Indicators for assessing the necessity of power system flexibility: a systematic review and literature meta-analysis

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***Abstract*—There are different flexibility options to align power systems to volatile feed-in of renewable electricity sources. The flexibility options differ in the dimensions of time, spatiality, and resource type. To make policy decisions on future energy systems, it is necessary to get a top-down indication of how much power system flexibility is needed. With the ongoing energy transition, there is yet no comprehensive overview of indicators that describe which dimension of flexibility will be necessary to what extent for different energy systems. Therefore, this paper provides a first overview of indicators that can be used to assess the necessity of power system flexibility. Thus, we do a systematic literature review to identify indicators that allow us to estimate the necessity of power system flexibility. We conduct a meta-analysis of these indicators and categorize them as indicators that either stand for an increasing or decreasing necessity of power system flexibility. Our paper can help inform policy, assess needed changes to system operations, increase stakeholder acceptance and investor confidence in implementing new technology and measures.**

Index Terms-- Flexibility; Indicators; Meta-analysis; Power system; Systematic review

I. INTRODUCTION

Published research and international reports refer to the need for power systems flexibility in a country to primarily cope with the intermittency problem associated with variable renewable energy (VRE) sources [1], [2], [3]. According to [4], [5] power system flexibility means the ability of power systems to adapt to dynamic and changing conditions, in terms of balancing supply and demand by the day, hour, or minute. To effectively cope with the intermittency problem associated with variable renewable energy (VRE) sources i.e., solar and wind, power systems will need flexibility options. There are different options for power system flexibility and research has categorized the available flexibility options into supply, demand, grid, storage, and markets [6], [7]. These flexibility options have various dimensions, including the time dimension which depends on whether it is needed for short, medium, or long term, and other dimensions such as spatiality (space), and resource type [8], [9]. Based on these dimensions, flexibility options can be distinguished into two types: long-term planning flexibility and short-term operational flexibility [10]. Short-term operational flexibility concentrates on the short-term system flexibility to balance supply and demand in short time intervals and shows the response time over a few minutes or hours. Long-term planning flexibility focuses on long-term system planning and illustrates the changes such as generation combination, legislation policies, and altering the consumption pattern over a few months or years [10].

Planning and decision making for the future of national power systems is complex and requires large long-term investments and adequate policies. All the above-mentioned aspects of power system flexibility such as different flexibility options, different dimensions of these options can make decision making and planning more complex. Therefore, to make informed political and policy decisions on future electricity systems regarding different flexibility options and to prioritize the needed actions, it is necessary to get an indication of how much flexibility is needed in the national power system. This will allow for strategic planning for the flexibility options to be aligned with the actual needs.

Currently, literature lacks a comprehensive overview of how the different dimensions of flexibility are affected by political, economic, social, technological, environmental, and legal (PESTEL) factors. As literature relates the necessity of power system flexibility to VRE capacity, we also lack an overview of how other relevant indicators can help us to estimate the necessity of flexibility in national power systems.

Thus, in this paper, we examine how different indicators related to PESTEL factors might be able to assess the necessity of power system flexibility in a country. Therefore, we aim to answer the following research question: "Which indicators allow us to estimate the necessity of flexibility in national power systems?" By assessing all the relevant indicators policy makers, power system planners, operators, and regulators can estimate and evaluate the necessity of flexibility in national power systems and prioritize the needed actions for the future.

In this regard, we perform a systematic literature review in section two to identify relevant indicators that can help us to estimate the necessity of flexibility in national power systems. Then we conduct a meta-analysis of these indicators and categorize them into PESTEL factors in section three. This categorization will help us to differentiate the indicators. We distinguish these indicators based on whether an indicator is positively or negatively related to the necessity of power system flexibility. Here indicators with positive relation refer to flexibility need increasing indicators and indicators with negative relation to flexibility need decreasing indicators. Also in section three, we give a description of the identified indicators and describe the significance as well as effect of these indicators on the necessity of power system flexibility according to prior research. In section four, we discuss our results and findings. Finally, section five ends with a conclusion where we summarise our findings, mention the limitation of our work and scope for future research. In this section we also describe how our research is policy relevant and how decision makers can make use of our paper.

Our paper can help inform policy makers, assess the needed changes to system operations, increase stakeholder acceptance, and increase investor confidence for new measures and technology implementation in power systems. As an outlook, these indicators will also allow us to conduct a quantitative assessment of the necessity of power system flexibility in different countries on a global scale.

