP	concentrating solar thermal power
DAC	direct air capture
DACCS	direct air carbon capture and storage
DLR	German Aerospace Center
e-fuels	electricity-based fuels
EPBT	energy payback time
EROI	energy return on investment
ESM	energy system models
GHG	greenhouse gas
IAM	Integrated Assessment Model
IBRs	inverter-based resources
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LUT-ESTM	LUT Energy System Transition Model
NCS	natural climate solutions
NETs	negative emission technologies
NUTS	nomenclature of territorial units for statistics
NZE	Net Zero Emissions
PE	primary energy
PtX	Power-to-X
PV	solar photovoltaics
PyPSA	Python for Power System Analysis
RE	renewable energy
SSPs	shared socio-economic pathways
TES	thermal energy storage
TPED	total primary energy demand
VRE	variable RE
WEO	World Energy Outlook

REFERENCES

[1] [IEA] International Energy Agency. (2011). *Energy Policies of IEA Countries: Denmark 2011 Review*. IEA, Paris, France. [Online]. Available: https://iea.blob.core.windows.net/assets/3df26d26-9271-490b-ae10-1e9a14350412/EnergyPoliciesofIEACountriesDenmark2011.pdf

[2] [CVF]. (2016). *Climate Vulnerable Forum, Geneva, Rotterdam, Dhaka*. Accessed: Dec. 12, 2021. [Online]. Available: https://thecvf.org/about/

[3] [REN21] Renewable Energy Policy Network for the 21st Century. (2020). *Renewables 2020 Global Status Report*. Paris, France. [Online]. Available: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_repor_en.pdf

[4] [IPCC] Intergovernmental Panel on Climate Change. (2018). *Global Warming of 1.5°C*. IPCC, Geneva, Switzerland. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf

[5] [IRENA] International Renewable Energy Agency. (2012). *Towards 100% Renewable Energy: Status, Trends and Lessons Learned*. Abu Dhabi. [Online]. Available: https://coalition.irena.org/-/media/Files/IRENA/Coalition-for-Action/IRENA_Coalition_100percentRE_2019.pdf

[6] [IRENA] International Renewable Energy Agency (2020). (2015). *Towards 100% Renewable Energy: Utilities in Transition*. Abu Dhabi. [Online]. Available: https://coalition.irena.org/-/media/Files/IRENA/Coalition-for-Action/IRENA_Coalition_utilities_2020.pdf

[7] [IRENA] International Renewable Energy Agency. (2021). *Antigua & Barbuda Renewable Energy Roadmap*. Abu Dhabi. [Online]. Available: https://irena.org/-/media/Files/IRENA/Agency/Publication/2021/March/IRENA_Antigua_Barbuda_RE_Roadmap_2021.pdf

[8] [IRENA] International Renewable Energy Agency. (2021). *World Energy Transitions Outlook 1.5°C Pathway*. Abu Dhabi. [Online]. Available: https://irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook

[9] [IEA] International Energy Agency. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris, France. [Online]. Available: https://www.iea.org/reports/net-zero-by-2050

[10] [IEA] International Energy Agency. (2021). *Conditions and Requirements for the Technical Feasibility of a Power System with a High Share of Renewables in France Towards 2050*. Paris, France. [Online]. Available: https://assets.rte-france.com/prod/public/2021-01/RTE-AIE_rapportcompletENRhorizon2050_EN.pdf

[11] [EC] European Commission. (2018). *A Clean Planet for All a—European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*. Brussels, Belgium. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773

[12] T. B. Johansson, N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri, *Global Energy Assessment—Toward a Sustainable Future*. Laxenburg, Austria: Cambridge Univ. Press, 2012.

[13] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, S. J. Coughlin, C. A. Hay, I. P. Manogaran, Y. Shu, and A.-K. von Krauland, ''Impacts of green new deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries,'' *One Earth*, vol. 1, no. 4, pp. 449–463, Dec. 2019, doi: 10.1016/j.oneear.2019.12.003.

[14] D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A. S. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. D. S. N. S. Barbosa, M. Fasihi, S. Khalili, T. Traber, and C. Breyer, ''Low-cost renewable electricity as the key driver of the global energy transition towards sustainability,'' *Energy*, vol. 227, Jul. 2021, Art. no. 120467, doi: 10.1016/j.energy.2021.120467.

[15] N. Eyre, ''From using heat to using work: Reconceptualising the zero carbon energy transition,'' *Energy Efficiency*, vol. 14, no. 7, pp. 1–20, Oct. 2021, doi: 10.1007/s12053-021-09982-9.

[16] B. V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnøe, K. Sperling, and F. K. Hvelplund, ''Smart energy systems for coherent 100% renewable energy and transport solutions,'' *Appl. Energy*, vol. 145, pp. 139–154, May 2015, doi: 10.1016/j.apenergy.2015.01.075.

[17] [IRENA] International Renewable Energy Agency. (2021). *Renewable Capacity Highlights*. Abu Dhabi. [Online]. Available: https://www.scribd.com/document/514718917/IRENA-RE-Capacity-Highlights-2021

[18] N. Haegel and S. Kurtz, ''Global progress toward renewable electricity: Tracking the role of solar,'' *IEEE J. Photovolt.*, vol. 11, no. 6, pp. 1335–1342, Nov. 2021, doi: 10.1109/JPHOTOV.2021.3104149.

[19] K. Hansen, C. Breyer, and H. Lund, ''Status and perspectives on 100% renewable energy systems,'' *Energy*, vol. 175, pp. 471–480, May 2019, doi: 10.1016/j.energy.2019.03.092.

[20] [IEA] International Energy Agency. (2022). *Data and Statistics*. Accessed: Feb. 19, 2022. [Online]. Available: https://www.iea.org/data-and-statistics

[21] O. Kraan, E. Chappin, G. J. Kramer, and I. Nikolic, ''The influence of the energy transition on the significance of key energy metrics,'' *Renew. Sustain. Energy Rev.*, vol. 111, pp. 215–223, Sep. 2019, doi: 10.1016/j.rser.2019.04.032.

[22] A. Bloess, W.-P. Schill, and A. Zerrahn, ''Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials,'' *Appl. Energy*, vol. 212, pp. 1611–1626, Feb. 2018, doi: 10.1016/j.apenergy.2017.12.073.

[23] C.-J. Winter and J. Nitsch, ''Hydrogen as an energy carrier,'' in *Technologies, Systems, Economy*. Berlin, Germany: Springer, 1988.

[24] H. Heinrichs, O. Tlili, L. Welder, C. Mansilla, H. Blanco, H. Heinrichs, J. Leaver, N. J. Samsatli, P. Lucchese, M. Robinius, and S. Samsatli, ''The curious case of the conflicting roles of hydrogen in global energy scenarios,'' *Sustain. Energy Fuels*, vol. 4, no. 1, pp. 80–90, 2019, doi: 10.1039/C9SE00833K.

[25] M. Fasihi and C. Breyer, ''Baseload electricity and hydrogen supply based on hybrid PV-wind power plants,'' *J. Cleaner Prod.*, vol. 243, Jan. 2020, Art. no. 118466, doi: 10.1016/j.jclepro.2019.118466.

[26] E. Vartiainen, C. Breyer, D. Moser, E. R. Medina, C. Busto, G. Masson, E. Bosch, and A. Jäger-Waldau, ''True cost of solar hydrogen,'' *Sol. RRL*, vol. 6, no. 5, May 2022, Art. no. 2100487, doi: 10.1002/solr.202100487.

[27] M. Sterner, *Bioenergy and Renewable Power Methane in Integrated 100% Renewabe Energy Systems*. Kassel, Germany: Kassel Univ., 2009.

[28] H. Blanco and A. Faaij, ''A review at the role of storage in energy systems with a focus on power to gas and long-term storage,'' *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1049–1086, Jan. 2018, doi: 10.1016/j.rser.2017.07.062.

[29] S. Drünert, U. Neuling, T. Zitscher, and M. Kaltschmitt, ''Power-to-Liquid fuels for aviation—Processes, resources and supply potential under German conditions,'' *Appl. Energy*, vol. 277, Nov. 2020, Art. no. 115578, doi: 10.1016/j.apenergy.2020.115578.

[30] M. Fasihi, D. Bogdanov, and C. Breyer, ''Techno-economic assessment of power-to-liquids (PtL) fuels production and global trading based on hybrid PV-wind power plants,'' *Energy Proc.*, vol. 99, pp. 243–268, Nov. 2016, doi: 10.1016/j.egypro.2016.10.115.

[31] M. Fasihi, R. Weiss, J. Savolainen, and C. Breyer, ''Global potential of green ammonia based on hybrid PV-wind power plants,'' *Appl. Energy*, vol. 294, Jul. 2021, Art. no. 116170, doi: 10.1016/j.apenergy.2020.116170.

[32] O. Osman, S. Sgouridis, and A. Sleptchenko, ''Scaling the production of renewable ammonia: A techno-economic optimization applied in regions with high insolation,'' *J. Cleaner Prod.*, vol. 271, Oct. 2020, Art. no. 121627, doi: 10.1016/j.jclepro.2020.121627.

[33] F. Lonis, V. Tola, and G. Cau, ''Assessment of integrated energy systems for the production and use of renewable methanol by water electrolysis and CO_2 hydrogenation,'' *Fuel*, vol. 285, Feb. 2021, Art. no. 119160, doi: 10.1016/j.fuel.2020.119160.

[34] M. Fasihi and C. Breyer, ''Synthetic methanol and dimethyl ether production based on hybrid PV-wind power plants,'' in *Proc. Conf. 11th Int. (RES)*, 2017. [Online]. Available: https://www.researchgate.net/publication/315066937

[35] A. Hoekstra, ''The underestimated potential of battery electric vehicles to reduce emissions,'' *Joule*, vol. 3, no. 6, pp. 1412–1414, Jun. 2019, doi: 10.1016/j.joule.2019.06.002.

[36] H. Lund, P. A. Østergaard, M. Chang, S. Werner, S. Svendsen, P. Sorknæs, J. E. Thorsen, F. Hvelplund, B. O. G. Mortensen, B. V. Mathiesen, C. Bojesen, N. Duic, X. Zhang, and B. Möller, ''The status of 4th generation district heating: Research and results,'' *Energy*, vol. 164, pp. 147–159, Dec. 2018, doi: 10.1016/j.energy.2018.08.206.

[37] C. Breyer, E. Tsupari, V. Tikka, and P. Vainikka, ''Power-to-gas as an emerging profitable business through creating an integrated value chain,'' *Energy Proc.*, vol. 73, pp. 182–189, Jun. 2015, doi: 10.1016/j.egypro.2015.07.668.

[38] H. Lund, B. Möller, B. V. Mathiesen, and A. Dyrelund, ''The role of district heating in future renewable energy systems,'' *Energy*, vol. 35, no. 3, pp. 1381–1390, Mar. 2010, doi: 10.1016/j.energy.2009.11.023.

[39] D. Bogdanov, A. Gulagi, M. Fasihi, and C. Breyer, ''Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination,'' *Appl. Energy*, vol. 283, Feb. 2021, Art. no. 116273, doi: 10.1016/j.apenergy.2020.116273.

[40] H. Lund, P. A. Østergaard, D. Connolly, I. Ridjan, B. V. Mathiesen, J. Z. Thellufsen, and P. Sorknæs, ''Energy storage and smart energy systems,'' *Int. J. Sustain. Energy Planning Manage.*, vol. 11, pp. 3–14, Oct. 2016, doi: 10.5278/ijsepm.2016.11.2.

[41] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, ''The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system,'' *Energy Convers. Manage.*, vol. 201, Dec. 2019, Art. no. 111977, doi: 10.1016/j.enconman.2019.111977.

[42] J. Haas, F. Cebulla, W. Nowak, C. Rahmann, and R. Palma-Behnke, ''A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply,'' *Energy Convers. Manage.*, vol. 178, pp. 355–368, Dec. 2018, doi: 10.1016/j.enconman.2018.09.087.

[43] M. Sterner and I. Stadler, *Handbook of Energy Storage Demand, Technologies, Integration*. Berlin, Germany: Springer-Verlag, 2019.

[44] T. M. Gür, ''Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage,'' *Energy Environ. Sci.*, vol. 11, no. 10, pp. 2696–2767, Oct. 2018, doi: 10.1039/c8ee01419a.

[45] D. L. Peter, L. Lindgren, J. Mikkola, and J. Salpakari, ''Review of energy system flexibility measures to enable high levels of variable renewable electricity,'' *Renew. Sustain. Energy Rev.*, vol. 45, pp. 785–807, May 2015, doi: 10.1016/j.rser.2015.01.057.

[46] M. Stocks, R. Stocks, B. Lu, C. Cheng, and A. Blakers, ''Global atlas of closed-loop pumped hydro energy storage,'' *Joule*, vol. 5, no. 1, pp. 270–284, Jan. 2021, doi: 10.1016/j.joule.2020.11.015.

[47] J. Haas, L. Prieto-Miranda, N. Ghorbani, and C. Breyer, ''Revisiting the potential of pumped-hydro energy storage: A method to detect economically attractive sites,'' *Renew. Energy*, vol. 181, pp. 182–193, Jan. 2022, doi: 10.1016/j.renene.2021.09.009.

[48] C. Jakiel, S. Zunft, and A. Nowi, ''Adiabatic compressed air energy storage plants for efficient peak load power supply from wind energy: The European project AA-CAES,'' *Int. J. Energy Technol. Policy*, vol. 5, no. 3, pp. 296–306, 2007, doi: 10.1504/IJETP.2007.014736.

[49] A. Aghahosseini and C. Breyer, ''Assessment of geological resource potential for compressed air energy storage in global electricity supply,'' *Energy Convers. Manage.*, vol. 169, pp. 161–173, Aug. 2018, doi: 10.1016/j.enconman.2018.05.058.

[50] J. Xu, R. Z. Wang, and Y. Li, ''A review of available technologies for seasonal thermal energy storage,'' *Sol. Energy*, vol. 103, pp. 610–638, May 2014, doi: 10.1016/j.solener.2013.06.006.

[51] B. V. Mathiesen and H. Lund, ''Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources,'' *IET Renew. Power Gener.*, vol. 3, no. 2, pp. 190–204, Jun. 2009, doi: 10.1049/iet-rpg:20080049.

[52] F. Trieb and H. Müller-Steinhagen, ''Concentrating solar power for seawater desalination in the middle east and north Africa,'' *Desalination*, vol. 220, nos. 1–3, pp. 165–183, Mar. 2008, doi: 10.1016/j.desal.2007.01.030.

[53] U. Caldera and C. Breyer, ''Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems,'' *Energy*, vol. 200, Jun. 2020, Art. no. 117507, doi: 10.1016/j.energy.2020.117507.

[54] C. Breyer, M. Fasihi, C. Bajamundi, and F. Creutzig, ''Direct air capture of CO_2: A key technology for ambitious climate change mitigation,'' *Joule*, vol. 3, no. 9, pp. 2053–2057, Sep. 2019, doi: 10.1016/j.joule.2019.08.010.

[55] B. Sørensen, ''Energy and Resources,'' *Energy*, vol. 189, no. 4199, pp. 255–260, 1975.

[56] A. B. Lovins, *The Most Important Issue We've Ever Published*, vol. 6, no. 20. New York, NY, USA: New York Times, 1977.

[57] A. B. Lovins, ''Long-term constraints on human activity,'' *Environ. Conservation*, vol. 3, no. 1, pp. 3–14, 1976, doi: 10.1017/S0376892900017641.

[58] S. Sgouridis, C. Kimmich, J. Solé, M. Cerný, M.-H. Ehlers, and C. Kerschner, ''Visions before models: The ethos of energy modeling in an era of transition,'' *Energy Res. Social Sci.*, vol. 88, Jun. 2022, Art. no. 102497, doi: 10.1016/j.erss.2022.102497.

[59] B. Sørensen, ''Scenarios for greenhouse warming mitigation,'' *Energy Convers. Manage.*, vol. 37, nos. 6–8, pp. 693–698, Jun. 1996.

[60] [SEI] Stockholm Environment Institute. (1993). *Towards a Fossil Free Energy Future*. Amsterdam, The Netherlands. [Online]. Available: http://www.energycommunity.org/documents/greenpeacereport.pdf

[61] M. Z. Jacobson and M. A. Delucchi, ''A path to sustainable energy by 2030,'' *Sci. Amer.*, vol. 301, no. 5, pp. 58–65, Nov. 2009, doi: 10.1038/scientificamerican1109-58.

[62] M. Z. Jacobson and M. A. Delucchi, ''Providing all global energy with wind, water, and solar power—Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials,'' *Energy Policy*, vol. 39, no. 3, pp. 1154–1169, Mar. 2011, doi: 10.1016/j.enpol.2010.11.040.

[63] M. A. Delucchi and M. Z. Jacobson, ''Providing all global energy with wind, water, and solar power—Part II: Reliability, system and transmission costs, and policies,'' *Energy Policy*, vol. 39, no. 3, pp. 1170–1190, Mar. 2011, doi: 10.1016/j.enpol.2010.11.045.

[64] M. L. A. Junginger, *Technological Learning in the Transition to a Low-Carbon Energy System*. New York, NY, USA: Academic, 2019.

[65] M. Z. Jacobson, M. A. Delucchi, Z. A. Bauer, S. C. Goodman, W. E. Chapman, M. A. Cameron, C. Bozonnat, L. Chobadi, and H. A. Clonts, ''100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world,'' *Joule*, vol. 1, no. 1, pp. 108–121, Sep. 2017, doi: 10.1016/j.joule.2017.07.005.

[66] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, and B. V. Mathiesen, ''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*, vol. 123, pp. 236–248, Aug. 2018, doi: 10.1016/j.renene.2018.02.009.

[67] M. Z. Jacobson, ''On the correlation between building heat demand and wind energy supply and how it helps to avoid blackouts,'' *Smart Energy*, vol. 1, Feb. 2021, Art. no. 100009, doi: 10.1016/j.segy.2021.100009.

[68] M. Z. Jacobson, ''The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected,'' *Renew. Energy*, vol. 179, pp. 1065–1075, Dec. 2021, doi: 10.1016/j.renene.2021.07.115.

[69] M. Z. Jacobson, A.-K. von Krauland, S. J. Coughlin, E. Dukas, A. J. H. Nelson, F. C. Palmer, and K. R. Rasmussen, ''Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries,'' *Energy Environ. Sci.*, to be published, doi: 10.1039/d2ee00722c.

