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Review

Large scale photovoltaics and the future energy system requirement

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Abstract: Supported by conducive policy and technology cost decline, PV capacity addition is increasing rapidly. The capacity addition is forecasted to continue at a faster rate over the coming decades. With such an increase, it is important to ask about system requirement to effectively integrate large system into a power grid. This paper presents the analysis of literature data in order to clarify system requirement for large PV integration. The review shows that the most important challenges of large-scale PV penetration are matching, variability, uncertainty and system adequacy. To overcome these challenges, several enabling techniques, such as energy storage, curtailment, transmission interconnection, demand response, resource complementarities, increased grid flexibility, improved forecasting, geographic distribution of generation resources, were among the most discussed by various researcher. A closer look at some systematic studies shows that developing theoretical framework for the future system is the best way to guide the smooth development of an effective and secure system. This argument is based on the observation that (i) the role and importance of one technology, for instance specific storage technology, may change as VRE penetration increases; (ii) the increase in use of one application decreases the importance of the other; (iii) the use of some of the discussed solutions may depend on level of penetration as they also depend on season. Thus, it is important to design the system based on a criteria formulated with the understanding of system level science/theoretical framework.

Keywords: photovoltaic; curtailment; penetration-curtailment-storage nexus; demand response; system adequacy; balancing

1. Introduction

Over the past decade, new solar photovoltaics (PV) capacity addition was growing at a significant pace as compared to other energy technology additions including wind energy conversion system (WECS). This spectacular growth is largely a result of fast cost decline. Forecasts show further cost decline and a continued increase in PV capacity as we drive to cleaner energy future. With such a promising trend, which responds to market drivers and ongoing policies, also comes a significant pressure to solve the challenge that results with utilizing very large-scale variable PV energy.

Currently, PV capacity penetration is occurring both as distribution system and centralized standalone power plants. The total PV capacity grew from approximately 39 GWp in 2010 to 400 GWp in 2017, a growth of nearly 10 folds in 7 years [1]. According to [1], the global PV capacity addition in 2017 was 99.1 GWp per annum, about 27.9 GWp of this new capacity was rooftop PV installations. Rooftop PV is naturally suitable to reduce land required by utility scale solar PV and to produce electricity at the spot of consumption. Consequently, policy makers encourage the expansion of these particular installations as a part of the effort to increase use of cleaner energy sources. However, expanding distributed PV requires setting up appropriate platform for financing as well as developing technical standard to guide the installation and secure system operation for grid-connected systems. At the same time, there is a question of understanding the upper limit to rooftop PV potential due to various technical reasons. Researchers estimate maximum national rooftop PV potential using an assessment of suitable rooftop areas. For example, rooftop PV was estimated to produce 40% and 35% of the annual electricity demand of USA [2] and EU [3], respectively. However, these estimates could be further reduced if an upper limits on PV generation set by factors, such as limits of low voltage feeders, load type and their distribution, are applied [4]. Despite low accuracy of the estimate, the gap between their present status and estimated potential is an evidence of the presence of significant opportunities for its expansion. On the other hand, utility scale PV is much easier to deploy because it does not require educating consumers. This is one of the reasons why the present PV capacity growth is dominated by centralized ground-mounted type systems. Nevertheless, the potential technical upper limits to the large use of utility scale PV, for location with good solar resource, lies on the ability to avail the required enabling technologies.

Despite the large increase in capacity, due to the inherent nature of solar resource, our estimate shows that PV energy supplied approximately 2% of the total global electricity demand in 2017. At such a small level of energy penetration, the need for enabling technology is low, however its need significantly increases as its electrical energy share in a given grid increases. Note that the need of the enabling technology type and size depends on the combined electrical energy penetration of wind and solar PV technologies, not on solar alone. At global scale the wind electricity penetration is also approximately 4%. However, special spots of high wind electricity penetration such as Denmark exists, where it supplied about 43% of the electricity generation demand in 2017 [5–7]. However, it is worth to note that the high penetration of wind energy to the Danish grid was credited to its strong interconnection with neighboring grids that absorb the impact of wind variability. Thus, rather than looking at small spot in a large grid, such as this one, it's better to look at the penetration of intermittent resources to a broader network. Despite the large wind electricity penetration to the Danish grid, its penetration at European level was approximately 14% over the same year [6,7]. To understand the real need for enabling technologies, it is essential to look at system wide indicators that presents combined effect of Variable Renewable Energy (VRE) technologies (wind and solar technologies).

