

REVIEW

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A critical review of the integration of renewable energy sources with various technologies

Erdiwansyah^{1,2*} , Mahidin^{3*}, H. Husin³, Nasaruddin⁴, M. Zaki³ and Muhibbuddin⁵

Abstract

Wind power, solar power and water power are technologies that can be used as the main sources of renewable energy so that the target of decarbonisation in the energy sector can be achieved. However, when compared with conventional power plants, they have a significant difference. The share of renewable energy has made a difference and posed various challenges, especially in the power generation system. The reliability of the power system can achieve the decarbonization target but this objective often collides with several challenges and failures, such that they make achievement of the target very vulnerable. Even so, the challenges and technological solutions are still very rarely discussed in the literature. This study carried out specific investigations on various technological solutions and challenges, especially in the power system domain. The results of the review of the solution matrix and the interrelated technological challenges are the most important parts to be developed in the future. Developing a matrix with various renewable technology solutions can help solve RE challenges. The potential of the developed technological solutions is expected to be able to help and prioritize them especially cost-effective energy. In addition, technology solutions that are identified in groups can help reduce certain challenges. The categories developed in this study are used to assist in determining the specific needs and increasing transparency of the renewable energy integration process in the future.

Keywords: Integration RE, Energy source, Technology system energy, Power system, Variable RE

1 Introduction

Decentralization in the electricity sector is a major step in the spread of renewable energy sources that can reduce dependence on fossil fuels [56]. Global growth of photovoltaics (PV) and wind power in recent years has been 4% and 7%, respectively. The average increase over the past 5 years reached 27% PV and 13% wind [37, 80, 109, 116]. Variable renewable energy (VRE) has differences, in various ways, from conventional generation. There are six main characteristics of VRE generator output, such as: the main resource has variable, small

and modular VRE generators, which are different from conventional generators and are non-synchronous and an unpredictable type of VRE, although there may be low costs in the short-term [5, 50, 59]. These characteristics can create various challenges to the existing power system. In this case, power system performance characteristics can be affected because of some predefined challenges, e.g. the capacity for transmission line loss or inadequate generation. In addition, the inability of portfolio generation available for matching the demand for power to the needs at any time [11, 31, 39, 40, 63, 88, 113, 129].

Existing energy technologies can be used to overcome these challenges. In this case, modification technology and renewable technology can reduce some of the effects, such as the expansion of transmission networks

* Correspondence: erdi.wansyah@yahoo.co.id; mahidin@unsyah.ac.id

¹Doctoral Program, School of Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia

³Department of Chemical Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia

Full list of author information is available at the end of the article

and centralized or distributed storage devices. Integration of VREs connected to power systems requires technological solutions to achieve the decarbonization target. However, the application of a technology can cause complications caused by three main factors. First, technology choices include the implicit or explicit application of the costs, and the maturity and technological preferences of policymakers as well as companies [46, 90, 95, 115]. Second, the decision on a specific solution technology is not via a single entity but rather several actors, such as utilities, system operators and regulators [57, 66, 94, 124]. Finally, designated technologies vary by region including the VRE share of generator portfolios or individual power configurations for interconnected island systems [21, 69, 82].

From the opinions of several practitioners and researchers on energy transition, we can say that there is not enough transparency on the scope of the technologies to overcome these challenges [53, 60, 75]. The individual analysis offered by some proposes specific technologies, e.g. voltage management solutions for networks distributed through VRE penetration [70, 77, 98, 131]. However, there are several technologies presented in this paper that have the potential to overcome broader challenges such as battery storage. In addition, scenarios for investigating the deployment of specific technologies to increase storage and transmission capacity have also been discussed [33, 49, 101]. However, from several studies, the substitution effects of different technology solutions are very rarely considered. Other studies focus only on some aggregate challenges, especially the challenges of flexibility [10, 74, 81, 84, 110, 118]. However, challenges are defined at an aggregate level such that they do not necessarily lead to a particular solution technology. While some technology solutions and individual challenges might be known, some of the available literature does not provide a transparent picture. It is very important that decision-makers and researchers alike are aware of these factors when considering energy transition. When so informed, they will be better able to determine the road map and strategy on technology for the development of power system plants.

Renewable energy technology is widely covered in the literature and clearly various challenges still exist. The review carried out in this study aims to map the challenges of VRE by describing what technology solutions are appropriate to overcome these challenges. The approach taken in this paper is the analysis of data from the literature used to compile and map the list of technology solutions and challenges based on their interrelations, and to identify any lack of consistency and classify challenges to VRE. This approach aims to distinguish the observed symptoms, e.g. performance characteristics that change. Furthermore, this analysis is complemented

with information from several experts to strengthen and ensure more accurate results. The findings on challenges and their linkages to technology solutions are also discussed. The relevant implications for policymakers and companies are presented in the next section. The main contribution of this review is to provide up-to-date information and useful knowledge in the deployment of RET so that energy access across the country can be improved. The systemic approach within an RE framework for information on important components of the RE ecosystem is a feature of this article.

The outline of this paper is as follows. Part one is an overview. Part two describes the materials and methods used. Part three gives the results and discusses the review and analysis regarding RET. Part three presents the findings and solutions of RET in detail. The final part is the conclusion.

2 Materials and methodology

2.1 Collecting challenges and technology solutions

Analysis of the challenges and technological solutions contained in this study were collected from literature published in journals, conferences and from some institutions in the English language. The samples analysed in this paper were mostly collected from internationally recognized journals and sources from established publishers such as Elsevier (Science Direct), Springer, Wiley, etc. [13, 38, 117] and from various online websites published by several official government and private institutions and research institutions. The journals analysed and reviewed in this paper contained 132 articles deemed relevant to technological challenges and solutions, especially for renewable energy.