[70] M. Z. Jacobson, W. G. Colella, and D. M. Golden, ''Atmospheric science: Cleaning the air and improving health with hydrogen fuel-cell vehicles,'' *Science*, vol. 308, no. 5730, pp. 1901–1905, Jun. 2005, doi: 10.1126/science.1109157.

[71] O. H. Hohmeyer and S. Bohm, ''Trends toward 100% renewable electricity supply in Germany and Europe: A paradigm shift in energy policies,'' *WIREs Energy Environ.*, vol. 4, no. 1, pp. 74–97, Jan. 2015, doi: 10.1002/wene.128.

[72] C. Breyer, D. Bogdanov, A. Aghahosseini, A. Gulagi, and M. Fasihi, ''On the techno-economic benefits of a global energy interconnection,'' *Econ. Energy Environ. Policy*, vol. 9, no. 1, pp. 83–102, Jan. 2020, doi: 10.5547/2160-5890.9.1.cbre.

[73] G. Czisch, *Szenarien Zur Zukünftigen Stromversorgung Kostenoptimierte Variationen zur Versorgung Europas Und Seiner Nachbarn MIT Strom aus erneuerbaren Energien*. Kassel, Germany: Kassel Univ., 2005.

[74] M. Biberacher, *Modelling and Optimisation of Future Energy Systems Using Spatial and Temporal Methods*. Minneapolis, MN, USA: Augsburg Univ., 2004.

[75] F. Trieb and H. Müller-Steinhagen, ''Europe–middle east–north Africa cooperation for sustainable electricity and water,'' *Sustainability Sci.*, vol. 2, no. 2, pp. 205–219, Sep. 2007, doi: 10.1007/s11625-007-0025-x.

[76] F. Trieb, C. Schillings, T. Pregger, and M. O'Sullivan, ''Solar electricity imports from the middle east and north Africa to Europe,'' *Energy Policy*, vol. 42, pp. 341–353, Mar. 2012, doi: 10.1016/j.enpol.2011.11.091.

[77] Y. Scholz, *Renewable Energy Based Electricity Supply at Low Costs Development of the REMix Model and Application for Europe*. Stuttgart, Germany: Stuttgart Univ., 2012.

[78] H. C. Gils, Y. Scholz, T. Pregger, D. Luca de Tena, and D. Heide, ''Integrated modelling of variable renewable energy-based power supply in Europe,'' *Energy*, vol. 123, pp. 173–188, Mar. 2017, doi: 10.1016/j.energy.2017.01.115.

[79] D. Heide, L. von Bremen, M. Greiner, C. Hoffmann, M. Speckmann, and S. Bofinger, ''Seasonal optimal mix of wind and solar power in a future, highly renewable Europe,'' *Renew. Energy*, vol. 35, no. 11, pp. 2483–2489, Nov. 2010, doi: 10.1016/j.renene.2010.03.012.

[80] E. H. Eriksen, L. J. Schwenk-Nebbe, B. Tranberg, T. Brown, and M. Greiner, ''Optimal heterogeneity in a simplified highly renewable European electricity system,'' *Energy*, vol. 133, pp. 913–928, Aug. 2017, doi: 10.1016/j.energy.2017.05.170.

[81] R. A. Rodriguez, S. Becker, and M. Greiner, ''Cost-optimal design of a simplified, highly renewable pan-European electricity system,'' *Energy*, vol. 83, pp. 658–668, Apr. 2015, doi: 10.1016/j.energy.2015.02.066.

[82] R. A. Rodríguez, S. Becker, G. B. Andresen, D. Heide, and M. Greiner, ''Transmission needs across a fully renewable European power system,'' *Renew. Energy*, vol. 63, pp. 467–476, Mar. 2014, doi: 10.1016/j.renene.2013.10.005.

[83] M. G. Rasmussen, G. B. Andresen, and M. Greiner, ''Storage and balancing synergies in a fully or highly renewable pan-European power system,'' *Energy Policy*, vol. 51, pp. 642–651, Dec. 2012, doi: 10.1016/j.enpol.2012.09.009.

[84] T. V. Jensen and M. Greiner, ''Emergence of a phase transition for the required amount of storage in highly renewable electricity systems,'' *Eur. Phys. J. Special Topics*, vol. 223, no. 12, pp. 2475–2481, Oct. 2014, doi: 10.1140/epjst/e2014-02216-9.

[85] H. Lund, ''Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply,'' *Renew. Energy*, vol. 31, no. 4, pp. 503–515, Apr. 2006, doi: 10.1016/j.renene.2005.04.008.

[86] H. Lund. *EnergyPLAN: Advanced Energy System Analysis Computer Model*. Accessed: Nov. 18, 2021. [Online]. Available: https://www.energyplan.eu

[87] H. Lund, J. Z. Thellufsen, P. A. Østergaard, P. Sorknæs, I. R. Skov, and B. V. Mathiesen, ''EnergyPLAN—Advanced analysis of smart energy systems,'' *Smart Energy*, vol. 1, Feb. 2021, Art. no. 100007, doi: 10.1016/j.segy.2021.100007.

[88] B. V. Mathiesen, H. Lund, and K. Karlsson, ''100% renewable energy systems, climate mitigation and economic growth,'' *Appl. Energy*, vol. 88, no. 2, pp. 488–501, Feb. 2011, doi: 10.1016/j.apenergy.2010.03.001.

[89] H. Lund and B. V. Mathiesen, ''Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050,'' *Energy*, vol. 34, no. 5, pp. 524–531, May 2009, doi: 10.1016/j.energy.2008.04.003.

[90] D. Connolly, H. Lund, and B. V. Mathiesen, ''Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European union,'' *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1634–1653, Jul. 2016, doi: 10.1016/j.rser.2016.02.025.

[91] H. Lund, A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, and D. Connolly, ''From electricity smart grids to smart energy systems—A market operation based approach and understanding,'' *Energy*, vol. 42, no. 1, pp. 96–102, Jun. 2012, doi: 10.1016/j.energy.2012.04.003.

[92] H. Lund, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, ''Smart energy and smart energy systems,'' *Energy*, vol. 137, pp. 556–565, Oct. 2017, doi: 10.1016/j.energy.2017.05.123.

[93] J. Ikäheimo, J. Kiviluoma, R. Weiss, and H. Holttinen, ''Power-to-ammonia in future north European 100% renewable power and heat system,'' *Int. J. Hydrogen Energy*, vol. 43, no. 36, pp. 17295–17308, Sep. 2018, doi: 10.1016/j.ijhydene.2018.06.121.

[94] K. Zhu, M. Victoria, T. Brown, G. B. Andresen, and M. Greiner, ''Impact of CO_2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe,'' *Appl. Energy*, vol. 236, pp. 622–634, Feb. 2019, doi: 10.1016/j.apenergy.2018.12.016.

[95] D. Keiner, L. D. S. N. S. Barbosa, D. Bogdanov, A. Aghahosseini, A. Gulagi, S. Oyewo, M. Child, S. Khalili, and C. Breyer, ''Global-local heat demand development for the energy transition time frame up to 2050,'' *Energies*, vol. 14, no. 13, p. 3814, Jun. 2021, doi: 10.3390/en14133814.

[96] A. Nadolny, C. Cheng, B. Lu, A. Blakers, and M. Stocks, ''Fully electrified land transport in 100% renewable electricity networks dominated by variable generation,'' *Renew. Energy*, vol. 182, pp. 562–577, Jan. 2022, doi: 10.1016/j.renene.2021.10.039.

[97] M. Robinius, A. Otto, K. Syranidis, D. S. Ryberg, P. Heuser, L. Welder, T. Grube, P. Markewitz, V. Tietze, and D. Stolten, ''Linking the power and transport sectors—Part 2: Modelling a sector coupling scenario for Germany,'' *Energies*, vol. 10, no. 7, p. 957, Jul. 2017, doi: 10.3390/en10070957.

[98] S. Khalili, E. Rantanen, D. Bogdanov, and C. Breyer, ''Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world,'' *Energies*, vol. 12, no. 20, p. 3870, Oct. 2019, doi: 10.3390/en12203870.

[99] K. Ohkawa, K. Hashimoto, A. Fujishima, Y. Noguchi, and S. Nakayama, ''Electrochemical reduction of carbon dioxide on hydrogen-storing materials—Part 1. The effect of hydrogen absorption on the electrochemical behavior on palladium electrodes,'' *J. Electroanal. Chem.*, vol. 345, nos. 1–2, pp. 445–456, 1993, doi: 10.1016/0022-0728(93)80495-4.

[100] A. Bandi, M. Specht, T. Weimer, and K. Schaber, ''CO_2 recycling for hydrogen storage and transportation-electrochemical CO_2 removal and fixation,'' *Energy Convers. Manag.*, vol. 36, nos. 6–9, pp. 899–902, 1995, doi: 10.1016/0196-8904(95)00148-7.

[101] M. Specht, F. Staiss, A. Bandi, and T. Weimer, ''Comparison of the renewable transportation fuels, liquid hydrogen and methanol, with gasoline—Energetic and economic aspects,'' *Int. J. Hydrogen Energy*, vol. 23, no. 5, pp. 387–396, 1998, doi: 10.1016/s0360-3199(97)00077-3.

[102] M. Fasihi, O. Efimova, and C. Breyer, ''Techno-economic assessment of CO_2 direct air capture plants,'' *J. Cleaner Prod.*, vol. 224, pp. 957–980, Jul. 2019, doi: 10.1016/j.jclepro.2019.03.086.

[103] D. Connolly, B. V. Mathiesen, and I. Ridjan, ''A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system,'' *Energy*, vol. 73, pp. 110–125, Aug. 2014, doi: 10.1016/j.energy.2014.05.104.

[104] M. S. Kany, B. V. Mathiesen, I. R. Skov, A. D. Korberg, J. Z. Thellufsen, H. Lund, P. Sorknæs, and M. Chang, ''Energy efficient decarbonisation strategy for the Danish transport sector by 2045,'' *Smart Energy*, vol. 5, Feb. 2022, Art. no. 100063, doi: 10.1016/j.segy.2022.100063.

[105] B. V. Mathiesen and H. P. L. Nørgaard, ''Integrated transport and renewable energy systems,'' *Utilities Policy*, vol. 16, no. 2, pp. 107–116, Jun. 2008, doi: 10.1016/j.jup.2007.11.007.

[106] M. Sterner and M. Specht, ''Power-to-gas and power-to-X—The history and results of developing a new storage concept,'' *Energies*, vol. 14, no. 20, p. 6594, Oct. 2021, doi: 10.3390/en14206594.

[107] P. Gabrielli, M. Gazzani, and M. Mazzotti, ''The role of carbon capture and utilization, carbon capture and storage, and biomass to enable a net-zero-CO_2 emissions chemical industry,'' *Ind. Eng. Chem. Res.*, vol. 59, no. 15, pp. 7033–7045, Apr. 2020, doi: 10.1021/acs.iecr.9b06579.

[108] Á. Galán-Martín, V. Tulus, I. Díaz, C. Pozo, J. Pérez-Ramírez, and G. Guillén-Gosálbez, ''Sustainability footprints of a renewable carbon transition for the petrochemical sector within planetary boundaries,'' *One Earth*, vol. 4, no. 4, pp. 565–583, Apr. 2021, doi: 10.1016/j.oneear.2021.04.001.

[109] V. Becattini, P. Gabrielli, and M. Mazzotti, ''Role of carbon capture, storage, and utilization to enable a net-zero-CO_2-emissions aviation sector,'' *Ind. Eng. Chem. Res.*, vol. 60, no. 18, pp. 6848–6862, May 2021, doi: 10.1021/acs.iecr.0c05392.

[110] S. Horvath, M. Fasihi, and C. Breyer, ''Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040,'' *Energy Convers. Manage.*, vol. 164, pp. 230–241, May 2018, doi: 10.1016/j.enconman.2018.02.098.

[111] B. Stolz, M. Held, G. Georges, and K. Boulouchos, ''Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe,'' *Nature Energy*, vol. 7, no. 2, pp. 203–212, Feb. 2022, doi: 10.1038/s41560-021-00957-9.

[112] T. Galimova *et al.*, ''Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals,'' 2022.

[113] C. Hepburn, E. Adlen, J. Beddington, E. A. Carter, S. Fuss, N. M. Dowell, J. C. Minx, P. Smith, and C. K. Williams, ''The technological and economic prospects for CO_2 utilization and removal,'' *Nature*, vol. 575, no. 7781, pp. 87–97, Nov. 2019, doi: 10.1038/s41586-019-1681-6.

[114] C. Sapart, ''CCU as a solution to mitigate climate change: State of the art and perspectives,'' in *Proc. 16th Int. Conf. Greenhouse Gas Control Technol. (GHGT)*, 2022.

[115] R. J. Detz and B. van der Zwaan, ''Transitioning towards negative CO_2 emissions,'' *Energy Policy*, vol. 133, Oct. 2019, Art. no. 110938, doi: 10.1016/j.enpol.2019.110938.

[116] L. Desport and S. Selosse, ''An overview of CO_2 capture and utilization in energy models,'' *Resour., Conservation Recycling*, vol. 180, May 2022, Art. no. 106150, doi: 10.1016/j.resconrec.2021.106150.

[117] D. P. Schlachtberger, T. Brown, S. Schramm, and M. Greiner, ''The benefits of cooperation in a highly renewable European electricity network,'' *Energy*, vol. 134, pp. 469–481, Sep. 2017, doi: 10.1016/j.energy.2017.06.004.

[118] H. Ostovari, A. Sternberg, and A. Bardow, ''Rock 'n' use of CO, doi: 10.1016/j.energy.2017.06.004.: Carbon footprint of carbon capture and utilization by mineralization,'' *Sustain. Energy Fuels*, vol. 4, no. 9, pp. 4482–4496, Aug. 2020, doi: 10.1039/d0se00190b.

[119] T. Bruhn, H. Naims, and B. Olfe-Kräutlein, ''Separating the debate on CO_2 utilisation from carbon capture and storage,'' *Environ. Sci. Policy*, vol. 60, pp. 38–43, Jun. 2016, doi: 10.1016/j.envsci.2016.03.001.

[120] *Energy [R]evolution—A Sustainable World Energy Outlook*, Greenpeace International, European Renewable Energy Council (EREC), Amsterdam, The Netherlands, 2010, doi: 10.1136/bmj.h4754.

[121] *Energy [R]evolution—A Sustainable World Energy Outlook 2015*, Greenpeace International, Amsterdam, The Netherlands, 2015, doi: 10.1007/978-981-15-6751-3_4.

[122] S. Teske, T. Pregger, S. Simon, T. Naegler, W. Graus, and C. Lins, ''Energy [R]evolution 2010—A sustainable world energy outlook,'' *Energy Efficiency*, vol. 4, no. 3, pp. 409–433, Aug. 2011, doi: 10.1007/s12053-010-9098-y.

[123] S. Teske, T. Pregger, S. Simon, and T. Naegler, ''High renewable energy penetration scenarios and their implications for urban energy and transport systems,'' *Current Opinion Environ. Sustainability*, vol. 30, pp. 89–102, Feb. 2018, doi: 10.1016/j.cosust.2018.04.007.

[124] S. Teske, *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*. Switzerland, Cham: Springer, 2019.

[125] S. Teske, T. Pregger, S. Simon, T. Naegler, J. Pagenkopf, Ö. Deniz, B. van den Adel, K. Dooley, and M. Meinshausen, "It is still possible to achieve the Paris climate agreement: Regional, sectoral, and land-use pathways," *Energies*, vol. 14, no. 8, p. 2103, Apr. 2021, doi: 10.3390/en14082103.

[126] H. C. Gils and S. Simon, "Carbon neutral archipelago– 100% renewable energy supply for the Canary islands," *Appl. Energy*, vol. 188, pp. 342–355, Feb. 2017, doi: 10.1016/j.apenergy.2016.12.023.

[127] Openmod. *Open Energy Modelling Initiative*. Accessed: Feb. 15, 2022. [Online]. Available: https://openmod-initiative.org

[128] S. Pfenninger, "Opening the black box of energy modelling: Strategies and lessons learned," *Energy Strategy Rev.*, vol. 19, pp. 63–71, Jan. 2018, doi: 10.1016/j.esr.2017.12.002.

[129] Openmod. *Energypedia*. Accessed: Feb. 15, 2022. [Online]. Available: https://wiki.openmod-initiative.org/wiki/Open_Models

[130] T. Brown, J. Hörsch, and D. Schlachtberger, "PyPSA: Python for power system analysis," *J. Open Res. Softw.*, vol. 6, no. 1, p. 4, Jan. 2018, doi: 10.5334/jors.188.

[131] J. Hörsch, F. Hofmann, D. Schlachtberger, and T. Brown, "PyPSA-eur: An open optimisation model of the European transmission system," *Energy Strategy Rev.*, vol. 22, pp. 207–215, Nov. 2018, doi: 10.1016/j.esr.2018.08.012.

[132] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system," *Energy*, vol. 160, pp. 720–739, Oct. 2018, doi: 10.1016/j.energy.2018.06.222.

[133] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, "Early decarbonisation of the European energy system pays off," *Nature Commun.*, vol. 11, no. 1, p. 6223, Dec. 2020, doi: 10.1038/s41467-020-20015-4.

[134] M. Victoria, E. Zeyen, and T. Brown, "Speed of technological transformations required in Europe to achieve different climate goals," *Joule*, vol. 6, no. 5, pp. 1066–1086, May 2022, doi: 10.1016/j.joule.2022.04.016.

[135] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, "Classification and challenges of bottom-up energy system models—A review," *Renew. Sustain. Energy Rev.*, vol. 129, Sep. 2020, Art. no. 109917, doi: 10.1016/j.rser.2020.109917.

[136] D. Bogdanov, A. Toktarova, and C. Breyer, "Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan," *Appl. Energy*, vol. 253, Nov. 2019, Art. no. 113606, doi: 10.1016/j.apenergy.2019.113606.

[137] U. Caldera, D. Bogdanov, S. Afanasyeva, and C. Breyer, "Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia," *Water*, vol. 10, no. 3, Jan. 2018, Art. no. 3, doi: 10.3390/w10010003.

[138] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. de Souza Noel Simas Barbosa, and C. Breyer, "Radical transformation pathway towards sustainable electricity via evolutionary steps," *Nature Commun.*, vol. 10, no. 1, p. 1077, Dec. 2019, doi: 10.1038/s41467-019-08855-1.

[139] D. Bogdanov and C. Breyer, "North-east Asian super grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options," *Energy Convers. Manage.*, vol. 112, pp. 176–190, Mar. 2016, doi: 10.1016/j.enconman.2016.01.019.

