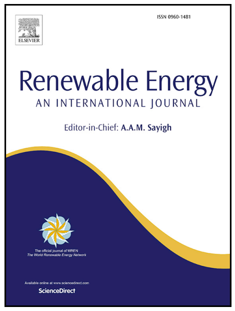
Accepted Manuscript



Challenges and solution technologies for the integration of variable renewable energy sources—a review

Simon R. Sinsel, Rhea L. Riemke, Volker H. Hoffmann

PII: S0960-1481(19)30987-5

DOI: https://doi.org/10.1016/j.renene.2019.06.147

Reference: RENE 11879

To appear in: *Renewable Energy*

Received Date: 11 October 2018

Revised Date: 1 June 2019

Accepted Date: 25 June 2019

Challenges and solution technologies for the integration of variable renewable energy sources—a review

Simon R. Sinsel*, Rhea L. Riemke, Volker H. Hoffmann

Swiss Federal Institute of Technology Zurich (ETH Zurich), Department of Management, Technology, and Economics, Group for Sustainability and Technology, Weinbergstrasse 56/58, 8092 Zurich, Switzerland

* Corresponding author: Phone: +41 44 632 98 89, E-mail address: ssinsel@ethz.ch (S. Sinsel)

Declarations of interest: none

Abstract

Variable renewables such as solar photovoltaics and wind power are key technologies for achieving the decarbonization of the power sector. However, they differ significantly from conventional power generation sources. As the share of variable renewables increases, these differences lead to numerous challenges in power systems. Failure to deal with these challenges may jeopardize power system reliability or the achievement of decarbonization targets. Various solution technologies are available to mitigate these challenges. The extant literature, however, lacks clarity on the scope of the challenges and the solution technologies to address them. This study provides a comprehensive overview of challenges and solution technologies among all domains of the power system. The interrelation matrix of challenges and solution technologies developed in this study provides important insights: First, solution technologies vary significantly in their potential to solve certain challenges. The solution potential of different technologies can therefore help prioritize solution technologies in addition to focusing on cost-effective options. Second, it is possible to identify groups of solution technologies that can help mitigate certain challenge groups. The categorization developed in this paper helps to better specify the need for specific solution technologies and enhances transparency of the complex process of renewable energy integration.

Key words

Variable renewable energy sources, Renewable integration, Power system transformation, Challenges, Solution technologies

Challenges and solution technologies for the integration of variable renewable energy sources—a review

Declarations of interest: none

Abstract

Variable renewables such as solar photovoltaics and wind power are key technologies for achieving the decarbonization of the power sector. However, they differ significantly from conventional power generation sources. As the share of variable renewables increases, these differences lead to numerous challenges in power systems. Failure to deal with these challenges may jeopardize power system reliability or the achievement of decarbonization targets. Various solution technologies are available to mitigate these challenges. The extant literature, however, lacks clarity on the scope of the challenges and the solution technologies to address them. This study provides a comprehensive overview of challenges and solution technologies among all domains of the power system. The interrelation matrix of challenges and solution technologies developed in this study provides important insights: First, solution technologies vary significantly in their potential to solve certain challenges. The solution potential of different technologies can therefore help prioritize solution technologies in addition to focusing on cost-effective options. Second, it is possible to identify groups of solution technologies that can help mitigate certain challenge groups. The categorization developed in this paper helps to better specify the need for specific solution technologies and enhances transparency of the complex process of renewable energy integration.

Key words

Variable renewable energy sources, Renewable integration, Power system transformation, Challenges, Solution technologies

1. Introduction

The deployment of renewable energy sources is a major lever to decarbonize the power sector and mitigate the effects of climate change [1]. In the last decades, there has been unprecedented growth in two technologies in particular—solar photovoltaics (PV) and wind power—with respective global shares of 4% and 7% in installed capacity and average annual increases of 27% and 13% over the last 5 years [2,3]. These variable renewables (VRE) differ in various aspects from conventional generation technologies. Mueller et al. [4] summarize those aspects in six characteristics: VRE generator output (1) varies due to its primary resource variability and (2) is unpredictable; (3) VRE generators are modular and small in size; (4) they are location-constrained; (5) unlike conventional generators, VRE generators are mostly non-synchronous types; and (6) they have low short-run costs. These characteristics create challenges in existing power systems. In this context, challenges are defined as causes that adversely affect the performance characteristics of an interconnected power system.[1] Examples of such challenges include missing transmission grid capacity or insufficient generation adequacy, the latter of which relates to the ability of an existing generation portfolio to match power demand at all times [5–8].

These challenges can be addressed by various solution technologies. In our context, these new or modified technologies mitigate the effects of one or more challenges[2]. Examples of solution technologies related to previously mentioned challenges include transmission grid expansions as well as distributed or centralized storage devices. Solution technologies are important for integrating VRE into power systems and ultimately achieving decarbonization targets, but deploying these technologies may create complications due to three primary reasons: First, the choice of solution technologies depends on various factors, such as cost, maturity, range of applications, and explicit or implicit technological preferences of firms or policy makers [9,10]. Second, decisions about the use of specific solution technologies are not made by a single entity but rather by a number of actors, including system operators, utilities or regulators [11,12]. Third, solution technology needs vary by region based on VRE share in power generator portfolios or individual power system configurations, such as island systems versus strongly interconnected systems [13,14].

Most importantly, however, energy transition researchers and practitioners lack sufficient transparency regarding the scope of challenges and the available solution technologies to address these challenges [6,12,15]. Some authors offer analyses of individual challenges and propose specific solution technologies, such as voltage management solutions for transmission and distribution grids with high VRE penetration [16–18]. However, these studies may undervalue solution technologies that can potentially address a wider range of challenges such as battery storage, which can also help to address generation adequacy challenges. Similarly, others investigate scenarios for the deployment of specific solution technologies [19–21] such as increased transmission or storage capacities, but these studies only rarely consider substitution effects between the different solution technologies. Still other authors focus on several or aggregated challenges, particularly on the flexibility challenge [22–26], but define challenges on a rather aggregate level, which may lead to excluding certain solution technologies[3]. In

[1] For the purpose of this study, an interconnected power system ranges from the generating unit on one side to the grid connection of the end user on the other side.
[2] Our review only covers solution technologies that are currently commercially available.
[3] Not differentiating between insufficient short- or long-term generation adequacy, for example, excludes demand response as solution technology since it is only effective in the shorter term.

summary, while individual challenges and solution technologies may be known, the literature lacks a transparent overview of each. This is specifically important for energy transition researchers as well as decision makers in policy and businesses who define strategies and technology roadmaps for the future development of power systems. This study offers such an overview by addressing the question *what are the challenges of VRE integration and which solution technologies are available to address these challenges.*

This study is structured as follows: Section 2 describes the research approach consisting of three steps: First, data from a structured literature analysis is used to iteratively compile lists of challenges and solution technologies and map their interrelations. Second, to address the lack of consistency in identifying and classifying challenges, a root-cause analysis is used to structure the collected challenges. This approach helps to differentiate between the observable symptoms, i.e. changes in key performance characteristics of the electricity system, and the sequence of causes that can be traced back to the VRE characteristics. Third, the analysis is further complemented by information gained from expert interviews to ensure robustness of the results. In Section 3, results are presented regarding the challenges, solution technologies, and their interrelations, while relevant implications for firms and policy makers are discussed in Section 4. Section 5 concludes with the main contributions of the study and areas for future research.

2. Method and Materials

This section introduces the methodological approach and the data sources that form the basis of this analysis. The section is structured in three parts. First, it explains how challenges and solution technologies have been collected and clustered for this study. The second section introduces the logic of the root cause analysis that helped to structure the challenges in a consistent way. Third, the validation of the interrelation analysis through expert interviews is described.

2.1 Collection of challenges and solution technologies

The collection of challenges and solution technologies was based on a structured analysis of journal publications, conference proceedings, and grey literature from institutional authors written in English. The analyzed sample consisted of literature from two sources. The first source was a sample of publications retrieved from the Web of Science [27] database. This sample was developed in a two-step iterative process: (1) bottom-up, by adapting the search query, and (2) top-down, by determining whether publications deemed relevant prior to the database search were included in the chosen sample. The sample was finalized in May 2019—the final search query, including further details on the search rationale, can be found in Appendix A. The second source consisted of studies by institutional authors who were not in Web of Science. These studies were obtained through a targeted web search for technical reports published by larger research and consulting institutions. Like the database query, this sample was collected in May 2019. In total, 130 studies were obtained and analyzed in May 2019.

In order to reduce the sample size to studies that provide a comprehensive overview of challenges and solution technologies, the literature was categorized as follows: In the first step, the sample was split between studies that deal with single challenges or solution technologies (focus studies) and multiple challenges or solution technologies (systemic studies). In the second step, a distinction was made between studies which specifically focus on challenges or solution technologies and other foci such as VRE diffusion or case studies of VRE integration in a specific region. This two-step process reduced the sample to 57 studies, of which 25 focus on market or regulatory issues and 32 present a technological or operational perspective on challenges and solution technologies for VRE integration. The studies of the latter group were subsequently used as a basis for extracting challenges and solution technologies. Focusing on studies with a technological and operational perspective eliminated ambiguity in identifying challenges, as doing so relies on underlying technical phenomena. This argument can be illustrated through the following example: Several studies [19,23] identify the merit-order effect as a result of increased VRE penetration at zero marginal cost as an important challenge for the integration of renewables. However, there are ambiguities in defining the challenge from an economic perspective, as lower spot market prices for power may be desirable from a societal perspective. However, defining the challenge from a technical perspective, i.e. insufficient generation adequacy, resolves this ambiguity because the potential effects (load shedding or black-outs) are not desirable for stakeholders. As this example illustrates, the chosen focus does not mean that institutional or organizational challenges are overlooked—by departing from a technical point of view, institutional or organizational changes are in fact measures that ultimately lead to a reconfiguration of the technical system, i.e. to increase the share of one or more solution technologies in the power system. Appendix B illustrates the literature analysis process and the relative size of the literature groups identified in the analysis, and Appendix C provides an overview of the studies reviewed in detail.

The final sample constituted the body of literature for collecting challenges, solution technologies and their interrelations, and served as input for the interviews that were conducted at a later stage of the research process. Due to the intangible nature of challenges, their wording and descriptions vary among studies. Therefore, challenges were first collected in long form and then iteratively clustered, rephrased, and aggregated. For the collection of solution technologies, two requirements were defined. First, the technology in question needs to independently mitigate one or more of the challenges of VRE integration. This requirement is important because it prevents classifying sub-technologies as solution technologies. Smart meters are an example of such a sub-technology: they enable technologies such as demand response, but do not independently mitigate VRE integration challenges. Therefore, demand response was classified as a solution technology, but smart meters were not. Second, the study followed the approach of Arthur [28] and defined solution technologies via their functions. This helps to exclude solution technologies that are only incrementally different from each other. Sticking with the example of demand response, the function of this technology is to reduce the power consumption of certain devices at a specified time. Yet, performing demand response operations with different devices, such as heat pumps or electric heaters, does not constitute different solution technologies since they ultimately serve the same function.

The interrelations between challenges and solution technologies that this study developed were also based on the reviewed literature. To identify these interrelations, all solution technologies mentioned in connection with a specific challenge were listed. On this basis, an interrelation matrix between all challenges and solution technologies was built, which was subsequently validated through expert interviews.