The literature review conducted in this paper is divided into several categories to map various technological challenges and solutions comprehensively. The first category reviewed related to challenges and technological solutions from a systemic viewpoint, looking at the differences between systematic studies that focus specifically on technological solutions and challenges as well as other foci relating to VRE in an integrated manner in certain areas such as islands or villages. Reviews relating to market share issues or regulations are set in perspective from a technological or operational solution integrated directly with VRE. The final category analysed is the basis for extracting technological solutions and challenges. Studies relating to perspective technology and operations are used to eliminate ambiguity for the identification of challenges. This is due to dependence on fundamental technical phenomena. Various sequential effects in increasing the yield of VRE penetration have been reported in several studies [35, 71, 97, 120]. This is done because it does not have the marginal cost that is important to the challenges of integrating

renewable energy. However, the ambiguity of challenge that is defined on the economic perspective has a lower spot price so that it is following the wishes of the community in perspective. To define various technical challenges including generation, it is inadequate to adjust ambiguity because it has potential effects that are not desired by stakeholders. For example, the selection of problems, in particular, is not an institutional or organizational challenge. As such, it is very easy to overlook storage from a technical point of view. Organizations or institutions that have changed are in fact steps for technical reconfiguration. In addition, it can increase more than one market share for technology solutions to power systems.

Integration of challenges and technological solutions collected and analysed from a variety of literature is a function as well as interview input for further research processes. This challenge is not tangible, in this case, the description and the words conveyed have differences. First, the challenges are collected in a long form, then iteratively collected and repeated. The technological solutions collected are determined with two requirements, first; independently this technology must be able to mitigate one another and automatically the challenges are integrated directly into VRE. Such requirements are very necessary to prevent the grouping of sub-technologies used as technological solutions. One example of sub-technology is Smart Meter, which is very possible to respond to requests as needed. However, it cannot independently reduce challenges that are integrated directly with VRE. Therefore, it is important to classify responses to requests for technological solutions, however, not for Smart Meters. As for the second category, it is done to define technology solutions based on their respective functions as explained by [16, 76, 93]. Thus, the exclusion of technological solutions can gradually be helped by the differences between one another. Given the example of the request-response, the main function of this technology is to reduce power at certain times and devices. However, response requests are operated on different devices, for example, electric heaters and heat pumps so that different technological solutions cannot serve similar functions. This study develops the challenges and technological solutions based on the various literature reviewed. The identification of all interrelated technological solutions is described with specific challenges.

The list of challenges as explained earlier will be refined with literature and reviews relating to challenges according to their level and challenges related to overall causality (Table 1). The relationship between the challenges and the technological solutions analysed shows that the two are mutually exclusive. Therefore, the analysis methodology applied in this study aims to find out

the causes, management tools and the standard tools. Besides, the purpose of applying this method is to identify the main causes of certain problems and events as the root causes [14, 36, 112]. Categories with failure modes on micro-networks that can be used to find various errors and resolutions are found in the method [34, 48, 52]. The method is applied to identify the increasing symptoms of penetration of VRE collected from various literature. The symptoms analysed represent various effects that have adverse effects on performance characteristics for the power system. The identification of challenges found in the literature is then mapped based on the symptoms of each specific VRE characteristic that is the root of the problem.

3 Result and discussion

3.1 Defiance

There are eight categories of problems in increasing VRE penetration found in some of the literature as shown in Table 2. Furthermore, the problems that have been identified were divided into four main categories as requirements for basic performance for power systems. The dominant performance requirement for end consumers is one of sufficient power quality. This power quality consists of a continuous and uninterrupted power supply with a steady-state of voltage and current. In addition, if there is an instant matching, it is better to stay awake and safe. The basic category of VRE can be responsible for power quality challenges that include the modularity of the VRE generator and the fact of dissonance. Furthermore, the flow was categorized as transmission and distributed power efficiency. Multiple stream categories were the cause of the challenge compared to the other categories. Modularity, location constraints and VRE were the biggest part of the flow of challenges. The frequency of controls and challenges was categorized as stability to the power system to restore the system after a blackout. The cause of the stability of this challenge was due to the modularity of the VRE generator and the synchronization of the generator. The relationship between the challenges with the balance of supply and demand for active power in the short and long term of the system was categorized into power balance. This included a wider coordination system of speed capacity in the power system to the generator and ramp to a minimum. The main cause of the challenges was the uncertainty and variability of VRE. The main problem from the results of the analysis has given a bottom-up challenge category that was consistent by adjusting the problems contained in the power system to increase VRE penetration. A detailed review of the inter-related challenges between VRE characteristics and challenges is the basis of the review in this paper.

Table 1 An overview of interviews by experts

Part	<ol style="list-style-type: none"> 1. Consultant of Senior 2. Innovation Leader 3. Senior consultant for power system 4. Chief Executive Operations 5. Senior of Technology consultant 6. Senior Grid technology engineer 7. Senior Consultant in Transmission Technology 8. An entrepreneur for storage options 9. Executive Operations 10. Head of the company for HVDC solutions 11. Head of Technical generator marketing
Participant	<ol style="list-style-type: none"> 1. Consultancy of Policy and Consultancy on Power System 2. System operator distribution and Traffic system operator 3. Consultancy on power system 4. Provider of intelligent Grid technology 5. Utility of Electricity 6. Technology supplier for transmission systems 7. The utility of Integrated Electricity 8. Technology storage provider 9. Application response provider 10. Technology supplier for transmission systems 11. Arbitrer of technology generation

The results of the analysis of the main problems contained in an electricity network problem that includes a mismatch of demand and electricity supply are shown in Fig. 1. Schematic description of the analysed problem was categorized into five chains, i.e. the causal effects of different VRE characteristics. Further analysis was carried out to ascertain the level of detail of each so that the problem can be resolved as quickly as possible before the selection of challenges interrelation analysis. Demand and supply that do not have in common certainly have a variety of different reasons besides increasing VRE penetration. For example, delivery limitation from nuclear power plants and coal is one of the reasons because the power system is less flexible [74]. However, the main focus of this paper discusses the challenges and integrated technological solutions and causes of the connection to the increased VRE penetration. The main problems analysed are eight causes caused by the increased VRE penetration as summarized in Fig. 1. A list of the challenges that has been summarized includes descriptions and categories of each as well as the symptoms observed and references as shown in Table 3. Twenty six challenges have been identified as a whole and most of them are challenges related to power system stability and power flow.