II. RESEARCH APPROACH

Following the guidelines of [11] and [12], we conduct a systematic literature review to identify existing and previously used indicators to examine the necessity of power system flexibility. Regarding the database for our search, we choose Scopus as it is the largest abstract and citation database of peer-reviewed literature – scientific journals, books, and conference proceedings [13]. We derive a search string where a connection of the topics is established by boolean operators: ("factors" OR "indicators") AND (("power" AND "system" AND "flexibility") OR ("electricity" AND "system" AND "flexibility")). We derived the given search string to cover a wide field of research regarding different flexibility options, as the goal of the literature review is to derive the relevant indicators for an overall necessity of power system flexibility, agnostic to the available flexibility options and their utilization in power systems. Therefore, we do not yet distinguish between different options and usage of flexibility. For our systematic literature review, we consider the period from 2015 to 2022. We choose this time period of 2015-2022 as we want to keep the literature search recent, short, and comprehensive enough to answer our research question. Also, the works of literature in this period have already cited relevant literature from the previous few years and are based on literature from 2010 onwards. Also, we only take into account articles written in the English language. Regarding the subject area, we specify via a filter option on Scopus to only consider articles with a focus on energy and engineering as these are the relevant areas for our research question. With literature indicated as energy, we cover the indicators related to the energy system as the field of engineering covers related indicators related to the technical sides of the flexibility options. We apply the search string to the title, abstract, and keywords, obtaining 541 articles as a result of our initial search. To further narrow down the number of eligible articles, we proceed with the article selection process, which consists of three steps: title screening, abstract screening, and full-text screening. As inclusion criteria, we define that exclusively papers for which a full text is available are considered. As a first step of the selection process, we screen the titles and reduce the number of papers to 128, for which we additionally screen the abstract. After the abstract screening, 51 papers remain for full-text screening. As a result of the full-text screening, we obtain 38 articles that are relevant to our research question.

In addition to academic literatures, we looked for grey literatures (GL) using Google Scholar (GS). According to [14] Google Scholar can identify a large body of GL in excess of that found by either traditional academic citation databases or GL identification methods. Thus, making GS attractive for comprehensive GL searches for systematic reviews. GL refers to informally published written material, not indexed by major database vendors. GL is usually attributed to government, academia, NGO, pressure groups, trade unions, industries and is not rigorously peer-reviewed [15]. Some examples of GL are reports (progress, market research), theses, conference proceedings, technical specifications and standards, official documents, company white papers, and discussion papers. Using the same methodology, search string and steps for searching literature on Scopus, we searched for GL on GS and finalised 6 pieces of GL in the last step.

We followed the concept-centric organization of results as proposed by [11]. We developed a concept matrix listing the identified articles from the literature review and the identified content assorted to indicators and corresponding units of analysis. Hence, for each article, we analysed which indicators were identified or used in order to examine the 'need for flexibility' in the respective article. We used the following concepts for the classification of results from the literature review: type of indicators, e.g., PESTEL. The classification was carried out by a joint discussion of the author team.

III. Results

From our systematic review, we identified 44 articles in total including 6 from GL. Here [7], [16]–[31], [32]–[51] are academic articles, [52]–[54] are reports from international organisations, [55], [56] are reports from the European Commission, [57] is a report from an international energy consultancy, and [58] is a publication from an energy research laboratory. After analysing these 44 shortlisted literatures, we identified 17 indicators. These indicators are listed in table 1. In this table below, we have categorised these indicators into political, economic, social, technological, environmental, and legal/regulatory factors accordingly.

Table 1: List of 17 indicators categorised into PESTEL factors [7], [16]–[31], [32]–[51], [52]–[54], [55], [56], [57], [58]

Technological indicators			
1	High share of inflexible VRE in power system	**2**	High share of flexible generators in power system
3	High interconnection capacity	**4**	Small grid size & low grid quality
5	High storage capacity		

Economic indicators			
1	Fluctuating and uncertain fuel price	**2**	Volatile electricity price
3	Negative electricity price	**4**	High curtailment

Legal / Regulatory indicators			
1	Inadequate grid regulations	**2**	Inadequate market mechanisms

Political indicators			
1	VRE targets for GHG reduction	**2**	Electrification of end use sectors

Environmental indicators			
1	Weather and seasonal variability	**2**	Availability of resources

Social indicators			
1	Usage of DER	**2**	Predictability of load profile

Describtion of indicators and their relation to the necessity of power system flexibility

Here we briefly describe the 17 identified indicators and describe whether these indicators are positively or negatively related with the necessity of power system flexibility. If an indicator has a positive relationship, it means that this indicator has the potential to increase the necessity of flexibility in national power systems and a negative relation means vice-versa.