2.2 Root cause analysis

As mentioned in Section 2, the refined list of challenges from the reviewed literature still contained challenges with different levels of detail, as well as challenges with causal relations between each other. To analyze the interrelations between challenges and solution technologies, it is important that challenges are mutually exclusive[4]. Therefore, the study applied the root cause analysis methodology, a standard tool from the area of quality management. The objective of this method is to identify ultimate causes for specific problems or events through causal chains that lead from the observable symptom of the problem to its root cause [29]. For instance, Hare et al. [30] use this method to categorize failure modes of micro-grids in order to accelerate fault-finding and resolution. To apply this method, the symptoms of increased VRE penetration were identified from the literature sample. As stated in Section 1, these symptoms represent observable impacts that have an adverse effect on the performance characteristics of the power system. The challenges identified in the literature were then mapped using tree structures, each starting with a symptom and ending with one or more specific VRE characteristics as root causes. To ensure reliability of this approach, two authors independently created the tree structures. The agreement between authors was 90%. This process resulted in a mutually exclusive list of challenges structured via the observable symptoms of increased VRE penetration.

2.3 Semi-structured interviews

In order to ensure that the lists of challenges, solution technologies, and their interrelations were comprehensive, semi-structured interviews with different experts from the power sector were conducted. For this purpose, only interviewees with technical expertise in the overall power system or with different solution technologies were chosen. The expert sample covered representatives from technology providers, consultancies and system operators, as well as different power market participants. A total of fourteen interviews were conducted. All interviews lasted approximately 60 minutes. Table 1 provides an overview of the interviewees. In order to validate the findings of the analysis, the consolidated list of challenges, solution technologies, and interrelation matrix were sent to the interviewees prior to the interview. As the interviews progressed, there were increasingly fewer new insights gained from the interviewees. Therefore, the number of interviews was deemed sufficient to validate the findings of the analysis.

Table 1

Overview of expert interviews.

#	Stakeholder	Role
1	Policy consultancy	Senior consultant
2	Power system consultancy	Senior consultant
3	Storage technology provider	Business developer for storage solutions
4	Transmission system operator	Product manager for renewable energies
5	Demand response provider	Operations manager
6	Transmission system technology provider	Product manager for HVDC solutions
7	Generation technology provider	Head of technical marketing for generators
8	Distribution system operator	Head of innovation
9	Transmission system operator	Head of innovation
10	Power system consultancy	Senior power system consultant
11	Transmission system technology provider	Senior design engineer for grid technologies
12	Smart grid technology provider	Chief Operations Officer
13	Integrated electric utility	Senior Transmission Technology Advisor
14	Electric utility	Senior Technology Advisor

[4] For solution technologies, mutual exclusiveness was established by differentiating each by their functions, as explained in the previous section.

3. Results

This section is structured as follows: First, the challenge categories and the list of challenges compiled using the root cause analysis are presented. Second, the solution categories and the solution technologies are described in detail. Lastly, challenges and solution technologies are combined in an interrelation matrix and main observations are pointed out.

3.1 Challenges

Table 2 provides an overview of the eight symptoms of increasing VRE penetration identified through the review of the literature. The symptoms can be grouped into four categories that align with basic performance requirements of the power system. In the following, the categories are briefly characterized.

Sufficient power *quality* is the dominant performance requirement for end consumers. The power quality category comprises the requirements for uninterrupted power supply and stable conditions of voltage and current, as well as safe conditions in case of outages. The underlying VRE characteristics largely responsible for power quality challenges include the modularity of VRE generators and the fact that they are non-synchronous. The *flow* category is related to the efficient transmission and distribution of power. Root causes for challenges in the flow category are manifold in comparison to the other categories. VRE variability, modularity, and location-constraints result in the largest share of flow challenges. The *stability* category is concerned with the control of frequency and voltage in the power system as well as system recovery after blackouts. *Stability* challenges are mostly caused by the modularity of VRE generators and the fact that those generators are non-synchronous. The power *balance* category comprises challenges connected to the short- to long-term balance of supply and demand of active power in the system. This includes the system-wide coordination of the ramp rate capacities and the minimum generation levels of a power system[5]. Balancing challenges are caused by VRE variability and uncertainty. In sum, the root cause analysis provides a consistent bottom-up categorization of challenges according to the symptoms present in power systems with increasing VRE penetration. A detailed overview of the relation between the challenges and their underlying VRE characteristics is included in Appendix D.

Table 2

Challenge categorization according to the root cause analysis.

Category	Symptom
Quality	- local trips, shorter lifetime or damage to equipment at end consumer - safety hazards
Flow	- regional trips, shorter lifetime or damage to transmission and distribution equipment - loop flows, redispatch or curtailment due to congestion - increased losses
Stability	- increased dynamic stability violations, redispatch or curtailment due to stability concerns - controllability or resonance issues
Balance	- increasing mismatches between supply & demand

[5] Analytically, balancing challenges are addressed with the help of different concepts, such as net load or the load carrying capacity of renewables [24,71].

Figure 1 provides a schematic overview of the root cause analysis performed on a power grid symptom, in this case, mismatches between power supply and demand. This symptom is the origin of five causal chains that originate from different VRE characteristics. In order to ensure an appropriate level of granularity for further analysis, the cause immediately preceding the root cause is chosen as the challenge for the interrelation analysis[6]. It should be noted here that mismatches between supply and demand may have many other reasons in addition to increased VRE penetration. Lund et al. [24], for example, identify the limited dispatchability of coal and nuclear power plants as a reason for insufficient flexibility of power systems. However, since this study solely focuses on challenges of VRE integration, only root causes connected to increased VRE penetration were considered for this analysis.

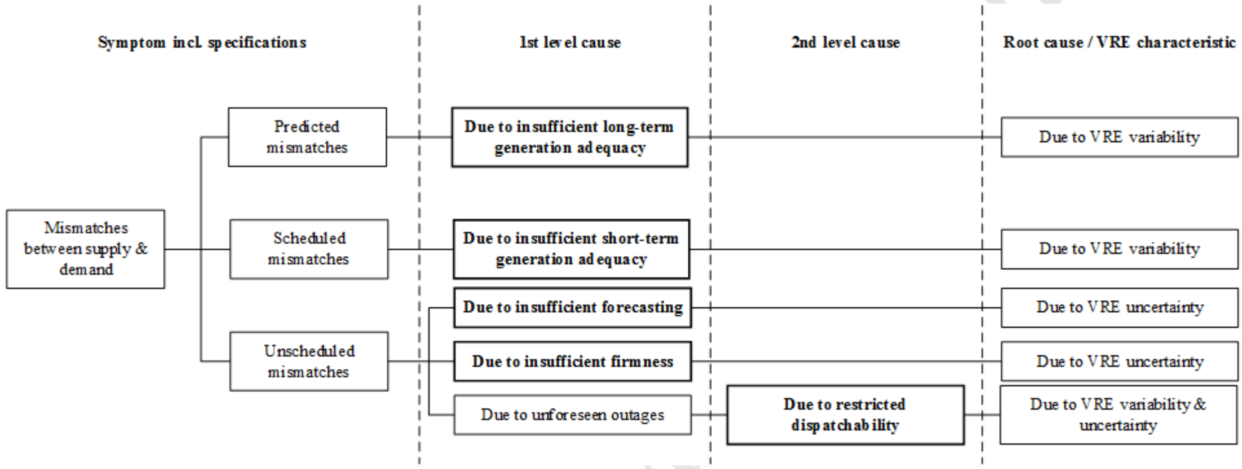


Fig. 1. *Root cause analysis for balancing challenges (challenges in bold).*

Root cause analyses similar to that which is summarized in Figure 1 were performed for all eight symptoms caused by increased penetration of VRE. Table 3 summarizes the list of challenges, including a categorization and description of each challenge as well as a reference to the observable symptom. In total, 26 challenges were identified. The greatest number of challenges were connected to power flow and stability of the power system.

[6] Choosing the root cause itself (on the right of Figure 2) always leads to one of the six VRE characteristics, while choosing higher level causes (on the left in Figure 2) would lead to defining challenges on a rather aggregated level to obtain meaningful results.

Table 3

Challenges of VRE integration.

[4–6,11,13,14,19,22,23,31–58]

Category	Challenge	Description	Source
Quality	**Increasing flicker**	VRE generator feed-in via power electronic-based inverters increases flicker content locally. This leads to reduced equipment lifetime, trips or equipment damage at end consumers.	[31,32]
	Increasing harmonic distortions	VRE generator feed-in via power electronic-based inverters increases harmonic distortions. This leads to reduced equipment lifetime, trips or equipment damage at end consumers.	[34,54]
	Unreliable shut-down during blackouts	VRE generators that continue generating electricity within areas that are disconnected from the larger network constitute safety hazards for maintenance or repair operations.	[30,35]
	Increasing local voltage excursions	VRE generator feed-in in lower grid levels at times of low consumption increases the system voltage at end consumers. This leads to overloading and results in reduced equipment lifetime, trips or equipment damage.	[13,18]
Flow	**Increasing regional voltage excursions**	VRE generator feed-in in radial distribution grid feeders increases the system voltage in these areas. This leads to overloading of feeder equipment and results in reduced lifetime, feeder trips or equipment damage.	[34]
	Missing distribution grid capacity	The existing distribution grid environment is insufficiently sized to accommodate power feed-ins from VRE generators. If insufficient sizing is recognized, this will result in curtailment of VRE generators. If insufficient sizing is unrecognized, this will result in reduced lifetime, feeder trips or equipment damage.	[19,23]
	Increasingly volatile flow patterns from lower grid levels	VRE generation on lower voltage levels makes power flows more volatile and less predictable. This leads to increased continuous or temporal curtailment of VRE generators.	[41]
	Inadequate protection design	Protection schemes in lower voltage grid areas are not designed for increasingly dynamic load flows due to VRE generation. Inadequate protection scheme design causes unintended trips or overloading, resulting in shorter lifetime or equipment damage.	[33]
	Increasing short-circuit currents	VRE generators connected on lower voltages levels increase short circuit currents in case of faults on the network. The increased currents can lead to further trips or equipment damage.	[52]
	Missing controllability of VRE generation	Small VRE generators are traditionally not equipped with a remote control interface. Uncontrolled feed-in of VRE generation leads to unplanned power flows resulting in reduced equipment lifetime, trips or equipment damage.	[5,41]
	Missing visibility of VRE generation	Grid equipment in the lower voltage levels do not measure load flow or equipment loading. VRE feed-in in these areas leads to unplanned flows that result in reduced lifetime, feeder trips or equipment damage.	[39]
	Narrow voltage trip limits	VRE generators are required to trip outside a specified voltage band. Increasing voltage deviations due to VRE generation therefore leads to increased tripping of VRE generators. This in turn causes trips in larger grid areas, shorter equipment lifetime or potential equipment damage.	[33]
	Missing transmission grid capacity	Insufficient transmission capacity between VRE generation and consumption locations leads to curtailment of VRE generation, redispatch activities or unintended transmission flow, such as loop flows.	[23]
	Increasing transmission distances	The location dependency of VRE generation requires increasingly long transmission distances between generation and consumption locations leading to higher transmission losses.	[5]
Stability	**Insufficient reactive power provision**	In comparison to conventional generators, VRE generators have lower reactive power output. VRE deployment and simultaneous power transmission expansion requires higher levels of reactive power to maintain system voltage. The undersupply of reactive power leads to violations of dynamic stability regulations, redispatch or curtailment of VRE generation.	[40]
	Decreasing level of short-circuit power	VRE generators produce significantly less short-circuit power in comparison to synchronous generators. A low level of short-circuit power increases voltage instability and complicates fault detection. This leads to violations of dynamic stability regulations, redispatch or curtailment of VRE generation.	[55,40]
	Decreasing level of inertia	VRE generators provide significantly less rotational inertia in comparison to synchronous generators. This leads to faster frequency excursions in cases of imbalance in supply and demand. Faster frequency changes violate dynamic stability regulations and lead to redispatch or curtailment of VRE generation.	[4,40]
	Inadequate coordination of frequency trip limits	VRE generators are required to trip outside a specified frequency band. With increasing VRE penetration levels this requirement leads to violations of stability regulation by tripping an increasing amount of generation at a specific point.	[5,56]
	Inadequate coordination of voltage trip limits	VRE generators are required to trip outside a specified voltage band. Increasing voltage deviations due to VRE generation therefore leads to increased tripping of VRE generators. This in turn leads to cascading trips, violations of dynamic stability regulations or amplification of stability incidents.	[46]
	Decreasing frequency control reserves	Short-term variability of VRE generation increases the need for frequency control reserves in order to stabilize system frequency. At the same time, VRE generators are not providing frequency reserves. The lack of these reserves leads to the violation of dynamic stability regulations, redispatch or curtailment of VRE generation.	[46,57]
	Increasing control interactions	VRE generators connected via controlled inverters can interact with the electricity grid leading to unobserved power oscillations. If uncontrolled they can lead to reduced equipment lifetime, trips or equipment damage.	[35,45]
Balance	**Insufficient short-term generation adequacy**	Increasing VRE generation leads to changed performance requirements for conventional generation, like faster ramping requirements. Insufficient adequacy for these performance requirements can lead to predictable short-term mismatches between generation and load, redispatch or curtailment.	[14]
	Insufficient long-term generation adequacy	Increasing VRE generation leads to changed performance requirements of conventional generation, like night-time or seasonal balancing of power generation. Insufficient adequacy for these performance requirements can lead to predictable long-term mismatches between generation and load.	[22,23]
	Insufficient firmness of VRE generators	Variability of VRE generation increases the uncertainty of firm generation capacity estimations. This leads to higher reserve requirements and increasing unscheduled mismatches between generation and load, balancing power activation, redispatch or curtailment.	[19,58]
	Insufficient forecasting of VRE generators	Variability of VRE generation leads to increasing forecast inaccuracies. The results are unscheduled mismatches between generation and load, balancing power activation, redispatch or curtailment.	[46,49]
	Restricted dispatchability of VRE generators	The performance range of VRE generators is restricted by their fluctuating primary resource provision. Using VRE generators to balance unforeseen outages of other generators is therefore limited. This leads to unscheduled mismatches between generation and load and balancing power activation.	[50]