3.2 Technologies of Solutions

Categorical and technological solutions and challenges are generally not specifically available in the literature. This is because most categories are implicit and have differences in the focus of each research. The study of power systems are flexible such as technology that can consume and produce power actively [25, 97]. Meanwhile, research on electricity networks tends to focus on technology for power distribution and transmission only ([99, 100]. Technology solutions that are comprehensively registered are not included in the technology identification as reported in the study [63]. Categorization of technology solutions is determined such as transformation in the energy sector and conclusions with a higher level. Research on top-line classification using two characteristics assigned to technological solutions has been reported by [54]. Transformations in the energy sector that lead to distributed or centralized systems are characteristics as reflected in the literature [19, 22, 26]. Therefore, the difference between distributed and centralized technology solutions can be used at a higher or lower level of system challenge. Technology with one side of generation and transmitted technology that is distributed with the other side can be categorized into the second as reported in several kinds of literature. Technology flexibility can be classified as technological solutions such as technology that contributes to system flexibility producing or consuming active power or better known as grid technology that is also classified as a technological solution. The characteristics of technological solutions can be divided into four groups through two assignments. The group which is categorized as two assignments includes a description, e.g. potential applications and solutions for each technology solution as shown in Table 4. Twenty one technology solutions have been identified; 10 of which are distributed technology solutions, while the remaining 11 technological solutions are centralized. Besides, 21 technological solutions are also distinguished from the flexibility and grid technology systems. Whereas, there are 8 flexibility technologies and 13 grid technologies.

Grid technology is considered more attractive than flexibility technology because grid technology can serve both centralized and distributed systems. An estimation solution in a grid distribution system can estimate or measure a particular grid area. While responding to

Table 2 The categorization of challenges according to the root cause analysis

Categories	Balance	Quality	Stability	Flow
Phenomenon	<ul style="list-style-type: none"> ✓Growing inequalities among supply and demand 	<ul style="list-style-type: none"> ✓Local trips, shorter service life or damage to end-consumer equipment ✓Dangers to safety 	<ul style="list-style-type: none"> ✓Increased stabilization breaches, dispatch or limitation due to stability apprehensions ✓Problems with contractility or resonance 	<ul style="list-style-type: none"> ✓Area journeys, shorter lifetime or damage to transmission equipment and distribution ✓Loop flows, re-dispatch or congestion cuts Increase losses

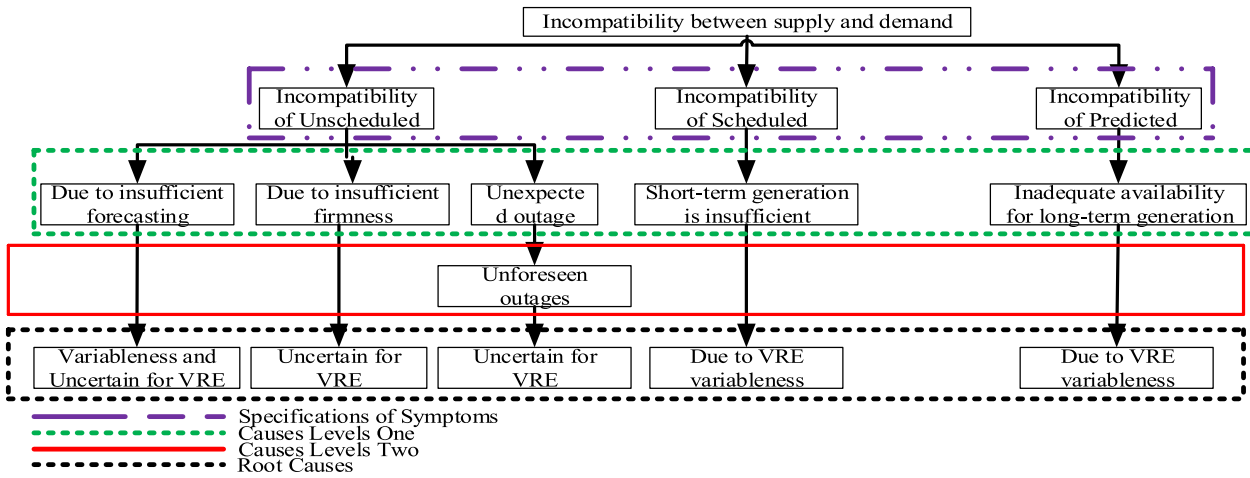


Fig. 1 Analysing the root cause to balance challenges

requests to serve multiple applications can be done with technology flexibility. Centrally distributed and distributed technology systems are very similar when they were first seen. However, more closely, the design between the two shows the difference. Where the ability to serve the application is distinguished from the operator and the owner himself. This difference is illustrated in the case of a stored and distributed system. On the other hand, storage with a distributed system is generally a battery unit installed at the household level with a closed state. Optimized independent consumption of these units is generally found in households, e.g. end consumers or stand-alone. While centralized storage systems such as water pump storage units or batteries are connected. The purpose of this application is for a short period during peak periods or to maintain the system's power stability. Whereas centralized distributed storage is generally found in the operator or utility system.

3.3 Interrelationships between solutions to challenges

After completing the identification of technological solutions and challenges for integrated VRE, an analysis was carried to overcome the challenges as shown in Table 5. Challenges contained in the scope of solutions can ignore the number of technological solutions so that defined challenges can be addressed. Successful solution spaces are identified as illustrated in Table 6. Where the potential solutions contained in technological solutions that refer to several challenges can be addressed as quickly as possible. Because the space and potential of qualitative solutions are numerical comparisons and very limited to be used. Observation matrices made from the perspective of solutions such as high potential solutions and overall challenges are technological flexibility. VRE generators and distributed conventional generators that have a high level of potential solutions are included in

the flexibility technology group, for example, large conventional generators with low potential solutions and conventional generation. Furthermore, distributed technological solutions tend to be higher compared to centralized systems. However, distributed grid technology has special exceptions especially for limiter or harmonic filter devices. Finally, the unique value that grid technology has on specific challenges include direct current control systems that have high voltage (HVDC) and power flow that can accurately solve problems such as long transmission distances. However, these challenges can generally be addressed by utilizing flexible technology.