Large use of VRE resources requires overcoming various important challenges. The first one relates to secure handling of added incoming fluctuating power using an electromechanical system designed to handle an already fluctuating demand. The existing power system can be dispatched in well predictable fashion to manage demand variation that follows human business cycle and weather. The VRE sources vary depending on local weather pattern adding uncertainty to the power system. Thus, the second challenge to overcome is handling the uncertainty that comes with added intermittent energy sources. The third challenge is achieving an optimal matching between VRE output pattern and demand profile. The level of each challenge and the range of technologies needed to solve them depends on the level of VRE penetration to particular grid. This review paper will analyze the present and future PV and wind penetration to electricity grid and factors affecting it based on quantitative data reported in various literatures in order to assess future system requirement to accommodate large PV penetration. Potential role of various technologies during energy transition will also be discussed as relevant.

2. Analysis of ongoing situation

In order to understand the real implication of the ongoing PV growth, it is important to take a closer look at the market using various indicators. In this section, we will start by studying the real capacity growth with the achieved energy penetration. Because the capacity growth also varies with location, it is important to examine energy penetration to specific countries in order to understand system level meaning of the specific capacity growth. However, system level challenges of its intermittency cannot be explained if the increased share of energy from WECS is neglected. Thus, where appropriate we will also discuss the corresponding growth in wind penetration. Here it is important to distinguish two terminologies widely used in literature, namely capacity penetration and energy penetration. Capacity penetration is the share of PV/wind technology capacity as a percentage of peak load. Energy (grid or VRE) penetration is a share of PV/wind electrical energy or a mix of both (termed as variable renewable) as a percentage of total electricity annual generation required to meet the annual demand of a given power grid. Due to the variability and diffused nature of wind and solar resources, capacity penetration does not reflect the energy penetration of these technologies. As a result, it is important to study both in parallel.

2.1. Ongoing growth in capacity and its meaning

PV capacity grew by more than 12 folds from 2010 to 2018, when it reached a cumulative capacity of about 506 GWp [1]. Even if the reported nameplate capacity growth was very large, the achieved energy penetration increase remains very low. Figure 1a and 1b presents the global nameplate capacity growth and the corresponding energy penetration, respectively, for wind and solar technologies. As shown in the figure, solar penetration (even by including solar thermal) provides less than 2% of annual electricity generation on global scale on 2017. More broadly, wind and solar combined supplies approximately 6% of the global electricity demand on the same year. Based on literature data and the level of the achieved global energy penetration, we may assume that utility operators experienced manageable intermittency caused challenges. However, global data obscures high penetrations in some countries. Thus, it is better to take a closer examination of specific cases. For that purpose, we chose top 5-countries each based on their achieved energy penetration from wind and solar PV on 2017 as given in Table 1.