[140] G. Pleßmann, M. Erdmann, M. Hlusiak, and C. Breyer, "Global energy storage demand for a 100% renewable electricity supply," *Energy Proc.*, vol. 46, pp. 22–31, Jan. 2014, doi: 10.1016/j.egypro.2014.01.154.

[141] M. Ram, D. Bogdanov, A. Aghahosseini, A. Gulagi, A. S. Oyewo, T. N. O. Mensah, M. Child, U. Caldera, K. Sadovskaia, L. D. S. N. S. Barbosa, M. Fasihi, S. Khalili, T. Traber, and C. Breyer, "Global energy transition to 100% renewables by 2050: Not fiction, but much needed impetus for developing economies to leapfrog into a sustainable future," *Energy*, vol. 246, May 2022, Art. no. 123419, doi: 10.1016/j.energy.2022.123419.

[142] A. Gulagi, D. Bogdanov, and C. Breyer, "The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India," *J. Energy Storage*, vol. 17, pp. 525–539, Jun. 2018, doi: 10.1016/j.est.2017.11.012.

[143] A. Gulagi, M. Ram, and C. Breyer, "Solar-wind complementarity with optimal storage and transmission in mitigating the monsoon effect in achieving a fully sustainable electricity system for India," in *Proc. 1st Int. Conf. LS Grid Integ RE India*, 2017. [Online]. Available: https://www.researchgate.net/publication/319516069.

[144] C. Breyer, D. Bogdanov, S. Khalili, and D. Keiner, "Solar photovoltaics in 100% renewable energy systems," *Encycl. Sustain. Sci. Technol.*, to be published, doi: 10.1007/978-1-4939-2493-6_1071-1.

[145] E. Pursiheimo, H. Holttinen, and T. Koljonen, "Inter-sectoral effects of high renewable energy share in global energy system," *Renew. Energy*, vol. 136, pp. 1119–1129, Jun. 2019, doi: 10.1016/j.renene.2018.09.082.

[146] G. Luderer, S. Madeddu, L. Merfort, F. Ueckerdt, M. Pehl, R. Pietzcker, M. Rottoli, F. Schreyer, N. Bauer, L. Baumstark, C. Bertram, A. Dirnaichner, F. Humpenöder, A. Levesque, A. Popp, R. Rodrigues, J. Strefler, and E. Kriegler, "Impact of declining renewable energy costs on electrification in low-emission scenarios," *Nature Energy*, vol. 7, no. 1, pp. 32–42, Jan. 2022, doi: 10.1038/s41560-021-00937-z.

[147] N. Helistö, J. Kiviluoma, H. Holttinen, J. D. Lara, and B. Hodge, "Including operational aspects in the planning of power systems with large amounts of variable generation: A review of modeling approaches," *WIREs Energy Environ.*, vol. 8, no. 5, pp. 1–34, Sep. 2019, doi: 10.1002/wene.341.

[148] [ESIG] Energy Systems Integration Group. (2021). *Transmission Planning for 100% Clean Electricity*. Reston. Accessed: Mar. 11. 2022. [Online]. Available: https://www.esig.energy/transmission-planning-for-100-clean-electricity

[149] J. Taouba, M. Uros, and G. Dominic. (2018). *Deliverable 3.3: New Options for Existing System Services and Needs for New System Services*. [Online]. Available: https://www.h2020-migrate.eu/_Resources/Persistent/5c5beff0d5bef78799253aae9b19f50a9cb6eb9f/D3.2-Localcontrolandsimulationtoolsforlargetransmissionsystems.pdf

[150] H. Holttinen, J. Kiviluoma, D. Flynn, J. C. Smith, A. Orths, P. B. Eriksen, N. Cutululis, L. Soder, M. Korpas, A. Estanqueiro, J. MacDowell, A. Tuohy, T. K. Vrana, and M. OaMalley, "System impact studies for near 100% renewable energy systems dominated by inverter based variable generation," *IEEE Trans. Power Syst.*, vol. 37, no. 4, pp. 3249–3258, Jul. 2022, doi: 10.1109/tpwrs.2020.3034924.

[151] M. N. J. Fischedick, O. Langniß, *Nach Dem Ausstieg*. Hirzel, Stuttgart: Zukunftskurs Erneuerbare Energien, 2000.

[152] *Ministries of Economic Affairs and Environment for the Federal Government*, Energiekonzept Für Eine Umweltschonende, Zuverlässige und Bezahlbare Energieversorgung, Ministries, Berlin, Germany, 2010.

[153] T. Pregger, J. Nitsch, and T. Naegler, "Long-term scenarios and strategies for the deployment of renewable energies in Germany," *Energy Policy*, vol. 59, pp. 350–360, Aug. 2013, doi: 10.1016/j.enpol.2013.03.049.

[154] J. Nitsch. (2012). *Long-Term Scenarios and Strategies for the Deployment of Renewable Energies in Germany in View of European and Global Developments Summary of the Final Report*. Berlin, Germany. [Online]. Available: https://elib.dlr.de/76044/

[155] A. Palzer and H.-M. Henning, "A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part II: Results," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 1019–1034, Feb. 2014, doi: 10.1016/j.rser.2013.11.032.

[156] J. Nitsch. (2016). *Die Energiewende Nach COP 21–Aktuelle Szenarien Der Deutschen Energieversorgung*. [Online]. Available: https://www.bee-ev.de/fileadmin/Publikationen/Studien/Joachim_Nitsch_Energiewende_nach_COP21_Langversion.pdf

[157] G. Hagedorn, "The concerns of the young protesters are justified: A statement by scientists for future concerning the protests for more climate protection," *GAIA Ecolog. Perspect. Sci. Soc.*, vol. 28, no. 2, pp. 79–87, Jan. 2019, doi: 10.14512/gaia.28.2.3.

[158] C. Gerhards, "Klimaverträgliche Energieversorgung Für deutschland 16 Orientierungspunkte," *Germany, Diskussionsbeiträge der Scientists Future*, vol. 7, p. 55, Apr. 2021, doi: 10.5281/zenodo.4409334.

[159] [UBA] German Environment Agency. (2019). *Resource-Eficient Pathways towards Greenhouse-Gas-Neutrality RESCUE Summary Report*. Berlin, Germany. [Online]. Available: https://www.umweltbundesamt.de/en/rescue

[160] G. Luderer, C. Kost, and D. Sörgel, *Deutschland Auf Dem Weg Zur Klimaneutralität 2045 Szenarien und Pfade im Modellvergleich (Ariadne-Report)*. Potsdam, Germany: PIK, 2021, doi: 10.48485/pik.2021.006.

[161] S. Simon, M. Xiao, C. Harpprecht, S. Sasanpour, H. Gardian, and T. Pregger, "A pathway for the German energy sector compatible with a 1.5 °C carbon budget," *Sustainability*, vol. 14, p. 1025, Jan. 2022, doi: 10.3390/su14021025.

[162] K. Hansen, B. V. Mathiesen, and I. R. Skov, "Full energy system transition towards 100% renewable energy in Germany in 2050," *Renew. Sustain. Energy Rev.*, vol. 102, pp. 1–13, Mar. 2019, doi: 10.1016/j.rser.2018.11.038.

[163] H. K. Bartholdsen, "Pathways for Germany's low-carbon energy transformation towards 2050," *Energies*, vol. 14, no. 15, p. 2988, 2019, doi: 10.3390/en12152988.

[164] T. Traber, F. S. Hegner, and H.-J. Fell, "An economically viable 100% renewable energy system for all energy sectors of Germany in 2030," *Energies*, vol. 14, no. 17, p. 5230, Aug. 2021, doi: 10.3390/en14175230.

[165] C. Breyer. (2013). *Vergleich Und Optimierung Von Zentral Und Dezentral Orientierten Ausbaupfaden Zu Einer Stromversorgung Aus Erneuerbaren Energien in Deutschland*. Reiner Lemoine Institut, Berlin, Germany. Accessed: Mar. 11, 2022. [Online]. Available: https://reiner-lemoine-institut.de/wp-content/publications/0_Vergleich_und_Optimierung_zentral_und_dezentral_071_100EE/Breyer2013.pdf

[166] S. Weitemeyer, D. Kleinhans, T. Vogt, and C. Agert, "Integration of renewable energy sources in future power systems: The role of storage," *Renew. Energy*, vol. 75, pp. 14–20, Mar. 2015, doi: 10.1016/j.renene.2014.09.028.

[167] [BMWi]–Bundesministerium Für Wirtschaft und Klimaschutz. (2022). *Entwurf eines Gesetzes zu Sofortmaßnahmen Für Einen Beschleunigten Ausbau der Erneuerbaren Energien Und Weiteren Maßnahmen im Stromsektor*. Berlin, Germany. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Downloads/E/referentenentwurf-erneuerbaren-energien-und-weiteren-massnahmen-im-stromsektor.pdf?__blob=publicationFile&v=6

[168] S. Khalili and C. Breyer, "Review on 100% renewable energy system analyses—A bibliometric perspective," 2022.

[169] G. Lopez, A. Aghahosseini, M. Child, S. Khalili, M. Fasihi, D. Bogdanov, and C. Breyer, "Impacts of model structure, framework, and flexibility on perspectives of 100% renewable energy transition decision-making," *Renew. Sustain. Energy Rev.*, vol. 164, Aug. 2022, Art. no. 112452, doi: 10.1016/j.rser.2022.112452.

[170] N. Duic and M. da Graça Carvalho, "Increasing renewable energy sources in island energy supply: Case study Porto Santo," *Renew. Sustain. Energy Rev.*, vol. 8, no. 4, pp. 383–399, Aug. 2004, doi: 10.1016/j.rser.2003.11.004.

[171] B. Ćosić, G. Krajacić, and N. Duić, "A 100% renewable energy system in the year 2050: The case of macedonia," *Energy*, vol. 48, no. 1, pp. 80–87, Dec. 2012, doi: 10.1016/j.energy.2012.06.078.

[172] A. Pfeifer, V. Dobravec, L. Pavlinek, G. Krajačić, and N. Duić, "Integration of renewable energy and demand response technologies in interconnected energy systems," *Energy*, vol. 161, pp. 447–455, Oct. 2018, doi: 10.1016/j.energy.2018.07.134.

[173] K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert, and C. von Hirschhausen, "Designing a model for the global energy system—GENeSYS-MOD: An application of the open-source energy modeling system (OSeMOSYS)," *Energies*, vol. 10, no. 10, p. 1468, Sep. 2017, doi: 10.3390/en10101468.

[174] T. Burandt, B. Xiong, K. Löffler, and P.-Y. Oei, "Decarbonizing China's energy system—Modeling the transformation of the electricity, transportation, heat, and industrial sectors," *Appl. Energy*, vol. 255, Dec. 2019, Art. no. 113820, doi: 10.1016/j.apenergy.2019.113820.

[175] G. Pleßmann and P. Blechinger, "How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050," *Energy Strategy Rev.*, vol. 15, pp. 19–32, Mar. 2017, doi: 10.1016/j.esr.2016.11.003.

[176] E. Kötter, L. Schneider, F. Sehnke, K. Ohnmeiss, and R. Schröer, "The future electric power system: Impact of power-to-gas by interacting with other renewable energy components," *J. Energy Storage*, vol. 5, pp. 113–119, Feb. 2016, doi: 10.1016/j.est.2015.11.012.

[177] F. Keck, M. Lenzen, A. Vassallo, and M. Li, "The impact of battery energy storage for renewable energy power grids in Australia," *Energy*, vol. 173, pp. 647–657, Apr. 2019, doi: 10.1016/j.energy.2019.02.053.

[178] M. Lenzen, B. McBain, T. Trainer, S. Jütte, O. Rey-Lescure, and J. Huang, "Simulating low-carbon electricity supply for Australia," *Appl. Energy*, vol. 179, pp. 553–564, Oct. 2016, doi: 10.1016/j.apenergy.2016.06.151.

[179] L. Reichenberg, F. Hedenus, M. Odenberger, and F. Johnsson, "The marginal system LCOE of variable renewables—Evaluating high penetration levels of wind and solar in Europe," *Energy*, vol. 152, pp. 914–924, Jun. 2018, doi: 10.1016/j.energy.2018.02.061.

[180] M. Taljegard, V. Walter, L. Göransson, M. Odenberger, and F. Johnsson, "Impact of electric vehicles on the cost-competitiveness of generation and storage technologies in the electricity system," *Environ. Res. Lett.*, vol. 14, no. 12, Dec. 2019, Art. no. 124087, doi: 10.1088/1748-9326/ab5e6b.

[181] O. Johanna, "The Impact of ERS on the electricity system—An energy system model comparison for Sweden and Germany," in *Proc. 3rd Electr. Road Syst. Conf. Frankfurt Am Main, Ger.*, 2019. [Online]. Available: https://electricroads.org/wp-content/uploads/ers-conference-2019/abstracts/S6_-_Olovsson_et_al_-_The_Impact_of_ERS_on_the_electricity_system_-_an_energy_system_model_comparison_for_S.pdf

[182] A. Blakers, B. Lu, and M. Stocks, "100% renewable electricity in Australia," *Energy*, vol. 133, pp. 471–482, Aug. 2017, doi: 10.1016/j.energy.2017.05.168.

[183] B. Lu, A. Blakers, and M. Stocks, "90–100% renewable electricity for the south west interconnected system of western Australia," *Energy*, vol. 122, pp. 663–674, Mar. 2017, doi: 10.1016/j.energy.2017.01.077.

[184] H. Lund, F. Arler, P. Østergaard, F. Hvelplund, D. Connolly, B. Mathiesen, and P. Karnøe, "Simulation versus optimisation: Theoretical positions in energy system modelling," *Energies*, vol. 10, no. 7, p. 840, Jun. 2017, doi: 10.3390/en10070840.

[185] A. Kätelhön, R. Meys, S. Deutz, S. Suh, and A. Bardow, "Climate change mitigation potential of carbon capture and utilization in the chemical industry," *Proc. Nat. Acad. Sci. USA*, vol. 116, no. 23, pp. 11187–11194, Jun. 2019, doi: 10.1073/pnas.1821029116.

[186] K.-K. Cao, F. Cebulla, J. J. Gómez Vilchez, B. Mousavi, and S. Prehofer, "Raising awareness in model-based energy scenario studies—A transparency checklist," *Energy, Sustainability Soc.*, vol. 6, no. 1, pp. 1–20, Dec. 2016, doi: 10.1186/s13705-016-0090-z.

[187] F. D. M. Parzan and L. Franken. (2022). *Global Socio-Economic and Environmental Data for PyPSA-Earth: An Open Optimisation Model of the Earth Energy System*. Accessed: Feb. 19, 2022. [Online]. Available: https://zenodo.org/record/5895010#.YhFIb-hBxPY

[188] S. Teske, T. Morris, and K. Nagrath, "100% Renewable energy for tanzania—Access to renewable and affordable energy for all within one generation. Report prepared by ISF for bread for the world," Inst. Sustain. Futures, Univ. Technol. Sydney, Ultimo, NSW, Australia, Tech. Rep., 2017.

[189] S. Teske, T. Morris, and K. Nagrath, *100% Renewable Energy for Bangladesh—Access to renewable energy for all within one generation. Report prepared by ISF for Coastal Development Partnership (CDP Bangladesh; Bread for the World*. Hamburg, Germany: World Future Council, 2019.

[190] S. Teske, T. Morris, and K. Nagrath, "100% renewable energy for Costa Rica. Report prepared by ISF for the world future council/Germany and the one earth foundation," Inst. Sustain. Futures, Univ. Technol. Sydney, Ultimo, NSW, Australia, Tech. Rep., 2020.

[191] S. Sgouridis, D. Csala, and U. Bardi, "The sower's way: Quantifying the narrowing net-energy pathways to a global energy transition," *Environ. Res. Lett.*, vol. 11, no. 9, Sep. 2016, Art. no. 094009, doi: 10.1088/1748-9326/11/9/094009.

[192] C. Breyer, D. Bogdanov, A. Gulagi, A. Aghahosseini, L. S. N. S. Barbosa, O. Koskinen, M. Barasa, U. Caldera, S. Afanasyeva, M. Child, J. Farfan, and P. Vainikka, "On the role of solar photovoltaics in global energy transition scenarios," *Prog. Photovolt., Res. Appl.*, vol. 25, no. 8, pp. 727–745, Aug. 2017, doi: 10.1002/pip.2885.

[193] Y. Y. Deng, K. Blok, and K. van der Leun, "Transition to a fully sustainable global energy system," *Energy Strategy Rev.*, vol. 1, no. 2, pp. 109–121, Sep. 2012, doi: 10.1016/j.esr.2012.07.003.

[194] S. Afanasyeva, D. Bogdanov, and C. Breyer, "Relevance of PV with single-axis tracking for energy scenarios," *Sol. Energy*, vol. 173, pp. 173–191, Oct. 2018, doi: 10.1016/j.solener.2018.07.029.

[195] M. Z. Jacobson, A.-K. von Krauland, S. J. Coughlin, F. C. Palmer, and M. M. Smith, "Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage," *Renew. Energy*, vol. 184, pp. 430–442, Jan. 2022, doi: 10.1016/j.renene.2021.11.067.

[196] [ITRPV] International Technology Roadmap for Photovoltaic. (2022). *International Technology Roadmap for Photovoltaic (ITRPV) Results 2021*. Frankfurt. [Online]. Available: https://www.vdma.org/international-technology-roadmap-photovoltaic

[197] E. Vartiainen, G. Masson, C. Breyer, D. Moser, and E. Román Medina, "Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity," *Prog. Photovolt., Res. Appl.*, vol. 28, no. 6, pp. 439–453, Jun. 2020, doi: 10.1002/pip.3189.

[198] FAOSTAT. (2021). *Food and Agriculture Organization of the United Nations FAOSTAT Land Use*. Rome. [Online]. Available: https://www.fao.org/faostat/en/#home

[199] R. E. A. Almond, M. Grooten, and T. Petersen, Eds., *Living Planet Report 2020 Bending the Curve of Biodiversity Loss*. Gland, Switzerland: World Wildlife Fund, WWF, 2020.

[200] [UN] United Nations. (2019). *World Population Prospects 2019, UN Department of Economic and Social Affairs*. [Online]. Available: https://population.un.org/wpp/

[201] A. Chaudhary, D. Gustafson, and A. Mathys, "Multi-indicator sustainability assessment of global food systems," *Nature Commun.*, vol. 9, no. 1, p. 848, Dec. 2018, doi: 10.1038/s41467-018-03308-7.