Technological indicators:

1. *High share of inflexible VRE in power system [16], [19], [25], [46], [52], [55], [57], [58]:*

This indicator refers to the amount of VRE capacity in national installed capacity and also the amount of power generation from VRE sources in the total power generation of a country. With a high share of VRE in the power system, most of the demand has to be supplied by utilising weather dependent VRE sources. This increases the chance of supply fluctuations. A high share of this indicator has a positive relation to the necessity of power system flexibility.

2. *High share of flexible generators in power system [17], [19], [22], [25], [28], [43], [52], [54], [55], [57], [58]:*

Gas-fueled power plants (Gas CCGT, Gas CHP), oil-fueled power plants, hydro-power plants, geothermal power plants, and coal-fired power plants are flexible types of generators, easily dispatchable when needed and have good ramping capabilities and are thus able to provide supply-side flexibility in power systems. If there is a high dispatchable and flexible generation portfolio in the national installed capacity to satisfy most of the demand, then there is less necessity of additional flexibility options. A high share of this indicator has a negative relation to the necessity of power system flexibility.

3. *High storage capacity [7], [25], [52], [55]–[58]:*

Different types of storage technologies such as electric (i.e., battery), thermal, pumped hydro, and power-to-x (P2X) have a negative relation to the necessity of power system flexibility because of the ability of these technologies to store excess electricity and supply it at a later time when needed to balance any fluctuations.

4. *High interconnection capacity [7], [25], [27], [54]–[56], [58]:*

An interconnected grid with neighbouring countries can provide a larger resource pool to balance surplus and deficit generation through electricity export and import when compared to an individual nation's grid. Higher collaboration and network connection with neighbouring power systems can lead to a lower necessity of power system flexibility. Thus, interconnections have a negative relation to the necessity of power system flexibility. However, if the variability profile and share of VRE sources are similar in neighbouring power systems, then there is less additional benefit from higher interconnections.

5. *Small grid size & low grid quality [28], [37], [54], [55]:*

Grid size refers to the amount of area of a country that is covered by the transmission and distribution lines of the power grid. In a widely spread national power grid, potential regional fluctuations can be balanced over a larger area. Grid quality refers to the transmission line's capacity to transmit electricity by maintaining frequency and voltage, without congestion and bottlenecks, and always maintaining a balance of electricity demand and supply at every second. A small size grid with a lot of constraints, transmission bottlenecks, fluctuating frequency and voltage, can increase the need for flexibility and thus showcases a positive relation to the necessity of power system flexibility.

Economic indicators:

6. *Fluctuating and uncertain fuel price [16]:*

Fluctuating and uncertain fuel prices are positively related to the necessity of power system flexibility. The fuel prices of conventional energy sources such as natural gas and coal can fluctuate, and their availability is also uncertain at times, for example, in the case of the recent 2022 crisis between Russia & Ukraine. Fuel price volatility and uncertain availability of fuel affect the conventional and dispatchable power plants in terms of higher power generation costs. It results in the increased necessity of power system flexibility to reduce overall system costs.

7. *Volatile electricity price [38], [48]:*

High electricity price volatility means swings between low and high prices. It reflects limited transmission capacity, limited availability of ramping, fast response, and peaking supplies, and limited ability to reduce demand. This indicator has a positive relation to the necessity of power system flexibility.

8. *Negative electricity price [17], [58]:*

Negative prices may occur when conventional plants cannot reduce output, load that cannot absorb excess supply, surplus of renewable energy, and limited transmission capacity to balance supply and demand across broader geographic areas. Negative prices in electricity markets can signal a need for power system flexibility and thus has a positive relation to the necessity of power system flexibility.

9. *High curtailment [17], [39], [58]:*

The term “curtailment” refers to the reduction of power production (“generation curtailment”) when there is too much electricity in the grid. It also refers to the reduction of power consumption (“load curtailment”) when there is not enough power in the grid for the consumer. A high amount of curtailment leads to growing costs for the system operators and consequently for the whole system. Flexibility in power systems can reduce this growing cost. Thus, high curtailment indicates a positive relation to the necessity of power system flexibility.

Legal / Regulatory indicators:

10. *Inadequate grid regulations [28], [31], [32], [38]:*

Enabling flexibility in power systems depends on the regulations of electricity grid operations in a country. Before additional investments for power system flexibility are made, grid regulations should be designed to use existing and potential flexibility. The use of industrial demand-side flexibility for example can result in high load peaks. These load peaks are getting penalized by current regulations in Germany with high grid charges. Therefore, industrial demand-side flexibility potential remains unused. Grid regulation should ensure compatibility between the availability of flexibility and the demand for flexibility through the usage of the electricity grid. When regulations are not adequate, it increases the necessity for additional flexibility in power systems. Thus, this indicator is positively related to the necessity of power system flexibility.