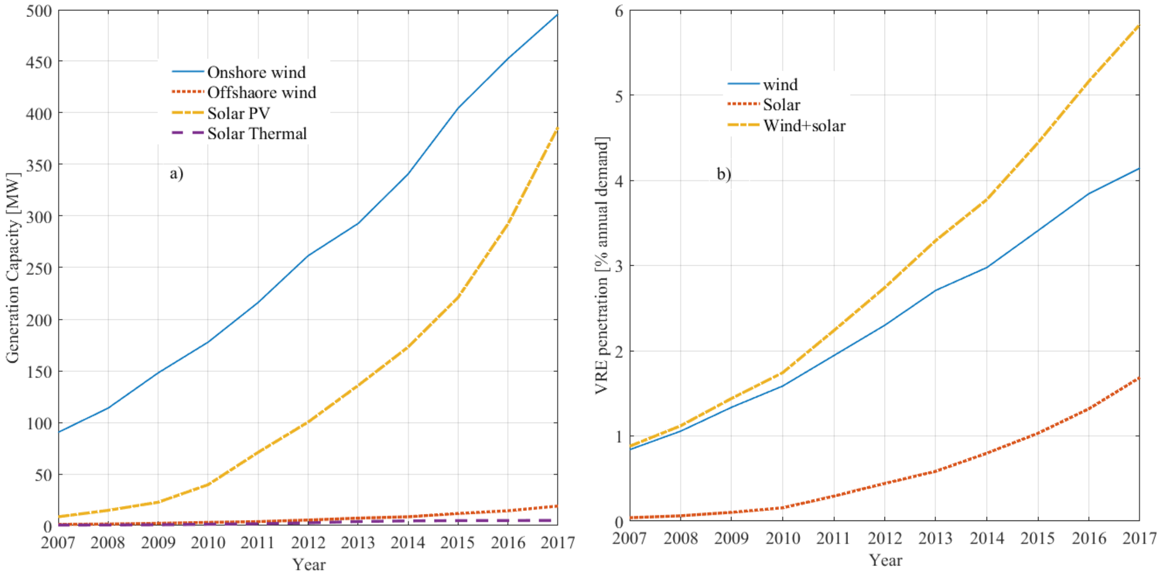

Figure 1. Annual increase in: (a) wind and solar technology cumulative capacity; (b) the corresponding energy penetration at global level.

Table 1. Wind and solar capacity and the corresponding energy penetration on 2017 at selected countries, data source [6,8].

Country	Solar Capacity [MW]	Wind Capacity [MW]	Energy Penetration [% of annual demand]		
			solar	wind	Total
Japan	49040	3392	5.8	1.0	6.8
Honduras	451.1	225	10.3	8.4	18.7
Denmark	906.4	5522.3	2.3	43.4	45.8
Germany	42339	55718	6.1	16.3	22.4
Greece	2605.5	2624	7.1	10.3	17.5
Ireland	15.7	3318	0.0	25.4	25.4
Italy	19688.4	9736.6	7.5	6.1	13.6
Portugal	579.2	5124.1	1.5	20.8	22.3
Spain	7029	23100	5.0	17.8	22.8

Though China is the lead in terms of the PV capacity installations, the country that generated the largest share of its electricity demand from solar PV was Honduras, generating 10% of its 2017 electricity demand [9,10]. Other countries [10], such as Italy, Greece, Germany, and Japan, also produces more than 5% of their electricity using solar PV. On the other hand, wind generation share of about 43% was achieved to the Danish grid [6,7], which achieved the global highest penetration from wind. Several other countries [6,7], such as Ireland (25%), Germany (17%), Spain and Portugal, have achieved double digit electricity generation share of its 2017 electricity generation demand using WECS. Collectively, these 9 countries will make up the world's highest electricity generation from both wind and solar combined. Table 1 shows that all of them obtain double digit shares of their electricity from these resources. Note that about 43% of the solar electricity (which constitute a total electricity demand of 5%) in Spain was from Concentrated solar Power. The above data shows that despite the low energy penetration at global level, VRE penetration in some country is already too high.

Denmark has achieved a VRE penetration of 45% by 2017, though all other countries are close to or lower than 30%. However, no serious challenges were reported in relation to the achieved high penetration. This is because the countries with large VRE penetration already has sufficient enabling resources. We will return to this subject later.