[202] M. Springmann, "Options for keeping the food system within environmental limits," *Nature*, vol. 562, no. 7728, pp. 519–525, Oct. 2018, doi: 10.1038/s41586-018-0594-0.

[203] K.-H. Erb, C. Lauk, T. Kastner, A. Mayer, M. C. Theurl, and H. Haberl, "Exploring the biophysical option space for feeding the world without deforestation," *Nature Commun.*, vol. 7, no. 1, Sep. 2016, Art. no. 11382, doi: 10.1038/ncomms11382.

[204] F. Creutzig, "Bioenergy and climate change mitigation: An assessment," *GCB Bioenergy*, vol. 7, no. 5, pp. 916–944, Sep. 2015, doi: 10.1111/gcbb.12205.

[205] T. N. O. Mensah, A. S. Oyewo, and C. Breyer, "The role of biomass in sub-Saharan Africa's fully renewable power sector—The case of Ghana," *Renew. Energy*, vol. 173, pp. 297–317, Aug. 2021, doi: 10.1016/j.renene.2021.03.098.

[206] T. Mensah, A. Oyewo, D. Bogdanov, A. Aghahosseini, and C. Breyer, "Pathway for a fully renewable power sector of Africa by 2050: Emphasising on flexible generation from biomass," 2022.

[207] K. M. Kennedy, T. H. Ruggles, K. Rinaldi, J. A. Dowling, L. Duan, K. Caldeira, and N. S. Lewis, "The role of concentrated solar power with thermal energy storage in least-cost highly reliable electricity systems fully powered by variable renewable energy," *Adv. Appl. Energy*, vol. 6, Jun. 2022, Art. no. 100091, doi: 10.1016/j.adapen.2022.100091.

[208] D. E. H. J. Gernaat, P. W. Bogaart, D. P. V. Vuuren, H. Biemans, and R. Niessink, "High-resolution assessment of global technical and economic hydropower potential," *Nature Energy*, vol. 2, no. 10, pp. 821–828, Oct. 2017, doi: 10.1038/s41560-017-0006-y.

[209] [IEA] International Energy Agency. (2021). *World Energy Outlook 2021*. Paris, France. [Online]. Available: www.iea.org/weo

[210] N. V. Emodi, T. Chaiechi, and A. B. M. R. A. Beg, "The impact of climate variability and change on the energy system: A systematic scoping review," *Sci. Total Environ.*, vol. 676, pp. 545–563, Aug. 2019, doi: 10.1016/j.scitotenv.2019.04.294.

[211] X. Lu, S. Chen, C. P. Nielsen, C. Zhang, J. Li, H. Xu, Y. Wu, S. Wang, F. Song, C. Wei, K. He, M. B. McElroy, and J. Hao, "Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system," *Proc. Nat. Acad. Sci. USA*, vol. 118, no. 42, Oct. 2021, doi: 10.1073/pnas.2103471118.

[212] C. Breyer, "Low-cost solar power enables a sustainable energy industry system," *Proc. Nat. Acad. Sci. USA*, vol. 118, no. 49, pp. 49–51, Dec. 2021, doi: 10.1073/pnas.2116940118.

[213] A. Gulagi, M. Ram, D. Bogdanov, S. Sarin, T. Mensah, and C. Breyer, "Assessing the role of renewables for rapid transitioning of the power sector across states in India," *Nature Commun.*, to be published.

[214] A. S. Oyewo, A. A. Solomon, D. Bogdanov, A. Aghahosseini, T. N. O. Mensah, M. Ram, and C. Breyer, "Just transition towards defossilised energy systems for developing economies: A case study of Ethiopia," *Renew. Energy*, vol. 176, pp. 346–365, Oct. 2021, doi: 10.1016/j.renene.2021.05.029.

[215] A. Oyewo, D. Bogdanov, A. Aghahosseini, T. Mensah, and C. Breyer, *Contextualizing the Scope, Scale, and Speed of Energy Pathways Toward Sustainable Development in Africa*. Cambridge, MA, USA: iScience, 2022.

[216] J. C. Osorio-Aravena, A. Aghahosseini, D. Bogdanov, U. Caldera, N. Ghorbani, T. N. O. Mensah, S. Khalili, E. Muñoz-Cerón, and C. Breyer, "The impact of renewable energy and sector coupling on the pathway towards a sustainable energy system in Chile," *Renew. Sustain. Energy Rev.*, vol. 151, Nov. 2021, Art. no. 111557, doi: 10.1016/j.rser.2021.111557.

[217] T. Galimova, M. Ram, and C. Breyer, "Mitigation of air pollution during the global energy transition towards 100% renewable energy systems by 2050," 2022.

[218] A. Lohrmann, J. Farfan, U. Caldera, C. Lohrmann, and C. Breyer, "Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery," *Nature Energy*, vol. 4, no. 12, pp. 1040–1048, Dec. 2019, doi: 10.1038/s41560-019-0501-4.

[219] M. Ram, J. C. Osorio-Aravena, A. Aghahosseini, D. Bogdanov, and C. Breyer, "Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050," *Energy*, vol. 238, Jan. 2022, Art. no. 121690, doi: 10.1016/j.energy.2021.121690.

[220] A. Azzuni and C. Breyer, "Global energy security index and its application on national level," *Energies*, vol. 13, no. 10, p. 2502, May 2020, doi: 10.3390/en13102502.

[221] T. Junne, N. Wulff, C. Breyer, and T. Naegler, "Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt," *Energy*, vol. 211, Nov. 2020, Art. no. 118532, doi: 10.1016/j.energy.2020.118532.

[222] E. White and G. J. Kramer, "The changing meaning of energy return on investment and the implications for the prospects of post-fossil civilization," *One Earth*, vol. 1, no. 4, pp. 416–422, Dec. 2019, doi: 10.1016/j.oneear.2019.11.010.

[223] A. Krumm, D. Süsser, and P. Blechinger, "Modelling social aspects of the energy transition: What is the current representation of social factors in energy models?" *Energy*, vol. 239, Jan. 2022, Art. no. 121706, doi: 10.1016/j.energy.2021.121706.

[224] [IRENA] International Renewable Energy Agency. (2016). *Renewable Energy Benefits: Measuring the Economics*. Abu Dhabi. [Online]. Available: www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Measuring-the-Economics_2016.pdf

[225] C. T. M. Clack, "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 26, pp. 6722–6727, Jun. 2017, doi: 10.1073/pnas.1610381114.

[226] T. Trainer, "Some problems in storing renewable energy," *Energy Policy*, vol. 110, pp. 386–393, Nov. 2017, doi: 10.1016/j.enpol.2017.07.061.

[227] B. P. Heard, B. W. Brook, T. M. L. Wigley, and C. J. A. Bradshaw, "Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 1122–1133, Sep. 2017, doi: 10.1016/j.rser.2017.03.114.

[228] J. D. Jenkins, M. Luke, and S. Thernstrom, "Getting to zero carbon emissions in the electric power sector," *Joule*, vol. 2, no. 12, pp. 2498–2510, Dec. 2018, doi: 10.1016/j.joule.2018.11.013.

[229] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, and B. A. Frew, "Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes," *Proc. Nat. Acad. Sci. USA*, vol. 112, no. 49, pp. 15060–15065, Dec. 2015, doi: 10.1073/pnas.1510028112.

[230] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, and B. A. Frew, "The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 26, pp. 5021–5023, Jun. 2017, doi: 10.1073/pnas.1708069114.

[231] A. Aghahosseini, D. Bogdanov, and C. Breyer, "A techno-economic study of an entirely renewable energy-based power supply for north America for 2030 conditions," *Energies*, vol. 10, no. 8, p. 1171, Aug. 2017, doi: 10.3390/en10081171.

[232] A. Aghahosseini, D. Bogdanov, L. S. N. S. Barbosa, and C. Breyer, "Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030," *Renew. Sustain. Energy Rev.*, vol. 105, pp. 187–205, May 2019, doi: 10.1016/j.rser.2019.01.046.

[233] T. W. Brown, T. Bischof-Niemz, K. Blok, C. Breyer, H. Lund, and B. V. Mathiesen, "Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems,'" *Renew. Sustain. Energy Rev.*, vol. 92, pp. 834–847, Sep. 2018, doi: 10.1016/j.rser.2018.04.113.

[234] M. Diesendorf and B. Elliston, "The feasibility of 100% renewable electricity systems: A response to critics," *Renew. Sustain. Energy Rev.*, vol. 93, pp. 318–330, Oct. 2018, doi: 10.1016/j.rser.2018.05.042.

[235] M. Ram, M. Child, A. Aghahosseini, D. Bogdanov, A. Lohrmann, and C. Breyer, "A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015–2030," *J. Cleaner Prod.*, vol. 199, pp. 687–704, Oct. 2018, doi: 10.1016/j.jclepro.2018.07.159.

[236] M. Seibert and W. Rees, "Through the eye of a needle: An eco-heterodox perspective on the renewable energy transition," *Energies*, vol. 14, no. 15, p. 4508, Jul. 2021, doi: 10.3390/en14154508.

[237] M. Diesendorf, "Comment on Seibert, M.K.; Rees, W.E. through the eye of a needle: An eco-heterodox perspective on the renewable energy transition. Energies 2021, 14, 4508," *Energies*, vol. 15, no. 3, p. 964, Jan. 2022, doi: 10.3390/en15030964.

[238] M. Diesendorf, "Comment on Seibert, M.K.; Rees, W.E. through the eye of a needle: An eco-heterodox perspective on the renewable energy transition. Energies 2021, 14, 4508," *Energies*, vol. 15, no. 3, p. 964, Jan. 2022, doi: 10.3390/en15030964.

[239] T. Trainer, "Estimating the EROI of whole systems for 100% renewable electricity supply capable of dealing with intermittency," *Energy Policy*, vol. 119, pp. 648–653, Aug. 2018, doi: 10.1016/j.enpol.2018.04.045.

[240] F. Ferroni and R. J. Hopkirk, "Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation," *Energy Policy*, vol. 94, pp. 336–344, Jul. 2016, doi: 10.1016/j.enpol.2016.03.034.

[241] P. Moriarty and D. Honnery, "Feasibility of a 100% global renewable energy system," *Energies*, vol. 13, no. 21, p. 5543, Oct. 2020.

[242] N. Georgescu-Roegen, *The Entropy Law and the Economic Process*. Cambridge, U.K.: Harvard Univ Press, 1971.

[243] R. Ayres, "Comments on Georgescu–Roegen," *Ecol. Econ.*, vol. 22, no. 3, pp. 285–287, 1997, doi: 10.1016/S0921-8009(97)00082-7.

[244] R. U. Ayres, "Eco-thermodynamics: Economics and the second law," *Ecol. Econ.*, vol. 26, no. 2, pp. 189–209, 1998, doi: 10.1016/S0921-8009(97)00101-8.

[245] G. Hammond and A. Winnett, "The influence of thermodynamic ideas on ecological economics: An interdisciplinary critique," *Sustainability*, vol. 1, no. 4, pp. 1195–1225, Dec. 2009, doi: 10.3390/su1041195.

[246] C. Kerschner, "Economic de-growth vs. steady-state economy," *J. Cleaner Prod.*, vol. 18, no. 6, pp. 544–551, Apr. 2010, doi: 10.1016/j.jclepro.2009.10.019.

[247] C. Levallois, "Can de-growth be considered a policy option? A historical note on Nicholas Georgescu–Roegen and the club of Rome," *Ecolog. Econ.*, vol. 69, no. 11, pp. 2271–2278, Sep. 2010, doi: 10.1016/j.ecolecon.2010.06.020.

[248] C. Hall, M. Lavine, and J. Sloane, "Efficiency of energy delivery systems: I. An economic and energy analysis," *Environ. Manage.*, vol. 3, no. 6, pp. 493–504, Nov. 1979, doi: 10.1007/BF01866318.

[249] C. J. Cleveland, "Energy quality and energy surplus in the extraction of fossil fuels in the U.S.," *Ecol. Econ.*, vol. 6, no. 2, pp. 139–162, 1992, doi: 10.1016/0921-8009(92)90010-P.

[250] A. R. Brandt, "Oil depletion and the energy efficiency of oil production: The case of California," *Sustainability*, vol. 3, no. 10, pp. 1833–1854, Oct. 2011, doi: 10.3390/su3101833.

[251] L. Delannoy, P.-Y. Longaretti, D. J. Murphy, and E. Prados, "Peak oil and the low-carbon energy transition: A net-energy perspective," *Appl. Energy*, vol. 304, Dec. 2021, Art. no. 117843, doi: 10.1016/j.apenergy.2021.117843.

[252] L. Delannoy, P.-Y. Longaretti, D. J. Murphy, and E. Prados, "Assessing global long-term EROI of gas: A net-energy perspective on the energy transition," *Energies*, vol. 14, no. 16, p. 5112, Aug. 2021, doi: 10.3390/en14165112.

[253] N. Gagnon, C. Hall, and L. Brinker, "A preliminary investigation of energy return on energy investment for global oil and gas production," *Energies*, vol. 2, no. 3, pp. 490–503, Jul. 2009, doi: 10.3390/en20300490.

[254] J. S. Lansing, A. Lavacchi, and U. Bardi, "The role of energy return on energy invested (EROEI) in complex adaptive systems," *Annu. Rev. Anthropol.*, vol. 32, pp. 183–204, Dec. 2003, doi: 10.1146/annurev.anthro.32.061002.093440.

[255] P. E. Brockway, A. Owen, L. I. Brand-Correa, and L. Hardt, "Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources," *Nature Energy*, vol. 4, no. 7, pp. 612–621, Jul. 2019, doi: 10.1038/s41560-019-0425-z.

[256] M. Raugei, S. Sgouridis, D. Murphy, V. Fthenakis, R. Frischknecht, C. Breyer, U. Bardi, C. Barnhart, A. Buckley, M. Carbajales-Dale, and D. Csala, "Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response," *Energy Policy*, vol. 102, pp. 377–384, Mar. 2017, doi: 10.1016/j.enpol.2016.12.042.

[257] M. Diesendorf and T. Wiedmann, "Implications of trends in energy return on energy invested (EROI) for transitioning to renewable electricity," *Ecolog. Econ.*, vol. 176, Oct. 2020, Art. no. 106726, doi: 10.1016/j.ecolecon.2020.106726.

[258] D. Murphy, M. Carbajales-Dale, and D. Moeller, "Comparing apples to apples: Why the net energy analysis community needs to adopt the life-cycle analysis framework," *Energies*, vol. 9, no. 11, p. 917, Nov. 2016, doi: 10.3390/en9110917.

[259] A. Solomon, N. B. Manjong, and C. Breyer, "The necessity to standardize primary energy quality in achieving a meaningful quantification of related indicators," 2022.

[260] M. Raugei, "Net energy analysis must not compare apples and oranges," *Nature Energy*, vol. 4, no. 2, pp. 86–88, Feb. 2019, doi: 10.1038/s41560-019-0327-0.

[261] P. Parthasarathy and S. K. Narayanan, "Energy learning curves of PV systems," *Environ. Prog. Sustain. Energy*, vol. 33, no. 3, pp. 676–680, 2014, doi: 10.1002/ep.

[262] M. Carbajales-Dale, M. Raugei, V. Fthenakis, and C. Barnhart, "Energy return on investment (EROI) of solar PV: An attempt at reconciliation [point of view]," *Proc. IEEE*, vol. 103, no. 7, pp. 995–999, Jul. 2015, doi: 10.1109/JPROC.2015.2438471.

[263] G. Palmer and J. Floyd, "An exploration of divergence in EPBT and EROI for solar photovoltaics," *BioPhys. Econ. Resource Qual.*, vol. 2, no. 4, pp. 1–20, Dec. 2017, doi: 10.1007/s41247-017-0033-0.

[264] M. J. (Mariska) de Wild-Scholten, "Energy payback time and carbon footprint of commercial photovoltaic systems," *Sol. Energy Mater. Sol. Cells*, vol. 119, pp. 296–305, Dec. 2013, doi: 10.1016/j.solmat.2013.08.037.

[265] S. A. Mann, M. J. de Wild-Scholten, V. M. Fthenakis, W. G. van Sark, and W. C. Sinke, "The energy payback time of advanced crystalline silicon PV modules in 2020: A prospective study," *Prog. Photovolt. Res. Appl.*, vol. 20, no. 1, pp. 6–11, 2015, doi: 10.1002/pip.

[266] V. Fthenakis and E. Leccisi, "Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends," *Prog. Photovolt., Res. Appl.*, vol. 29, no. 10, pp. 1068–1077, Oct. 2021, doi: 10.1002/pip.3441.

[267] I. M. Peters, J. Hauch, C. Brabec, and P. Sinha, "The value of stability in photovoltaics," *Joule*, vol. 5, no. 12, pp. 3137–3153, 2021, doi: 10.1016/j.joule.2021.10.019.

[268] [US DoE] United States Department of Energy. (2021). *Funding Opportunity Announcement: Solar Energy Technologies Office Fical Year 2021 Photovoltaics and Concentrating Solar-Thermal Power Funding Program*. Accessed: Feb. 19, 2022. [Online]. Available: https://www.energy.gov/eere/solar/funding-opportunity-announcement-solar-energy-technologies-office-fiscal-year-2021-0

[269] I. Kubiszewski, C. J. Cleveland, and P. K. Endres, "Meta-analysis of net energy return for wind power systems," *Renew. Energy*, vol. 35, no. 1, pp. 218–225, Jan. 2010, doi: 10.1016/j.renene.2009.01.012.

[270] M. Raugei, A. Peluso, E. Leccisi, and V. Fthenakis, "Life-cycle carbon emissions and energy return on investment for 80% domestic renewable electricity with battery storage in California (U.S.A.)," *Energies*, vol. 13, no. 15, p. 3934, 2020, doi: 10.3390/en13153934.

[271] T. G. Walmsley, M. R. W. Walmsley, and M. J. Atkins, "Energy return on energy and carbon investment of wind energy farms: A case study of New Zealand," *J. Cleaner Prod.*, vol. 167, pp. 885–895, Nov. 2017, doi: 10.1016/j.jclepro.2017.08.040.

[272] I. Capellán-Pérez, C. de Castro, and L. J. M. González, "Dynamic energy return on energy investment (EROI) and material requirements in scenarios of global transition to renewable energies," *Energy Strategy Rev.*, vol. 26, Nov. 2019, Art. no. 100399, doi: 10.1016/j.esr.2019.100399.