3.2 Solution technologies

Similar to challenges, the literature does not provide means to categorize solution technologies. Most categorizations are implicit due to the focus of different studies. Studies on power system flexibility, for instance, primarily focus on technologies that generate or consume active power [14,23], while studies on electricity networks tend to focus on technologies for power transmission and distribution [40]. Overview studies, such as those comprehensively listing solution technologies, do not classify these technologies [5]. By establishing a categorization for solution technologies, this study (1) contributes to current debates on the transformation of the power sector, and (2) is able to draw higher level conclusions. Similar to Houseman [49], this study uses a top-down classification of two characteristics assigned to each solution technology.

The first *characteristic* reflects a debate in the literature about whether the transformation of the power sector will lead to a more distributed system or whether it will remain centralized [59,60]. Therefore, this analysis differentiates between whether a solution technology is deployed in a *distributed* or *centralized* manner, i.e. whether it is deployed on higher voltage or lower voltage levels in the system. The second characteristic follows the implicit categorization between generation technologies on the one hand and transmission and distribution technologies on the other hand, as has been done in previous studies. Solution technologies are therefore classified as *flexibility technologies*, i.e. technologies that contribute to system flexibility by generating or consuming active power, or as *grid technologies*. Through the assignment of two characteristics per technology, solution technologies can be divided into four groups. Table 4 illustrates the nested hierarchy of groups including a description, a solution example, and potential applications of each solution technology. In total, 21 solution technologies are identified, of which 10 solution technologies are distributed and 11 solution technologies are centralized. When differentiating grid versus flexibility technologies thirteen solution technologies are grid technologies, while eight are flexibility technologies.

Interestingly, grid technologies, independent of whether they are distributed or centralized, serve more specific applications than flexibility technologies (see column *application example*). For example, the sole purpose of *state estimation solutions* for distribution grids is to measure or estimate the state of a certain grid area, while *demand response*, a flexibility technology, can serve several applications. Another observation is that, at first glance, distributed and centralized flexibility technologies seem to be quite similar. A closer look, however, reveals that the technologies largely differ in their design, their ability to serve different applications and their respective owners and operators. This can be illustrated with the case of distributed vs. centralized storage. Distributed storage technologies, on the one hand, are usually enclosed battery units installed at household-level. Their prime application to date is optimized self-consumption and the units are mostly owned by the households (i.e. the end consumers) themselves. Centralized storage, on the other hand, can, for example, be hydro pump-storage units or large, connected stacks of batteries. Their prime application is short-term power supply for peak periods or maintaining power system stability. As opposed to distributed storage, centralized storage is usually owned by utilities or system operators.

Table 4

Solution technologies for the integration of VRE.

		Solution	Description	Solution example	Application example	Sources
Distributed technologies	Flexibility technologies	**Modifications on distributed VRE generators**	Modifications in the primary equipment, the control or operation of distributed VRE generators	Grid friendly PV plant	Solar tracking, low voltage ride through, reactive power provision	[39,56]
		Distributed conventional generators	Conventional generators with increased performance in ramping capability, number of starts or partial load operation in commercial and household environments	Reciprocating engine	Optimization of self-consumption, peak shaving, balancing power provision, peak load provision	[13]
		Distributed storage	Distributed storage devices in household, commercial or small industrial environments	Lithium(Li)-Ion battery, lead acid battery	Optimization of self-consumption, peak shaving, balancing power provision, peak load provision	[6]
		Distributed demand response	Controlled decrease or increase of electricity consumption of electric devices, mostly in households or commercial environments	Control of an electric heater or heat pump	Peak shaving, balancing power provision, peak load provision	[5,6]
	Grid technologies	**Distribution grid reinforcement / expansion**	Grid reinforcement or expansion in the distribution grid using conventional equipment	Overhead line, cable, transformer	Transmission capacity increase, active and reactive power flow optimization, grid reliability improvement	[41]
		Adapted equipment protection strategies	Revision of protection functions and protection schemes to ensure fault detection and prevent false protective events	Direct transfer trip scheme, reclosure interlock	Avoidance of relay desensitation, avoidance of nuisance tripping	[37]
		Voltage management solutions for distribution grids	Devices that facilitate the control of voltage fluctuations in distribution grid areas or feeders	On-load tap changer for distribution transformers, static var compensator	Voltage control in distribution grid feeders	[34,37]
		State estimation solutions for distribution grids	Technology to measure and estimate the electric status of a network area	Phasor measurement unit	Real-time VRE feed-in monitoring and control	[5]
		Current limiter devices	Devices for limiting fault currents	High impedance transformer, current limiting fuse	Fault current limitation	[30,33]
		Harmonic filters	Devices to filter harmonic distortions	Active or passive filters	Reduction of harmonic distortions	[32,54]
Centralized technologies	Flexibility technologies	**Modifications on large VRE generators**	Modifications in the primary equipment, the control or operation of large VRE generators	Grid friendly wind turbine	Wind turbine deloading, low voltage ride through, synthetic inertia provision, reactive power provision	[5,6]
		New or modified large conventional generators	Conventional generators with increased performance in ramping capability, number of starts or partial load operation in industrial or utility environments	Gas turbine, reciprocating engine	Balancing power provision, peak load provision	[14]
		Centralized storage	Storage devices in industrial or utility environments	Pumped hydro storage, Li-Ion or lead acid battery, hydrogen storage	Balancing power provision, peak load provision	[5,44]
		Centralized demand response	Controlled decrease or increase of electricity consumption of electric devices at large consumers, mostly in industrial environments	Control of an aluminium smelter	Peak shaving, balancing power provision, peak load provision	[5]
	Grid technologies	**VRE forecasting technology**	Technology to improve predictability of VRE production in the short and medium term	Probabilistic forecasting, meteorological forecasting	Day-ahead forecasting, nowcasting	[13,37]
		Transmission grid reinforcement / expansion	Grid reinforcement or expansion in the transmission grid using conventional equipment	Overhead line, cable, transformer	Transmission capacity increase, active and reactive power flow optimization, grid reliability improvement	[14,39]
		High-voltage direct current (HVDC) transmission systems	Technology for the conversion of high voltage alternating current to direct current and the transmission of high voltage direct current	Thyristor-based converter, transistor-based converter	Transmission capacity increase over long distances, active and reactive power flow control, grid reliability improvement	[40,56]
		Power flow controller	Technology to control active power flow in transmission grids	Phase-shifting transformer, back-to-back HVDC, controllable series compensator	Temporary increase or decrease of transmission capacity, active and reactive power flow optimization	[5,40]
		Reactive power controller	Technology to control reactive power balance in transmission grids	Static var compensator, static synchronous compensator	Prevention of fault induced delayed voltage recovery, reactive power support for the transmission connection of wind farms	[37,40]
		Inertia or short-circuit power providers	Technologies that provide inertia or short-circuit power to stabilize grid areas during fault conditions	Flywheel	Inertia provision, short circuit power increase, reactive power provision	[14]
		Central feed-in monitoring & control	Means to enable monitoring and facilitate central control over distributed VRE generators	Supervisory Control and Data Acquisition (SCADA) integration	Real-time curtailment of VRE generators	[58]

3.3 Challenge – solution interrelations

After determining both the challenges and solution technologies for VRE integration, this study analyzed which solution technologies address the identified challenges, as shown in Figure 2. Thereby, the “solution space” of a challenge refers to the number of solution technologies that address one challenge (on the right of Figure 2), and the “solution potential” of a solution technology refers to the number of challenges one solution technology could potentially address (on the bottom). Due to the qualitative nature of solution potential and solution space, numeric comparisons are of limited use. The values on the right side and the bottom of Figure 2 should therefore be seen merely as qualitative proxies to identify high, medium, or low solution space or potential.

Three observations can be made when looking at the matrix from the solution perspective (i.e., interpreting the columns of the matrix): First, flexibility technologies have the highest solution potential overall and within single challenge categories. Within the flexibility technology group, *modifications to distributed VRE generators* and *distributed conventional generators* have the highest solution potential. In comparison, *centralized demand response* and *new or modified large conventional generators* have the lowest solution potential. Second, distributed solution technologies tend to have a higher solution potential than centralized solution technologies, with the exception of specific distributed grid technologies such as *current limiter devices* or *harmonic filters*. Third, grid technologies have unique value in specific challenges, such as *power flow controllers* and *high-voltage direct current (HVDC) systems*, for solving the issue of increasing transmission distances. Most challenges, however, can be addressed with flexibility technologies.

By looking at which solution technologies contribute to solving corresponding challenges (i.e., interpreting the rows of the matrix), the following observations can be drawn. *Quality* challenges are local and location-specific—they have a narrow solution space and can only be solved by distributed solution technologies. These can either be modified distributed VRE generators or add-on solution technologies, such as harmonic filters. *Flow* challenges can be solved with technologies from all groups. One notable exception is that of centralized flexibility technologies, which have limited contributions to solving flow problems. Challenges in this category have differing solution spaces, from rather narrow (e.g. increasing transmission distances) to rather broad (e.g. increasing regional voltage excursions). *Stability* challenges can only be solved by solution technologies coordinated on a system level, i.e. in a centralized manner. Therefore, unlike with flow challenges, distributed grid technologies do not help to solve stability challenges unless they get aggregated on a system level. Challenges in the stability category have a rather broad solution space, with the exception of increasing control interactions. *Balancing* challenges can be only solved by flexibility technologies since solving these challenges requires the generation or consumption of active power. A notable exception is improved VRE forecasting. Challenges in the balance category generally have a broad solution space, except for long-term generation adequacy, which may be indicative of the relative complexity for solving this challenge in comparison to others.