2.2. Future scenarios and its implication

Market forecast of the future PV scenario is extremely positive. PV cost decrease is expected to continue, which will drive to an even larger increase in PV capacity. According to a forecast by [1], PV capacity will increase by approximately 100% from nearly 500 GWp in 2018 to about 1000 GWp in 2022. Distributed PV makes up 39% of the new total PV capacity additions in year 2017 [1]. Distributed PV is expected to continue playing a vital role in the forecasted PV capacity increase even though the increase in ground mounted system dominated PV market for the past few years. Looking into the post 2022 scenarios, studies indicated a PV conducive market all the way to 2050. In recent study, Hageal et al. [11] estimated total PV capacity of approximately 10 TW by 2030, which is forecasted to increase to 30–50 TW capacity by 2050. This will convert solar PV to a major supplier of the global electricity demand rather than a key contributor. Such circumstance calls for close examination of system requirements as we proceed to such a high penetration of PV. In the preceding sections, we have seen that grid penetration depends on the country of focus. It may also vary depending on a region or location in a given country. For example, California has achieved PV penetration of approximately 14% by 2018 [12] as compared to approximately 1% for the entire USA [13] electricity demand. Due to a variety of reasons, such as policy and local resources, PV use variation with geographic location will continue. Regions with suitable other resources will likely push for a mixed alternative or even low solar options if the solar resource quality is poor as compared to its other resources. On the other hand, for regions with good solar resources, such as most sun-belt countries, major use of solar could be technically and economically plausible. Thus, these regions may even push towards a predominantly solar dependent electricity system. Some techno-economic studies are already suggesting these options, with the share of solar varying depending on location. For example, solar share of over 90% was found to be economically plausible for several sun-belt countries such as Israel [14], Saudi Arebia [15], India [16] and Nigeria [17], etcetera. On the other hand, comparatively lower solar share was reported for European countries [18] and Australia [19], etcetera. The reported level of penetration may have resulted due to the modelling details and assumptions of each study. However, let us focus on the most important question of interest, which is regarding system requirement for its smooth operation and effective transition.

The present system is designed anticipating dispatch-able conventional generators, as a result arrival of variable renewable resource will reduce the envisioned controllability and predictability of its operation. New technical challenge, such as energy curtailment, is becoming part of the operational standards as VRE integration progress. The reported amount of curtailment depends on geographic location and power system condition. For example, the reported curtailment in 2017 is 2% [11] and 9% [6] in California and China, respectively. The corresponding VRE penetration to both grids were also approximately 20% and 4%, respectively. At these level of VRE penetration, curtailment should not be a concern had the existing grid been initially designed in anticipation of these variable resources. The main driver of the curtailment at these levels of VRE penetration was low grid flexibility, transmission congestion and poor interconnection with neighboring grid. The difference in these factors were why California state has lower curtailment despite achieving higher VRE penetration as compared to China, which has much lower grid penetration. The much higher penetration reported by Denmark was attributed to its interconnection with larger neighboring grids of Germany, Sweden and Norway. Particularly, its connection to Norway allowed an access to pumped hydro storage during times of high wind generation; as a result, the curtailed amount was very low. Variability of electrical output of wind and solar depends on geographic location, weather, and time of the day, season and various topographic condition. The above difference in the reported VRE penetration and its impact relates to system capability/limitation at certain spot in the related bulk power system.