11. *Inadequate market mechanisms [28], [31], [32], [38]:*

The necessity of flexibility in power systems is tied to the regulatory and market rules that help shape operations in a country. In some power systems, sufficient flexibility may exist to cope with variability of supply and demand, but this flexibility may not be fully accessible without changes to regulatory and legal aspects. For example, the absence of capacity market, i.e., certain remuneration for supply guaranty in times of need, indicates a necessity of power system flexibility. Regulatory and legal constraints can also impede access to available flexibility. For example, in some markets, the terms of certain power purchase agreements (PPA) may constrain the physically available flexibility that could otherwise help balance the system in times of need. This indicator is positively related to the necessity of additional power system flexibility.

Political indicators:

12. *VRE targets for GHG reduction [7], [31], [52]:*

If a country has political and policy targets of installing a large amount of VRE sources for reducing greenhouse gas (GHG) emissions and for increasing energy autarky, then it is positively related with the necessity of power system flexibility in the future.

13. *Electrification of end use sectors [23], [35], [45]:*

Policy towards the electrification of different end-use sectors, i.e., building, industry, and transport, could lead to increased power demand and higher fluctuations across the daily demand profiles of consumers. High fluctuation is the difference between peak and average demand. For example, in many countries government policies are encouraging the adoption of electric vehicles (EV) and installation of electric heat pumps to replace natural gas heating systems. Thus, this indicator is positively related to the necessity of power system flexibility.

Environmental indicators:

14. *Weather and seasonal variability [29], [55]:*

Variations in daily weather and seasonal component, such as temperature, rain, etc., can affect both the production of electricity i.e., from hydro, VRE sources, and the demand for electricity i.e., cooling need during warm weather. This indicator is thus positively related to the necessity of power system flexibility.

15. *Availability of resources [20], [40]:*

The necessity of power system flexibility can vary depending on the type of available resources and geographical conditions. If a country has natural and geological resources, i.e., hydro potential, fossil fuel reserve, then the country might utilise these resources to expand flexible power generation capacities, e.g., pumped hydro storage. Thus, reducing the necessity of power system flexibility in the future. On the other hand, favourable geographical conditions, i.e., sufficient wind speed, may lead to the expansion of inflexible wind energy capacity resulting in a higher necessity of power system flexibility in future. Thus, this indicator is both positively and negatively related to the necessity of power system flexibility. The availability of resources also influences the share of VRE and flexible generators in the power system.

Social indicators:

16. Usage of DER [19], [38], [42], [42], [46]:
In many places, there is an upward trend in installing distributed energy resources (DER). DER include, inter alia, roof-top solar PV and heat pumps. Roof-top solar PV is for self-generation and consumption of electricity by the consumer. Heat pumps are for space heating using electricity. Additionally, people are increasingly switching to electric vehicles (EV) from fossil fuel-powered internal combustion engine vehicles. It is happening due to the falling cost of these technologies and rising consumer concern for reducing climate change and GHG emissions. An increased amount of distributed power generation in the system results in bi-directional power flows, an increase in the variance of operating scenarios, and a decrease in the quality of power supply in general. Also, a considerable number of heat pumps and EV increase the demand for electricity in the power system. Thus, this indicator is positively related to the necessity of power system flexibility.

17. Predictability of load profile [16], [37], [50]:
If system operators can accurately predict the demand and load profile of electricity consumers, then system operators can plan power generation accordingly to match expected demand. This can occur when there are no high and sudden fluctuations in demand and the load profile of a consumer is predictable. High predictability can reduce the necessity of power system flexibility. Thus, this indicator is negatively related to the necessity of power system flexibility.

IV. Discussion

From our systematic literature review and the analysis of indicators, we identified 5 indicators related to the technological factor, 4 indicators related to the economical factor, and 2 indicators each for political, environmental, and social and legal/regulatory factors. Thus, we derived 17 indicators from literature to assess the necessity of power system flexibility and then we associated these indicators to the factors of PESTEL-analysis: political, economic, social, technological, environmental, and legal/regulatory factors.

Our results indicate that most indicators are related to technological factors when it comes to assessing the necessity of flexibility in power systems. This is the case, especially due to the circumstances given by the electricity generation landscape, (i.e., the share of VRE resources), the ability of the electricity grid to accommodate further demand, and accommodate distributed and intermittent generation, and therefore, also energy flexibility. Thus, technological indicators provide a first look into the increased necessity of flexibility in a power system. This increased necessity can be counteracted by other technological indicators as, e.g., the installed storage capacity.