[273] J. M. Pearce, *Limitations of Greenhouse Gas Mitigation Technologies Set by Rapid Growth and Energy Cannibalism*. Kingston, ON, Canada: Queen Univ., 2008.

[274] U. Bardi and S. Sgouridis, "In support of a physics-based energy transition planning: Sowing our future energy needs," *BioPhys. Econ. Resource Qual.*, vol. 2, no. 4, pp. 1–5, Dec. 2017, doi: 10.1007/s41247-017-0031-2.

[275] M. R. Shaner, S. J. Davis, N. S. Lewis, and K. Caldeira, "Geophysical constraints on the reliability of solar and wind power in the United States," *Energy Environ. Sci.*, vol. 11, no. 4, pp. 914–925, 2018, doi: 10.1039/c7ee03029k.

[276] M. Yuan, F. Tong, L. Duan, J. A. Dowling, S. J. Davis, N. S. Lewis, and K. Caldeira, "Would firm generators facilitate or deter variable renewable energy in a carbon-free electricity system?" *Appl. Energy*, vol. 279, Dec. 2020, Art. no. 115789, doi: 10.1016/j.apenergy.2020.115789.

[277] M. Victoria, N. Haegel, I. M. Peters, R. Sinton, A. Jäger-Waldau, C. del Cañizo, C. Breyer, M. Stocks, A. Blakers, I. Kaizuka, K. Komoto, and A. Smets, "Solar photovoltaics is ready to power a sustainable future," *Joule*, vol. 5, no. 5, pp. 1041–1056, May 2021.

[278] M. Child, C. Kemfert, D. Bogdanov, and C. Breyer, "Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe," *Renew. Energy*, vol. 139, pp. 80–101, Aug. 2019, doi: 10.1016/j.renene.2019.02.077.

[279] H. C. Gils, "Economic potential for future demand response in Germany—Modeling approach and case study," *Appl. Energy*, vol. 162, pp. 401–415, Jan. 2016, doi: 10.1016/j.apenergy.2015.10.083.

[280] L. Juuso, N. Rami, and L. P. D., "Effectiveness of smart charging of electric vehicles under power limitations," *Arch. Thermodyn.*, vol. 33, no. 4, pp. 23–40, 2013, doi: vol. 38.pp. 404–414.

[281] M. Child, A. Nordling, and C. Breyer, "The impacts of high V2G participation in a 100% renewable Åland energy system," *Energies*, vol. 11, no. 9, p. 2206, Aug. 2018, doi: 10.3390/en11092206.

[282] T. Boström, B. Babar, J. B. Hansen, and C. Good, "The pure PV-EV energy system—A conceptual study of a nationwide energy system based solely on photovoltaics and electric vehicles," *Smart Energy*, vol. 1, Feb. 2021, Art. no. 100001, doi: 10.1016/j.segy.2021.100001.

[283] H. Qazi. (2020). *Technical Shortfalls for Pan European Power System With High Levels of Renewable Generation*. Accessed: Feb. 19, 2022. [Online]. Available: https://eu-sysflex.com/documents/

[284] ENTSO-E. (2019). *High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters*. Brussels, Belgium. [Online]. Available: https://euagenda.eu/upload/publications/untitled-292051-ea.pdf

[285] [ESIG] Energy Systems Integration Group. (2019). *Toward 100% Renewable Energy Pathways: Key Research Needs*. Accessed: Mar. 8, 2022. [Online]. Available: https://www.esig.energy/resources/toward-100-renewable-energy-pathways-key-research-needs/

[286] Global PST Consortium. (2021). *Inaugural Research Agenda*. California. [Online]. Available: https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf

[287] B. S. Hodge, H. Jain, C. Brancucci, G. Seo, M. Korpås, J. Kiviluoma, H. Holttinen, J. C. Smith, A. Orths, A. Estanqueiro, L. Söder, D. Flynn, T. K. Vrana, R. W. Kenyon, and B. Kroposki, "Addressing technical challenges in 100% variable inverter-based renewable energy power systems," *WIREs Energy Environ.*, vol. 9, no. 5, pp. 1–19, Sep. 2020, doi: 10.1002/wene.376.

[288] H. Holttinen, A. Groom, E. Kennedy, D. Woodfin, L. Barroso, A. Orths, K. Ogimoto, C. Wang, R. Moreno, K. Parks, and T. Ackermann, "Variable renewable energy integration: Status around the world," *IEEE Power Energy Mag.*, vol. 19, no. 6, pp. 86–96, Nov. 2021, doi: 10.1109/MPE.2021.3104156.

[289] X. Zhao and D. Flynn, "Stability enhancement strategies for a 100% grid-forming and grid-following converter-based Irish power system," *IET Renew. Power Gener.*, vol. 16, no. 1, pp. 125–138, Jan. 2022, doi: 10.1049/rpg2.12346.

[290] X. Zhao, P. G. Thakurta, and D. Flynn, "Grid-forming requirements based on stability assessment for 100% converter-based Irish power system," *IET Renew. Power Gener.*, vol. 16, no. 3, pp. 447–458, Feb. 2022, doi: 10.1049/rpg2.12340.

[291] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge, and B. Hannegan, "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 61–73, Mar. 2017.

[292] P. Denholm, D. J. Arent, S. F. Baldwin, D. E. Bilello, G. L. Brinkman, J. M. Cochran, W. J. Cole, B. Frew, V. Gevorgian, J. Heeter, B.-M.-S. Hodge, B. Kroposki, T. Mai, M. J. O'Malley, B. Palmintier, D. Steinberg, and Y. Zhang, "The challenges of achieving a 100% renewable electricity system in the United States," *Joule*, vol. 5, no. 6, pp. 1331–1352, Jun. 2021, doi: 10.1016/j.joule.2021.03.028.

[293] W. J. Cole, D. Greer, P. Denholm, A. W. Frazier, S. Machen, T. Mai, N. Vincent, and S. F. Baldwin, "Quantifying the challenge of reaching a 100% renewable energy power system for the United States," *Joule*, vol. 5, no. 7, pp. 1732–1748, Jul. 2021, doi: 10.1016/j.joule.2021.05.011.

[294] M. Xiao, T. Junne, J. Haas, and M. Klein, "Plummeting costs of renewables—Are energy scenarios lagging?" *Energy Strategy Rev.*, vol. 35, May 2021, Art. no. 100636, doi: 10.1016/j.esr.2021.100636.

[295] F. Creutzig, P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet, and R. C. Pietzcker, "The underestimated potential of solar energy to mitigate climate change," *Nature Energy*, vol. 2, no. 9, pp. 1–9, Sep. 2017, doi: 10.1038/nenergy.2017.140.

[296] M. Jaxa-Rozen and E. Trutnevyte, "Sources of uncertainty in long-term global scenarios of solar photovoltaic technology," *Nature Climate Change*, vol. 11, no. 3, pp. 266–273, Mar. 2021, doi: 10.1038/s41558-021-00998-8.

[297] M. Grubb, C. Wieners, and P. Yang, "Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation," *WIREs Climate Change*, vol. 12, no. 3, pp. 1–26, May 2021, doi: 10.1002/wcc.698.

[298] V. Krey, "Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models," *Energy*, vol. 172, pp. 1254–1267, Apr. 2019, doi: 10.1016/j.energy.2018.12.131.

[299] J. Eom, J. Edmonds, V. Krey, N. Johnson, T. Longden, G. Luderer, K. Riahi, and D. P. Van Vuuren, "The impact of near-term climate policy choices on technology and emission transition pathways," *Technolog. Forecasting Social Change*, vol. 90, pp. 73–88, Jan. 2015, doi: 10.1016/j.techfore.2013.09.017.

[300] V. Lundaev, A. A. Solomon, T. Le, A. Lohrmann, and C. Breyer, "Review of critical materials for the energy transition, an analysis of global resources and production databases and the state of material circularity," 2022.

[301] C. Xu, Q. Dai, L. Gaines, M. Hu, A. Tukker, and B. Steubing, "Future material demand for automotive lithium-based batteries," *Commun. Mater.*, vol. 1, no. 1, pp. 1–10, Dec. 2020, doi: 10.1038/s43246-020-00095-x.

[302] [IEA] International Energy Agency. (2021). *The Role of Critical Minerals in Clean Energy Transitions*. Paris, France. [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[303] P. Greim, A. A. Solomon, and C. Breyer, "Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation," *Nature Commun.*, vol. 11, p. 4570, Sep. 2020, doi: 10.1038/s41467-020-18402-y.

[304] U. Bardi, "Extracting minerals from seawater: An energy analysis," *Sustainability*, vol. 2, no. 4, pp. 980–992, Apr. 2010, doi: 10.3390/su2040980.

[305] Z. Li, C. Li, X. Liu, L. Cao, P. Li, R. Wei, X. Li, D. Guo, K.-W. Huang, and Z. Lai, "Continuous electrical pumping membrane process for seawater lithium mining," *Energy Environ. Sci.*, vol. 14, no. 5, pp. 3152–3159, May 2021, doi: 10.1039/d1ee00354b.

[306] H. Zhang, Y. Ren, X. Wu, and N. Wang, "An interface-modified solid-state electrochemical device for lithium extraction from seawater," *J. Power Sources*, vol. 482, Jan. 2021, Art. no. 228938, doi: 10.1016/j.jpowsour.2020.228938.

[307] C. Liu, Y. Li, D. Lin, P.-C. Hsu, B. Liu, G. Yan, T. Wu, Y. Cui, and S. Chu, "Lithium extraction from seawater through pulsed electrochemical intercalation," *Joule*, vol. 4, no. 7, pp. 1459–1469, Jul. 2020, doi: 10.1016/j.joule.2020.05.017.

[308] L. Tang, S. Huang, Y. Wang, D. Liang, Y. Li, J. Li, Y. Wang, Y. Xie, and W. Wang, "Highly efficient, stable, and recyclable hydrogen manganese oxide/cellulose film for the extraction of lithium from seawater," *ACS Appl. Mater. Interface*, vol. 12, no. 8, pp. 9775–9781, Feb. 2020, doi: 10.1021/acsami.9b21612.

[309] V. Lundaev, A. A. Solomon, U. Caldera, and C. Breyer, "Material extraction potential of desalination brines: A technical and economic evaluation of brines as a possible new material source," *Minerals Eng.*, vol. 185, Jul. 2022, Art. no. 107652, doi: 10.1016/j.mineng.2022.107652.

[310] Y.-S. Hu and Y. Li, "Unlocking sustainable Na-ion batteries into industry," *ACS Energy Lett.*, vol. 6, no. 11, pp. 4115–4117, Nov. 2021, doi: 10.1021/acsenergylett.1c02292.

[311] S. W. D. Gourley, T. Or, and Z. Chen, "Breaking free from cobalt reliance in lithium-ion batteries," *iScience*, vol. 23, no. 9, Sep. 2020, Art. no. 101505, doi: 10.1016/j.isci.2020.101505.

[312] Reuters. (2020). *Exclusive: Tesla in Talks to Use CATL's Cobalt-Free Batteries in China-Made Cars Sources*. [Online]. Available: https://www.reuters.com/article/us-tesla-china-electric-exclusive-idUSKBN20C0RP.

[313] T. Grelle, C. Schmülling, and P. Zimmerschied, "Magnet-free HV traction drives with contactless power transmission," *MTZ Worldwide*, vol. 82, no. 4, pp. 28–33, Apr. 2021, doi: 10.1007/s38313-021-0623-5.

[314] M. Moats, L. Alagha, and K. Awuah-Offei, "Towards resilient and sustainable supply of critical elements from the copper supply chain: A review," *J. Cleaner Prod.*, vol. 307, Jul. 2021, Art. no. 127207, doi: 10.1016/j.jclepro.2021.127207.

[315] [NREL] National Renewable Energy Laboratory. (2013). *The Present, Mid-Term, and Long-Term Supply Curves for Tellurium; and Updates in the Results From NREL's CdTe PV Module Manufacturing Cost Model*. NREL/PR-6A20-60430. Accessed: Nov. 4, 2021. [Online]. Available: https://www.nrel.gov/docs/fy13osti/60430.pdf

[316] CIGS-PV Copper Indium Gallium Selenide Solar Cell PV. (2021). *CIGS Thin Film Photovoltaics for EU's Prosperity, Energy Transition and Enabling Net Zero Emission Targets*. Accessed: Apr. 11, 2022. [Online]. Available: https://cigs-pv.net/wortpresse/wp-content/uploads/2021/07/Indium_Availability_for_CIGS_thin-film_solar_cells_in_Europe.pdf

[317] V. Fthenakis, ''Sustainability metrics for extending thin-film photovoltaics to terawatt levels,'' *MRS Bull.*, vol. 37, no. 4, pp. 425–430, Apr. 2012, doi: 10.1557/mrs.2012.50.

[318] Fraunhofer Institute for Solar Energy Systems. (2022). *Photovoltaics Report*. Fraunhofer. [Online]. Available: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

[319] P. J. Verlinden, ''Future challenges for photovoltaic manufacturing at the terawatt level,'' *J. Renew. Sustain. Energy*, vol. 12, no. 5, Sep. 2020, Art. no. 053505, doi: 10.1063/5.0020380.

[320] L. Grandell, A. Lehtilä, M. Kivinen, T. Koljonen, S. Kihlman, and L. S. Lauri, ''Role of critical metals in the future markets of clean energy technologies,'' *Renew. Energy*, vol. 95, pp. 53–62, Sep. 2016, doi: 10.1016/j.renene.2016.03.102.

[321] P. P. Altermatt, Y. Chen, Y. Yang, and Z. Feng, ''Riding the workhorse of the industry: PERC,'' *Photovolt. Int.*, vol. 41, pp. 54–64, Jan. 2018. [Online]. Available: https://www.pv-tech.org/technical-papers/riding-the-workhorse-of-the-industry-perc

[322] H. U. Sverdrup, A. H. Olafsdottir, and K. V. Ragnarsdottir, ''On the long-term sustainability of copper, zinc and lead supply, using a system dynamics model,'' *Resour., Conservation Recycling, X*, vol. 4, Dec. 2019, Art. no. 100007, doi: 10.1016/j.rcrx.2019.100007.

[323] G. G. O. Vidal, Z. Rostom, and C. Francois, ''Prey—Predator long-term modeling of copper reserves, production, recycling, price, and cost of production,'' *Environ. Sci. Technol.*, vol. 53, pp. 11323–11336, Aug. 2019.

[324] A. Elshkaki, T. E. Graedel, L. Ciacci, and B. K. Reck, ''Copper demand, supply, and associated energy use to 2050,'' *Global Environ. Change*, vol. 39, pp. 305–315, Jul. 2016, doi: 10.1016/j.gloenvcha.2016.06.006.

[325] R. Kleijn and E. van der Voet, ''Resource constraints in a hydrogen economy based on renewable energy sources: An exploration,'' *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 2784–2795, Dec. 2010, doi: 10.1016/j.rser.2010.07.066.

[326] [UNEP] United Nations Environment Programme. (2020). *Mineral Resource Governance in the 21st Century Gearing Extractive Industries Towards Sustainable Development*. Paris, France. [Online]. Available: www.resourcepanel.org/reports/mineral-resource-governance-21st-century

[327] J. R. J. Goddin, ''The role of a circular economy for energy transition,'' *Mater. Basis Energy Transitions*, to be published, doi: 10.1016/B978-0-12-819534-5.00012-X.

[328] D. Mulvaney, R. M. Richards, M. D. Bazilian, E. Hensley, G. Clough, and S. Sridhar, ''Progress towards a circular economy in materials to decarbonize electricity and mobility,'' *Renew. Sustain. Energy Rev.*, vol. 137, Mar. 2021, Art. no. 110604, doi: 10.1016/j.rser.2020.110604.

[329] B. K. Sovacool, ''Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation,'' *Energy Res. Social Sci.*, vol. 73, Mar. 2021, Art. no. 101916, doi: 10.1016/j.erss.2021.101916.

[330] J. Burger and M. Gochfeld, ''A conceptual framework evaluating ecological footprints and monitoring renewable energy: Wind, solar, hydro, and geothermal,'' *Energy Power Eng.*, vol. 4, no. 4, pp. 303–314, 2012, doi: 10.4236/epe.2012.44040.

[331] B. K. Sovacool, J. Kim, and M. Yang, ''The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities,'' *Energy Res. Social Sci.*, vol. 72, Feb. 2021, Art. no. 101885, doi: 10.1016/j.erss.2020.101885.

[332] K. Asmal, ''Introduction: World commission on dams report, dams and development kader asmal introduction: World commission on,'' *Amer. Univ. Int. Law Rev.*, vol. 16, no. 6, pp. 1411–1433, 2001. [Online]. Available: http://digitalcommons.wcl.american.edu/auilr

[333] B. K. Sovacool, M. A. M. Perea, A. V. Matamoros, and P. Enevoldsen, ''Valuing the manufacturing externalities of wind energy: Assessing the environmental profit and loss of wind turbines in northern Europe,'' *Wind Energy*, vol. 19, no. 9, pp. 1623–1647, Sep. 2016, doi: 10.1002/we.1941.

[334] G. Barbose, N. Darghouth, B. Hoen, and R. Wiser. (2018). *Income Trends of Residential PV Adopters: An Analysis of Household-Level Income Estimates*. Berkeley. [Online]. Available: http://eta-publications.lbl.gov/sites/default/files/income_trends_of_residential_pv_adopters_final_0.pdf

[335] W. Strielkowski, D. Štreimikiene, and Y. Bilan, ''Network charging and residential tariffs: A case of household photovoltaics in the United Kingdom,'' *Renew. Sustain. Energy Rev.*, vol. 77, pp. 461–473, Sep. 2017, doi: 10.1016/j.rser.2017.04.029.

[336] E. O'Shaughnessy, G. Barbose, R. Wiser, S. Forrester, and N. Darghouth, ''The impact of policies and business models on income equity in rooftop solar adoption,'' *Nature Energy*, vol. 6, no. 1, pp. 84–91, Jan. 2021, doi: 10.1038/s41560-020-00724-2.

[337] H. K. Salim, R. A. Stewart, O. Sahin, and M. Dudley, ''Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review,'' *J. Cleaner Prod.*, vol. 211, pp. 537–554, Feb. 2019, doi: 10.1016/j.jclepro.2018.11.229.

[338] J. Cross and D. Murray, ''The afterlives of solar power: Waste and repair off the grid in Kenya,'' *Energy Res. Social Sci.*, vol. 44, pp. 100–109, Oct. 2018, doi: 10.1016/j.erss.2018.04.034.