		Distributed technologies										Centralized technologies											Solution space
		Flexibility technologies				Grid technologies						Flexibility technologies				Grid technologies							
		Modifications to distributed VRE generators	Distributed conventional generators	Distributed storage	Distributed demand response	Distribution grid reinforcement / expansion	Adapted equipment protection strategies	Voltage management solutions for distribution grids	State estimation solutions for distribution grids	Current limiter devices	Harmonic filters	Modifications to large VRE generators	New or modified large conventional generators	Centralized storage	Centralized demand response	VRE forecasting technology	Transmission grid reinforcement / expansion	HVDC transmission systems	Power flow controller	Reactive power controller	Inertia or short-circuit power providers	Central feed-in monitoring & control	
Quality	Increasing flicker	●																					1
	Increasing harmonic distortions	●									●												2
	Unreliable shut-down during blackouts	●					●																2
	Increasing local voltage excursions	●				●	●																3
Flow	Increasing regional voltage excursions	●	●	●	●	●	●	●	●											●		●	10
	Missing distribution grid capacity	●	●	●	●	●		●														●	7
	Increasingly volatile flow patterns from lower grid levels	●	●	●	●	●			●							●	●					●	9
	Inadequate protection design						●		●	●													3
	Increasing short-circuit currents	●				●	●			●													4
	Missing controllability of VRE generation			●	●				●													●	4
	Missing visibility of VRE generation	●				●			●							●	●						5
	Narrow voltage trip limits	●	●					●				●											4
	Missing transmission grid capacity		●	●										●	●		●	●	●				7
	Increasing transmission distances																●	●					2
Stability	Insufficient reactive power provision	●	●									●		●				●		●	●		7
	Decreasing level of short-circuit power											●	●	●							●		4
	Decreasing level of inertia											●		●			●				●		4
	Inadequate coordination of frequency trip limits	●	●	●	●							●	●	●	●						●	●	10
	Inadequate coordination of voltage trip limits	●	●									●		●						●	●		6
	Decreasing frequency control reserves	●	●	●	●							●	●	●	●								8
	Increasing control interactions											●							●				2
Balance	Insufficient short-term generation adequacy	●	●	●	●							●	●	●	●	●							9
	Insufficient long-term generation adequacy		●	●									●	●									4
	Insufficient firmness of VRE generators	●	●	●	●							●	●	●	●	●							9
	Insufficient forecasting of VRE generators		●	●	●							●	●	●	●	●							8
	Restricted dispatchability of VRE generators	●	●	●	●							●	●	●	●	●							9
Solution potential		17	14	12	10	6	5	3	5	2	1	12	8	12	7	6	5	3	2	3	5	5	

Fig. 2. *Interrelations between challenges and solution technologies.*

4. Discussion

This study provides three important insights relevant for VRE integration and the decarbonization of the power sector. The first two insights elucidate the processes that address the challenges of VRE integration within and among different power systems, while the third insight illustrates how the results of this study can improve policy making for the energy transition.

The first point focuses on the solution space of the different challenges. While the observation that more than one type of technology can solve a specific challenge seems intuitive from an analytical standpoint, the expert interviews confirm that business and policy makers do not sufficiently recognize solution technologies as substitutes for solving certain challenges. This is particularly evident for technologies belonging to different categories. Not incorporating developments of other solution technologies can, however, reduce the market potential and economic viability of single technologies. Such misinterpretations can contribute to temporary market price declines, as is the case in Germany's balancing power markets, where changes in the institutional framework and simultaneous development of storage, demand response and improved VRE forecasting has led to a significant decline in market size and prices over the last years [61]. To further illustrate this point, stability and balance challenges are used as an example. Interviewed experts clearly see other technologies in their respective category as substitutes for their own technology. For example, a demand response provider focused on *centralized* solutions would perceive large-scale storage and conventional generation as competitive technologies. *Distributed* flexibility technologies, however, are often out of focus when analyzing the competitive technology landscape. Such perceptions can be even more pronounced with respect to the potential influence of *grid* technologies on flexibility technologies. For example, improved VRE forecasting can significantly reduce the market size for demand response or storage technologies since these technologies are predominantly used in balancing markets whose market size is determined, among other factors, by the forecasting quality of the market participants. The reason for potentially underestimating cross-influences is primarily attributed to the lack of knowledge on the development of technologies in different technology groups. By providing an overview of the competitive landscape of technologies, analyses can be used to inform companies' strategic decision-making, potentially making the energy transition process smoother.

Second, the extant literature remains rather generic when specifying the deployment of portfolios of solution technologies for VRE integration in different regions. As a result, such recommendations fail to provide any guidance to firms and policy makers for developing adequate business strategies and policies. The interrelation matrix can assist in future decision-making when, for example, drafting national technology roadmaps or proposals for nationally determined contributions to power sector decarbonization in line with the Paris Agreement. This function of the interrelation matrix can be exemplified for each of the four challenge categories with historic examples from different countries. As mentioned in Section 4, *quality challenges* occur regionally in areas of high distributed VRE penetration and require the deployment of distributed flexibility and grid technologies. Regions with particularly high penetration of distributed VRE generators include Southern Germany, the southern part of the United Kingdom, and regions in the north and south of Italy [3]. While there is no data available on the deployment of distributed flexibility and grid technologies in these regions, data from Colak et al. [62] on smart grid RD&D projects show that these are high-priority technologies for firms and policy makers in these countries. Countries facing *flow challenges* on a transmission level, such as Germany, require mostly centralized grid technologies, such as transmission grid reinforcement or expansion, HVDC transmission systems, or reactive power controllers. After an assessment phase to determine the size and design of these complex installations, German transmission system operators are currently working on several large projects utilizing these technologies[7]. Similar trends can be seen in Spain and Ireland, both of which face *stability challenges*. Here, transmission system operators have established means to centrally control VRE generators, either requiring VRE generators to support grid stability [63] or investigate possibilities to ease restrictions on the stability criteria of their grid codes[8]. Lastly, *balance challenges* are solved solely through flexibility technologies. California serves as a good example of this, as the state system operator faces difficulties in maintaining the power balance during sunset hours when VRE generation sharply decreases [64]. In order to address this challenge, California has introduced several new market products to incentivize investment in storage, flexible conventional generators, and system-friendly renewables [65]. Summing up, the interrelation matrix can serve as a guide for businesses and policy makers to identify groups of solution technologies that help mitigate prevalent challenges in specific regions and devise strategies and policy measures to support these technologies.

The third point is linked to the debate around how actors should prioritize solution technologies to manage the integration of VRE and the energy transition. Agricola et al. [40], Bird et al. [13], and DNV GL [19] prioritize solution technologies for VRE integration via their cost or ease of implementation. While this perspective has its merits in the short term, it overlooks their differing solution potential to address challenges. Prioritizing solution technologies based on their solution potential would render flexibility technologies as most suitable for solving challenges of VRE integration. Extant literature [40,41] as well as the expert interviewees support the potential of flexibility technologies for solving stability challenges, provided they are given sufficient incentive to perform the required services. Therefore, the results of this analysis support the call for policy makers to adapt existing market rules or implement new deployment policies, such as updated remuneration schemes for reactive power or introducing regional power markets. However, solely ranking technologies by their solution potential does not account for (1) other solution technologies that can equally contribute to solving a challenge, and (2) differences in the solution space among challenges. When these factors are considered, technologies are ranked according to their potential to uniquely solve challenges. Doing so still largely gives preference to the deployment of flexibility technologies, specifically system-friendly centralized and distributed VRE. However, technologies that solve specific challenges, such as adapted equipment protection strategies, would gain higher importance following this perspective. At the same time, solution technologies including large and small demand response as well as new or modified large conventional generators would be lower priority due to their limited unique solution potential. The latter two examples are particularly relevant for the current debate on VRE integration, which emphasizes the deployment of small and large demand response and flexible large conventional generators. While these solutions may be cost-effective and realizable in the short term, they may

[7] In 2015, German TSOs have awarded contracts for two high-voltage direct current transmission projects, several reactive power compensators and transmission grid expansion projects [72,73].
[8] In 2016, the Irish transmission system operator also awarded contracts for a centralized battery storage as well as a flywheel to mitigate the decrease of inertia in the system (Interview #09).

not adequately address the scope of existing or potential challenges. In summation, it is assumed that the aspects discussed confirm the merits of this analysis for business and policy makers.

However, this analysis also has limitations that are important to consider when interpreting the results. As stated in Section 1, the aim of this study is to examine the challenges that arise specifically due to the increasing penetration of VRE. Yet, power systems may also face additional challenges beyond those listed in this study. At the same time, the challenges listed in this analysis may also occur in power systems with low VRE penetration. When focusing on the challenges specific to this analysis, especially regarding the range of challenges one solution technology can address, the analysis does not attempt to quantify the extent to which one solution technology is able to solve a specific challenge. Additionally, future challenges could also be mitigated by developments that lie outside the scope of this analysis, such as new emerging solution technologies, changing frequency stability criteria or the widespread use of more resilient end-use appliances, such as variable frequency drives. In addition, this analysis does not consider the urgency of challenges, challenge-specific costs of solution technologies, or the feasibility of deploying solution technologies due to environmental constraints, for example in high altitude areas or deserts, and social constraints, such as the public acceptance of transmission lines. Such quantifications will be (1) highly context-specific due to the differing characteristics of power systems, and (2) prone to high levels of uncertainty when considering, for example, the cost and revenue potential of solution technologies for different applications. These limitations, however, highlight the need to think in terms of technology groups or portfolios instead of focusing on silver bullets for solving the challenges of VRE integration.

5. Conclusion

This paper identifies the challenges of integrating VRE into modern power systems and the solution technologies available to address these challenges. Thereby, the study provides an overview of the technological needs of power systems with increasing shares of VRE and adds transparency to the complex process of VRE integration. Building on the extant literature, the study collects existing challenges and solution technologies for the integration of VRE. In order to consistently structure the challenges of VRE integration, a root cause analysis is performed. The analysis is complemented with data from expert interviews that were particularly helpful for investigating the interrelations between challenges and solution technologies.

Several insights can be drawn from this analysis: First, challenges of VRE integration affect all major performance characteristics of power systems. Second, while solution technologies vary significantly in the number of challenges they can address, flexibility technologies generally have a higher solution potential in comparison to grid technologies. Third, the analysis facilitates the identification of solution technologies for tackling challenges of different categories. One example is the need for centralized versus distributed solution technologies. Although distributed solution technologies mostly aid in solving challenges related to local power flow, centralized solution technologies help tackle stability challenges.

The analysis makes two important contributions to the literature. First, existing challenges identified in the literature and in practice have been collected and structured with the help of a root cause analysis. This results in a mutually exclusive designation and categorization of challenges. Second, solution technologies are collected and categorized to examine which challenges a single solution technology is capable of addressing. Through the analysis in this paper, both the solution potential of specific technologies and the solution space of single challenges can be identified. The solution potential is a measure that can be of importance for firms and policy makers in devising measures for promoting certain technologies, while the solution space can be understood as an explanatory factor for the complexity of specific challenges.