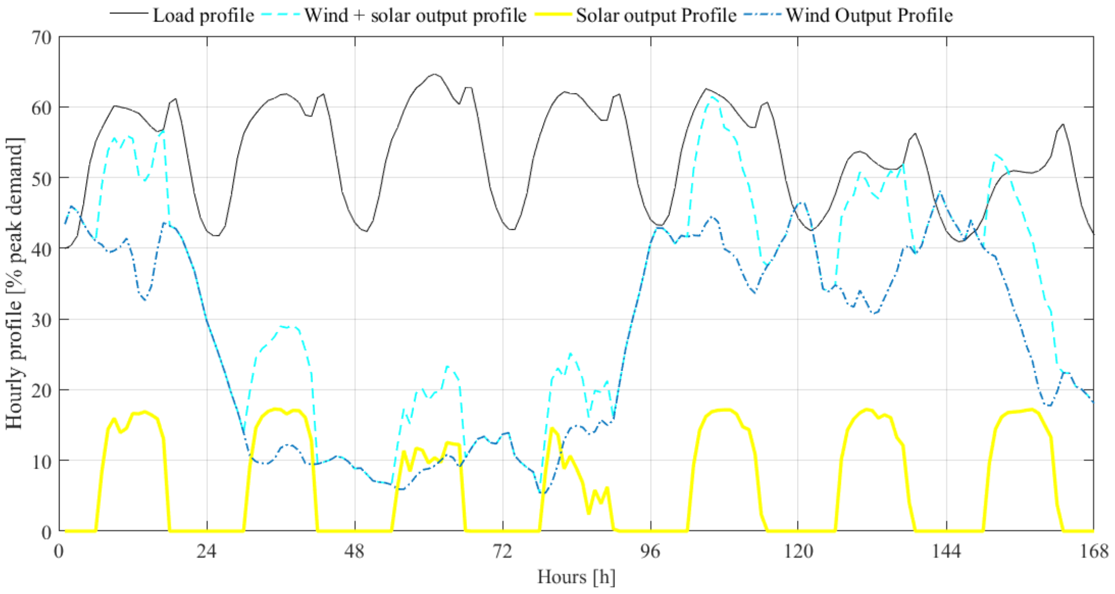

Figure 2. Simulated hourly profiles of wind, solar, wind-solar hybrid system output and the corresponding load profile for one spring week in California. The total capacity of wind-solar hybrid in this simulation was 40.9 GW (11.1 GW solar and 29.8 GW wind). The system was distributed throughout California and would have supplied the maximum possible energy (38.3% of the annual demand) that California could have obtained from intermittent renewables in the year 2011 without energy dumping or storage. Note that achieving the same penetration with solar or wind technologies alone would have required some energy dumping, storage or both[1].

Figure 2 presents one-week aggregated/separated hourly output of wind and solar plants, and the corresponding demand profile for California. The gradual increase of solar generation until solar noon and the corresponding decrease after the solar noon on a typical clear day (day 5–7) is clearly shown in the figure. As can be seen on days 1–4, clouds add more variability to its generation by temporarily reducing/blocking solar irradiance. Unlike solar, wind has less defined diurnal output profile but for most geographic places, it is reported to reach its peak generation during the evening time. However, wind tends to demonstrate some sort of periodic output, i.e., few continuous days of good generation (which depends on season) after/before days of poor generation. These diurnal behaviors of both resources is common to most places depending on local weather. But seasonal variability and resource quality shows significant differences from place to place. An optimal use of these resources can be achieved if the output of wind or solar or their composite is matched to a

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demand that varies forming its own independent profile based on geographic location [20]. An optimal matching and its reliable operation is not a problem to be solved by simple economic optimization but a question that requires answering several fundamental questions that may be important to put future operational rules and standards on sound scientific ground. Present progress in an increased use of these variable resources are encouraging but not a good reflection of the challenges that we will be facing as energy penetration increases. To understand these challenges judging the achievements in terms of the high penetrations achieved by small spots in a large network will be misleading. For example, let us return to the case of the Danish grid that currently enjoys high use of VRE. It is connected to three larger neighboring grids (namely Norway, Germany and Sweden) that can serve it as a sink at times of excess generation and source of balancing at a time of low wind generation. If we take annual electricity consumption by the three neighboring grids, the annual electricity consumption of the Danish grid is 24.3% of the Norwegian, 5.6% the German and 24.3% of the Swedish grids during year 2017 [5,6]. More importantly, the wind generation capacity in 2017 was 89% of its peak load and 67.3% of the minimum load plus the annual export capacity [6]. This export capacity allowed the Danish system access to the neighboring grids, which achieved only 24.3%, 13% and 2% VRE penetration of 2017 annual demands of their respective countries, namely Germany, Sweden and Norway, respectively. Because of this Denmark was able to export its wind over generation to these countries for sale or access to storage facilities. Particularly, the large pumped hydro storage facility of Norway was a notable facility that reduced possible curtailment. The Danish system identified the congestion of these transmission interconnections (eg, to Germany and Sweden) as a possible inhibitor to increase more wind in the future. Without these enabling factors, the Danish grid could have curtailed significant part of its export (which could have constituted about 15% of annual wind generation in 2017). As a result, to overcome possible future challenges Energinet (the Danish grid operator) considers expanding interconnection to new markets [5]. While this interconnection may provide a short-term relief, from system perspective their role might diminish as the VRE share in all adjacent markets increases. Due to difference in system compositions, the impact of more VRE penetration may differ from one system to another system. For example [5], on the year 2017 Germany has reported more negative spot market price than Denmark despite its lower VRE penetration (22.4% versus 45% in Denmark). The situation of other high penetration spot is not different from the Danish case. They benefit either from their interconnection or existing flexibility within the system itself. Such capability may help most power systems to arrive at up to 30–35% VRE (wind and solar) penetration over the entire system with smaller curtailment. However, as VRE system increases further, addressing the challenges of grid matching requires simultaneous increase of both curtailment and storage (see details below). After this point, an efficient design and operation requires better theoretical framework of the future system because of a possible fundamental changes of the power system. At present VRE integration dominantly depends on the understanding of the legacy grid, at times decisions are guided based on analysis that used much specified resource conditions. But, transition is better guided based on understanding of broader resource and technology compositions in order to identify the most effective system and its need based on various criteria including long term role of the presently popular solutions. Below we will revise some key system requirements to achieve increased PV penetration to a bulk power system.

