The role of flexibility in the light of the COVID-19 pandemic and beyond

Heffron, Raphael J.; Körner, Marc-Fabian; Schöpf, Michael; Wagner, Jonathan; Weibelzahl, Martin

DOI:
10.1016/j.rser.2021.110743

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

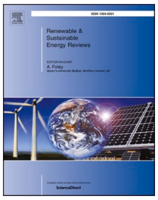
Citation for published version (APA):
Heffron, R. J., Körner, M-F., Schöpf, M., Wagner, J., & Weibelzahl, M. (2021). The role of flexibility in the light of the COVID-19 pandemic and beyond: Contributing to a sustainable and resilient energy future in Europe. *Renewable and Sustainable Energy Reviews*, *140*, [110743]. https://doi.org/10.1016/j.rser.2021.110743

Renewable and Sustainable Energy Reviews 140 (2021) 110743

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser



The role of flexibility in the light of the COVID-19 pandemic and beyond: Contributing to a sustainable and resilient energy future in Europe

Raphael J. Heffron[a,b,*], Marc-Fabian Körner[c,d], Michael Schöpf[e], Jonathan Wagner[d], Martin Weibelzahl[c,d]

[a] University of Dundee, Centre for Energy, Petroleum and Mineral Law and Policy, Scotland, UK
[b] Senior Counsel, Jansen, Brussels, Belgium
[c] FIM Research Center, University of Bayreuth, Bayreuth, Germany
[d] Project Group Business & Information Systems Engineering of the Fraunhofer FIT, Bayreuth, Germany
[e] SnT – Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg, Luxembourg

ARTICLE INFO

Keywords:
COVID-19
Electricity system flexibility
Renewable energy sources
Resilience
Sustainability
Sustainable development goals

ABSTRACT

The energy sector provides fuel for much of everyday life, particularly economically and socially. Fighting against the COVID-19 pandemic, a well-functioning and resilient energy sector is vital for maintaining the operation of critical infrastructures, including, most importantly, the health sector, and timely economic recovery. Notwithstanding its importance in everyday life and crises, the energy sector itself is currently in a complex and far-reaching transformation to combat climate change whilst supporting the transition to a low-carbon economy and society, mainly through the development of variable renewable energy sources (RES) such as wind and solar photovoltaics. This paper highlights the need for energy resilience as countries face the triple challenge of the COVID-19 health crisis, the consequent economic crisis, and the climate crisis. Focusing on Europe, it is advanced here that with the ability to balance fluctuating electricity generation and demand, flexibility allows the energy sector to utilise low-carbon RES reliably, ensuring a more resilient and sustainable energy future. This paper derives five urgent policy recommendations for Europe that address possible impacts of COVID-19 on the economic and societal prerequisites for flexibility in energy systems.

1. Introduction

In everyday life, energy forms the basis of economic welfare and the satisfaction of societal needs, including education, nutrition, and leisure activities. The COVID-19 pandemic and the consequent economic recession stress the crucial role of a well-functioning energy system in times of crises [1]. While energy access has proved pivotal for healthcare and households during the current crisis [2], it will also be a precondition for a smooth post-COVID-19 economic recovery.

With the global economy shutting down almost completely within only a couple of weeks of the declaration of the pandemic, electricity systems around the world faced severe shocks both on the supply and demand side. For example, countries experienced an overall decrease in electricity consumption, altered consumption profiles, and a temporally strong decrease of fuel prices that affected the dispatch of power plants [3–8]. Despite these shocks, initial evidence indicates that in many countries, electricity systems operated without far-reaching blackouts [9]. Hence, if one were to see the COVID-19 pandemic as a stress test on the resilience of global electricity systems, one could draw the preliminary conclusion that electricity systems worked quite well. While COVID-19 underlines the importance of reliable electricity supply in crises situations, this paper argues that resilience cannot be taken for granted in future electricity systems.

With the ongoing complex energy transition from high-carbon towards low-carbon systems and an increasing share of renewable energy sources (RES), a stable operation of the electricity system is at risk [10–12]. While RES such as wind and solar photovoltaics (PV) allow for a more sustainable generation of electricity and are therefore a means to combat climate change [13], they are, however, also highly variable [14]. The limited controllability of RES threatens the stable operation of future electricity systems, potentially leading to an increase in the costs of system operation when a high level of energy security is desired [11]. For instance, costs for grid interventions and in-feed management reached 1.2 billion Euros in 2019 in Germany [15]. As such costs are often directly passed on to end consumers [16], they threaten the

---

* Corresponding author.
E-mail address: r.heffron@dundee.ac.uk (R.J. Heffron).

https://doi.org/10.1016/j.rser.2021.110743
Received 11 July 2020; Received in revised form 13 December 2020; Accepted 16 January 2021
Available online 30 January 2021

Nomenclature

CO_2	Carbon dioxide
COVID-19	Corona Virus Disease 2019
GHG	Greenhouse gas
PV	Photovoltaics
RES	Renewable energy sources
SDGs	Sustainable Development Goals

general affordability of energy. Above all, such costs may contribute to energy poverty, which is a severe worldwide challenge to be solved [17].

This paper considers the current COVID-19 pandemic as an instigator for change. Given the coincidence of three different crises at the same time – the COVID-19 health crisis, the consequent economic crisis, and the climate crisis – this paper aims to advance the role of flexibility in the electricity system. In particular, it highlights how the COVID-19 pandemic can contribute to successfully integrating RES into the energy system and delivering increased resilience, preparing the electricity system for future shocks that may, for instance, also stem from natural disasters [18,19].