The identified indicators are interlinked with each other, and in this paper, we did our best efforts to disjunct them. Furthermore, there are indicators that show a more short-term, urgent necessity of power system flexibility (i.e., technological indicators) and other indicators that are rather long-term (i.e., political indicators, environmental indicators). Future research can bring the indicators in a temporal order, from short to long term.

Further, the derived indicators from our systematic literature review, which are not related to technological factors, exhibit strong relations with indicators related to technological factors. Indicators related to environmental factors often are related to the renewable power output and their ease of forecasting, therefore, indicates a growing need for flexibility. Indicators related to social factors on the other side, directly affect the availability of distributed energy flexibility. e.g., the available battery capacity of a rooftop solar PV and battery storage system. Indicators related to legal/regulatory factors and political factors can heavily influence the future need for flexibility. Political indicators, such are targets for end use electrification and installation of high amount of VRE sources, play a particularly significant role in increasing the future need for power system flexibility. On the one hand, they have a strong influence on shaping the future state of the considered power system by, e.g., putting in place legislation for a higher share of renewables in the future. On the other hand, electricity market design can foster or hinder the provision of energy flexibility to the energy system by providing financial incentives.

V. Conclusion

In this paper, we conducted a systematic literature research followed by a meta-analysis of the identified indicators to help estimate the necessity of flexibility in a power system. First, we presented the 17 indicators and categorized these indicators by the factors from the PESTEL-analysis. Second, we derived a relationship between the identified indicators to the necessity of power system flexibility, i.e., a higher amount of what is subject to the indicators result in an increased necessity of flexibility in power systems or vice versa. Our work, however, is limited to only estimating the necessity of power system flexibility and these indicators does not quantify the necessity.

To our knowledge, with our work, we provide a new, macro-level overview over the literature stream regarding the necessity of flexibility in power systems, which can support in the estimation of the ‘flexibility’ in such systems. Different national power systems and their expected development can be analysed and even assessed using these indicators. Therefore, we also conducted a meta-analysis of these indicators and their relation to the necessity of power system flexibility. From our review, we clearly see that, in addition to higher share of VRE in power systems, there are other highly relevant indicators, which can indicate the necessity of flexibility in power systems.

Decision makers and policy-makers can use the identified indicators in our paper to assess the necessity of power system flexibility before making any long- or short-term decisions regarding future power systems. Thus, this literature review and meta-analysis can be useful at the initial stage of policy making and before going further into planning for flexibility in power systems.

Future research can use these indicators and conduct a quantitative analysis of different power systems in the world and their – present and future – necessity of power system flexibility. Following these results, also, a type of needed flexibility, i.e., long-term or short-term, or further specific recommendations for action, e.g., needed grid reinforcement, can be derived.

VI. CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Rajon Bhuiyan: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration. **Jan Weissflog**: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Michael Schoepf**: Conceptualization, Validation, Writing - review & editing, Supervision. **Gilbert Fridgen**: Conceptualization, Writing – review & editing, Supervision.

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REFERENCES

[1] H. Kondziella and T. Bruckner, ‘Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies’, *Renew. Sustain. Energy Rev.*, vol. 53, pp. 10–22, Jan. 2016, doi: 10.1016/j.rser.2015.07.199.

[2] ‘Power system flexibility for the energy transition, Part 1: Overview for policy makers’, p. 48.

[3] L. Bird *et al.*, ‘Wind and solar energy curtailment: A review of international experience’, *Renew. Sustain. Energy Rev.*, vol. 65, pp. 577–586, Nov. 2016, doi: 10.1016/j.rser.2016.06.082.

[4] ‘Status of Power System Transformation 2018 – Analysis’, *IEA*. https://www.iea.org/reports/status-of-power-system-transformation-2018 (accessed Jul. 27, 2021).

[5] ‘Electric Power System Flexibility: Challenges and Opportunities’, p. 44.

[6] P. D. Lund, J. 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.

[7] G. Papaefthymiou, E. Haesen, and T. Sach, ‘Power System Flexibility Tracker: Indicators to track flexibility progress towards high-RES systems’, *Renew. Energy*, vol. 127, pp. 1026–1035, Nov. 2018, doi: 10.1016/j.renene.2018.04.094.

[8] E. Hillberg *et al.*, ‘Flexibility needs in the future power system’, p. 48.