[339] A. Atalay, D. Serasu, and L. Wassenhove, ''The dark side of solar power,'' *Harv. Bus. Rev.*, 2021. [Online]. Available: https://hbsp.harvard.edu/product/H06DN6-PDF-ENG

[340] R. Galvin, J. Schuler, A. T. Atasoy, H. Schmitz, M. Pfaff, and J. Kegel, ''A health research interdisciplinary approach for energy studies: Confirming substantial rebound effects among solar photovoltaic households in Germany,'' *Energy Res. Social Sci.*, vol. 86, Apr. 2022, Art. no. 102429, doi: 10.1016/j.erss.2021.102429.

[341] B. K. Sovacool, M. L. Barnacle, A. Smith, and M. C. Brisbois, ''Towards improved solar energy justice: Exploring the complex inequities of household adoption of photovoltaic panels,'' *Energy Policy*, vol. 164, May 2022, Art. no. 112868, doi: 10.1016/j.enpol.2022.112868.

[342] K. Ramirez-Tejeda, D. A. Turcotte, and S. Pike, ''Unsustainable wind turbine blade disposal practices in the United States: A case for policy intervention and technological innovation,'' *New Solutions, J. Environ. Occupational Health Policy*, vol. 26, no. 4, pp. 581–598, Feb. 2017, doi: 10.1177/1048291116676098.

[343] K. Yenneti and R. Day, ''Procedural (in)justice in the implementation of solar energy: The case of Charanaka solar park, Gujarat, India,'' *Energy Policy*, vol. 86, pp. 664–673, Nov. 2015, doi: 10.1016/j.enpol.2015.08.019.

[344] K. Yenneti and R. Day, ''Distributional justice in solar energy implementation in India: The case of Charanka solar park,'' *J. Rural Stud.*, vol. 46, pp. 35–46, Aug. 2016, doi: 10.1016/j.jrurstud.2016.05.009.

[345] K. Yenneti, R. Day, and O. Golubchikov, ''Spatial justice and the land politics of renewables: Dispossessing vulnerable communities through solar energy mega-projects,'' *Geoforum*, vol. 76, pp. 90–99, Nov. 2016, doi: 10.1016/j.geoforum.2016.09.004.

[346] N. Argenti and D. M. Knight, ''Sun, wind, and the rebirth of extractive economies: Renewable energy investment and metanarratives of crisis in Greece,'' *J. Roy. Anthropolog. Inst.*, vol. 21, no. 4, pp. 781–802, Dec. 2015, doi: 10.1111/1467-9655.12287.

[347] P. V. Calzadilla and R. Mauger, ''The UN's new sustainable development agenda and renewable energy: The challenge to reach SDG7 while achieving energy justice,'' *J. Energy Natural Resour. Law*, vol. 36, no. 2, pp. 233–254, Apr. 2018.

[348] E. A. H. Shoeib, E. Hamin Infield, and H. C. Renski, ''Measuring the impacts of wind energy projects on U.S. rural counties' community services and cost of living,'' *Energy Policy*, vol. 153, Jun. 2021, Art. no. 112279, doi: 10.1016/j.enpol.2021.112279.

[349] A. Gorayeb, C. Brannstrom, A. J. de Andrade Meireles, and J. de Sousa Mendes, ''Wind power gone bad: Critiquing wind power planning processes in northeastern Brazil,'' *Energy Res. Social Sci.*, vol. 40, pp. 82–88, Jun. 2018, doi: 10.1016/j.erss.2017.11.027.

[350] C. E. Hoicka, K. Savic, and A. Campney, ''Reconciliation through renewable energy? A survey of indigenous communities, involvement, and peoples in Canada,'' *Energy Res. Social Sci.*, vol. 74, Apr. 2021, Art. no. 101897, doi: 10.1016/j.erss.2020.101897.

[351] C. Haggett, T. Brink, A. Russell, M. Roach, T. Dalton, and B. J. Mccay. (2020). *Offshore Wind Projects and Fisheries: Conflict and Engagement in the United Kingdom and the United States*. [Online]. Available: https://tos.org/oceanography/article/offshore-wind-projects-and-fisheries-conflict-and-engagement-in-the-united-kingdom-and-the-united-states

[352] N. Healy, J. C. Stephens, and S. A. Malin, ''Embodied energy injustices: Unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains,'' *Energy Res. Social Sci.*, vol. 48, pp. 219–234, Feb. 2019, doi: 10.1016/j.erss.2018.09.016.

[353] C. Daggett, "Petro-masculinity: Fossil fuels and authoritarian desire," *Millennium, J. Int. Stud.*, vol. 47, no. 1, pp. 25–44, Sep. 2018, doi: 10.1177/0305829818775817.

[354] M. T. Huber and J. McCarthy, "Beyond the subterranean energy regime? Fuel, land use and the production of space," *Trans. Inst. Brit. Geographers*, vol. 42, no. 4, pp. 655–668, Dec. 2017, doi: 10.1111/tran.12182.

[355] C. Parenti, *Tropic of Chaos: Climate Change and the New Geography of Violence*. New York, NY, USA: Bold Type Books, 2012.

[356] B. K. Sovacool, B. Turnheim, A. Hook, A. Brock, and M. Martiskainen, "Dispossessed by decarbonisation: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways," *World Develop.*, vol. 137, Jan. 2021, Art. no. 105116, doi: 10.1016/j.worlddev.2020.105116.

[357] J. M. af Rosenschöld, J. G. Rozema, and L. A. Frye-Levine, "Institutional inertia and climate change: A review of the new institutionalist literature," *Wiley Interdiscipl. Rev., Climate Change*, vol. 5, no. 5, pp. 639–648, Sep. 2014, doi: 10.1002/wcc.292.

[358] S. Sareen, "Metrics for an accountable energy transition? Legitimating the governance of solar uptake," *Geoforum*, vol. 114, pp. 30–39, Aug. 2020, doi: 10.1016/j.geoforum.2020.05.018.

[359] S. P. Philipps, C. Kost, and T. Schlegl. (Sep. 2014). *Up-to-Date Levelized Cost of Electricity of Photovoltaics. Background From Fraunhofer ISE Relating to IPCC WGIII 5th Assessment Report, Final Draft*. Fraunhofer. [Online]. Available: https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html

[360] C. Breyer and M. Jefferson, "Use and abuse of energy and climate scenarios-a week of controversy on scenarios," *Econ. Energy Environ. Policy*, vol. 9, pp. 7–19, Mar. 2020, doi: 10.5547/2160-5890.9.1.mjef.

[361] A. Hoekstra, M. Steinbuch, and G. Verbong, "Creating agent-based energy transition management models that can uncover profitable pathways to climate change mitigation," *Complexity*, vol. 2017, pp. 1–23, Dec. 2017, doi: 10.1155/2017/1967645.

[362] A. Abeysinghe. (2019). *Joint Letter to the IEA*. [Online]. Available: https://idahoea.org/reporter/stakeholders-issue-joint-letter-on-funding-formula/

[363] [IEA] International Energy Agency. (2020). *World Energy Outlook 2020*. Paris, France. [Online]. Available: https://iea.blob.core.windows.net/assets/a72d8abf-de08-4385-8711-b8a062d6124a/WEO2020.pdf

[364] L. Sens, U. Neuling, and M. Kaltschmitt, "Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines—Development by 2050," *Renew. Energy*, vol. 185, pp. 525–537, Feb. 2022, doi: 10.1016/j.renene.2021.12.042.

[365] N. Haegel, H. Atwater Jr., T. Barnes, C. Breyer, A. Burrell, Y. M. Chiang, S. D. Wolf, B. Dimmler, D. Feldman, S. Glunz, and J. C. Goldschmidt, "Terawatt-scale photovoltaics?: Transform the global energy system," *Science*, vol. 364, no. 6443, pp. 836–838, 2019.

[366] M. Roser and H. Ritchie. (2021). *The International Energy Agency Publishes the Detailed, Global Energy Data We All Need, But its Funders Force it Behind Paywalls. Let's Ask Them to Change it*. Accessed: Feb. 19, 2022. [Online]. Available: https://ourworldindata.org/iea-open-data

[367] Openmod. (2022). *Open Letter to IEA and Member Countries Requesting Open Data*. Accessed: Feb. 19, 2022. [Online]. Available: https://forum.openmod.org/t/open-letter-to-iea-and-member-countries-requesting-open-data/2949/9

[368] O. Y. Edelenbosch, D. L. McCollum, D. P. van Vuuren, C. Bertram, S. Carrara, H. Daly, S. Fujimori, A. Kitous, P. Kyle, E. Ó Broin, P. Karkatsoulis, and F. Sano, "Decomposing passenger transport futures: Comparing results of global integrated assessment models," *Transp. Res. D, Transp. Environ.*, vol. 55, pp. 281–293, Aug. 2017, doi: 10.1016/j.trd.2016.07.003.

[369] C. McKerracher. (2021). *The EV Price Gap Narrows. Bloomberg NEF*. Accessed: Feb. 19, 2022. [Online]. Available: https://about.bnef.com/blog/the-ev-price-gap-narrows/

[370] S. G. Carroll. (2021). *EU Signals End of Internal Combustion Engine by 2035*. Accessed: Mar. 22, 2022. [Online]. Available: https://www.euractiv.com/section/electric-cars/news/eu-signals-end-of-internal-combustion-engine-by-2035

[371] HM Government. (2020). *The Ten Point Plan for a Green Industrial Revolution. HM Government*. Accessed: Mar. 8, 2022. [Online]. Available: https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

[372] [ICCT]—The International Council on Clean Transportation. (2021). *European Union CO_2 Standards for New Passenger Cars and Vans*. [Online]. Available: https://theicct.org/wp-content/uploads/2021/12/eu-co2-FS5-jun2021.pdf

[373] T. Brown and L. Reichenberg, "Decreasing market value of variable renewables can be avoided by policy action," *Energy Econ.*, vol. 100, Aug. 2021, Art. no. 105354, doi: 10.1016/j.eneco.2021.105354.

[374] S. Müller, H. Holttinen, E. Taibi, J. Smith, D. Fraile, and T.-K. Vrana, "System integration costs—A useful concept that is complicated to quantify," in *Proc. 17th Int. Workshop Large-Scale Integr. Wind Power Power Syst. Well Transmiss. Netw. Offshore Wind Power Plants*, 2018. Accessed: Feb. 19, 2022. [Online]. Available: https://iea-wind.org/task25/

[375] P. A. Østergaard, "Ancillary services and the integration of substantial quantities of wind power," *Appl. Energy*, vol. 83, no. 5, pp. 451–463, May 2006, doi: 10.1016/j.apenergy.2005.04.007.

[376] F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer, "Potential and risks of hydrogen-based e-fuels in climate change mitigation," *Nature Climate Change*, vol. 11, no. 5, pp. 384–393, May 2021.

[377] F. Creutzig, C. Breyer, J. Hilaire, J. Minx, G. P. Peters, and R. Socolow, "The mutual dependence of negative emission technologies and energy systems," *Energy Environ. Sci.*, vol. 12, no. 6, pp. 1805–1817, Jun. 2019, doi: 10.1039/c8ee03682a.

[378] C. Breyer, M. Fasihi, and A. Aghahosseini, "Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: A new type of energy system sector coupling," *Mitigation Adaptation Strategies Global Change*, vol. 25, no. 1, pp. 43–65, Jan. 2020, doi: 10.1007/s11027-019-9847-y.

[379] F. M. Brethomé, N. J. Williams, C. A. Seipp, M. K. Kidder, and R. Custelcean, "Direct air capture of CO_2 via aqueous-phase absorption and crystalline-phase release using concentrated solar power," *Nature Energy*, vol. 3, no. 7, pp. 553–559, Jul. 2018, doi: 10.1038/s41560-018-0150-z.

[380] T. M. P. Ratouis, S. Ó. Snæbjörnsdóttir, M. J. Voigt, B. Sigfusson, G. Gunnarsson, E. S. Aradóttir, and V. Hjörleifsdóttir, "Carbfix 2: A transport model of long-term CO_2 and H_2S injection into basaltic rocks at hellisheidi, SW-iceland," *Int. J. Greenhouse Gas Control*, vol. 114, Feb. 2022, Art. no. 103586, doi: 10.1016/j.ijggc.2022.103586.

[381] C. Chen and M. Tavoni, "Direct air capture of CO_2 and climate stabilization: A model based assessment," *Climatic Change*, vol. 118, no. 1, pp. 59–72, May 2013, doi: 10.1007/s10584-013-0714-7.

[382] B. K. Sovacool, "Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering," *Energy Strategy Rev.*, vol. 35, May 2021, Art. no. 100656, doi: 10.1016/j.esr.2021.100656.

[383] S. Sgouridis, M. Carbajales-Dale, D. Csala, M. Chiesa, and U. Bardi, "Comparative net energy analysis of renewable electricity and carbon capture and storage," *Nature Energy*, vol. 4, no. 6, pp. 456–465, Jun. 2019, doi: 10.1038/s41560-019-0365-7.

[384] J. Rogelj, P. M. Forster, E. Kriegler, C. J. Smith, and R. Séférian, "Estimating and tracking the remaining carbon budget for stringent climate targets," *Nature*, vol. 571, no. 7765, pp. 335–342, Jul. 2019, doi: 10.1038/s41586-019-1368-z.

[385] T. M. Lenton, J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, and H. J. Schellnhuber, "Climate tipping points—Too risky to bet against," *Nature*, vol. 575, pp. 593–595, Nov. 2019.

[386] M. R. Turetsky, B. W. Abbott, M. C. Jones, K. W. Anthony, D. Olefeldt, E. A. G. Schuur, G. Grosse, P. Kuhry, G. Hugelius, C. Koven, D. M. Lawrence, C. Gibson, A. B. K. Sannel, and A. D. McGuire, "Carbon release through abrupt permafrost thaw," *Nature Geosci.*, vol. 13, no. 2, pp. 138–143, Feb. 2020, doi: 10.1038/s41561-019-0526-0.

[387] M. D. King, I. M. Howat, S. G. Candela, M. J. Noh, S. Jeong, B. P. Y. Noel, M. R. van den Broeke, B. Wouters, and A. Negrete, "Dynamic ice loss from the Greenland ice sheet driven by sustained glacier retreat," *Commun. Environ.*, vol. 1, no. 1, pp. 1–7, Dec. 2020, doi: 10.1038/s43247-020-0001-2.

[388] A. Levermann and J. Feldmann, "Scaling of instability timescales of Antarctic outlet glaciers based on one-dimensional similitude analysis," *Cryosphere*, vol. 13, no. 6, pp. 1621–1633, Jun. 2019, doi: 10.5194/tc-13-1621-2019.

[389] J. Hansen, M. Sato, P. Kharecha, K. Von Schuckmann, and D. J. Beerling, "Earth system dynamics young people's burden: Requirement of negative CO_2 emissions," *Earth Syst. Dyn.*, vol. 8, no. 3, pp. 577–616, 2017.

[390] C. Azar and H. Rodhe, "Targets for stabilization of atmospheric CO_2," *Science*, vol. 276, pp. 1818–1819, Jun. 1997.

[391] R. W. Howarth and M. Z. Jacobson, "How green is blue hydrogen?" *Energy Sci. Eng.*, vol. 9, no. 10, pp. 1676–1687, Oct. 2021, doi: 10.1002/ese3.956.

[392] A. Otto, M. Robinius, T. Grube, S. Schiebahn, A. Praktiknjo, and D. Stolten, ''Power-to-steel: Reducing CO_2 through the integration of renewable energy and hydrogen into the German steel industry,'' *Energies*, vol. 10, no. 4, p. 451, Apr. 2017, doi: 10.3390/en10040451.

[393] M. Fischedick, J. Marzinkowski, P. Winzer, and M. Weigel, ''Techno-economic evaluation of innovative steel production technologies,'' *J. Cleaner Prod.*, vol. 84, pp. 563–580, Dec. 2014, doi: 10.1016/j.jclepro.2014.05.063.

[394] M. Bailera, P. Lisbona, B. Peña, and L. M. Romeo, ''A review on CO_2 mitigation in the iron and steel industry through power to X processes,'' *J. CO_2 Utilization*, vol. 46, Apr. 2021, Art. no. 101456, doi: 10.1016/j.jcou.2021.101456.

[395] Z. J. Schiffer and K. Manthiram, ''Electrification and decarbonization of the chemical industry,'' *Joule*, vol. 1, no. 1, pp. 10–14, Sep. 2017.

[396] A. González-Garay, N. M. Dowell, and N. Shah, ''A carbon neutral chemical industry powered by the sun,'' *Discover Chem. Eng.*, vol. 1, no. 1, pp. 1–22, Dec. 2021, doi: 10.1007/s43938-021-00002-x.

[397] [IPCC] Intergovernmental Panel on Climate Change. (2021). *Climate Change 2021—The Physical Science Basis, Working Group I Contribution to the Sixth Assessment Report*. Geneva. [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/

[398] J. C. Minx, W. F. Lamb, M. W. Callaghan, L. Bornmann, and S. Fuss, ''Fast growing research on negative emissions,'' *Environ. Res. Lett.*, vol. 12, no. 3, Mar. 2017, Art. no. 035007, doi: 10.1088/1748-9326/aa5ee5.

[399] M. Mengel, A. Nauels, J. Rogelj, and C.-F. Schleussner, ''Committed sea-level rise under the Paris agreement and the legacy of delayed mitigation action,'' *Nature Commun.*, vol. 9, no. 1, pp. 1–10, Dec. 2018, doi: 10.1038/s41467-018-02985-8.

[400] S. Fuss, J. G. Canadell, G. P. Peters, M. Tavoni, R. M. Andrew, P. Ciais, R. B. Jackson, C. D. Jones, F. Kraxner, N. Nakicenovic, C. L. Quéré, M. R. Raupach, A. Sharifi, P. Smith, and Y. Yamagata, ''Betting on negative emissions,'' *Nature Climate Change*, vol. 4, no. 10, pp. 850–853, Oct. 2014.

[401] O. Rueda, J. M. Mogollón, A. Tukker, and L. Scherer, ''Negative-emissions technology portfolios to meet the 1.5 °C target,'' *Global Environ. Change*, vol. 67, Mar. 2021, Art. no. 102238, doi: 10.1016/j.gloenvcha.2021.102238.

[402] C. Breyer, S. Heinonen, and J. Ruotsalainen, ''New consciousness: A societal and energetic vision for rebalancing humankind within the limits of planet Earth,'' *Technological Forecasting Social Change*, vol. 114, pp. 7–15, Jan. 2017, doi: 10.1016/j.techfore.2016.06.029.