Flexibility is defined as the ability of the electricity system to react to changes in supply and demand to ensure a corresponding spatiotemporal balance in the underlying electricity grid [20]. Against this background, flexibility is a precondition for a stable and resilient electricity system. To successfully integrate RES, and to maintain or even increase the resilience of future electricity (and, ultimately, energy) systems, post-COVID-19 energy policy formulation needs to ensure that the flexibility of future electricity systems is further strengthened through adequate policy measures and corresponding flexibility investments. The development of sufficient flexibility has a two-fold benefit of meeting societies' energy and climate targets and ensuring that the electricity system plays its role in securing sustainable, long-term economic growth while contributing to the United Nations' Sustainable Development Goals (SDGs). In this context, a stable and resilient electricity system that activates and integrates the relevant flexibility suppliers (including, for example, industrial companies, households, owners of electric vehicles, or storage facility operators) may lead to a more inclusive and just energy system benefitting all relevant stakeholders, that is, citizens, society, industrial companies, the environment, etc. While this paper focuses on European countries, its implications may be relevant for all countries facing the challenges described above.

The remainder of this paper is structured as follows. Section 2 briefly reflects on the need for resilience in future electricity systems. Section 3 reviews the concept of flexibility as a basis for a resilient electricity system. Section 4 draws on possible challenges concerning the flexibility transition and derives specific recommendations for policymakers during and after COVID-19. Finally, Section 5 presents the conclusions.

2. Need for resilience in the electricity system

Given external short-run shocks in various supply networks and shortages of certain goods during the COVID-19 pandemic [21–23], the term resilience has gained increasing attention as a design principle for future critical infrastructure, including food systems [21,24], health systems [25,26], and electricity systems [27–29]. Resilience as the "ability to absorb shocks and still retain function" [12] has been discussed in the electricity system literature for several years already. In the United States, the National Research Council [30] defines resilience as "the ability to prepare, plan for, store, recover from, and more successfully adapt to adverse events". Notwithstanding its long tradition, the importance of electricity system resilience should not be underestimated, as it helps to counter short-run shocks that would otherwise destabilise the entire electricity system [18]. In turn, a collapsed electricity system may directly have detrimental effects on economic and social life. Regardless of whether it is the agricultural, the educational, or the industrial sector, none can function without electricity [31]. In this context, even short electricity supply interruptions may have adverse effects on safety, product quality, or production waste [31].

There are many examples of disastrous power outages in the past. In 2012, two major blackouts in India left around 600 million people without electricity [32]. More recently, in 2019, Argentina, Paraguay, and Uruguay were affected by a massive blackout, demonstrating the detrimental effects of cascading failures in coupled electricity systems [33]. Globally, lack of resilience is typically associated with increased costs for operating an electricity system [34]. Such costs comprise not only necessary grid interventions and supply re-storage, but also insurance needed by companies, necessary repair work at production plants and home appliances, or increased production waste. Additionally, lack of resilience can incur social costs and lead to social unrest due to blackouts [35]. In many countries, the above costs are directly passed on to society in its role as consumers [36], which then may also challenge energy affordability and contribute to energy poverty [37]. This issue is also stressed by current governmental measures to protect energy consumers in the COVID-19 crisis from the consequences of energy poverty [38].

With respect to energy law and policy which build the governance framework of an electricity system, literature calls for seven core principles for law and policy formulation, where resilience is among these guiding principles [39]. Against this background, modern law, regulations, and rules must set the right incentives to strengthen resilience in electricity systems [40]. One key component lies in new system flexibility, as will be further elaborated in the next section.

3. What is electricity system flexibility?

Endeavours to decarbonise the electricity system have been initiated globally to counteract and possibly reverse the detrimental effects of climate change. Generally, electricity system transformations build on an increasing share of RES, such as solar PV and wind, which are highly variable [14]. Such variability is due to the fact that the sun does not always shine, and the wind does not always blow. As the laws of physics (e.g., Kirchhoff's Laws) require electricity supply and demand to be balanced, such variability particularly challenges a reliable electricity grid operation [41]. With the storage capacity of traditional technologies being limited in several European countries due to social, economic, technical, or environmental constraints (e.g., pumped hydropower [42]) and with new storage technologies not yet being available at reasonable costs in large scales (e.g., batteries and power-to-gas), other options for electricity system flexibility must additionally compensate for the growing variability on the supply side stemming from the increasing feed-in from RES [20,31,43,44,89]. In this way, flexibility may directly contribute to the resilience of future low-carbon electricity systems.

Flexibility may come in different forms, serve specific purposes in an electricity system, and be characterised by different time frames [45]. In particular, there are five main technical flexibility options to be developed in future electricity systems [20,31] including (1) supply-side flexibility (provided, e.g., by highly efficient gas power plants), (2) transmission flexibility (i.e., by an extension of the electricity grid), (3) demand-side flexibility (e.g., demand-side management of industry or households), (4) inter-sectoral flexibility (i.e., connecting the energy sector with other sectors such as mobility or heat), and (5) storage flexibility (provided, e.g., by electric batteries) [20,46–52]. Depending on the technical flexibility option chosen, flexibility may allow for balancing local and temporal mismatches between supply and demand [43,53].