[9] G. Kara, A. Tomasgard, and H. Farahmand, ‘Characterization of flexible electricity in power and energy markets’, *ArXiv210903000 Econ Q-Fin*, Sep. 2021, Accessed: Apr. 14, 2022. [Online]. Available: http://arxiv.org/abs/2109.03000

[10] A. AKRAMI, M. DOOSTIZADEH, and F. AMINIFAR, ‘Power system flexibility: an overview of emergence to evolution’, *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 5, pp. 987–1007, Sep. 2019, doi: 10.1007/s40565-019-0527-4.

[11] J. Webster and R. T. Watson, ‘Analyzing the Past to Prepare for the Future: Writing a Literature Review’, *MIS Q.*, vol. 26, no. 2, pp. xiii–xxiii, 2002.

[12] J. vom Brocke, A. Simons, K. Riemer, B. Niehaves, R. Plattfaut, and A. Cleven, ‘Standing on the Shoulders of Giants: Challenges and Recommendations of Literature Search in Information Systems Research’, *Commun. Assoc. Inf. Syst.*, vol. 37, no. 1, Aug. 2015, doi: 10.17705/1CAIS.03709.

[13] ‘About | Elsevier Scopus Blog’. https://blog.scopus.com/about (accessed Apr. 18, 2022).

[14] N. R. Haddaway, A. M. Collins, D. Coughlin, and S. Kirk, ‘The Role of Google Scholar in Evidence Reviews and Its Applicability to Grey Literature Searching’, *PLOS ONE*, vol. 10, no. 9, p. e0138237, Sep. 2015, doi: 10.1371/journal.pone.0138237.

[15] O. Osayande and C. O. U. Mr, ‘Grey Literature Acquisition and Management: Challenges in Academic Libraries in Africa’, p. 14.

[16] E. Kaushik, V. Prakash, O. P. Mahela, B. Khan, A. El-Shahat, and A. Y. Abdelaziz, ‘Comprehensive Overview of Power System Flexibility during the Scenario of High Penetration of Renewable Energy in Utility Grid’, *Energies*, vol. 15, no. 2, Art. no. 2, Jan. 2022, doi: 10.3390/en15020516.

[17] M. Poncela, A. Purvins, and S. Chondrogiannis, ‘Pan-European Analysis on Power System Flexibility’, *Energies*, vol. 11, no. 7, Art. no. 7, Jul. 2018, doi: 10.3390/en11071765.

[18] F. D’Ettorre *et al.*, ‘A set of comprehensive indicators to assess energy flexibility: a case study for residential buildings’, *E3S Web Conf.*, vol. 111, p. 04044, 2019, doi: 10.1051/e3sconf/201911104044.

[19] V. Oree, S. Z. Sayed Hassen, and P. J. Fleming, ‘Generation expansion planning optimisation with renewable energy integration: A review’, *Renew. Sustain. Energy Rev.*, vol. 69, pp. 790–803, Mar. 2017, doi: 10.1016/j.rser.2016.11.120.

[20] C. Jahns, C. Podewski, and C. Weber, ‘Supply Curves for Hydro Reservoirs - Estimation and Usage in Large-Scale Electricity Market Models’, Social Science Research Network, Rochester, NY, SSRN Scholarly Paper 3326372, Jan. 2019. doi: 10.2139/ssrn.3326372.

[21] D. Flynn *et al.*, ‘Technical impacts of high penetration levels of wind power on power system stability’, *WIREs Energy Environ.*, vol. 6, no. 2, Mar. 2017, doi: 10.1002/wene.216.

[22] S. Bellocchi, M. Manno, M. Noussan, and M. Vellini, ‘Impact of Grid-Scale Electricity Storage and Electric Vehicles on Renewable Energy Penetration: A Case Study for Italy’, *Energies*, vol. 12, no. 7, Art. no. 7, Jan. 2019, doi: 10.3390/en12071303.

[23] L. Göransson and F. Johnsson, ‘A comparison of variation management strategies for wind power integration in different electricity system contexts’, *Wind Energy*, vol. 21, no. 10, pp. 837–854, 2018, doi: 10.1002/we.2198.

[24] C. Finck, R. Li, R. Kramer, and W. Zeiler, ‘Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems’, *Appl. Energy*, vol. 209, pp. 409–425, Jan. 2018, doi: 10.1016/j.apenergy.2017.11.036.

[25] M. R. M. Cruz, D. Z. Fitiwi, S. F. Santos, and J. P. S. Catalão, ‘A comprehensive survey of flexibility options for supporting the low-carbon energy future’, *Renew. Sustain. Energy Rev.*, vol. 97, pp. 338–353, Dec. 2018, doi: 10.1016/j.rser.2018.08.028.