Contributions made by the solution technology to solve the challenges are described in Tables 5 and 6. Challenges that are local and site-specific have a narrower scope because the solution can only be done by the distributed solution technology, modified distributed VRE generators or additional technology solutions, e.g. harmonic filter. The whole technology group can solve various flow challenges, except technology-centred flexibility that has limitations in solving flow problems. The difference in solution space is included in the category of flow challenges starting from a narrow space to a wider space. The challenge of stability can be solved by a system technology solution by controlling at the system level centrally. Thus, the challenges of flow and distributed technology networks cannot solve challenges to stability, unless the system level can be aggregated. Stability categories such as challenges have wider solution space; however, systems in control interactions cannot be improved. To be able to balance, challenges can only be done by flexibility technology so that existing challenges can be tailored to the needs and active power consumption, except for the increase in the more important VRE estimates. In general, the challenges in the balance

Table 3 Result of VRE Implementation Challenges

Defiance	Descriptions	Ref.
Balance		
Insufficient appropriateness of short-term generation	Increasing generation of VRE results in changed performance requirements for conventional generation, such as speedier ramping requirements. Insufficient adequacy for these performance requirements can result in predictable short-term mismatches between generation and load, re-deployment or curtailment.	[25]
Insufficient adequacy for long term generation	A growing generation of VRE leads to changed performance requirements for traditional generation, such as night-time or seasonal power generation balancing. Insufficient adequacy can lead to predictable long-term mismatches between generation and load for these performance requirements.	[10, 31, 118]
Inadequate firmness of VRE generators	Variability of the generation of VRE increases the uncertainty of estimates of firm capacity to generate. This results in higher reserve requirements and an increase in unplanned mismatches between generation and load, power activation balancing, re-dispatch or curtailment.	[18, 23, 73]
Insufficient VRE generator forecast	Variability of the generation of VRE leads to increasing inaccuracies in the forecast. The results are unplanned mismatches between generation and load, activation of the power balance, dispatch or curtailment.	[54, 65, 104]
Limited VRE generator dispatch-ability	The output range of VRE generators is limited by their fluctuating primary resource provision. Use VRE generators to offset unexpected outages of other generators is therefore minimal. This leads to unplanned inconsistencies between activation of generation and load and balance of electricity.	[1, 4]
Quality		
Increased flicker	The feed-in of VRE generators via electronic power inverters increases the flicker content locally. This leads to the shorter lifespan of equipment, trips or damage to equipment at end users.	[72, 92, 121]
Stepping up harmonic distortions	Feed-in of VRE generators via electronic power inverters increases harmonic distortions. This leads to the shorter lifespan of equipment, trips or damage to equipment at end users.	[8, 58]
Unstable shutdown at blackout	VRE generators which continue to generate electricity in areas disconnected from the larger network constitute security hazards for maintenance or repair operations.	[48, 62, 106]
Increasing excursions at the a local voltage	VRE generator feed-in to lower grid rates at low-consumption times raises device voltage for end users. This results in overloading and reduced damage to the equipment, trips or equipment.	[12, 111, 131]
Stability		
Insufficient supply of reactive capacity	VRE generators have lower reactive power output, compared to conventional generators. To maintain system voltage, the VRE deployment and simultaneous power transmission expansion require higher levels of reactive power. The under-supply of reactive power contributes to breaches of dynamic stability legislation, redeployment or VRE generation curtailment.	[99, 100]
Reducing short-circuit power	Compared to synchronous generators, VRE generators produce significantly less short-circuit power. A low short-circuit power level increases voltage instability and makes identification of faults more difficult. This leads to breaches of dynamic stability legislation, dispatch or curtailment of VRE production.	[55, 99, 100]
Reducing inertia	VRE generators offer considerably less rotational inertia compared to synchronous generators. In cases of imbalance between supply and demand, this leads to faster frequency excursions. Faster frequency changes infringe dynamic stability regulations and lead to VRE generation being dispatched or curtailed.	[5, 99, 100]
Failure to manage frequency travel limits	The VRE generators must fly beyond a specified frequency range. With rising rates of VRE penetration, this requirement leads to violations of the stability regulations by tripping a growing amount of generation at a particular stage.	[20, 42, 91]
Insufficient synchronization of the voltage trip limits	The VRE generators must travel outside a specified voltage band. Consequently, increased voltage variations due to the VRE generation lead to increased tripping of VRE generators. This in turn, leads to cascading journeys, breaches of regulations on dynamic stability or an accumulation of incidents of stability.	[27, 103, 127]
Diminishing reserves of frequency control	To stabilize system frequency, short-term instability of the VRE generation increases the need for frequency control reserves. At the same time, VRE generators do not deliver reserves of power. The lack of these reserves leads to dynamic stability regulations being violated, VRE generation being dispatched or curtailed.	[15, 47, 79]
Increasing interactions between controls	Connected VRE generators that controlled inverters can interact with the electricity grid, leading to unattended power oscillations. They can lead to reduced equipment life, trips or damage to equipment if uncontrolled.	[6, 64, 89]
Flow		

Table 3 Result of VRE Implementation Challenges (*Continued*)