In many countries, the RES-driven demand for new flexibility is additionally fuelled by the phaseout of conventional power plants such as coal power plants [43]. In Germany, coal-fired power plants currently provide a large share of the necessary energy system flexibility from the supply side to solve grid bottlenecks – as can be seen from recent data on redispatch in Germany, see, for example, [54]. Generally, these power plants are expected to run with higher ramping rates in the future [43,45,54,55]. In addition, the ongoing electrification of sectors traditionally based on fossil fuels, for example, the mobility sector, results in growing electricity demand, which, if met by RES, will require even more system flexibility to counteract volatility in electricity generation [56].

Against this background, research has identified an increasing demand for flexibility in electricity systems where the energy transition is based on variable RES, such as wind and solar PV, that replace conventional power plants for electricity supply [14,55–57]. For example, [58] provide an overview of the flexibility needs of the European energy system in 2030. Applying a similar time frame, [59] discuss the flexibility requirements in Europe for a system in which RES make up a 50% share. Additionally, the European transmission system operators make projections of a strongly increasing flexibility demand for 2025, 2030, and 2040 [60]. For an even longer time frame, [61,62] project the increasing flexibility needs in Europe in 2050.

Research refers to these flexibility needs as the “flexibility gap” that is expected to appear in the future [45,63,64] and needs to be addressed using specific policy targets for flexibility expansion in analogy to the targets for RES expansion set in countries such as Germany [45]. Otherwise, lack of flexibility may directly lead to a decrease in supply security and pose a threat to the resilience of future electricity systems [31]. Such a decrease would also result in high societal costs, as highlighted in the previous section. In Europe, the COVID-19 pandemic has highlighted the importance of electricity supply security – which, to a large degree, builds on electricity system flexibility in the future [65–67]. However, the pathway towards a successful expansion of flexibility is still non-existing or highly vague in many countries [31] and may even be further obscured by the COVID-19 pandemic. As such, this paper emphasises the mid-to-long-term perspective on flexibility. In contrast, the short-term mechanisms to deploy flexibility such as balancing power markets, for example, seem to work correctly, which is also reflected by the so far maintained stability of the electricity system during the COVID-19 pandemic [68]. However, such short-term stability cannot be generalised for the upcoming decades and, therefore, flexibility needs to be a crucial component of the future energy system and must be considered from a holistic context [43].

It is only very recently that research has explored the wider societal implications of energy system flexibility [69–72]. Overall, there is a growing consensus over the negatives resulting from electricity generation, transmission, and consumption, all of which may affect the environment, the wider society, or the economy (which directly relates to the three dimensions of the energy trilemma) [73]. Recently, the 2015 Paris climate agreement and the United Nations’ SDGs have stressed the importance of the energy transition happening in a way that is “just”. Taking up this call for a just transition from a high-carbon towards a low-carbon economy and society [74], researchers started to analyse how the development of and investment in electricity system flexibility may affect justice in the electricity system and the wider society [31,69,75]. There are multiple goals to which flexibility may actually contribute to – from SDG7 (affordable and clean energy) to the other 16 SDGs [76].

In this context, the term “flexibility justice” has been introduced by [69], which is further advanced in [31] for the flexibility option of industrial demand-side flexibility. Being an applied form of justice [69], flexibility justice is a key for the overall energy system transformation of countries and calls for an active involvement of all the relevant stakeholders concerning the investment in new flexibility, the actual trade and supply of flexibility, as well as the fair distribution of overall flexibility costs and benefits (e.g., reduced electricity bills) in a future electricity system. Stakeholders shall be involved in the formulation of appropriate energy laws and policies already from the beginning, which builds the basis for an inclusive flexibility transition towards a low-carbon, resilient, and just electricity system (see also the previous section). In this context, COVID-19 has significantly affected the economic and societal prerequisites for flexibility [18,77] (including a possible change in public attitudes and, therefore, societal acceptance) and these effects must be considered when designing the actual pathway.

4. Potential of flexibility during and after COVID-19

This section derives five policy recommendations that address the possible impacts of COVID-19 on the economic and societal prerequisites for flexibility. While these policy recommendations mainly focus on Europe, they may also be highly relevant for all countries coping with the issues mentioned above.

i. Ensuring flexibility is at the heart of the energy transition

Adverse effects and shocks will always produce winners and losers, tending to polarise society [17]. COVID-19 might inhibit similar effects. Policy faces the challenging tasks of balancing corresponding gains and costs that may intertwine with the effects of the energy transition itself. Countries are generally on a critical path to a successful energy transition without really knowing how the path will look. With COVID-19, it seems that additional fog has emerged that reduces the policy vision in many countries [78]. However, policymakers and the broader public must know flexibility is indispensable. Therefore, flexibility must play an important role in a future low-carbon electricity system and a targeted pathway towards such a future – complementary to other objectives. As the European Union has discussed the first European Climate Law during COVID-19, policymakers need to immediately understand the role of flexibility and ascribe it the required role in law. Here, it is necessary to define long-term goals for the flexibility expansion in an electricity system, which complement the goals for the expansion of RES feed-in capacities [79]. These goals must then be translated into specific measures and corresponding investments [80] (for more details see also the next subsections).

ii. Ensuring immediate policy action to increase flexibility investments in the electricity system during COVID-19