[26] T. Wang *et al.*, 'Expanding flexibility with P2H for integrated energy systems', in *8th Renewable Power Generation Conference (RPG 2019)*, Oct. 2019, pp. 1–6. doi: 10.1049/cp.2019.0670.

[27] H. Liu, T. Brown, G. B. Andresen, D. P. Schlachtberger, and M. Greiner, 'The role of hydro power, storage and transmission in the decarbonization of the Chinese power system', *Appl. Energy*, vol. 239, pp. 1308–1321, Apr. 2019, doi: 10.1016/j.apenergy.2019.02.009.

[28] Y. W. Huang, N. Kittner, and D. M. Kammen, 'ASEAN grid flexibility: Preparedness for grid integration of renewable energy', *Energy Policy*, vol. 128, pp. 711–726, May 2019, doi: 10.1016/j.enpol.2019.01.025.

[29] S. Pelka, L. J. De Vries, and M. Deissenroth, 'The Impact of Weather and of Batteries on the Investment Risk for Backup Gas Power Plants in a Largely Renewable Energy System', in *2019 16th International Conference on the European Energy Market (EEM)*, Ljubljana, Slovenia, Sep. 2019, pp. 1–6. doi: 10.1109/EEM.2019.8916469.

[30] S. Klyapovskiy, S. You, A. Michiorri, G. Kariniotakis, and H. W. Bindner, 'Incorporating flexibility options into distribution grid reinforcement planning: A techno-economic framework approach', *Appl. Energy*, vol. 254, p. 113662, Nov. 2019, doi: 10.1016/j.apenergy.2019.113662.

[31] W. Suwala and A. Wyrwa, 'Factors affecting the transition of the Polish power system', *E3S Web Conf.*, vol. 108, p. 01001, Jan. 2019, doi: 10.1051/e3sconf/201910801001.

[32] Quentin Hoarau and Yannick Perez, 'INTERACTIONS BETWEEN ELECTRIC MOBILITY AND PHOTOVOLTAIC GENERATION: A REVIEW'. Feb. 2018. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01713968/file/18-02-20-WP-2018-02.pdf

[33] M. Kumar and C. Samuel, 'Selection of Best Renewable Energy Source by Using VIKOR Method', *Technol. Econ. Smart Grids Sustain. Energy*, vol. 2, no. 1, p. 8, Dec. 2017, doi: 10.1007/s40866-017-0024-7.

[34] T. Koivunen, S. Syri, and N. Veijalainen, 'Contributing factors for electricity storage in a carbon-free power system', *Int. J. Energy Res.*, vol. 46, no. 2, pp. 1339–1360, 2022, doi: 10.1002/er.7252.

[35] M. Hall and A. Geissler, 'Comparison of Flexibility Factors and Introduction of A Flexibility Classification Using Advanced Heat Pump Control', *Energies*, vol. 14, p. 8391, Dec. 2021, doi: 10.3390/en14248391.

[36] V. Vita, C. Christodoulou, I. Zafeiropoulos, I. Gonos, M. Asprou, and E. Kyriakides, 'Evaluating the Flexibility Benefits of Smart Grid Innovations in Transmission Networks', *Appl. Sci.*, vol. 11, no. 22, Art. no. 22, Jan. 2021, doi: 10.3390/app112210692.

[37] G. Airò Farulla *et al.*, 'A Review of Key Performance Indicators for Building Flexibility Quantification to Support the Clean Energy Transition', *Energies*, vol. 14, no. 18, Art. no. 18, Jan. 2021, doi: 10.3390/en14185676.

[38] C. D. Iweh, S. Gyamfi, E. Tanyi, and E. Effah-Donyina, 'Distributed Generation and Renewable Energy Integration into the Grid: Prerequisites, Push Factors, Practical Options, Issues and Merits', *Energies*, vol. 14, no. 17, Art. no. 17, Jan. 2021, doi: 10.3390/en14175375.

[39] T. H. Ruggles, J. A. Dowling, N. S. Lewis, and K. Caldeira, 'Opportunities for flexible electricity loads such as hydrogen production from curtailed generation', *Adv. Appl. Energy*, vol. 3, p. 100051, Aug. 2021, doi: 10.1016/j.adapen.2021.100051.

[40] D. Ribó-Pérez, M. Heleno, and C. Álvarez-Bel, 'The flexibility gap: Socioeconomic and geographical factors driving residential flexibility', Jun. 2021, doi: 10.1016/j.enpol.2021.112282.