[403] J. C. Goldschmidt, L. Wagner, R. Pietzcker, and L. Friedrich, ''Technological learning for resource efficient terawatt scale photovoltaics,'' *Energy Environ. Sci.*, vol. 14, no. 10, pp. 5147–5160, Oct. 2021, doi: 10.1039/d1ee02497c.

[404] I. Overland, ''The geopolitics of renewable energy: Debunking four emerging myths,'' *Energy Res. Social Sci.*, vol. 49, pp. 36–40, Mar. 2019, doi: 10.1016/j.erss.2018.10.018.

[405] G. A. Heath, T. J. Silverman, M. Kempe, M. Deceglie, D. Ravikumar, T. Remo, H. Cui, P. Sinha, C. Libby, S. Shaw, K. Komoto, K. Wambach, E. Butler, T. Barnes, and A. Wade, ''Research and development priorities for silicon photovoltaic module recycling to support a circular economy,'' *Nature Energy*, vol. 5, no. 7, pp. 502–510, Jul. 2020, doi: 10.1038/s41560-020-0645-2.

[406] H. Lütkehaus, C. Pade, M. Oswald, U. Brand, T. Naegler, and T. Vogt, ''Measuring raw-material criticality of product systems through an economic product importance indicator: A case study of battery-electric vehicles,'' *Int. J. Life Cycle Assessment*, vol. 27, no. 1, pp. 122–137, Jan. 2022, doi: 10.1007/s11367-021-02002-z.

[407] D. E. H. J. Gernaat, H. S. de Boer, V. Daioglou, S. G. Yalew, C. Müller, and D. P. van Vuuren, ''Climate change impacts on renewable energy supply,'' *Nature Climate Change*, vol. 11, no. 2, pp. 119–125, Feb. 2021, doi: 10.1038/s41558-020-00949-9.

[408] E. K. Gøtske and M. Victoria, ''Future operation of hydropower in Europe under high renewable penetration and climate change,'' *iScience*, vol. 24, no. 9, Sep. 2021, Art. no. 102999, doi: 10.1016/j.isci.2021.102999.

[409] T. Galimova *et al.*, ''Role of e-fuels and e-chemicals trading in enabling the global energy transition towards 100% renewable energy across the power, heat, transport, and industry sectors by 2050,'' 2022.

[410] D. Connolly, H. Lund, B. V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P. A. Østergaard, and S. Nielsen, ''Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system,'' *Energy Policy*, vol. 65, pp. 475–489, Feb. 2014, doi: 10.1016/j.enpol.2013.10.035.

[411] K. Hansen and B. V. Mathiesen, ''Comprehensive assessment of the role and potential for solar thermal in future energy systems,'' *Sol. Energy*, vol. 169, pp. 144–152, Jul. 2018, doi: 10.1016/j.solener.2018.04.039.

[412] B. V. Mathiesen, H. Lund, and D. Connolly, ''Limiting biomass consumption for heating in 100% renewable energy systems,'' *Energy*, vol. 48, no. 1, pp. 160–168, Dec. 2012, doi: 10.1016/j.energy.2012.07.063.

[413] I. Ridjan, B. V. Mathiesen, and D. Connolly, ''Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: A review,'' *J. Cleaner Prod.*, vol. 112, pp. 3709–3720, Jan. 2016, doi: 10.1016/j.jclepro.2015.05.117.

[414] B. K. Sovacool, C. G. Monyei, and P. Upham, ''Making the internet globally sustainable: Technical and policy options for improved energy management, governance and community acceptance of Nordic datacenters,'' *Renew. Sustain. Energy Rev.*, vol. 154, Feb. 2022, Art. no. 111793, doi: 10.1016/j.rser.2021.111793.

[415] C. Koronen, M. Åhman, and L. J. Nilsson, ''Data centres in future European energy systems—Energy efficiency, integration and policy,'' *Energy Efficiency*, vol. 13, no. 1, pp. 129–144, Jan. 2020, doi: 10.1007/s12053-019-09833-8.

[416] S. Werner, ''International review of district heating and cooling,'' *Energy*, vol. 137, pp. 617–631, Oct. 2017, doi: 10.1016/j.energy.2017.04.045.

[417] W. Xiong, Y. Wang, B. Vad Mathiesen, H. Lund, and X. Zhanga, ''Heat roadmap China: New heat strategy to reduce energy consumption towards 2030,'' *Energy*, vol. 81, pp. 274–285, Mar. 2015, doi: 10.1016/j.energy.2014.12.039.

[418] J. Zhang and L. D. Lucia, ''A transition perspective on alternatives to coal in Chinese district heating,'' *Int. J. Sustain. Energy Plan. Manag.*, vol. 6, pp. 49–68, Sep. 2015, doi: 10.5278/ijsepm.2015.6.5.

[419] S. Paardekooper, H. Lund, M. Chang, S. Nielsen, D. Moreno, and J. Z. Thellufsen, ''Heat roadmap chile: A national district heating plan for air pollution decontamination and decarbonisation,'' *J. Cleaner Prod.*, vol. 272, Nov. 2020, Art. no. 122744, doi: 10.1016/j.jclepro.2020.122744.

[420] B. Möller, E. Wiechers, U. Persson, L. Grundahl, R. S. Lund, and B. V. Mathiesen, ''Heat roadmap Europe: Towards EU-wide, local heat supply strategies,'' *Energy*, vol. 177, pp. 554–564, Jun. 2019, doi: 10.1016/j.energy.2019.04.098.

[421] M. Münster, P. E. Morthorst, H. V. Larsen, L. Bregnbæk, J. Werling, H. H. Lindboe, and H. Ravn, ''The role of district heating in the future Danish energy system,'' *Energy*, vol. 48, no. 1, pp. 47–55, Dec. 2012, doi: 10.1016/j.energy.2012.06.011.

[422] F. Wiese, R. Bramstoft, H. Koduvere, A. Pizarro Alonso, O. Balyk, J. G. Kirkerud, Å. G. Tveten, T. F. Bolkesjø, M. Münster, and H. Ravn, ''Balmorel open source energy system model,'' *Energy Strategy Rev.*, vol. 20, pp. 26–34, Apr. 2018, doi: 10.1016/j.esr.2018.01.003.

[423] J. Z. Thellufsen, H. Lund, P. Sorknæs, P. A. Østergaard, M. Chang, D. Drysdale, S. Nielsen, S. R. Djørup, and K. Sperling, ''Smart energy cities in a 100% renewable energy context,'' *Renew. Sustain. Energy Rev.*, vol. 129, Sep. 2020, Art. no. 109922, doi: 10.1016/j.rser.2020.109922.

[424] H. Lund, P. A. Østergaard, T. B. Nielsen, S. Werner, J. E. Thorsen, O. Gudmundsson, A. Arabkoohsar, and B. V. Mathiesen, ''Perspectives on fourth and fifth generation district heating,'' *Energy*, vol. 227, Jul. 2021, Art. no. 120520, doi: 10.1016/j.energy.2021.120520.

[425] P. Sorknæs, P. A. Østergaard, J. Z. Thellufsen, H. Lund, S. Nielsen, S. Djørup, and K. Sperling, ''The benefits of 4th generation district heating in a 100% renewable energy system,'' *Energy*, vol. 213, Dec. 2020, Art. no. 119030, doi: 10.1016/j.energy.2020.119030.

[426] R. Lund, D. S. Østergaard, X. Yang, and B. V. Mathiesen, ''Comparison of low-temperature district heating concepts in a long-term energy system perspective,'' *Int. J. Sustain. Energy Plan. Manag.*, vol. 12, pp. 5–18, Mar. 2017, doi: 10.5278/ijsepm.2017.12.2.

[427] K. Hedegaard, B. V. Mathiesen, H. Lund, and P. Heiselberg, ''Wind power integration using individual heat pumps—Analysis of different heat storage options,'' *Energy*, vol. 47, no. 1, pp. 284–293, Nov. 2012, doi: 10.1016/j.energy.2012.09.030.

[428] P. A. Østergaard, S. Werner, A. Dyrelund, H. Lund, A. Arabkoohsar, P. Sorknæs, O. Gudmundsson, J. E. Thorsen, and B. V. Mathiesen, ''The four generations of district cooling—A categorization of the development in district cooling from origin to future prospect,'' *Energy*, vol. 253, Aug. 2022, Art. no. 124098, doi: 10.1016/j.energy.2022.124098.

[429] Eurostat. (2021). *History of NUTS*. Accessed: Dec. 13, 2021. [Online]. Available: https://ec.europa.eu/eurostat/web/nuts/history

[430] J.-P. Sasse and E. Trutnevyte, ''Regional impacts of electricity system transition in central Europe until 2035,'' *Nature Commun.*, vol. 11, no. 1, p. 4972, Dec. 2020, doi: 10.1038/s41467-020-18812-y.

[431] N. B. Manjong, A. S. Oyewo, and C. Breyer, "Setting the pace for a sustainable energy transition in central Africa: The case of Cameroon," *IEEE Access*, vol. 9, pp. 145435–145458, 2021, doi: 10.1109/ACCESS.2021.3121000.

[432] A. Gulagi, S. Pathak, D. Bogdanov, and C. Breyer, "Renewable energy transition for the Himalayan countries Nepal and bhutan: Pathways towards reliable, affordable and sustainable energy for all," *IEEE Access*, vol. 9, pp. 84520–84544, 2021, doi: 10.1109/ACCESS.2021.3087204.

[433] M. Child, D. Bogdanov, A. Aghahosseini, and C. Breyer, "The role of energy prosumers in the transition of the Finnish energy system towards 100% renewable energy by 2050," *Futures*, vol. 124, Dec. 2020, Art. no. 102644, doi: 10.1016/j.futures.2020.102644.

[434] S. A. Alla, S. G. Simoes, and V. Bianco, "Addressing rising energy needs of megacities—Case study of greater Cairo," *Energy Buildings*, vol. 236, Apr. 2021, Art. no. 110789, doi: 10.1016/j.enbuild.2021.110789.

[435] M. Ram, A. Gulagi, A. Aghahosseini, D. Bogdanov, and C. Breyer, "Energy transition in megacities towards 100% renewable energy: A case for Delhi," *Renew. Energy*, vol. 195, pp. 578–589, Aug. 2022, doi: 10.1016/j.renene.2022.06.073.

[436] H. Meschede, P. Bertheau, S. Khalili, and C. Breyer, "A review of 100% renewable energy scenarios on islands," *WIREs Energy Environ.*, 2022, doi: 10.1002/wene.450.

[437] S. Selosse, S. Garabedian, O. Ricci, and N. Maïzi, "The renewable energy revolution of reunion island," *Renew. Sustain. Energy Rev.*, vol. 89, pp. 99–105, Jun. 2018, doi: 10.1016/j.rser.2018.03.013.

[438] A. Eras-Almeida, M. Egido-Aguilera, P. Blechinger, S. Berendes, E. Caamaño, and E. García-Alcalde, "Decarbonizing the galapagos islands: Techno-economic perspectives for the hybrid renewable mini-grid Baltra–Santa Cruz," *Sustainability*, vol. 12, no. 6, p. 2282, Mar. 2020, doi: 10.3390/su12062282.

[439] N. Dados and R. Connell, "The global south," *Contexts*, vol. 11, no. 1, pp. 12–13, Feb. 2012, doi: 10.1177/1536504212436479.

[440] [IRENA] International Renewable Energy. World Bank (2021) Agency. (2021). *Tracking SDG7—The Energy Progress Report 2021*. Washington, DC, USA. [Online]. Available: https://www.irena.org/publications/2021/Jun/Tracking-SDG-7-2021

[441] Afstor. (2021). *Best Way to Compensate CO_2 Emissions*. Accessed: Dec. 13, 2021. [Online]. Available: http://www.afstor.com/en/homepage/

[442] J. Leary, B. Menyeh, V. Chapungu, and K. Troncoso, "ECooking: Challenges and opportunities from a consumer behaviour perspective," *Energies*, vol. 14, no. 14, p. 4345, Jul. 2021, doi: 10.3390/en14144345.

[443] A. S. Oyewo, *Transition Towards Decarbonised Power Systems for Sub-Saharan Africa by 2050*. Lappeenranta, Finland: Lappeenranta Univ., 2021.

[444] R. Wallsgrove, J. Woo, J.-H. Lee, and L. Akiba, "The emerging potential of microgrids in the transition to 100% renewable energy systems," *Energies*, vol. 14, no. 6, p. 1687, Mar. 2021, doi: 10.3390/en14061687.

[445] S. Bahramara, M. P. Moghaddam, and M. Haghifam, "Optimal planning of hybrid renewable energy systems using HOMER: A review," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 609–620, Sep. 2016, doi: 10.1016/j.rser.2016.05.039.

[446] R. Khezri, A. Mahmoudi, H. Aki, and S. M. Muyeen, "Optimal planning of remote area electricity supply systems: Comprehensive review, recent developments and future scopes," *Energies*, vol. 14, no. 18, p. 5900, Sep. 2021, doi: 10.3390/en14185900.

[447] P. Bertheau, A. Oyewo, C. Cader, C. Breyer, and P. Blechinger, "Visualizing national electrification scenarios for sub-saharan African countries," *Energies*, vol. 10, no. 11, p. 1899, Nov. 2017, doi: 10.3390/en10111899.

[448] S. Pfenninger, A. Hawkes, and J. Keirstead, "Energy systems modeling for twenty-first century energy challenges," *Renew. Sustain. Energy Rev.*, vol. 33, pp. 74–86, May 2014, doi: 10.1016/j.rser.2014.02.003.

[449] W. Weimer-Jehle, J. Buchgeister, W. Hauser, H. Kosow, T. Naegler, W.-R. Poganietz, T. Pregger, S. Prehofer, A. von Recklinghausen, J. Schippl, and S. Vögele, "Context scenarios and their usage for the construction of socio-technical energy scenarios," *Energy*, vol. 111, pp. 956–970, Sep. 2016, doi: 10.1016/j.energy.2016.05.073.

[450] V. J. Schweizer and E. Kriegler, "Improving environmental change research with systematic techniques for qualitative scenarios," *Environ. Res. Lett.*, vol. 7, no. 4, Dec. 2012, Art. no. 044011, doi: 10.1088/1748-9326/7/4/044011.

[451] Y. Y. Deng, M. Haigh, W. Pouwels, L. Ramaekers, R. Brandsma, S. Schimschar, J. Grözinger, and D. de Jager, "Quantifying a realistic, worldwide wind and solar electricity supply," *Global Environ. Change*, vol. 31, pp. 239–252, Mar. 2015, doi: 10.1016/j.gloenvcha.2015.01.005.

[452] *A New World—The Geopolitics of the Energy Transformation*, [IRENA] International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, 2019.

[453] R. Vakulchuk, I. Overland, and D. Scholten, "Renewable energy and geopolitics: A review," *Renew. Sustain. Energy Rev.*, vol. 122, Apr. 2020, Art. no. 109547, doi: 10.1016/j.rser.2019.109547.

[454] A. Azzuni and C. Breyer, "Definitions and dimensions of energy security: A literature review," *Wiley Interdiscipl. Rev., Energy Environ.*, vol. 7, no. 1, p. e268, Jan. 2018, doi: 10.1002/wene.268.

[455] A. Azzuni and C. Breyer, "Energy security and energy storage technologies," *Energy Proc.*, vol. 155, pp. 237–258, Nov. 2018, doi: 10.1016/j.egypro.2018.11.053.

[456] A. Azzuni, A. Aghahosseini, M. Ram, D. Bogdanov, U. Caldera, and C. Breyer, "Energy security analysis for a 100% renewable energy transition in Jordan by 2050," *Sustainability*, vol. 12, no. 12, p. 4921, Jun. 2020, doi: 10.3390/SU12124921.

[457] N. Bolson, M. Yutkin, W. Rees, and T. Patzek, "Resilience rankings and trajectories of world's countries," *Ecological Econ.*, vol. 195, May 2022, Art. no. 107383, doi: 10.1016/j.ecolecon.2022.107383.

[458] S. Sterl, D. Fadly, S. Liersch, H. Koch, and W. Thiery, "Linking solar and wind power in eastern Africa with operation of the grand Ethiopian renaissance dam," *Nature Energy*, vol. 6, no. 4, pp. 407–418, Apr. 2021.

[459] D. Connolly, H. Lund, B. V. Mathiesen, and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems," *Appl. Energy*, vol. 87, pp. 1059–1082, Apr. 2010, doi: 10.1016/j.apenergy.2009.09.026.

[460] M. Kittel and W. Schill, "Renewable energy targets and unintended storage cycling: Implications for energy modeling," *iScience*, vol. 25, no. 104002, 2022, doi: 10.1016/j.isci.2022.104002.

[461] B. Müller, F. Gardumi, and L. Hülk, "Comprehensive representation of models for energy system analyses: Insights from the energy modelling platform for Europe (EMP-E) 2017," *Energy Strategy Rev.*, vol. 21, pp. 82–87, Aug. 2018, doi: 10.1016/j.esr.2018.03.006.

[462] H. C. Gils, T. Pregger, F. Flachsbarth, M. Jentsch, and C. Dierstein, "Comparison of spatially and temporally resolved energy system models with a focus on Germany's future power supply," *Appl. Energy*, vol. 255, Dec. 2019, Art. no. 113889, doi: 10.1016/j.apenergy.2019.113889.

[463] EMP. (2022). *Energy Modelling Platform for Europe*. Accessed: Feb. 15, 2022. [Online]. Available: https://www.energymodellingplatform.eu/

[464] EMF. *Energy Modeling Forum*. Accessed: Feb. 15, 2022. [Online]. Available: https://emf.stanford.edu/

[465] L. Clarke, J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni, "International climate policy architectures: Overview of the EMF 22 international scenarios," *Energy Econ.*, vol. 31, pp. S64–S81, Dec. 2009, doi: 10.1016/j.eneco.2009.10.013.

[466] G. Luderer, V. Krey, K. Calvin, J. Merrick, S. Mima, R. Pietzcker, J. Van Vliet, and K. Wada, "The role of renewable energy in climate stabilization: Results from the EMF27 scenarios," *Climatic Change*, vol. 123, nos. 3–4, pp. 427–441, Apr. 2014, doi: 10.1007/s10584-013-0924-z.

[467] S. J. Smith *et al.*, "The energy modeling forum (EMF)-30 study on short-lived climate forcers: Introduction and overview," *Climatic Change*, vol. 163, pp. 1399–1408, 2020, doi: 10.1007/s10584-020-02938-5.