Keeping the energy and flexibility transition going requires active policy endeavours to support flexibility investments, which are already needed during the COVID-19 pandemic. With huge rescue and economic recovery plans (e.g., there is a 130 billion Euros recovery package in Germany) being planned and implemented, governments must act now and not lose time in the flexibility transition. Here, it is important that the COVID-19 pandemic does not push the energy and flexibility transition off the political agenda. Instead, the momentum of governmental action, which has proven to be effective in the past wave of COVID-19, should also be used to integrate incentives for flexibility investments in economic recovery programs. The challenge is to align these incentives with national or supranational goals and principles, such as the avoidance of discrimination against specific flexibility technologies. If some mechanisms are, for instance, only open for conventional supply flexibility technologies, this may lead to a lock-in effect. Here, actual fuel prices must generally account for externalities, such as environmental costs associated with CO_2 emissions. Gas-fired power plants, for example, will undoubtedly play a decisive role in the future energy system due to the technological ability to ramp up quickly and the much lower greenhouse gas (GHG) emissions compared to coal power plants. Policymakers should, however, provide the incentives for, for instance, “green” gas being used in the energy system [81]. Overall, policymakers must consider early on possible trade-offs between the flexibility that different technologies can provide and the energy transition’s overall goal of decarbonising the energy system. Against this background, what policymakers should ultimately avoid are path dependencies, in which some technologies are preferred over others, although the flexibility potential of the former might be outpaced by the potential of the latter in the future, making the electricity system inflexible.

iii. Creating long-run investor certainty for flexibility options

Probably, the most direct economic impact of COVID-19 on flexibility was the temporary drop in fossil fuel prices due to a demand shock [82]. Low fuel prices generally increase the competitiveness of flexibility assets that are based on GHG-emitting fossil fuels. As a result, the economic prospects for non-fossil flexibility options such as storage declined temporarily and therefore created planning uncertainty, while the prospects for fossil fuels temporarily increased. Such uncertainty and the corresponding (dis-)incentives may impede the transition towards GHG neutral flexibility options that require high investments to realise the necessary new system flexibility. Indeed, during COVID-19, some electricity utilities made massive orders of oil and gas when corresponding fuel prices were low, even building new tanks to store them. Against this background, it is now vital to create certainty for flexibility investments and clear pathways for stakeholders to invest in flexibility, accounting for the fact that investments are typically associated with long-term rather than immediate rewards. The investment plans and programs mentioned must therefore be in line with reliable long-term climate goals of national governments based on a broad public consensus on these goals (see also the next paragraph on the role of stakeholders). These ambitions should also rely on a principle-based approach to legal formulation to ensure investor certainty and public consensus [39]. This will create a coherent, stable, and credible investment climate. Here, it is equally important that politicians acting as policymakers do not arbitrarily adjust or misuse corresponding programs to maximise their short-run chances of re-election. Otherwise, a non-credible investment environment will make private investors wait and postpone their flexibility investments.

iv. Increasing the role of stakeholders in the flexibility transition

The COVID-19 pandemic demonstrates that global crises affect every country and human on earth. Increased awareness of such global interdependencies may offer the opportunity to strengthen the involvement of various stakeholders in the transition to a low-carbon economy and society and the fight against climate change. As a current example, despite the COVID-19 pandemic and its negative economic effects, Germany has drafted legislation for its phaseout of coal by 2038 based on recommendations of a coal exit commission that collected the fears and hopes of the main stakeholders, which is also classed as part of the just transition to a low-carbon economy. In this way, the public (and, e.g., not only industrial companies) could actively influence the chosen pathway for Germany's energy future. However, some parts of the public may not accept the necessary measures to counteract the global challenges of climate change, as the threat of climate change is rather abstract [83] and the success of a (costly) countermeasure can only be observed with a high time delay. Here, it is important to inform and educate the public about the detrimental effects of climate change and the corresponding need for a flexibility transition. Possibly, the public perception about the "value of prevention" might also have changed with COVID-19 and the necessary lockdown measures. Against this background, research may further elaborate on the question of whether public acceptance for other preventative measures (e.g., measures to counteract climate change) has actually changed during the pandemic and whether society as a whole is now more open to the energy and flexibility transition than before. As many European countries currently draw new energy legislation, possibly increased public awareness may then directly translate into increased involvement of stakeholders during COVID-19.

v. Ensuring flexibility justice and contribution to the United Nations' SDGs

Electricity supply is pivotal for all countries and their future development, both in terms of economic growth and societal development. The actual pathways to a low-carbon electricity system need to be based on flexibility, the United Nations' SDGs, and energy justice (which incorporates the following key justice perspectives: procedural, distributive, recognition, cosmopolitanism, and restorative) [31,84,85]. In this context, policy measures to counteract energy poverty should continuously be implemented – also in times of no crisis. Here, energy flexibility may help to lower the overall costs of operating a low-carbon energy system [86–88], where end consumers may directly benefit from reduced electricity prices. Countries must also ensure that currently drafted short-term recovery programmes for the economy do not risk achieved success concerning justice and SDGs. This includes SDG 7, that is, access to affordable, reliable, and sustainable energy for all, but also other important goals that, for instance, focus on access to education, healthcare services, or food. In this context, current global cooperation (including funding initiatives) to help developing countries realising the benefits that new system flexibility will bring is undoubtedly a key to the worldwide success of the SDGs.