[41] M. Saber, M. S. Moteleb, H. Talaat, S. F. Mekhemer, and W. Omran, 'Power System Flexibility Metrics Evaluation and Power Ramping Analysis for High Variable Renewable Generation Shares', p. 165282, Jun. 2020, doi: 10.4108/eai.13-7-2018.165282.

[42] D. Efimov, 'Flexibility of the power system: background, relevance, and categorization', *E3S Web Conf.*, vol. 216, p. 01025, Jan. 2020, doi: 10.1051/e3sconf/202021601025.

[43] N. Voropai, 'Electric Power System Transformations: A Review of Main Prospects and Challenges', *Energies*, vol. 13, no. 21, Art. no. 21, Jan. 2020, doi: 10.3390/en13215639.

[44] B. Wang, Q. Cai, and Z. Sun, 'Determinants of Willingness to Participate in Urban Incentive-Based Energy Demand-Side Response: An Empirical Micro-Data Analysis', *Sustainability*, vol. 12, no. 19, Art. no. 19, Jan. 2020, doi: 10.3390/su12198052.

[45] P.-H. Li and S. Pye, 'Assessing the benefits of demand-side flexibility in residential and transport sectors from an integrated energy systems perspective', *Appl. Energy*, vol. 228, pp. 965–979, Oct. 2018, doi: 10.1016/j.apenergy.2018.06.153.

[46] A. Spisto, 'Impact of flexible technologies on end-users' price under different levels of renewable generation', *JRC Publications Repository*, Sep. 06, 2016. https://publications.jrc.ec.europa.eu/repository/handle/JRC99255 (accessed May 13, 2022).

[47] S. Agheb, X. Tan, B. Sun, and D. H. K. Tsang, 'Robust provisioning of demand-side flexibility under electricity price uncertainty', in *2016 IEEE International Conference on Industrial Technology (ICIT)*, Taipei, Taiwan, Mar. 2016, pp. 545–550. doi: 10.1109/ICIT.2016.7474808.

[48] F. J. de Sisternes, J. D. Jenkins, and A. Botterud, 'The value of energy storage in decarbonizing the electricity sector', *Appl. Energy*, vol. 175, pp. 368–379, Aug. 2016, doi: 10.1016/j.apenergy.2016.05.014.

[49] R. Miranda, P. Ferreira, R. Schaeffer, and A. Szklo, *Limitations of thermal power plants to solar and wind development in Brazil*. 2016.

[50] C. Li, Z. Y. Dong, G. Chen, J. Liu, and F. Luo, 'Flexible transmission expansion planning associated with large-scale wind farms integration considering demand response', *IET Gener. Transm. Distrib.*, vol. 9, pp. 2276–2283, Nov. 2015, doi: 10.1049/iet-gtd.2015.0579.

[51] V. Diakov, G. Brinkman, P. Denholm, T. Jenkin, and R. Margolis, 'Renewable generation effect on net regional energy interchange', in *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, USA, Jul. 2015, pp. 1–4. doi: 10.1109/PESGM.2015.7286252.

[52] 'Power system flexibility for the energy transition, Part 2: IRENA FlexTool methodology', p. 76.

[53] International Energy Agency, *Empowering Variable Renewables – Options for Flexible Electricity Systems*. OECD, 2009. doi: 10.1787/9789264077201-en.

[54] IEA, 'GIVAR III Flexibility Scoring Framework from IEA', IEA. [Online]. Available: www.iea.org/ topics/renewables/givar/

[55] D. Bauknecht, M. Vogel, and C. Heinemann, 'Study on the impact assessment for a new Directive mainstreaming deployment of renewable energy and ensuring that the EU meets its 2030 renewable energy target Task 3.1: Historical assessment of progress made since 2005 in integration of renewable electricity in Europe and first-tier indicators for flexibility'. European Commission. [Online].Available: https://ec.europa.eu/energy/sites/ener/files/res-mainstreaming-task3.1_170706.docx

[56] European Commission, 'Flexibility portfolios: Design of flexibility portfolios at Member State level to facilitate a cost-efficient integration of high shares of renewables', European Commission, Jul. 2017. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/mainstreaming_res_-_artelys_-_final_report_-_version_33.pdf

[57] G. Papaefthymiou, K. Grave, and K. Dragoon, 'Flexibility options in the electricity systems', Ecofys, Mar. 2014. [Online].Available: https://www.ourenergypolicy.org/wp-content/uploads/2014/06/Ecofys.pdf

[58] J. Cochran *et al.*, 'Flexibility in 21st Century Power Systems', NREL/TP-6A20-61721, 1130630, May 2014. doi: 10.2172/1130630.