This study constitutes a starting point for several strands of further research on this important topic. One potential research area is to quantify the interrelations between challenges and solution technologies by comparing cost estimates for different solution technologies or introducing comparative analyses of the overall environmental impacts of different solution technology combinations. This could be done with life-cycle assessments [66] or by measuring the VRE integration cost and externalities based on installed or projected capacities in the future [67]. Doing so could significantly enhance policy recommendations. Similarly, analyzing interdependencies between smaller groups of solution technologies or performing comparative case studies in specific regions may provide researchers a more systemic understanding of technical, economic, and environmental drivers and barriers for the deployment of solution technologies and the VRE integration process in power systems as a whole. Finally, analyzing drivers of the development of individual solution technologies for VRE integration could provide valuable insight into the sustainability transition of the power sector. In this context, it could be valuable to further investigate the relationship between geographical differences and power system characteristics on the one side and the occurrence of challenges and solution technologies on the other side.

Appendix A: Literature search query

The following search query was used for extracting the literature sample from the Web of Science database:

TS=((renewabl* NEAR (energy OR electr* OR power OR generat*)) AND (intermitt* OR distributed OR non-synchronous OR fluctuat* OR volatil*) AND (integrat* OR grid OR *connect* OR network OR "power system*" OR "energy system*") AND (challeng* OR problem* OR issue* OR impact*) NOT model* NOT simul* NOT optim* NOT vehicl*) AND TI=((challeng* OR issue*) AND (energ* OR grid OR network* or integrat*) NOT price* NOT tariff* NOT market* NOT waste* NOT osmosis NOT food)

The search query excludes studies that deal with modeling, simulations, or optimizations since these studies have proven to be concerned with only one challenge. Similarly, studies that deal with analyzing prices or tariffs were excluded due to their focus on technical challenges rather than economical or organizational challenges. Further exclusions that target studies connected to transportation, waste management, or osmosis were added during the iterative process in order to eliminate studies outside the scope of the sample.

Appendix B: Literature sampling

Fig. B 1 illustrates the process through which the sample was structured and reduced for analysis. The overall sample consists of 130 studies from two search processes (groups A and B in Fig. B 1). When analyzing this sample in more detail, it can be divided in two domains: about one third of the studies in the sample are focus studies that have a comparably narrow perspective on single challenges and solution technologies for VRE integration. The remaining two thirds are systemic studies that cover more than one challenge or solution technology. The systemic studies can be divided into three subgroups. The largest group of studies in this domain, covering about four fifths of the sample, are comprehensive challenges and solution studies. Studies in that category either analyze the current system and its needs and opportunities [6] or develop and investigate future scenarios [19,68]. The focus of these studies is typically either on the technological and operational side [40,44] or on regulatory and market issues [69,70]. Splitting comprehensive challenge and solution studies into two groups by focus results in two nearly equal groups: 32 studies focus on technological and operational issues, while the remaining 25 studies focus on regulatory and market issues. The research within this study focuses on comprehensive challenges and solution studies, which pertain to technological and operational issues (group C in Fig. B 1) for collecting challenges and solution technologies.

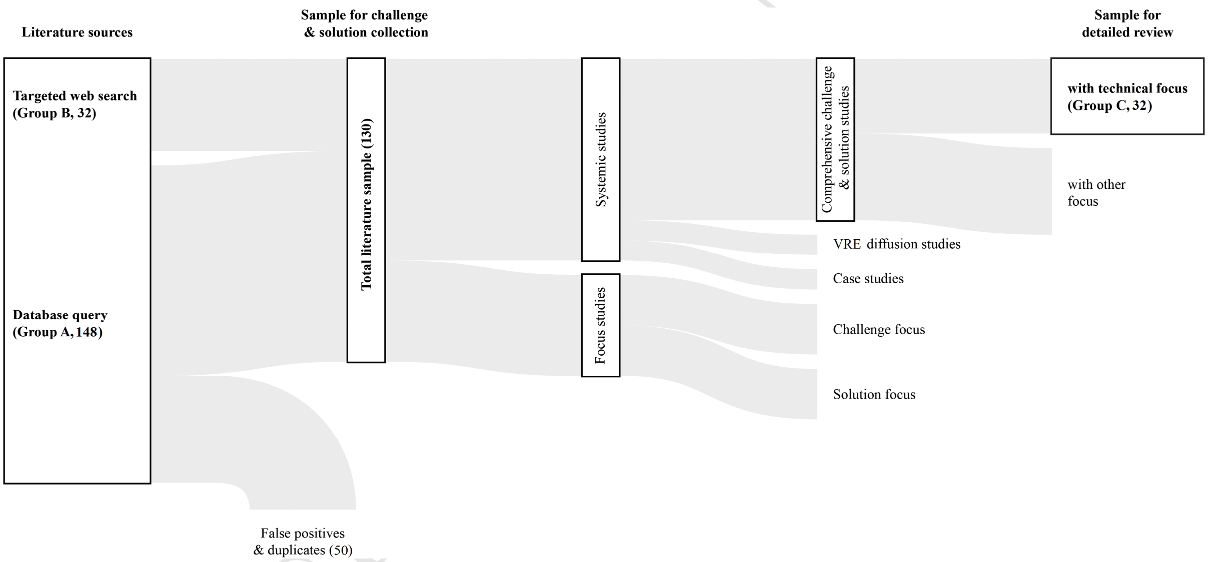


Fig. B 1. *Literature sample overview (number of studies indicated in brackets).*

Appendix C Literature overview

See Appendix Table C 1.

Table C 1

Detailed literature overview.

Author	Thematic focus	Literature source	Discussion of interrelations	Geographical focus, if any
Akom et al. 2018 [53]	Challenges and solution technologies for power quality and flow challenges	Conference paper	only aggregated interrelations	Ghana
Gupta and Seethalekshmi 2018 [51]	Challenges for power quality, grid stability and protection requirements	Conference paper	interrelations for system protection, stability and power quality challenges	-
Sajadi et al. 2018 [52]	Challenges for dynamics, automation and control of electrical power systems	Journal paper	unrelated listing of challenges	-
Liang (2017) [31]	Challenges and solution technologies for the integration of VRE with a focus on power quality	Journal paper	unrelated listing of solutions	-
Tareen et al. (2017) [32]	Solution technologies for power quality challenges due to VRE	Journal paper	interrelations for power quality challenges	-
Telukunta et al. (2017) [33]	Challenges for power system protection due to VRE integration	Journal paper	unrelated listing of solutions	-
Hung et al. (2016) [34]	Technical and non-technical challenges of integrating renewable energy, with an emphasis on security of supply	Conference paper	unrelated listing of solutions	Australia, USA
Karimi et al. (2016) [35]	Challenges for the integration of PV into the distribution network	Journal paper	interrelations for challenges in the distribution grid	-
Li et al. (2016) [36]	Challenges for the integration of VRE into the distribution system	Conference paper	unrelated listing of solutions	-
Alet et al. (2015) [37]	Challenges and solutions for the integration of PV into the power system	Conference paper	only aggregated interrelations	Europe
Stappel et al. (2015) [22]	Options and requirements for increasing the flexibility of power systems	Grey literature	interrelations for system flexibility challenges	Austria, Belgium, France, Germany, Luxembourg, Netherlands
Chaitusaney (2014) [38]	Challenges and measures for integrating distributed generation and renewable energies	Conference paper	no interrelations discussed	Thailand
Krauter and Japs (2014) [39]	Challenges and measures for the integration of PV into the power system	Conference paper	interrelations for system flexibility challenges	-
Agricola et al. (2014) [40]	Future provision of ancillary services in a system with high VRE penetration	Grey literature	interrelations for system stability challenges	Germany
DNV GL (2014) [19]	Technology and cost scenarios for future power systems with high VRE penetration	Grey literature	interrelations for system flexibility challenges	Europe
Mueller et al. (2014) [4]	Investigation of power system properties and requirements for the integration of large shares of VRE generation	Grey literature	interrelations for system flexibility challenges	Brazil, India, Italy, Japan, Norway, Sweden, USA
Meier (2014) [6]	Identification of VRE integration challenges and resulting research priorities	Grey literature	only aggregated interrelations	USA
Van Hulle et al. (2014) [41]	Capability assessment of VRE generation for the provision of ancillary services	Grey literature	investigation of challenges that can be addressed by one solution	Europe
Mirhosseini and Agelidis (2013) [42]	Challenges for the integration of large-scale PV systems into the power system	Conference paper	no interrelations discussed	-
Bird et al. (2013) [13]	Challenges due to the variability of VRE generation and their solutions	Grey literature	interrelations for system flexibility challenges	USA
Martinot (2013) [11]	Investigation of future power system designs with high VRE penetration	Grey literature	only aggregated interrelations	China, Europe, Japan, USA
Anees (2012) [43]	Challenges and solutions for the grid integration of large and small VRE generators	Conference paper	only aggregated interrelations	India
IEC MSB (2012) [44]	Investigation of challenges and solutions for the integration of large-scale VRE generation with a focus on electric-energy storage	Grey literature	interrelations for system flexibility challenges	Brazil, Canada, Denmark, Germany, Ireland, Japan, Spain, UK, USA
Katiraei and Aguero (2011) [45]	Challenges for the integration of PV generation	Journal paper	no interrelations discussed	Canada, USA
Meier (2011) [46]	Allocation of challenges for VRE integration along temporal and spatial dimensions	Conference paper	no interrelations discussed	USA
Zahedi (2011) [47]	Challenges and benefits of increasing VRE penetration	Journal paper	no interrelations discussed	-
Pierre et al. (2011) [23]	Investigation of generation adequacy and flexibility options with decreasing conventional generation	Grey literature	interrelations for system flexibility challenges	Europe
Chandler et al. (2011) [14]	Assessment of power system flexibility requirements	Grey literature	interrelations for system flexibility challenges	Canada, Denmark, Japan, Mexico, Norway, Spain, Sweden, UK, USA
Sims et al. (2011) [48]	Review of renewable energy technology characteristics and integration measures in different countries	Grey literature	interrelations for system flexibility challenges	Canada, China, Denmark, Germany, Greece, Ireland, Portugal, Switzerland, USA
Kassakian et al. (2011) [5]	Challenges for the electricity grid, specifically with the integration of VRE	Grey literature	only aggregated interrelations	USA
Houseman (2009) [49]	Challenges for the integration and operation of distributed and centralized renewable energy technologies	Conference paper	only aggregated interrelations	-
Guel and Stenzel (2005) [50]	Investigation of long- and short-term flexibility challenges and solutions for VRE integration	Grey literature	interrelations for system flexibility challenges	Denmark, Germany

Appendix D: Interrelations of challenges and VRE characteristics

In the following, the relation between challenges and the underlying VRE characteristics is investigated. This investigation reveals that each challenge category has a predominant set of VRE characteristics that is responsible for most of the challenges in this category (see Table D 1).

Table D 1

Relation between challenges and VRE characteristics[9].