5. Conclusion

The COVID-19 pandemic underlines the importance of well-functioning and resilient electricity systems. System flexibility will be crucial to ensure and strengthen the resilience of future low-carbon electricity systems that rely on an increasingly variable electricity supply from RES. Flexibility is defined as the ability to address imbalances between electricity demand and supply and can be delivered by various technical flexibility options, including electrical storage or sectoral coupling. Unfortunately, in the societal and economic spheres, the COVID-19 pandemic has impacted the pathway towards the necessary expansion of flexibility.

This paper highlights five policy recommendations for system flexibility during and after COVID-19 to keep the direction and accelerate the speed of the flexibility transition. As this paper argues, policymakers must act now and ensure that flexibility is an important component of an ongoing energy transition, which must not be paused but rather strengthened. Investment certainty is important to ensure sufficient flexibility and avoid lock-in into an electricity system that is based on fossil fuels. Finally, this paper calls for an active role and involvement of different stakeholders in the flexibility transition, ensuring (flexibility) justice and a successful contribution to the United Nations' SDGs. Future research must support policymakers in implementing corresponding measures quickly and this requires close and effective collaboration between different research disciplines. In this way, the COVID-19 pandemic can be a catalyst for the needed change in European energy systems in the battle against climate change.

Declaration of competing interest

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

Acknowledgments

The authors gratefully acknowledge the financial support of the Kopernikus-Project "SynErgie" by the BMBF – Federal Ministry of Education and Research, Germany and the project supervision by the project management organization Projektträger Jülich (PtJ). Supported by PayPal and the Luxembourg National Research Fund FNR (P17/IS/13342933/PayPal-FNR/Chair in DFS/Gilbert Fridgen).

References

[1] Birol F. The coronavirus crisis reminds us that electricity is more indispensable than ever [June 07, 2020]; Available from: https://www.iea.org/commentaries/the-coronavirus-crisis-reminds-us-that-electricity-is-more-indispensable-than-ever.

[2] Castán Broto V, Kirshner J. Energy access is needed to maintain health during pandemics. Nat Energy 2020;5(6):419–21. https://doi.org/10.1038/s41560-020-0625-6.

[3] Bahmanyar A, Estebsari A, Ernst D. The impact of different COVID-19 containment measures on electricity consumption in Europe. Energy Research & Social Science 2020;68:101683. https://doi.org/10.1016/j.erss.2020.101683.

[4] Norouzi N, Zarazua de Rubens G, Choupanpiesheh S, Enevoldsen P. When pandemics impact economies and climate change: exploring the impacts of COVID-19 on oil and electricity demand in China. Energy Research & Social Science 2020; 68:101654. https://doi.org/10.1016/j.erss.2020.101654.

[5] Abu-Rayash A, Dincer I. Analysis of the electricity demand trends amidst the COVID-19 coronavirus pandemic. Energy Research & Social Science 2020:101682. https://doi.org/10.1016/j.erss.2020.101682.

[6] Ghiani E, Galici M, Mureddu M, Pilo F. Impact on electricity consumption and market pricing of energy and ancillary services during pandemic of COVID-19 in Italy. Energies 2020;13(13):3357. https://doi.org/10.3390/en13133357.

[7] Global IEA. Energy Review 2020: the impacts of the Covid 19 crisis on global energy demand and CO2 emissions. 2020.

[8] Bildirici M, Guler Bayazit N, Ucan Y. Analyzing crude oil prices under the impact of COVID-19 by using LSTARGARCHLSTM. Energies 2020;13(11):2980. https://doi.org/10.3390/en13112980.

[9] European Commission. In focus: energy security in the EU [July 11, 2020]; Available from: https://ec.europa.eu/info/news/focus-energy-security-eu-2020-avr-27_en.

[10] Newbery D, Pollitt MG, Ritz RA, Strielkowski W. Market design for a high-renewables European electricity system. Renew Sustain Energy Rev 2018;91: 695–707. https://doi.org/10.1016/j.rser.2018.04.025.

[11] Coester A, Hofkes MW, Papyrakis E. Economics of renewable energy expansion and security of supply: a dynamic simulation of the German electricity market. Appl Energy 2018;231:1268–84.

[12] Nolting L, Praktiknjo A. Can we phase-out all of them? Probabilistic assessments of security of electricity supply for the German case. Appl Energy 2020;263:114704. https://doi.org/10.1016/j.apenergy.2020.114704.

[13] Coninck H de, Revi A, Babiker M, Bertoldi P, Buckeridge M, Cartwright A, et al. Strengthening and implementing the global response. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, et al., editors. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC; 2018. https://www.ipcc.ch/sr15/.

[14] Kondziella H, Bruckner T. Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies. Renew Sustain Energy Rev 2016;53:10–22. https://doi.org/10.1016/j.rser.2015.07.199.

[15] Bundesnetzagentur. Zahlen zu Netz- und Systemsicherheitsmaßnahmen - gesamtjahr 2019 [December 01, 2020]; Available from: https://www.bundesnetzagentur.de/SharedDocs/Mediathek/Berichte/2020/Quartalszahlen_Gesamtjahr_2019.pdf?__blob=publicationFile&v=9.

[16] Paraschiv F, Erni D, Pietsch R. The impact of renewable energies on EEX day-ahead electricity prices. Energy Pol 2014;73:196–210.

[17] Sovacool BK. The political economy of energy poverty: a review of key challenges. Energy for Sustain Dev 2012;16(3):272–82. https://doi.org/10.1016/j.esd.2012.05.006.