Defiance	Descriptions	Ref.
Missing capability on the power grid	The current grid distribution system is not large enough to handle power feed-ins from VRE generators. This will result in curtailment of the VRE generators if inadequate sizing is understood. If insufficient sizing is not recognized, this will lead to a reduced lifespan, feeder trips or damage to the equipment.	[35, 97]
Increasing excursions to the regional voltage	In radial distribution grid feeders, the VRE generator feed-in increases the system voltage in those areas. This leads to overloading of feeder equipment and leads to reduced service life, feeder trips or damage to equipment.	[58, 123]
Flow patterns from lower grid levels are increasingly volatile	At lower voltage levels VRE generation makes power flows more volatile and less predictable. This results in increased constant or temporary curtailment of VRE generators.	[44, 126, 130]
Narrow limits of the trip voltage	The VRE generators must move beyond a specified voltage band. Consequently, increased voltage variations due to the VRE generation lead to increased tripping of VRE generators. This, in turn, triggers journeys to wider grid areas, shorter lifespan of equipment or possible damage to equipment.	[122]
Increasing currents on short-circuits	VRE power plants connected at low temperatures increases narrow-circuit currents in the event of network failures. The heightened currents can cause further damage to trips or equipment.	[86, 105, 119]
Greater transmission distances	The area dependence of generating VRE includes increasingly long information and service among locations of generation and consumption resulting in higher energy losses.	[34, 63]
VRE generation lacking visibility	Power system equipment at small power does not evaluate the load flow or the loading of the equipment. VRE feed-in in these areas results in unplanned flows resulting in reduced service life, feeder trips or damage to the equipment.	[67, 68, 83]
Inadequate protection design	Protection schemes are not planned for increasingly dynamic load flows due to the VRE generation in lower voltage grid areas. Inadequate design of the protection scheme causes unintended trips or overloading, resulting in shorter lifetime or damage to the equipment.	[9, 61, 122]
Lack of grid transmission power	Insufficient transmit power between locations of VRE generation and consumption leads to curtailment of VRE generation, dispatch operations or unintended transmitting flow, including loop flows.	[97]
VRE generation lacks controllability	Simple VRE power stations are usually not fitted with a remote-controlled interface. Uncontrolled feed-in of VRE up the approval to unplanned energy flows resulting in decreased equipment life-time, trips or equipment damage.	[63, 96, 126]

category have a wider solution space than the availability of generations in the long run.

Three insights are very important in integrating VRE and decarbonization for the energy sector. The first process discusses two insights for overcoming integrated VRE challenges, e.g. a different power system. The last insight illustrates the results of research that can improve policymaking in the energy sector transition. Solution space for different challenges is the first point, while earlier observations are made for several types of technology that can solve specific challenges. However, the intuitive analysis of the results of expert interviews shows that business people and policymakers are not very familiar with the technological solutions that can be used to solve certain challenges. It is very clear that this technology falls into different categories. However, the development of different solution technologies can reduce the economic viability of a single technology and diminish market potential. Contributions in the decline in market price levels have a relationship with the things mentioned above. This is the same as the balancing power market in Germany. In this case, storage institutional frameworks, increasing VRE forecasts, changing

demand responses simultaneously can significantly reduce market prices [43, 51, 87].

An illustration of the balance and challenges of stability can be used further as an example. The results of the interviews with experts clearly show that each different technology category can function as technology e.g. request responses available only focus on a centralized solution. Therefore, large scale and conventional generation are competitive technologies. However, the distribution of technological flexibility is not focused on analysing the more competitive technological landscape. This can be said as a prominent relationship to the potential influence of grid technology on technology flexibility, e.g. VRE estimates that increase significantly. This is because the size of the market is reduced to the demand response and storage technology. Technology like this, in general, can be used as a counterweight to a certain size of the market by looking at the quality of market participants. Lack of knowledge of technology and its groups is the main reason since competitive technology can be used for decision-making information for processes in a smoother energy transition.

Table 4 Solution VRE integration technologies

Ref.	Example of Solution	Solution	Example Application of Solution	Illustration
[20, 45, 68]	Panel photovoltaic farm	Changes to Distributed VRE Generators	Solar tracking, low tension travel, reactive power supply	Changes in primary equipment, controlling or operating distributed VRE generators
[21, 82, 113]	Engine reconstruction	Conventional generators distributed	Self-consumption optimisation, peak shaving, power balancing, maximum load provision	Conventional generators with increased ramping performance, start number or partial load operation in commercial and household environments.
[17, 128]	Lithium (Li)-Battery with lead-acid	Handed out storage	Self-consumption optimisation, peak shaving, power balancing, maximum load provision	Housing equipment distributed in household, commercial or small industrial environments
[126]	Cable, transformer, overhead track,	Reinforcement of the distribution grid/expansion	Improvement of transmission capacity, optimisation of the active and reactive power flow, improvement of grid reliability	Grid reinforcement or extension using conventional equipment in the distribution grid
[7, 59]	Direct transfer journey scheme, interlock reclosure	Adapted security protection approaches	Avoiding relay desensitisation, stopping stumbling	Revision of security functions and systems to ensure the identification of faults and to avoid false safety events.
[7, 58, 67]	On-load tap changer, static var. compensator, for distribution transformers	Solutions for Voltage management of distribution grids	Voltage regulation in feeders for distribution grid	Equipment that facilitates the control of voltage fluctuations in distribution grid or feeder areas.
[34, 63]	Measuring units Phasor (MUP)	State approximate distribution grid solutions	Real-time monitoring and control of VRE feed-in	Technology for calculating and estimating the electrical status of a network region.
[48, 122]	High impedance transformer, fuse limiting current	Limiter systems currently in use	Present defect restriction	Devices designed to limit fault currents.
[121]	Passive or active filters	Filters in peace	Reduce harmonic distortions	Geräte for filtering harmonic distortions.
[63, 128]	Pleasant wind turbine grid	Changes to large VRE-generators	Wind turbine discharge, low tension flight, synthetic inertia	Changes in the primary machinery, regulating or running large VRE generators.
[25, 85]	A gas turbine, engine reciprocators	New or modified conventional, large generators	Equilibrium power, maximum load provision	Conventional generators with increased ramping performance, start number or partial load operation in industrial or utility environments
[63]	Pumped hydro storage, battery with li-ion or lead-acid, hydrogen storage	Storage of Centralized	Equilibrium power, maximum load provision	Tools located in manufacturing or utility environments
[7, 21]	Aluminium smelter check	Centralised response to demand	Peak rashing, power balance, full load supply	Controlled reduction or increase in electrical consumption of electrical appliances by large consumers, mainly in industrial environments
[25, 68]	Weather forecasting and probabilistic forecasting	VRE predictive technology	Predictions for the day ahead, now casting	Technology to improve short- and medium-term predictability of VRE production.
[63]	Converter based on thruster, Transistor-based	Transmission devices with high voltage direct current (HVDC)	Improvement of the transmission capacity over long distances, active and reactive power flow management, improvement of grid reliability.	Conversion of high voltage alternating current to continuous current and lower voltage direct current transmission systems
[7]	Transformer with phase shift, back-to-back HVDC, controllable series compensation	Power flow checker	Temporary increase or decrease in transmission capacity, and optimisation of active and reactive power flow.	Technology for controlling the active power flow through transmission grids
[25]	Static var. compensator, static synchronous equalizer	Power reaction controller	Prevention of delayed voltage recovery caused by the fault, reactive power support for wind farms' transmission connections.	Technology to control the balance of reactive power in transmission grids
[23]	Flywheel	Power providers inertia or short-circuit	Provision of inertia, rise in short-circuit control and provision in reactive power	Technologies to provide inertia or short-circuit power to stabilize grid areas under conditions of fault