		Variability Available power output fluctuates with availability of its resource	**Uncertainty** Resource availability can only be predicted with high accuracy in the short term	**Location-constraints** Resource quality is not equal across locations	**Modularity** VRE generator scale is much smaller than conventional generators	**Non-synchronous** VRE plants connect to the grid via power electronics
Quality	**Increasing flicker content**					•
	Increasing harmonic distortions					•
	Unrealiable shut-down during blackouts				•	
	Increasing local voltage excursions			•	•	
Flow	**Increasing regional voltage excursions**			•	•	
	Missing distribution grid capacity	•		•		
	Increasingly volatile flow patterns from lower grid levels	•		•		
	Inadequate protection design	•		•		
	Increasing short circuit currents				•	
	Missing controllability of VRE output		•		•	
	Missing visibilty of VRE output		•		•	
	Narrow voltage trip limits				•	
	Missing transmission grid capacity	•		•		
	Increasing transmission distances			•		
Stability	**Insufficient reactive power provision**			•		•
	Decreasing level of short-circuit power					•
	Decreasing level of inertia					•
	Inadequate coordination of frequency trip limits				•	
	Inadequate coordination of voltage trip limits				•	
	Decreasing frequency control reserves	•	•			
	Increasing control interactions					•
Balance	**Insufficient short-term generation adequacy**	•				
	Insufficient long-term generation adequacy	•				
	Insufficient firmness of VRE generators		•			
	Insufficient forecasting of VRE generation		•			
	Restricted dispatchablity of VRE generators	•	•			

[9] The VRE characteristic of low, short-run costs is excluded since it is not a technical integration issue.

References

[1] IPCC, Climate change 2014: Synthesis report, Geneva, 2014.

[2] EIA, Installed electricity capacity, (2018). https://www.eia.gov/beta/international/data/browser (accessed April 18, 2018).

[3] J.L. Sawin, K. Seyboth, F. Sverrisson, Renewables 2017: Global status report, Paris, 2017.

[4] S. Mueller, F. de Sisternes, E. Patriarca, A. Portellano, A. Goeritz, J.D. Moller, J. Peter, H. Holttinen, The power of transformation—wind, sun and the economics of flexible power systems, Paris, 2014.

[5] J.G. Kassakian, R. Schmalensee, The future of the electric grid, Cambridge, MA, 2011.

[6] A. Von Meier, Challenges to the integration of renewable resources at high system penetration, Berkeley, CA, 2014.

[7] E. Pean, M. Pirouti, M. Qadrdan, Role of the GB-France electricity interconnectors in integration of variable renewable generation, Renew. Energy. 99 (2016) 307–314. doi:10.1016/j.renene.2016.06.057.

[8] R.A. Rodríguez, S. Becker, G.B. Andresen, D. Heide, M. Greiner, Transmission needs across a fully renewable European power system, Renew. Energy. 63 (2014) 467–476. doi:10.1016/j.renene.2013.10.005.

[9] C. Hadjilambrinos, Understanding technology choice in electricity industries: A comparative study of France and Denmark, Energy Policy. 28 (2000) 1111–1126. doi:10.1016/S0301-4215(00)00067-7.

[10] B.K. Sovacool, The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse?, Util. Policy. 17 (2009) 288–296. doi:10.1016/j.jup.2008.07.001.

[11] E. Martinot, Renewables global futures report 2013, Paris, 2013.

[12] R. Passey, T. Spooner, I. MacGill, M. Watt, K. Syngellakis, The potential impacts of grid-connected distributed generation and how to address them: A review of technical and non-technical factors, Energy Policy. 39 (2011) 6280–6290. doi:10.1016/j.enpol.2011.07.027.

[13] L. Bird, M. Milligan, D. Lew, Integrating variable renewable energy: challenges and solutions, Golden, CO, 2013.

[14] H. Chandler, A. Tuohy, R. Chandra, Harnessing variable renewables—a guide to the balancing challenge, Paris, 2011.

[15] H. Holttinen, Wind integration: Experience, issues, and challenges, Wiley Interdiscip. Rev. Energy Environ. 1 (2012) 243–255. doi:10.1002/wene.18.

[16] N.A. Lahaçani, D. Aouzellag, B. Mendil, Contribution to the improvement of voltage profile in electrical network with wind generator using SVC device, Renew. Energy. 35 (2010) 243–248. doi:10.1016/j.renene.2009.04.020.

[17] J.D. Maddaloni, A.M. Rowe, G.C. van Kooten, Wind integration into various generation mixtures, Renew. Energy. 34 (2009) 807–814. doi:10.1016/j.renene.2008.04.019.

[18] J. Wong, Y.S. Lim, J.H. Tang, E. Morris, Grid-connected photovoltaic system in Malaysia: A review on voltage issues, Renew. Sustain. Energy Rev. 29 (2014) 535–545. doi:10.1016/j.rser.2013.08.087.

[19] DNV GL, Integration of renewable energy in Europe, Bonn, 2014.

[20] K. Hedegaard, P. Meibom, Wind power impacts and electricity storage - A time scale perspective, Renew. Energy. 37 (2012) 318–324. doi:10.1016/j.renene.2011.06.034.

[21] L. Reichenberg, F. Hedenus, M. Odenberger, F. Johnsson, Tailoring large-scale electricity production from variable renewable energy sources to accommodate baseload generation in Europe, Renew. Energy. 129 (2018) 334–346. doi:10.1016/j.renene.2018.05.014.

[22] M. Stappel, A.-K. Gerlach, A. Scholz, C. Pape, The European power system in 2030: Flexibility challenges and integration benefits, Berlin, 2015.

[23] I. Pierre, F. Bauer, R. Blasko, N. Dahlback, M. Dumpelmann, K. Kainurinne, S. Luedge, P. Opdenacker, I. Pescador Chamorro, D. Romano, F. Schoonacker, G. Weisrock, Flexible generation: Backing up renewables, Brussels, 2011.

[24] P.D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renew. Sustain. Energy Rev. 45 (2015) 785–807. doi:10.1016/j.rser.2015.01.057.

[25] M. McPherson, L.D.D. Harvey, B. Karney, System design and operation for integrating variable renewable energy resources through a comprehensive characterization framework, Renew. Energy. 113 (2017) 1019–1032. doi:10.1016/j.renene.2017.06.071.

[26] F. Ueckerdt, R. Brecha, G. Luderer, Analyzing major challenges of wind and solar variability in power systems, Renew. Energy. 81 (2015) 1–10. doi:10.1016/j.renene.2015.03.002.

[27] Clarivate Analytics, Web of Science, (2018). https://apps.webofknowledge.com/.

[28] B.W. Arthur, The nature of technology, Free Press, New York, NY, 2009.

[29] B. Andersen, T. Fagerhaug, Root cause analysis—simplified tools and techniques, ASQ Quality Press, Milwaukee, WI, 2000.

[30] J. Hare, X. Shi, S. Gupta, A. Bazzi, Fault diagnostics in smart micro-grids: A survey, Renew. Sustain. Energy Rev. 60 (2016) 1114–1124. doi:10.1016/j.rser.2016.01.122.

[31] X. Liang, Emerging power quality challenges due to integration of renewable energy sources, IEEE Trans. Ind. Appl. 53 (2017) 855–866. doi:10.1109/TIA.2016.2626253.

[32] W.U. Tareen, S. Mekhilef, M. Seyedmahmoudian, B. Horan, Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system, Renew. Sustain. Energy Rev. 70 (2017) 635–655. doi:10.1016/j.rser.2016.11.091.

[33] V. Telukunta, S. Member, J. Pradhan, S. Member, A. Agrawal, S. Member, M. Singh, S. Member, S.G. Srivani, Protection challenges under bulk penetration of renewable energy resources in power systems: A review, CSEE J. Power Energy Syst. 3 (2017) 365–379. doi:10.17775/CSEEJPES.2017.00030.

[34] D.Q. Hung, M.R. Shah, N. Mithulananthan, Technical challenges, security and risk in grid integration of renewable energy, in: D. Jayaweera (Ed.), Smart Power Syst. Renew. Energy Integr., Springer, Berlin, 2016: pp. 99–118. doi:10.1007/978-3-319-30427-4.

[35] M. Karimi, H. Mokhlis, K. Naidu, S. Uddin, A.H.A. Bakar, Photovoltaic penetration issues and impacts in distribution networks—a review, Renew. Sustain. Energy Rev. 53 (2016) 594–605. doi:10.1016/j.rser.2015.08.042.

[36] R. Li, W. Wang, L. Xu, Security impacts and key issues of the integration of REGs on distribution systems, in: 2nd Int. Conf. Ind. Econ. Syst. Ind. Secur. Eng., 2016: pp. 223–229. doi:10.1007/978-981-287-655-3.

[37] P.-J. Alet, F. Baccaro, M. De Felice, V. Efthymiou, C. Mayr, G. Graditi, M. Juel, D. Moser, M. Petitta, S. Tselepis, G. Yang, Quantification, challenges and outlook of PV integration in the power system: a review by the european PV technology platform, in: 31st Eur. Photovolt. Sol. Energy Conf., 2015.

[38] S. Chaitusaney, Key issues for the integration of renewable energy and distributed generation into Thailand's power grid, in: Proc. Int. Electr. Eng. Congr., IEEE, 2014.

[39] S. Krauter, E. Japs, Integration of PV into the energy system: Challenges and measures for generation and load management, in: 40th IEEE Photovolt. Spec. Conf., 2014: pp. 3123–3128. doi:10.1109/PVSC.2014.6925599.

[40] A.-C. Agricola, H. Seidl, S. Mischinger, P.C. Rehtanz, M. Greve, D.U. Haeger, D. Hilbrich, S. Kippelt, A. Kubis, V. Liebenau, T. Noll, S. Rueberg, T. Schlueter, J. Schwippe, C. Spieker, J. Teuwsen, dena Ancillary Services Study 2030—security and reliability of a power supply with a high percentage of renewable energy, Berlin, 2014.

[41] F. Van Hulle, I. Pinea, P. Wilczek, Economic grid support services by wind and solar PV, a review of system needs, technology options, economic benefits and suitable market mechanisms, Brussels, 2014.

[42] M. Mirhosseini, V.G. Agelidis, Interconnection of large-scale photovoltaic systems with the electrical grid: Potential issues, in: IEEE Int. Conf. Ind. Technol., 2013: pp. 728–733. doi:10.1109/ICIT.2013.6505762.

[43] A.S. Anees, Grid integration of renewable energy sources: Challenges, issues and possible solutions, in: 2012 IEEE 5th India Int. Conf. Power Electron., 2012: pp. 1–6. doi:10.1109/IICPE.2012.6450514.

[44] IEC MSB, Grid integration of large-capacity renewable energy sources and use of large-capacity electrical energy storage, Geneva, 2012.

[45] F. Katiraei, J.R. Aguero, Solar PV integration challenges, IEEE Power Energy Mag. 9 (2011) 62–71. doi:10.1109/MPE.2011.940579.

[46] A. von Meier, Integration of renewable generation in California: Coordination challenges in time and space, in: 11th Int. Conf. Electr. Power Qual. Util., 2011: pp. 1–6. doi:10.1109/EPQU.2011.6128888.

[47] A. Zahedi, A review of drivers, benefits, and challenges in integrating renewable energy sources into electricity grid, Renew. Sustain. Energy Rev. 15 (2011) 4775–4779. doi:10.1016/j.rser.2011.07.074.

[48] R. Sims, P. Mercado, W. Krewitt, Integration of renewable energy into present and future energy systems, in: O. Edenhofer (Ed.), IPCC Spec. Rep. Renew. Energy Sources Clim. Chang. Mitig., Cambridge University Press, Cambridge, 2011.

[49] D. Houseman, True integration challenges for distributed resources in the distribution grid, in: 20th Int. Conf. Exhib. Electr. Distrib., 2009: pp. 1–4. doi:10.1049/cp.2009.0499.

[50] T. Guel, T. Stenzel, Variability of wind power and other renewables: Management options and strategies, Paris, 2005.

[51] N. Gupta, K. Seethalekshmi, A review on Key Issues and Challenges in Integration of Distributed Generation System, 5th IEEE Uttar Pradesh Sect. Int. Conf. Electr. Electron. Comput. Eng. (2018) 1–7. doi:10.1109/UPCON.2018.8597014.