[18] Hynes W, Trump B, Love P, Linkov I. Bouncing forward: a resilience approach to dealing with COVID-19 and future systemic shocks. Environ Syst Decis 2020;40(2): 174–84. https://doi.org/10.1007/s10669-020-09776-x.

[19] Molyneaux L, Wagner L, Froome C, Foster J. Resilience and electricity systems: a comparative analysis. Energy Pol 2012;47:188–201. https://doi.org/10.1016/j.enpol.2012.04.057.

[20] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. https://doi.org/10.1016/j.rser.2015.01.057.

[21] Hobbs JE. Food supply chains during the COVID-19 pandemic. Canad J Agric Econ/Rev Canad Agroec 2020. https://doi.org/10.1111/cjag.12237.

[22] Ivanov D, Dolgui A. Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. Int J Prod Res 2020;58(10):2904–15. https://doi.org/10.1080/00207543.2020.1750727.

[23] Ivanov D. Viable supply chain model: integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the COVID-19 pandemic. Ann Oper Res 2020. https://doi.org/10.1007/s10479-020-03640-6.

[24] Moran D, Cossar F, Merkle M, Alexander P. UK food system resilience tested by COVID-19. Nat Food 2020;1. https://doi.org/10.1038/s43016-020-0082-1.

[25] Legido-Quigley H, Asgari N, Teo YY, Leung GM, Oshitani H, Fukuda K, et al. Are high-performing health systems resilient against the COVID-19 epidemic? Lancet 2020;395:848–50. https://doi.org/10.1016/S0140-6736(20)30551-1. 10227.

[26] Fridell M, Edwin S, Schreeb J von, Saulnier DD. Health system resilience: what are we talking about? A scoping review mapping characteristics and keywords. Int J Health Pol Manag 2020;9(1):6–16. https://doi.org/10.15171/ijhpm.2019.71.

[27] Ivanov D, Das A. Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: a research note. Int J Integrated Supply Manag 2020.

[28] Ivanov D. Predicting the impacts of epidemic outbreaks on global supply chains: a simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. Transp Res E Logist Transp Rev 2020;136:101922. https://doi.org/10.1016/j.tre.2020.101922.

[29] Madurai Elavarasan R, Shafiullah GM, Raju K, Mudgal V, Arif MT, Jamal T, et al. COVID-19: impact analysis and recommendations for power sector operation. Appl Energy 2020;279:115739. https://doi.org/10.1016/j.apenergy.2020.115739.

[30] National Research Council. Disaster resilience: a national imperative. Washington, DC: National Academies Press; 2012.

[31] Heffron R, Körner M-F, Wagner J, Weibelzahl M, Fridgen G. Industrial demand-side flexibility: a key element of a just energy transition and industrial development. Appl Energy 2020;269:115026. https://doi.org/10.1016/j.apenergy.2020.115026.

[32] Romero J. Blackouts illuminate India's power problems. IEEE Spectr 2012;49(10): 11–2. https://doi.org/10.1109/MSPEC.2012.6309237.

[33] Yuan P, Zhang Q, Zhang T, Chi C, Zhang X, Li P et al. Analysis and enlightenment of the blackouts in Argentina and New York. In: 2019 Chinese automation congress (CAC). IEEE, p. 5879–5884.

[34] Ji C, Wei Y, Mei H, Calzada J, Carey M, Church S, et al. Large-scale data analysis of power grid resilience across multiple US service regions. Nat Energy 2016;1(5). https://doi.org/10.1038/nenergy.2016.52.

[35] Matthewman S, Byrd Hugh. Blackouts: a sociology of electrical power failure. Soc Space 2013:31–55.

[36] Nooij M de, Lieshout R, Koopmans C. Optimal blackouts: empirical results on reducing the social cost of electricity outages through efficient regional rationing. Energy Econ 2009;31(3):342–7. https://doi.org/10.1016/j.eneco.2008.11.004.

[37] Smith-Nonini S. The debt/energy nexus behind Puerto Rico's long blackout: from fossil colonialism to new energy poverty. Lat Am Perspect 2020;47(3):64–86. https://doi.org/10.1177/0094582X20911446.

[38] Mastropietro P, Rodilla P, Batlle C. Emergency measures to protect energy consumers during the Covid-19 pandemic: a global review and critical analysis. Energy Research & Social Science 2020;68:101678. https://doi.org/10.1016/j.erss.2020.101678.

[39] Heffron RJ, Rønne A, Tomain JP, Bradbrook A, Talus K. A treatise for energy law. J World Energy Law Bus 2018;11(1):34–48. https://doi.org/10.1093/jwelb/jwx039.

[40] Newell B, Marsh DM, Sharma D. Enhancing the resilience of the Australian national electricity market: taking a systems approach in policy development. Ecol Soc 2011;16(2).

[41] Weibelzahl M. Nodal, zonal, or uniform electricity pricing: how to deal with network congestion. Front Energy 2017;11(2):210–32. https://doi.org/10.1007/s11708-017-0460-z.

[42] Steffen B. Prospects for pumped-hydro storage in Germany. Energy Pol 2012;45: 420–9.

[43] Fridgen G, Keller R, Körner M-F, Schöpf M. A holistic view on sector coupling. Energy Pol 2020;147:111913. https://doi.org/10.1016/j.enpol.2020.111913.