Table 5 The relationship between challenges and technological solutions to distributed technology

	Technologies of Flexibility				Technologies of Grid				Adapted protective equipment approaches	Strengthening/ expansion of distribution grid		
	Distributed response to demand	Conventional Generators Distributed	Storage of Distributed	Changes to distributed generators	Filters in harmony	Limiter systems currently in use	State approximate distribution grid solutions	Solutions for Voltage management of distribution grids				
Limited VRE generator dispatch-ability	✓	✓	✓	✓	X	X	X	X	X	X	X	Balance
Insufficient appropriateness of short-term generation	✓	✓	✓	✓	X	X	X	X	X	X	X	
Inadequate firmness of VRE engines	✓	✓	✓	✓	X	X	X	X	X	X	X	
Insufficient VRE generator forecast	✓	✓	✓	X	X	X	X	X	X	X	X	
Insufficient adequacy for long term generation	X	✓	✓	X	X	X	X	X	X	X	X	
Rising excursions at the local voltage	X	X	X	✓	X	X	X	X	X	X	X	Quality
Unreliable shutdown at blackout	X	X	X	✓	X	X	X	X	X	X	X	
Stepping up harmonic distortions	X	X	X	✓	✓	X	X	X	X	✓	X	
Increasing flicker	X	X	X	✓	X	X	X	X	X	✓	✓	Stability
Increasing interactions between controls	X	X	X	X	X	X	X	X	X	X	X	
Diminishing reserves of frequency control	✓	✓	✓	✓	X	X	X	X	X	X	X	
Insufficient synchronization of the voltage trip limits	X	✓	X	✓	X	X	X	X	X	X	X	
Insufficient coordination of frequency travel limits	✓	✓	✓	✓	X	X	X	X	X	X	X	
Decreasing level of inertia	X	X	X	X	X	X	X	X	X	X	X	
Diminishing short-circuit power	X	X	X	X	X	X	X	X	X	X	X	
Insufficient supply of reactive capacity	X	✓	X	✓	X	X	X	X	X	X	X	
Greater transmission distances	X	X	X	X	X	X	X	X	X	X	X	Flow
Missing capacity on the transmission grid	X	✓	✓	X	X	X	X	X	X	X	X	
Narrow limits of the trip voltage	✓	✓	X	X	X	X	X	✓	X	X	X	

Table 6 The relationship between challenges and technological solutions to centralized technologies (Continued)

	Technologies of Flexibility				Technologies of Grid					Central monitoring & control of the feed-in	
	Changes to large VRE-generators	New or modified conventional, large generators	Centralised stocking	Centralised response to demand	VRE predictive technology	Strengthening/ expansion of the transmission grid	Systems transmission of HVDC	Power flow controller	Power reaction controller		Power providers inertia or short-circuit
Narrow limits of the trip voltage	X	X	X	X	√	√	X	X	X	X	√
VRE generation lacking visibility	X	X	X	X	X	X	X	X	X	X	X
VRE generation lacks controllability	X	X	X	X	X	X	X	X	X	X	X
Increasing currents on short-circuits	X	X	X	X	X	X	X	X	X	X	√
Insufficient nature of the defines	X	X	X	X	√	√	X	X	X	X	X
Flow patterns from lower grid rates are highly erratic	√	X	X	X	X	X	X	X	X	X	X
Missing room on the distribution grid	X	X	√	√	√	√	√	√	X	X	X
Increasing excursions to the regional voltage	X	X	X	X	X	√	√	√	X	X	X

The distribution of solution technology portfolios in each region for VRE integration contained in the literature seems to be very generic. Thus, the guidance given to companies and policymakers always fails to develop business policies and strategies. For future decision making, it can be assisted through an interrelation matrix such as preparing proposals and technology roadmaps both nationally and internationally. This aims to be able to decarbonize the energy sector. Interrelation material functions to match each category as well as some of the history of each country. Every quality challenge has occurred regionally for high distributed VRE penetration so that the spread of flexibility is needed especially distributed technology networks. Countries with a high penetration of VRE generators are southern England, southern and northern Italy and southern Germany [109]. Although the availability of data spread flexibility is not available for distributed technology networks in certain regions, projects such as the RD&D smart grid are technologies with very high priority for policymakers and companies in these countries [24, 28, 78]. The challenge of flow for the transmission rate reached by countries such as Germany, in general, requires a technology system with a centralized network. Such systems, such as transmission networks or amplifications, must be expanded, active power control and HVDC transmission systems. Germany is currently preparing several large projects that can be utilized by using technology. This is done after the assessment phase in determining the design and size of the complex installation has been completed.