[468] M. Muratori, N. Bauer, S. K. Rose, M. Wise, V. Daioglou, Y. Cui, E. Kato, M. Gidden, J. Strefler, S. Fujimori, R. D. Sands, D. P. van Vuuren, and J. Weyant, "EMF-33 insights on bioenergy with carbon capture and storage (BECCS)," *Climatic Change*, vol. 163, no. 3, pp. 1621–1637, Dec. 2020, doi: 10.1007/s10584-020-02784-5.

[469] D. P. van Vuuren, E. Stehfest, D. E. H. J. Gernaat, J. C. Doelman, M. van den Berg, M. Harmsen, H. S. de Boer, L. F. Bouwman, V. Daioglou, O. Y. Edelenbosch, B. Girod, T. Kram, L. Lassaletta, P. L. Lucas, H. van Meijl, C. Müller, B. J. van Ruijven, S. van der Sluis, and A. Tabeau, "Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm," *Global Environ. Change*, vol. 42, pp. 237–250, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.05.008.

[470] O. Fricko, P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, M. Strubegger, H. Valin, M. Amann, and T. Ermolieva, "The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century," *Glob. Environ. Chang.*, vol. 42, pp. 267–521, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.06.004.

[471] S. Fujimori, T. Hasegawa, T. Masui, K. Takahashi, D. S. Herran, H. Dai, Y. Hijioka, and M. Kainuma, "SSP_3: AIM implementation of shared socioeconomic pathways," *Global Environ. Change*, vol. 42, pp. 268–283, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.06.009.

[472] K. Calvin, B. Bond-Lamberty, L. Clarke, J. Edmonds, J. Eom, C. Hartin, S. Kim, P. Kyle, R. Link, R. Moss, H. McJeon, P. Patel, S. Smith, S. Waldhoff, and M. Wise, ''The SSP4: A world of deepening inequality,'' *Global Environ. Change*, vol. 42, pp. 284–296, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.06.010.

[473] E. Kriegler, N. Bauer, A. Popp, F. Humpenöder, M. Leimbach, J. Strefler, L. Baumstark, B. L. Bodirsky, J. Hilaire, D. Klein, and I. Mouratiadou, ''Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century,'' *Global Environ. Change*, vol. 42, pp. 297–315, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.05.015.

[474] K. Riahi, D. P. Van Vuuren, E. Kriegler, J. Edmonds, B. C. O'neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, and W. Lutz, ''The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview,'' *Global Environ. Change*, vol. 42, pp. 153–168, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.05.009.

CHRISTIAN BREYER received the Diploma degrees in general business, physics, and energy system engineering and the Ph.D. degree in economics of hybrid PV power plants. He has started the Solar Economy Professorship at LUT University, in 2014. His major expertise is the integrated research of technological and economic characteristics of renewable energy systems specializing in hybrid energy solutions, energy systems modeling, and 100% renewable energy scenarios on a local but also global scale. He has been the Managing Director of the Reiner Lemoine Institut, Berlin, focused on research about renewable energy supply up to 100%. He worked previously several years for Q-Cells, a former world market leader in the PV industry in the Research and Development and the Market Development Departments. He has authored or coauthored about 350 scientific publications, thereof more than 140 in journals. He is a member of international working groups like ETIP PV and IEA-PVPS, the Chair for renewable energy at the Energy Watch Group, an Advisory Board Member of Global Alliance Power Fuels and CO_2 Value Europe, and a Founding Member of the DESERTEC Foundation.

SIAVASH KHALILI received the B.Sc. degree in electrical engineering from the University of Tehran and the M.Sc. degree in energy systems from LUT University, where he is currently pursuing the doctoral degree. He is a full-time Researcher with the Solar Economy Team. He is focused on systematic reviews and bibliometric analyses of 100% renewable energy scenarios and data visualization with different tools and programming languages. This comprises the investigation for 100% renewable articles and analyzing all energy sectors, the use of different technologies for a sustainable energy transition, and models used from a local to the global level. His research interests include sustainable mobility, renewable energy transition, sustainable energy systems, energy systems bibliometric analysis, and renewable energy review analysis.

DMITRII BOGDANOV received the B.Sc. and M.Sc. degrees in automation and control engineering from Saint Petersburg Electrotechnical University and the M.Sc. degree in industrial electronics and the Doctor of Science degree in electricity markets and solar economy from LUT University, Finland. He is a member of the Solar Economy Team and a Postdoctoral Researcher with LUT University. He is responsible for the development of the LUT energy systems transition model and its applications on global level and for regions in Europe, Eurasia, and Northeast Asia. He authored and coauthored more than 50 scientific publications in leading scientific journals. His research interests include renewable energy, energy systems modeling, integration of high shares of renewable energy generation into energy systems, energy systems modeling, renewable energy, smart grids, and energy systems transformation.

MANISH RAM received the M.B.A. degree in energy management from the Technical University of Berlin with a master's thesis on ''European Energy Transition: A Cost Analysis With High Shares of Renewable Energy Technologies.'' He is currently a Doctoral Researcher with the Solar Economy Group, LUT University, exploring socioeconomic impacts of the energy transition across various regions of the world, and in particular for India. He has been involved in the development of the renewable energy sector since the last decade. He has been conducting research and providing scientific consultancy services to clients across the spectrum on the energy transition with a focus on socioeconomic aspects and the role of solar PV prosumers and development of jobs in the energy transition.

AYOBAMI SOLOMON OYEWO received the Doctor of Science degree in electricity markets and solar economy from LUT University. He is a member of the Solar Economy Team, LUT University, Finland. He is an Energy Systems Transition Expert focusing on Africa and has also been involved in energy systems transition studies for East and Southeast Asia. His research interests include renewable energy, energy systems modeling, and integration of large shares of renewable energy generation into energy systems. His academic background is hydrology, environmental science, and processes of sustainable energetics with studies in Nigeria, Estonia, and Finland.

ARMAN AGHAHOSSEINI received the degree in mining engineering, structural geology, and sustainable technology and business. He is a Doctoral Researcher with the Group of Solar Economy, LUT University, Finland. His research focuses on the energy transitions in the Middle East and North Africa (MENA) and Americas, analyzing energy systems scenarios, and exploring complementary technologies to enable the transition. His research also covers geothermal energy and compressed air energy storage. His research interests include within energy systems modeling, energy scenarios, and analysis of renewable energy and systems flexibility measures suitable for the energy transition towards a 100% renewable energy systems.

ASHISH GULAGI received the master's degree in environmental engineering and technology. He is currently pursuing the doctoral degree with LUT University, Finland. He is a Researcher with the Group of Solar Economy. This work includes energy systems modeling and analysis with a special focus on energy storage. His expertise lies in the area of energy transition in Southeast Asia and the South Asian region. His special focus lies on India and its energy transition to a fully renewable energy-based system. He has published results on energy transition in leading scientific journals for India, Pakistan, Bangladesh, Southeast Asia, and SAARC. His research interests include the renewables-based energy systems optimization under economic and environmental constrains, renewable energy and sustainability, smart grids, and energy systems transformation.

A. A. SOLOMON received the Ph.D. degree in energy systems modeling from the Ben-Gurion University of the Negev, Israel. He was a Postdoctoral Researcher with the University of California at Berkeley, Berkeley, USA. Then, he moved to Addis Ababa University (AAU), Ethiopia, where he worked as an Assistant Professor of energy systems and the Head of the Center of Energy Technology. He is currently a Postdoctoral Researcher with LUT University, Finland. His findings are published in various journals and as a part of books. His research interests include energy transition, biophysical limits, as well as the question of power systems planning and optimization, particularly in addressing the challenge of variable renewable energy (VRE) integration and energy storage.

DOMINIK KEINER received the B.Eng. degree in renewable energy engineering and energy efficiency from OTH Regensburg, University of Applied Sciences, Germany, and the M.Sc. degree in sustainable electric energy supply from the University of Stuttgart, Germany. He is currently pursuing the doctoral degree with LUT University, Finland. He is a Researcher with the Solar Economy Group. His main research interests include the macro-economic modeling of energy demand within the 21st century, techno-economic research on negative emission technology portfolios, and global energy systems investigations for limiting global warming to less than 1.5°C until 2100. His previous and current research interests additionally include modeling of PV resources and PV prosumers.

GABRIEL LOPEZ received the master's degree in electrical engineering from LUT University, Finland, where he is currently pursuing the doctoral degree. He is a Researcher with the Group of Solar Economy. His field of research is the defossilization of energy-intensive industrial processes. His work also includes the study of energy transition for the Americas, having published results on energy transition for Bolivia. His research interests include electrification of industrial processes, defossilization of industrial feedstock, and the energy transition of industry.

POUL ALBERG ØSTERGAARD is a Full Professor in energy planning with the Department of Planning, Aalborg University, Denmark, listed on the Stanford list of top 2% scientist in the world. He has been working within the field of energy planning, since 1995, with a focus on simulation of energy systems based on high penetrations of renewable energy sources as well as on the design of renewable energy systems scenarios. He is the Head of the Study Board of Planning and Land Surveying with Aalborg University as well as the Program Director of the M.Sc. Program in Sustainable Energy Planning and Management with Aalborg University. He is the Editor-in-Chief of the *International Journal of Sustainable Energy Planning and Management* as well as a co-editor of a series of other energy journals.

HENRIK LUND received the M.Sc. degree in engineering, in 1985, the Ph.D. degree in implementation of sustainable energy systems, in 1990, and the Doctor of Technology degree in choice awareness and renewable energy systems, in 2009. He is a Danish Engineer and a Professor in energy planning with Aalborg University, Denmark. He is a highly ranked world leading researcher. He is listed on the Stanford list of top 2% scientist in the world and among ISI highly cited researchers ranking him among the top 1% researchers in the world within engineering. He is the author of more than 600 books and articles including the book *Renewable Energy Systems*. He is the Architect behind the advanced energy systems analysis software EnergyPLAN, which is a freeware used worldwide that have formed the basis of more than 200 peer-reviewed journal articles around the world. He is the Editor-in-Chief of the high-impact journal *Energy* (Elsevier) with annual over 10000 submissions.

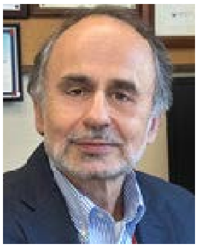
BRIAN V. MATHIESEN received the Ph.D. degree in fuel cells and electrolysers in future energy systems, in 2008. He is a Full Professor in energy planning and renewable energy systems with Aalborg University. His research focuses on technological and socio-economic transitions to renewables, energy storage, large-scale renewable energy integration, and the design of 100% renewable energy systems. His research interests include on the technological and socio-economy. He is one of the leading researchers behind the concepts of smart energy systems and electrofuels. He is on Thomson Reuters highly cited list, a global list of the top 1% cited researchers, a member of the EU Commission Expert Group on electricity interconnection targets in the EU, and a Principal Investigator (PI) of the RE-INVEST and sEEnergies projects. He is the Editor-in-Chief of *Smart Energy* (Elsevier).

MARK Z. JACOBSON received the B.Sc. degree in civil engineering, the A.B. degree in economics, and the M.Sc. degree in environmental engineering from Stanford University, in 1988, and the M.Sc. and Ph.D. degrees in atmospheric sciences from UCLA, in 1991 and 1994, respectively. He then joined the Faculty of Stanford University, in 1994. He is the Director of the Atmosphere/Energy Program and a Professor of civil and environmental engineering with Stanford University. His career focuses on better understanding air pollution and global warming problems and developing large-scale clean, renewable energy solutions to them. He has published six books and 175 peer-reviewed journal articles. He is also a Senior Fellow of the Woods Institute for the Environment and the Precourt Institute for Energy.

MARTA VICTORIA received the B.Sc. and M.Sc. degrees in aerospace engineering from the Technical University of Madrid and the Ph.D. degree in high-efficiency photovoltaic modules from the Solar Energy Institute, Technical University of Madrid. She is an Associate Professor with the Department of Mechanical and Production Engineering, Aarhus University, Denmark. Her research focuses on the modeling of large-scale energy systems with high renewable penetration paying special attention to the role of solar photovoltaics. She is a member of the Open Energy Modelling Initiative, which aims to promote openness and transparency in energy systems modeling, and she co-develops the open-source energy model PyPSA-Eur-Sec.

SVEN TESKE received the Ph.D. degree in economics from the University of Flensburg, Germany. He is an Associate Professor and the Research Director of the Institute for Sustainable Futures, University of Technology Sydney, Australia, with a research focus on energy decarbonisation pathways for specific industry sectors, countries, islands, and regions. 100% renewable energy concepts required to achieve the Paris Climate Agreement for countries, regions, cities, microgrids for islands, and the development of the national determined contribution (NDC) reports. This includes technical analysis of power grids regarding integration of solar electricity, onshore and offshore wind power generation, and electricity and heat storage systems. Furthermore, he has over 20 years' experience in renewable energy market and policy analysis. as well as solar and on- and offshore wind power grid integration concepts in public grids. In February 2019, he published the book *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* (Springer) as a lead author.

THOMAS PREGGER received the Diploma degree in environmental engineering from the TU Berlin and the Ph.D. degree in engineering from the University of Stuttgart. He is a Scientist and the Project Manager with the German Aerospace Center (DLR), Department of Energy Systems Analysis, Institute of Networked Energy Systems. He has nearly 25 years of experience in systems analysis and has been developing and evaluating long-term energy scenarios from national to global levels with his research group, since 2007. He has authored or coauthored more than 150 scientific publications, thereof around 40 in peer-reviewed journals. His main research interests include scenario and emissions modeling and evaluation, techno-economic assessment, and energy systems modeling.

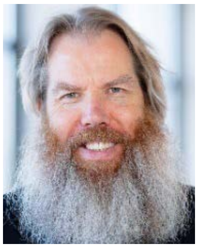


VASILIS FTHENAKIS (Fellow, IEEE) is the Founding Director of the Center for Life Cycle Analysis and a Professor of earth and environmental engineering with Columbia University, and a Distinguished Scientist Emeritus with the Brookhaven National Laboratory (BNL). His current research interests include solar water desalination, solar hydrogen, renewable energy systems integration, and life cycle analysis. He was the recipient of several awards and distinctions from the U.S.-Department of Energy (DOE), BNL, the National Renewable Energy Laboratory (NREL), and Institute of Electrical and Electronic Engineers (IEEE). He was the recipient of the 2018 IEEE William Cherry Award for his pioneering research at the interface of energy and the environment that catalyzed photovoltaic technology advancement and deployment worldwide; elected as a fellow of the IEEE, in 2021, for “contributions to photovoltaics technology; and has been a fellow of the American Institute of Chemical Engineers (AIChE), since 2002, in recognition and appreciation of superior attainments, valuable contributions and service to chemical engineering. He is world-known for his research at the interface of energy, water, and the environment. He is the author of two books, an editor of four more, and an author of about 400 publications on these topics.

MARCO RAUGEI received the degree in environmental engineering from the University of Florida, USA, and the Ph.D. degree in chemical sciences from the University of Siena, Italy. He is an expert in life cycle assessment (LCA), net energy analysis (NEA), and sustainability assessment. Currently, he is a Senior Research Fellow and a Senior Lecturer with the School of Engineering, Computing and Mathematics, Oxford Brookes University, U.K.; as well as a Visiting Scientist with the Center for Life Cycle Analysis, Columbia University, New York, USA; and a Senior Transport LCA Expert with Ricardo Energy and Environment. He has published over 60 scientific articles in peer-reviewed international journals, as well as over 100 other scientific documents among conference proceedings, reports, and chapters for scientific books and encyclopaedias. His main research interests include the theoretical improvement of existing approaches for environmental sustainability assessment, and their application to energy systems and the development of strategic energy supply and transport scenarios. He is a member of the International Energy Agency Photovoltaic Power Systems (PVPS) Program, Task 12.

HANNELE HOLTTINEN (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees from Helsinki Technical University. She has been a Docent with Helsinki Technical University, since 2014. She is a Partner with Recognis Oy and acting as an Operating Agent of IEAWIND Task 25 and the Pillar 5 Lead of G-PST. She is a Partner with Recognis Oy and acting as an Operating Agent of IEAWIND Task 25 and the Pillar 5 Lead of G-PST. Previously, she worked with the VTT Technical Research Centre of Finland for more than 25 years in different fields of wind energy and energy systems integration research, last years as a Principal Scientist.

UGO BARDI teaches physical chemistry at the University of Florence, Italy, where he is engaged in research on sustainability and energy with a special view on mineral resources, circular economy, and recycling. He is a member of the Club of Rome and several international scientific organizations. He is active in the dissemination of scientific results in sustainability and climate science on the blog "The Seneca Effect" (www.thesenecaeffect.blogspot.com). He is the author of numerous papers on sustainability and the books *The Limits to Growth Revisited* (Springer 2011), *Extracted: How the Quest for Mineral Wealth Is Plundering the Planet* (Chelsea Green, 2014), *The Seneca Effect* (Springer 2017), *Before the Collapse* (Springer 2019), and *The Empty Sea* (Springer 2021). His books have been translated into Italian, French, German, Spanish, and Rumenian. He is the Chief Editor of the *Biophysical Economics and Sustainability* (Springer).



AUKE HOEKSTRA works with the Eindhoven University of technology. He is the Founder and the Director of NEONresearch.nl that aims to "light the way to zero emission energy and mobility" with a focus on developing integral agent-based models of the energy and mobility transition. He specializes in the design of these models and in the planetary impact and adoption of electric cars and trucks. With his company Zenmo he translates this scientific knowledge for policy makers and companies. He is a frequent speaker on (mainly Dutch) TV, radio, podcasts, and webinars. In his previous career, he was an Independent Project Leader implementing Internet technology in telecom companies when that was still novel and before that he mastered in public administration with the University of Twente.

BENJAMIN K. SOVACOOL is a Professor of earth and environment with Boston University, USA, as well as a Professor of energy policy with the Science Policy Research Unit (SPRU), University of Sussex Business School, U.K. He is also a University Distinguished Professor of business and social sciences with Aarhus University, Denmark. He works as a Researcher and a Consultant on issues pertaining to energy policy, energy justice, energy security, climate change mitigation, and climate change adaptation. More specifically, his research focuses on renewable energy and energy efficiency, the politics of large-scale energy infrastructure, the ethics and morality of energy decisions, designing public policy to improve energy security and access to electricity, and building adaptive capacity to the consequences of climate change. With much coverage of his work in the international news media, he is one of the most highly cited global researchers on issues bearing on controversies in energy and climate policy.

• • •