[52] A. Sajadi, L. Strezoski, V. Strezoski, M. Prica, K.A. Loparo, Integration of renewable energy systems and challenges for dynamics, control, and automation of electrical power systems, Wiley Interdiscip. Rev. Energy Environ. 8 (2019) 1–14. doi:10.1002/wene.321.

[53] K. Akom, M.K. Joseph, T. Shongwe, Renewable energy sources and grid integration in Ghana: Issues, challenges and solutions, Int. Conf. Intell. Innov. Comput. Appl. (2018) 1–6. doi:10.1109/ICONIC.2018.8601219.

[54] K. Al-Haddad, Power quality issues under constant penetration rate of renewable energy into the electric network, in: Proc. 14th Int. Power Electron. Motion Control Conf., 2010: pp. 39–49. doi:10.1109/EPEPEMC.2010.5606699.

[55] D. Ilisiu, C. Munteanu, V. Topa, Renewable integration in the Romanian power system: Challenges for Transelectrica, in: 2009 Int. Conf. Clean Electr. Power, 2009: pp. 710–724. doi:10.1109/ICCEP.2009.5211974.

[56] M. Bazilian, E. Denny, M. O'Malley, Challenges of increased wind energy penetration in Ireland, Wind Eng. 28 (2004) 43–55. doi:10.1260/0309524041210883.

[57] C. Marinescu, I. Serban, About the Main Frequency Control Issues in Microgrids with Renewable Energy Sources, in: 4th Int. Conf. Clean Electr. Power, 2013: pp. 145–150.

[58] M. Cailliau, J. Ogando, H. Egeland, R. Ferreira, Integrating intermittent renewable sources into the EU electricity system by 2020: Challenges and solutions, Brussels, 2011.

[59] M.B. Blarke, B.M. Jenkins, SuperGrid or SmartGrid: Competing strategies for large-scale integration of intermittent renewables?, Energy Policy. 58 (2013) 381–390. doi:10.1016/j.enpol.2013.03.039.

[60] A. Battaglini, J. Lilliestam, A. Haas, A. Patt, Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources, J. Clean. Prod. 17 (2009) 911–918. doi:10.1016/j.jclepro.2009.02.006.

[61] L. Hirth, I. Ziegenhagen, Balancing power and variable renewables: Three links, Renew. Sustain. Energy Rev. 50 (2015) 1035–1051. doi:10.1016/j.rser.2015.04.180.

[62] I. Colak, G. Fulli, S. Sagiroglu, M. Yesilbudak, C.F. Covrig, Smart grid projects in Europe: Current status, maturity and future scenarios, Appl. Energy. 152 (2015) 58–70. doi:10.1016/j.apenergy.2015.04.098.

[63] T. Ackermann, N. Martensen, T. Brown, P.-P. Schierhorn, F.G. Boshell, M. Ayuso, Scaling up variable renewable power: The role of grid codes, Bonn, 2016.

[64] P. Denholm, M. O’Connell, G. Brinkman, J. Jorgenson, Overgeneration from solar energy in California: A field guide to the duck chart, Golden, CO, 2015.

[65] K.H. Abdul-Rahman, H. Alarian, M. Rothleder, P. Ristanovic, B. Vesovic, B. Lu, Enhanced system reliability using flexible ramp constraint in CAISO market, in: IEEE Power Energy Soc. Gen. Meet., IEEE, San Diego, CA, 2012: p. 6. doi:10.1109/PESGM.2012.6345371.

[66] G. Finnveden, M.Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, S. Suh, Recent developments in life cycle assessment, J. Environ. Manage. 91 (2009) 1–21. doi:10.1016/j.jenvman.2009.06.018.

[67] F. Ueckerdt, L. Hirth, G. Luderer, O. Edenhofer, System LCOE: What are the costs of variable renewables?, Energy. 63 (2013) 61–75. doi:10.1016/j.energy.2013.10.072.

[68] T. Mai, R. Wiser, D. Sandor, G. Brinkman, G. Heath, P. Denholm, D.J. Hostick, N. Darghouth, A. Schlosser, K. Strzepek, Exploration of high-penetration renewable electricity futures, Golden, CO, 2012.

[69] J. Cochran, L. Bird, J. Heeter, D.J. Arent, Integrating variable renewable energy in electric power markets: Best practices from international experience, Denver, CO, 2012.

[70] P. Vilaça Gomes, N. Knak Neto, L. Carvalho, J. Sumaili, J.T. Saraiva, B.H. Dias, V. Miranda, S.M. Souza, Technical-economic analysis for the integration of PV systems in Brazil considering policy and regulatory issues, Energy Policy. 115 (2018) 199–206. doi:10.1016/j.enpol.2018.01.014.

[71] C.G. Min, M.K. Kim, Net load carrying capability of generating units in power systems, Energies. 10 (2017). doi:10.3390/en10081221.

[72] TenneT, TenneT Onshore Projects Germany, (2017). http://www.tennet.eu/our-grid/onshore-projects-germany-2 (accessed January 19, 2017).

[73] Amprion, Annual Report 2014, Dortmund, 2014.

Acknowledgements

The authors would like to thank Nicola Blum, David Grosspietsch and Christof Knoeri for their valuable comments and input on earlier versions of this article. This research is part of the activities of the Swiss Competence Center for Energy Research (SCCER CREST), which is financially supported by *Innosuisse the Swiss Innovation Agency* under Grant No. 1155000154. The funders were not involved in the study design, the collection, analysis and interpretation of data, the writing of the report, or the decision to submit the article for publication.

Author	Thematic focus	Literature source	Discussion of interrelations	Geographical focus, if any
Akom et al. 2018 [53]	Challenges and solution technologies for power quality and flow challenges	Conference paper	only aggregated interrelations	Ghana
Gupta and Seethalekshmi 2018 [51]	Challenges for power quality, grid stability and protection requirements	Conference paper	interrelations for system protection, stability and power quality challenges	-
Sajadi et al. 2018 [52]	Challenges for dynamics, automation and control of electrical power systems	Journal paper	unrelated listing of challenges	-
Liang (2017) [31]	Challenges and solution technologies for the integration of VRE with a focus on power quality	Journal paper	unrelated listing of solutions	-
Tareen et al. (2017) [32]	Solution technologies for power quality challenges due to VRE	Journal paper	interrelations for power quality challenges	-
Telukunta et al. (2017) [33]	Challenges for power system protection due to VRE integration	Journal paper	unrelated listing of solutions	-
Hung et al. (2016) [34]	Technical and non-technical challenges of integrating renewable energy, with an emphasis on security of supply	Conference paper	unrelated listing of solutions	Australia, USA
Karimi et al. (2016) [35]	Challenges for the integration of PV into the distribution network	Journal paper	interrelations for challenges in the distribution grid	-
Li et al. (2016) [36]	Challenges for the integration of VRE into the distribution system	Conference paper	unrelated listing of solutions	-
Alet et al. (2015) [37]	Challenges and solutions for the integration of PV into the power system	Conference paper	only aggregated interrelations	Europe
Stappel et al. (2015) [22]	Options and requirements for increasing the flexibility of power systems	Grey literature	interrelations for system flexibility challenges	Austria, Belgium, France, Germany, Luxembourg, Netherlands
Chaitusaney (2014) [38]	Challenges and measures for integrating distributed generation and renewable energies	Conference paper	no interrelations discussed	Thailand
Krauter and Japs (2014) [39]	Challenges and measures for the integration of PV into the power system	Conference paper	interrelations for system flexibility challenges	-
Agricola et al. (2014) [40]	Future provision of ancillary services in a system with high VRE penetration	Grey literature	interrelations for system stability challenges	Germany
DNV GL (2014) [19]	Technology and cost scenarios for future power systems with high VRE penetration	Grey literature	interrelations for system flexibility challenges	Europe
Mueller et al. (2014) [4]	Investigation of power system properties and requirements for the integration of large shares of VRE generation	Grey literature	interrelations for system flexibility challenges	Brazil, India, Italy, Japan, Norway, Sweden, USA
Meier (2014) [6]	Identification of VRE integration challenges and resulting research priorities	Grey literature	only aggregated interrelations	USA
Van Hulle et al. (2014) [41]	Capability assessment of VRE generation for the provision of ancillary services	Grey literature	investigation of challenges that can be addressed by one solution	Europe
Mirhosseini and Agelidis (2013) [42]	Challenges for the integration of large-scale PV systems into the power system	Conference paper	no interrelations discussed	-
Bird et al. (2013) [13]	Challenges due to the variability of VRE generation and their solutions	Grey literature	interrelations for system flexibility challenges	USA
Martinot (2013) [11]	Investigation of future power system designs with high VRE penetration	Grey literature	only aggregated interrelations	China, Europe, Japan, USA
Anees (2012) [43]	Challenges and solutions for the grid integration of large and small VRE generators	Conference paper	only aggregated interrelations	India
IEC MSB (2012) [44]	Investigation of challenges and solutions for the integration of large-scale VRE generation with a focus on electric-energy storage	Grey literature	interrelations for system flexibility challenges	Brazil, Canada, Denmark, Germany, Ireland, Japan, Spain, UK, USA
Katiraei and Aguero (2011) [45]	Challenges for the integration of PV generation	Journal paper	no interrelations discussed	Canada, USA
Meier (2011) [46]	Allocation of challenges for VRE integration along temporal and spatial dimensions	Conference paper	no interrelations discussed	USA
Zahedi (2011) [47]	Challenges and benefits of increasing VRE penetration	Journal paper	no interrelations discussed	-
Pierre et al. (2011) [23]	Investigation of generation adequacy and flexibility options with decreasing conventional generation	Grey literature	interrelations for system flexibility challenges	Europe
Chandler et al. (2011) [14]	Assessment of power system flexibility requirements	Grey literature	interrelations for system flexibility challenges	Canada, Denmark, Japan, Mexico, Norway, Spain, Sweden, UK, USA
Sims et al. (2011) [48]	Review of renewable energy technology characteristics and integration measures in different countries	Grey literature	interrelations for system flexibility challenges	Canada, China, Denmark, Germany, Greece, Ireland, Portugal, Switzerland, USA
Kassakian et al. (2011) [5]	Challenges for the electricity grid, specifically with the integration of VRE	Grey literature	only aggregated interrelations	USA
Houseman (2009) [49]	Challenges for the integration and operation of distributed and centralized renewable energy technologies	Conference paper	only aggregated interrelations	-
Guel and Stenzel (2005) [50]	Investigation of long- and short-term flexibility challenges and solutions for VRE integration	Grey literature	interrelations for system flexibility challenges	Denmark, Germany

		Variability	Uncertainty	Location-constraints	Modularity	Non-synchronous
		Available power output fluctuates with availability of its resource	Resource availability can only be predicted with high accuracy in the short term	Resource quality is not equal across locations	VRE generator scale is much smaller than conventional generators	VRE plants connect to the grid via power electronics
Quality	**Increasing flicker content**					•
	Increasing harmonic distortions					•
	Unrealiable shut-down during blackouts				•	
	Increasing local voltage excursions			•	•	
Flow	**Increasing regional voltage excursions**			•	•	
	Missing distribution grid capacity	•		•		
	Increasingly volatile flow patterns from lower grid levels	•		•		
	Inadequate protection design	•		•		
	Increasing short circuit currents				•	
	Missing controllability of VRE output		•		•	
	Missing visibilty of VRE output		•		•	
	Narrow voltage trip limits				•	
	Missing transmission grid capacity	•		•		
	Increasing transmission distances			•		
Stability	**Insufficient reactive power provision**			•		•
	Decreasing level of short-circuit power					•
	Decreasing level of inertia					•
	Inadequate coordination of frequency trip limits				•	
	Inadequate coordination of voltage trip limits				•	
	Decreasing frequency control reserves	•	•			
	Increasing control interactions					•
Balance	**Insufficient short-term generation adequacy**	•				
	Insufficient long-term generation adequacy	•				
	Insufficient firmness of VRE generators		•			
	Insufficient forecasting of VRE generation		•			
	Restricted dispatchablity of VRE generators	•	•			