Countries such as Ireland and Spain have done similar things, both of which have faced stability challenges. On the other hand, the transmission operator system is set as the centralized controller of the VRE generator. It aims to the needs of VRE generators to support network stability [3, 102, 108]. Besides, the investigation was carried out to ease the limitation of the stability criteria. Finally, solving the challenge of balance can only be done through technology flexibility. California, for example, is a country that have difficulty of being able to maintain power balance when the sun changes night so that the VRE generation has decreased significantly [32]. To encourage investment in storage with more flexible generators and environmentally friendly renewable energy, the State of California has introduced several new products [2, 29, 30]. Thus, interrelation matrix can be concluded that its function can be carried out by business people and those who make policies in identifying solutions technology groups. Finally, the challenges that are prevalent in certain areas can be reduced and the formulation of steps and policy strategies in supporting the dissemination of technology can be easily carried out.

Frequent debates between actors to prioritize technological solutions in VRE and irrigation management in the energy sector have often been carried out. Priority for technology solutions in integrating VRE with costs and ease of implementation is reported by several researchers ([21, 35, 99, 100]). This perspective has short-term benefits, also, the potential solutions that are perpetuated from this perspective are differences in facing challenges. Technology solutions are prioritized based on their respective solutions so that technology flexibility can be used as a solution to the challenges of VRE. This is as stated by experts in supporting the potential of technological flexibility ([99, 100, 126]). The results of the analysis can support the call for decision-makers adjusted to market rules or the placement of newly applied policies. Remuneration schemes for reactive power are introduced in the regional market. However, technology ratings are determined solely based on their respective potential and do not take into account other technological solutions that contribute to solving challenges. Besides, the solution space is different among all challenges. To consider these factors, the ranking of technologies can be adjusted to their potential in solving challenges. The preference for the deployment of this flexibility technology is specifically found in distributed and centralized VRE. Protection strategies with appropriate equipment can solve specific challenges, and higher interests can be achieved by the following perspectives. Response to requests both small and large is part of the technology solution. In addition, there are large generators with lower priority because of the limitations of the potential for more unique solutions. Relevantly to distinguish VRE integration, there are two examples large, small demand response spreads and large flexible conventional generators. Cost savings from existing solutions can be realized in the short term. However, it is not enough to only deal with the scope of the existing challenges or potential. The aspects discussed can be assumed to confirm the benefits of the results of the analysis for policymakers as a whole.

The results of the analysis carried out have important limitations to be considered when interpreting the final results. A review of specific research on existing challenges can improve VRE penetration. However, additional challenges which are not listed in this study can also face challenges such as the electric power system. At the same time, analysis of challenges was also found in power systems with lower VRE penetration. Specifically, the analysis conducted in this study is a challenge that is directly related to technology solutions. This analysis does not measure one technology solution that can solve only certain challenges. In addition, the future developments beyond the scope of this analysis can be reduced, e.g. the emergence of new solution technologies

that can change frequency stability criteria or more robust end-user equipment such as variable frequency drives. Furthermore, the specific costs of the solution technology, the urgency of the challenges or the feasibility of implementing the solution technology are not considered. This is due to environmental constraints such as high land, social areas such as the public for receiving the final transmission line. This quantification is adapted to specific contexts with differences in power system characteristics. Furthermore, high levels of uncertainty are more vulnerable when considered such as revenue and costs than differences in applications and technology solutions. This need is needed for the need to think in grouping portfolios or technologies that focus on the completion of integrated VRE.

4 Conclusion

Specifically, the review in this research is to study the integration of VRE systems that are connected with modern power systems and technology to overcome challenges. Besides, the need for power system technology in increasing VRE market share with complex integration is also discussed. The collection of challenges undertaken in this study was drawn from a variety of literature relating to technology solutions in integrating VRE. The challenges developed can consistently integrate VRE which is the root problem of this analysis. The results of this analysis are supplemented by data from interviews of experts who have helped in investigations related to technology solutions and their challenges.

The results of the analysis with some insights outlined in the study can be summarized as follows

1. VRE integrated with challenges can affect the characteristics of the power system.
2. Technology solutions that vary with the number of challenges can be significantly overcome. In general, technology flexibility has a higher solution potential than the use of grid technology.
3. The identified technological solution facilities are intended to be able to overcome challenges in several categories.
4. Identification of challenges from various practice literature can be arranged and collected based on the root of the problem to produce each of the more exclusive challenge categories.
5. Categories and collections of technology solutions are used to test challenges that can be overcome by a single technology.
6. The size of potential solutions becomes very important for companies or policymakers in promoting certain technologies and their respective solutions.

Some of the descriptions presented in this review are a starting point for future research related to this topic. The relationship between technology solutions and challenges is one of the new fields of research. This is done with an estimated cost compared to the use of different solution technologies and can be introduced comparatively to the environment as a whole. Life Cycle Assessment (LCA) can be used to measure costs integrated with VRE because the installed capacity with future projections is available [41, 107, 114, 125]. This system can significantly improve recommendations on policies issued. Overall, the development of individual solutions technology that is integrated with VRE is an issue that has a high price for the transition in the energy sector in a sustainable manner. In this case, a further investigation between the characteristics of different power systems and geographies is on one side of the technology solutions and challenges with different sides.

5 Nomenclature

VRE Variable Renewable energy
HVDC High-Voltage Direct Current
RE Renewable Energy
LCA Life Cycle Assessment
RET Renewable Energy Technology
PV Photovoltaics

Acknowledgements

This research supported by PNBP Universitas Syiah Kuala, Research Institutions and Community Service.

About the authors

Erdiwansyah: Born in Desa Meunafa Kec. Salang, Kab. Simeulue Aceh Province at 14 March 1984. Erdiwansyah is a lecturer at the Faculty of Engineering, University Serambi Meekah, and Banda Aceh, Indonesia since 2014 until now. In 2020 this was registered as a PhD of Engineering Student at Universitas Syiah Kuala. The Master's degree was pursued at the Department of Electrical Engineering at Universitas Syiah Kuala, Banda Aceh, Indonesia, completed in 2016. Furthermore, the bachelor's degree was obtained in August 2012 from the Faculty of Engineering Department, Universitas Serambi Meekah Banda Aceh. Currently, besides studying, he also helps research professors at Universitas Syiah Kuala, Banda Aceh.