[44] Körner M-F, Bauer D, Keller R, Rösch M, Schlereth A, Simon P, et al. Extending the automation pyramid for industrial demand response. Procedia CIRP 2019;81: 998–1003. https://doi.org/10.1016/j.procir.2019.03.241.

[45] Papaefthymiou G, Haesen E, Sach T. Power System Flexibility Tracker: indicators to track flexibility progress towards high-RES systems. Renew Energy 2018;127: 1026–35. https://doi.org/10.1016/j.renene.2018.04.094.

[46] Schöpf M, Weibelzahl M, Nowka L. The impact of substituting production technologies on the economic demand response potential in industrial processes. Energies 2018;11(9):2217. https://doi.org/10.3390/en11092217.

[47] Grimm V, Martin A, Weibelzahl M, Zöttl G. On the long run effects of market splitting: why more price zones might decrease welfare. Energy Pol 2016;94: 453–67. https://doi.org/10.1016/j.enpol.2015.11.010.

[48] Haupt L, Schöpf M, Wederhake L, Weibelzahl M. The influence of electric vehicle charging strategies on the sizing of electrical energy storage systems in charging hub microgrids. Appl Energy 2020;273:115231. https://doi.org/10.1016/j.apenergy.2020.115231.

[49] Weibelzahl M, Märtz A. Optimal storage and transmission investments in a bilevel electricity market model. Ann Oper Res 2020;287(2):911–40. https://doi.org/10.1007/s10479-018-2815-1.

[50] Weibelzahl M, Märtz A. On the effects of storage facilities on optimal zonal pricing in electricity markets. Energy Pol 2018;113:778–94. https://doi.org/10.1016/j.enpol.2017.11.018.

[51] Grimm V, Martin A, Schmidt M, Weibelzahl M, Zöttl G. Transmission and generation investment in electricity markets: the effects of market splitting and network fee regimes. Eur J Oper Res 2016;254(2):493–509. https://doi.org/10.1016/j.ejor.2016.03.044.

[52] Haupt L, Körner M-F, Schöpf M, Schott P, Fridgen G. Structured analysis of demand response in the electricity system and deduction of a generic business model for (Energy-Intensive) companies. Z Energiewirtschaft 2020;44(2):141–60. https://doi.org/10.1007/s12398-020-00279-5.

[53] D'hulst R, Ridder F de, Claessens B, Knapen L, Janssens D. Decentralized coordinated charging of electric vehicles considering locational and temporal flexibility. Int. Trans. Electr. Energ. Syst. 2015;25(10):2562–75. https://doi.org/10.1002/etep.1983.

[54] Informationplatform of German TSOs - Netztransparenz.de. Redispatch-measures [December 10, 2020]; Available from: https://www.netztransparenz.de/EnWG/Redispatch.

[55] Martinot E. Grid integration of renewable energy: flexibility, innovation, and experience. Annu Rev Environ Resour 2016;41(1):223–51. https://doi.org/10.1146/annurev-environ-110615-085725.

[56] Papaefthymiou G, Dragoon K. Towards 100% renewable energy systems: uncapping power system flexibility. Energy Pol 2016;92:69–82. https://doi.org/10.1016/j.enpol.2016.01.025.

[57] Deason W. Comparison of 100% renewable energy system scenarios with a focus on flexibility and cost. Renew Sustain Energy Rev 2018;82:3168–78. https://doi.org/10.1016/j.rser.2017.10.026.

[58] European Commission - METIS Studies. The role and need of flexibility in 2030 focus on energy storage [November 30, 2020]; Available from: https://op.europa.eu/en/publication-detail/-/publication/2f3ff8c1-714e-11e9-9f05-01aa75ed71a1.

[59] Huber M, Dimkova D, Hamacher T. Integration of wind and solar power in Europe: assessment of flexibility requirements. Energy 2014;69:236–46. https://doi.org/10.1016/j.energy.2014.02.109.

[60] ENTSO-E. Connecting Europe: electricity - ENTSO-E 2025, 2030, 2040 network development plan [November 30, 2020]; Available from: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/tyndp-documents/TYNDP2018/consultation/Main%20Report/TYNDP2018_Executive%20Report.pdf; 2018.

[61] Bertsch J, Growitsch C, Lorenczik S, Nagl S. Flexibility in Europe's power sector — an additional requirement or an automatic complement? Energy Econ 2016;53:118–31. https://doi.org/10.1016/j.eneco.2014.10.022.

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

[63] Batas Bjelić I, Rajaković N, Krajačić G, Duić N. Two methods for decreasing the flexibility gap in national energy systems. Energy 2016;115:1701–9. https://doi.org/10.1016/j.energy.2016.07.151.

[64] Heydarian-Forushani E, Golshan M, Siano P. Evaluating the benefits of coordinated emerging flexible resources in electricity markets. Appl Energy 2017;199:142–54. https://doi.org/10.1016/j.apenergy.2017.04.062.

[65] Chiaramonti D, Maniatis K. Security of supply, strategic storage and Covid19: which lessons learnt for renewable and recycled carbon fuels, and their future role in decarbonizing transport? Appl Energy 2020;271:115216. https://doi.org/10.1016/j.apenergy.2020.115216.

[66] European Commission. Energy security: good practices to address pandemic risks: commission staff working document [November 30, 2020]; Available from: https://ec.europa.eu/energy/sites/ener/files/1_en_document_travail_service_part1_v3.pdf.