ACCEPTED MANUSCRIPT

#	Stakeholder	Role
1	Policy consultancy	Senior consultant
2	Power system consultancy	Senior consultant
3	Storage technology provider	Business developer for storage solutions
4	Transmission system operator	Product manager for renewable energies
5	Demand response provider	Operations manager
6	Transmission system technology provider	Product manager for HVDC solutions
7	Generation technology provider	Head of technical marketing for generators
8	Distribution system operator	Head of innovation
9	Transmission system operator	Head of innovation
10	Power system consultancy	Senior power system consultant
11	Transmission system technology provider	Senior design engineer for grid technologies
12	Smart grid technology provider	Chief Operations Officer
13	Integrated electric utility	Senior Transmission Technology Advisor
14	Electric utility	Senior Technology Advisor

Category	Symptom
Quality	- local trips, shorter lifetime or damage to equipment at end consumer - safety hazards
Flow	- regional trips, shorter lifetime or damage to transmission and distribution equipment - loop flows, redispatch or curtailment due to congestion - increased losses
Stability	- increased dynamic stability violations, redispatch or curtailment due to stability concerns - controllability or resonance issues
Balance	- increasing mismatches between supply & demand

Category	Challenge	Description
Quality	**Increasing flicker**	VRE generator feed-in via power electronic-based inverters increases flicker content locally. This leads to reduced equipment lifetime, trips or equ consumers.
	Increasing harmonic distortions	VRE generator feed-in via power electronic-based inverters increases harmonic distortions. This leads to reduced equipment lifetime, trips or equi consumers.
	Unreliable shut-down during blackouts	VRE generators that continue generating electricity within areas that are disconnected from the larger network constitute safety hazards for maint
	Increasing local voltage excursions	VRE generator feed-in in lower grid levels at times of low consumption increases the system voltage at end consumers. This leads to overloading equipment lifetime, trips or equipment damage.
Flow	**Increasing regional voltage excursions**	VRE generator feed-in in radial distribution grid feeders increases the system voltage in these areas. This leads to overloading of feeder equipmen lifetime, feeder trips or equipment damage.
	Missing distribution grid capacity	The existing distribution grid environment is insufficiently sized to accommodate power feed-ins from VRE generators. If insufficient sizing is re curtailment of VRE generators. If insufficient sizing is unrecognized, this will result in reduced lifetime, feeder trips or equipment damage.
	Increasingly volatile flow patterns from lower grid levels	VRE generation on lower voltage levels makes power flows more volatile and less predictable. This leads to increased continuous or temporal cur
	Inadequate protection design	Protection schemes in lower voltage grid areas are not designed for increasingly dynamic load flows due to VRE generation. Inadequate protectio unintended trips or overloading, resulting in shorter lifetime or equipment damage.
	Increasing short-circuit currents	VRE generators connected on lower voltages levels increase short circuit currents in case of faults on the network. The increased currents can lea damage.
	Missing controllability of VRE generation	Small VRE generators are traditionally not equipped with a remote control interface. Uncontrolled feed-in of VRE generation leads to unplanned reduced equipment lifetime, trips or equipment damage.
	Missing visibility of VRE generation	Grid equipment in the lower voltage levels do not measure load flow or equipment loading. VRE feed-in in these areas leads to unplanned flows t feeder trips or equipment damage.
	Narrow voltage trip limits	VRE generators are required to trip outside a specified voltage band. Increasing voltage deviations due to VRE generation therefore leads to incre generators. This in turn causes trips in larger grid areas, shorter equipment lifetime or potential equipment damage.
	Missing transmission grid capacity	Insufficient transmission capacity between VRE generation and consumption locations leads to curtailment of VRE generation, redispatch activiti flow, such as loop flows.
	Increasing transmission distances	The location dependency of VRE generation requires increasingly long transmission distances between generation and consumption locations lea losses.
Stability	**Insufficient reactive power provision**	In comparison to conventional generators, VRE generators have lower reactive power output. VRE deployment and simultaneous power transmis levels of reactive power to maintain system voltage. The undersupply of reactive power leads to violations of dynamic stability regulations, redisp generation.
	Decreasing level of short-circuit power	VRE generators produce significantly less short-circuit power in comparison to synchronous generators. A low level of short-circuit power increa complicates fault detection. This leads to violations of dynamic stability regulations, redispatch or curtailment of VRE generation.
	Decreasing level of inertia	VRE generators provide significantly less rotational inertia in comparison to synchronous generators. This leads to faster frequency excursions in and demand. Faster frequency changes violate dynamic stability regulations and lead to redispatch or curtailment of VRE generation.
	Inadequate coordination of frequency trip limits	VRE generators are required to trip outside a specified frequency band. With increasing VRE penetration levels this requirement leads to violatio tripping an increasing amount of generation at a specific point.
	Inadequate coordination of voltage trip limits	VRE generators are required to trip outside a specified voltage band. Increasing voltage deviations due to VRE generation therefore leads to incre generators. This in turn leads to cascading trips, violations of dynamic stability regulations or amplification of stability incidents.
	Decreasing frequency control reserves	Short-term variability of VRE generation increases the need for frequency control reserves in order to stabilize system frequency. At the same tim providing frequency reserves. The lack of these reserves leads to the violation of dynamic stability regulations, redispatch or curtailment of VRE
	Increasing control interactions	VRE generators connected via controlled inverters can interact with the electricity grid leading to unobserved power oscillations. If uncontrolled t equipment lifetime, trips or equipment damage.
Balance	**Insufficient short-term generation adequacy**	Increasing VRE generation leads to changed performance requirements for conventional generation, like faster ramping requirements. Insufficien performance requirements can lead to predictable short-term mismatches between generation and load, redispatch or curtailment.
	Insufficient long-term generation adequacy	Increasing VRE generation leads to changed performance requirements of conventional generation, like night-time or seasonal balancing of powe adequacy for these performance requirements can lead to predictable long-term mismatches between generation and load.
	Insufficient firmness of VRE generators	Variability of VRE generation increases the uncertainty of firm generation capacity estimations. This leads to higher reserve requirements and inc mismatches between generation and load, balancing power activation, redispatch or curtailment.
	Insufficient forecasting of VRE generators	Variability of VRE generation leads to increasing forecast inaccuracies. The results are unscheduled mismatches between generation and load, ba redispatch or curtailment.
	Restricted dispatchability of VRE generators	The performance range of VRE generators is restricted by their fluctuating primary resource provision. Using VRE generators to balance unfores generators is therefore limited. This leads to unscheduled mismatches between generation and load and balancing power activation.

		Solution	Description	Solution example	Application example	Sources
Distributed technologies	Flexibility technologies	**Modifications on distributed VRE generators**	Modifications in the primary equipment, the control or operation of distributed VRE generators	Grid friendly PV plant	Solar tracking, low voltage ride through, reactive power provision	[39,56]
		Distributed conventional generators	Conventional generators with increased performance in ramping capability, number of starts or partial load operation in commercial and household environments	Reciprocating engine	Optimization of self-consumption, peak shaving, balancing power provision, peak load provision	[13]
		Distributed storage	Distributed storage devices in household, commercial or small industrial environments	Lithium(Li)-Ion battery, lead acid battery	Optimization of self-consumption, peak shaving, balancing power provision, peak load provision	[6]
		Distributed demand response	Controlled decrease or increase of electricity consumption of electric devices, mostly in households or commercial environments	Control of an electric heater or heat pump	Peak shaving, balancing power provision, peak load provision	[5,6]
	Grid technologies	**Distribution grid reinforcement / expansion**	Grid reinforcement or expansion in the distribution grid using conventional equipment	Overhead line, cable, transformer	Transmission capacity increase, active and reactive power flow optimization, grid reliability improvement	[41]
		Adapted equipment protection strategies	Revision of protection functions and protection schemes to ensure fault detection and prevent false protective events	Direct transfer trip scheme, reclosure interlock	Avoidance of relay desensitation, avoidance of nuisance tripping	[37]
		Voltage management solutions for distribution grids	Devices that facilitate the control of voltage fluctuations in distribution grid areas or feeders	On-load tap changer for distribution transformers, static var compensator	Voltage control in distribution grid feeders	[34,37]
		State estimation solutions for distribution grids	Technology to measure and estimate the electric status of a network area	Phasor measurement unit	Real-time VRE feed-in monitoring and control	[5]
		Current limiter devices	Devices for limiting fault currents	High impedance transformer, current limiting fuse	Fault current limitation	[30,33]
		Harmonic filters	Devices to filter harmonic distortions	Active or passive filters	Reduction of harmonic distortions	[32,54]
tralized technologies	Flexibility technologies	**Modifications on large VRE generators**	Modifications in the primary equipment, the control or operation of large VRE generators	Grid friendly wind turbine	Wind turbine deloading, low voltage ride through, synthetic inertia provision, reactive power provision	[5,6]
		New or modified large conventional generators	Conventional generators with increased performance in ramping capability, number of starts or partial load operation in industrial or utility environments	Gas turbine, reciprocating engine	Balancing power provision, peak load provision	[14]
		Centralized storage	Storage devices in industrial or utility environments	Pumped hydro storage, Li-Ion or lead acid battery, hydrogen storage	Balancing power provision, peak load provision	[5,44]
		Centralized demand response	Controlled decrease or increase of electricity consumption of electric devices at large consumers, mostly in industrial environments	Control of an aluminium smelter	Peak shaving, balancing power provision, peak load provision	[5]
	ogies	**VRE forecasting technology**	Technology to improve predictability of VRE production in the short and medium term	Probabilistic forecasting, meteorological forecasting	Day-ahead forecasting, nowcasting	[13,37]
		Transmission grid reinforcement / expansion	Grid reinforcement or expansion in the transmission grid using conventional equipment	Overhead line, cable, transformer	Transmission capacity increase, active and reactive power flow optimization, grid reliability improvement	[14,39]
		High-voltage direct current (HVDC) transmission systems	Technology for the conversion of high voltage alternating current to direct current and the transmission of high voltage direct current	Thyristor-based converter, transistor-based converter	Transmission capacity increase over long distances, active and reactive power flow control, grid reliability improvement	[40,56]

Cen	**Grid technol**	**Power flow controller**	Technology to control active power flow in transmission grids	Phase-shifting transformer, back-to-back HVDC, controllable series compensator	Temporary increase or decrease of transmission capacity, active and reactive power flow optimization	[5,40]
		Reactive power controller	Technology to control reactive power balance in transmission grids	Static var compensator, static synchronous compensator	Prevention of fault induced delayed voltage recovery, reactive power support for the transmission connection of wind farms	[37,40]
		Inertia or short-circuit power providers	Technologies that provide inertia or short-circuit power to stabilize grid areas during fault conditions	Flywheel	Inertia provision, short circuit power increase, reactive power provision	[14]
		Central feed-in monitoring & control	Means to enable monitoring and facilitate central control over distributed VRE generators	Supervisory Control and Data Acquisition (SCADA) integration	Real-time curtailment of VRE generators	[58]

Highlights

- The study collects and structures challenges for the integration of renewables
- It collects solution technologies that are available to address these challenges
- It provides orientation on the scope and the potential of solution technologies
- This increases transparency of the complex process of renewable energy integration