Mahidin: Born in T. Gajah Kec. Tnh. Jambo Aye at 3 April 1970, the eldest one out of 6 siblings. Finished the elementary school in SDN Lhokbeuringen T. Gajah at 1982, Junior High School at SMPN 1 and Senior High School at SMAN 1 Pantan Labu, Kec. Tnh. Jambo Aye, North Aceh, in 1985 and 1988, respectively. Moreover, undergraduate degree was earned at August 1994 from Department of Chemical Engineering, Syiah Kuala University. Magister degree was pursued at Department of Chemical Engineering, ITB in October 1999, and received Doctor of Engineering in Resource and Energy Science from Graduate School of Science and Technology, Kobe University in September 2003. He was awarded a professor in chemical engineering in 2018. Fields of research are treatment and utilization of energy resources, especially renewable energy resources and mix of energy (energy diversification).

Husni Husin Ph. D, is a Professor of Chemical Reaction Engineering at Syiah Kuala University. She joined Chemical Engineering Department since December 1994; Born: 1965, Samalanga, Aceh, Indonesia; Education: Syiah Kuala University (1990); Institute Technology Bandung (2000); National Taiwan University Science and Technology (NTUST) Taiwan (2011); The title of her dissertation is "Fabrication of La-doped NaTaO₃ via H₂O₂ Assisted Sol-gel Route and Their Photocatalytic Activity for Hydrogen Production"; Her research interests are: Nanomaterial for Clean Energy production

(Photocatalytic, Solar cell, Biodiesel, Biofuel, Fuel Cell), Heterogeneous Catalyst and Application, Adsorbent and Application; Nasaruddin received the B.Eng. degree in Electrical Engineering from Sepuluh Nopember Institute of Technology, Surabaya, Indonesia in 1997. Then he received M. Eng and D. Eng in Physical Electronics and Informatics, Graduate School of Engineering, Osaka City University, Japan, in 2006 and 2009, respectively. He is a lecturer at Electrical Engineering Department, Syiah Kuala University. He was head of master of Electrical Engineering Programme; graduate school of Syiah Kuala University. Currently, he is head of Electrical and Computer Engineering Department, Faculty of Engineering, Syiah Kuala University. He has published several papers in international journals and accredited national journals. His research interests include digital communications, information theory, optical communications and ICT applications for disaster. He is a member of IEEE and IAES.

Dr. Ir. Muhammad Zaki, M. Sc is a lecturer and researcher in Chemical Engineering Department, Faculty of Engineering, Unsyiah since 1992. Received a Bachelor degree (Ir) in Chemical Engineering Department of Unsyiah, then continued S2 (M.Sc) and S3 (Dr.) at Universiti Kebangsaan Malaysia in Chemical and Process Engineering Department. Muhibbuddin I completed my Ph. D in Technical and Vocational in Mechanical Engineering from The State University of Padang, Indonesia, in 2016 under the supervision of Prof. Dr. Nizwardi Jalinus and finished Master of Engineering degree in Mechanical Engineering Joint Programme between Gadjah Mada University and Bandung Technology Institute, in 2012. Since 2007 worked as Trainee Machining at Sandvik Light Industrial Park PT. Freeport Indonesia Tembagapura Papua Indonesia and resigned in 2008 for graduating as civil servant. Since college, I have been interested in Energy Conversion Machines especially water turbines, windmills and applied engineering. Besides studying, I am also active in Laboratory and Micro Hydro Power Plants Development Centers and research final project Bachelor; "Design and Manufacture of Transmission System a Portable Propeller Water Turbine 4 kW Capacity for Micro Hydro Power Plants". The Master of Engineering focuses on the research; "Study of Utilization of Bamboo Parts as Blades of Pelton Water Turbine for Enhancing Rural Energy Technology to Support the Energy Independent Village Program". Doctoral Research; "The development of Cooperative Project-Based Learning (CPBL) models for Energy Conversion Machines in Technical Vocational Education and Training in Mechanical Engineering". I served as Head of Division Human Resources Teacher and Education Personnel (Echelon III) Southwest Aceh Regency Education and Culture Office from 2018 to 2019. Since October 1, 2019 until now I am joined as a lecturer in Mechanical and Industrial Engineering, Faculty of Engineering, Syiah Kuala University, Banda Aceh.

Authors' contributions

1. Erdiwansyah: The first author acts as the author of all article content and data collection such as literature searches and other data that support this research. 2. Mahidin: The second author acts as the draft writer of the article and also as a reviewer for the refinement of the article before it is sent to this journal. 3. H. Husin: The third author acts as a controller of the writing done by the first author. In addition, the third author is also tasked with analyzing the literature data collected and written by the first author. 4. Nasaruddin: The fourth author acts as a drafter and design of articles written by the first author. In addition, the fourth author is also a policy maker for this article and serves as the final review and editing of this journal. 5. M. Zaki: The fourth author acts as a contributor to research funding in addition to funding from the grand research. The fourth author also acts as analysis and refinement of the final article. 6. Muhibbuddin: This sixth author acts as a fund contributor for checking language and words and sentences for English language experts. The sixth author has also helped to revise the end of the journal jointly with all the authors in this article. The author(s) read and approved the final manuscript.

Funding

The funding of this research is the grand research of the professor with the contract number of (32/UN11.2.1/PT.01.03/PNBP/2020).

Competing interests

There are no conflicts to declare.

Author details

¹Doctoral Program, School of Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia. ²Faculty of Engineering, Universitas Serambi Mekkha, Banda Aceh 23245, Indonesia. ³Department of Chemical Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia. ⁴Department of Electrical and Computer Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia. ⁵Department of Mechanical and Industrial Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia.

Received: 13 July 2020 Accepted: 12 January 2021

Published online: 23 February 2021

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