[67] European Commission Department Energy. In focus: energy security in the EU [November 30, 2020]; Available from: https://ec.europa.eu/info/news/focus-energy-security-eu-2020-avr-27_en.

[68] Halbrügge S, Schott P, Weibelzahl M, Buhl HU, Fridgen G, Schöpf M. How did the German and other european electricity systems react to the COVID-19 pandemic? Appl Energy 2020;285.

[69] Powells G, Fell MJ. Flexibility capital and flexibility justice in smart energy systems. Energy Research & Social Science 2019;54:56–9. https://doi.org/10.1016/j.erss.2019.03.015.

[70] Roth S, Schott P, Ebinger K, Halbrügge S, Kleinertz B, Köberlein J, et al. The challenges and opportunities of energy-flexible factories: a holistic case study of the model region Augsburg in Germany. Sustainability 2020;12(1):360. https://doi.org/10.3390/su12010360.

[71] Smale R, van Vliet B, Spaargaren G. When social practices meet smart grids: flexibility, grid management, and domestic consumption in The Netherlands. Energy Research & Social Science 2017;34:132–40. https://doi.org/10.1016/j.erss.2017.06.037.

[72] Fell MJ, Shipworth D, Huebner GM, Elwell CA. Public acceptability of domestic demand-side response in Great Britain: the role of automation and direct load control. Energy Research & Social Science 2015;9:72–84. https://doi.org/10.1016/j.erss.2015.08.023.

[73] Heffron RJ, McCauley D. The concept of energy justice across the disciplines. Energy Pol 2017;105:658–67. https://doi.org/10.1016/j.enpol.2017.03.018.

[74] Heffron RJ, McCauley D. What is the 'just transition'? Geoforum 2018;88:74–7. https://doi.org/10.1016/j.geoforum.2017.11.016.

[75] Fell MJ. Just flexibility? Nat Energy 2020;5(1):6–7. https://doi.org/10.1038/s41560-019-0510-3.

[76] Fuso Nerini F, Tomei J, To LS, Bisaga I, Parikh P, Black M, et al. Mapping synergies and trade-offs between energy and the sustainable development goals. Nat Energy 2018;3(1):10–5. https://doi.org/10.1038/s41560-017-0036-5.

[77] Kuzemko C, Bradshaw M, Bridge G, Goldthau A, Jewell J, Overland I, et al. Covid-19 and the politics of sustainable energy transitions. Energy Research & Social Science 2020;68:101685. https://doi.org/10.1016/j.erss.2020.101685.

[78] Naidoo R, Fisher B. Reset sustainable development goals for a pandemic world. Nature Publishing Group; 2020.

[79] Markard J. The next phase of the energy transition and its implications for research and policy. Nat Energy 2018;3(8):628–33. https://doi.org/10.1038/s41560-018-0171-7.

[80] Ländner E-M, Märtz A, Schöpf M, Weibelzahl M. From energy legislation to investment determination: shaping future electricity markets with different flexibility options. Energy Pol 2019;129:1100–10. https://doi.org/10.1016/j.enpol.2019.02.012.

[81] Gonzalez-Salazar MA, Kirsten T, Prchlik L. Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. Renew Sustain Energy Rev 2018;82:1497–513. https://doi.org/10.1016/j.rser.2017.05.278.

[82] Nicola M, Alsafi Z, Sohrabi C, Kerwan A, Al-Jabir A, Iosifidis C, et al. The socio-economic implications of the coronavirus pandemic (COVID-19): a review. Int J Surg 2020;78:185–93. https://doi.org/10.1016/j.ijsu.2020.04.018.

[83] Dutt V, Gonzalez C. Why do we want to delay actions on climate change? Effects of probability and timing of climate consequences. J Behav Decis Making 2012;25(2):154–64. https://doi.org/10.1002/bdm.721.

[84] Jenkins K, McCauley D, Heffron R, Stephan H, Rehner R. Energy justice: a conceptual review. Energy Research & Social Science 2016;11:174–82. https://doi.org/10.1016/j.erss.2015.10.004.

[85] McCauley D, Ramasar V, Heffron RJ, Sovacool BK, Mebratu D, Mundaca L. Energy justice in the transition to low carbon energy systems: exploring key themes in interdisciplinary research. Appl Energy 2019;233–234:916–21. https://doi.org/10.1016/j.apenergy.2018.10.005.

[86] Gunkel PA, Bergaentzlé C, Græsted Jensen I, Scheller F. From passive to active: flexibility from electric vehicles in the context of transmission system development. Appl Energy 2020;277:115526. https://doi.org/10.1016/j.apenergy.2020.115526.

[87] McKenna R, Hernando DA, Brahim Tb, Bolwig S, Cohen JJ, Reichl J. Analyzing the energy system impacts of price-induced demand-side-flexibility with empirical data. J Clean Prod 2021;279:123354. https://doi.org/10.1016/j.jclepro.2020.123354.

[88] Strbac G, Pudjianto D, Aunedi M, Djapic D, Teng F, Zhang X, et al. Role and value of flexibility in facilitating cost-effective energy system decarbonisation. Prog Energy 2020;2(4):42001.

[89] Fridgen G., Körner M.-F., Walters S., Weibelzahl M. Not All Doom and Gloom: How Energy-Intensive and Temporally Flexible Data Center Applications May Actually Promote Renewable Energy Sources. Bus Inf Syst Eng. In press.