2.3. *Why to diversify and its dependence on location*

Geographic distribution of solar was reported to smooth PV output [21]. Similar condition was also reported for wind based on study of wind resource pattern [22]. The smoothing effect has the ability to reduce ramping requirement and the controlling challenge that may otherwise occur. The smoothing effect of wind geographic distribution was reported in [6]. Similarly, distributing solar PV also shows considerable potential of reducing ramping need [21]. Geographic distribution has also the potential to bring together diverse wind and solar resources that may ameliorate time synchronicity of the VRE resources with electricity demand over the bulk power system. This will increase energy penetration of these resources [23–25] while reducing ramping requirement. However, it is worth noting that distributing PV over small geographic location has negligible impact on electricity penetration [21].

Resource diversity is the other very important factor for future energy systems. It has the potential to increase grid penetration of VRE, improve power system controllability, and enhance energy system long-term reliability while also reducing the sustainability risk that may arise by depending on limited resource. Wind and solar resources complementarity was reported to increase penetration and ramping requirement [23,24]. Wind-solar hybrid was also reported to reduce storage capacity requirement to achieve same amount of penetration as compared to one of the two resources alone [24,25]. Beyond wind-solar hybrid, other renewable resources, such as hydropower, wave-energy, geothermal, play significant role in passing to net zero emission energy system at reduced use of wind and PV technologies or their tandem. Currently, some data imply over reliance on some technologies may cause limitation of some critical material [26]. Thus, resource diversity has the ability to enhance reliability and reduce the sustainability risk that might arise because of reliance on limited resource type.

3. System requirements and potential solutions

To discuss system requirement and potential solutions, it is better to start by a brief summary of the challenges of achieving high PV penetration.

3.1. Challenges of high PV penetration

The most important challenges of large-scale PV penetration can be grouped in to four, namely matching, variability, uncertainty and system adequacy.

3.1.1. Matching

Matching relates to the time coincidence between PV electricity output and electricity demand [27]. Several past studies tried to quantify PV matching to electricity demand. It was found that PV grid matching depends on the flexibility of conventional generators in the electricity grid [27,28]. Even if the generators are dispatched at 100% flexible mode, the matching capability of PV will still be low because the daytime solar output cannot match to nighttime electricity demand. On top of that, the daytime profile is also not a perfect match to the daytime electricity demand. PV was reported to provide 17.4% and 20% of Israeli [27] and ERCOT Texas grids [28] annual electricity demand at best(in case of the assumed fully flexible generators) without any other enabling techniques. Tracking system improves matching potential by changing the sharp peaking PV output profile to a flat peaking one. This will improve the energy penetration of PV. According to [21], single axis and dual axis trackers were reported to increase PV penetration from 17.4% to 22.7% and 23.2% of the annual demand, respectively, under the same strict no curtailment condition. VRE Penetration was shown to increase significantly under the same condition but when wind resource is allowed to expand with PV [23,24]. From studies of the Israeli grid, VRE penetration of approximately 19% of the annual demand was achieved with wind PV hybrid [23] under the strict no curtailment rule. Similarly, the wind-PV tandem was reported to achieve the annual VRE penetration of 38% to the grid of the state of California [24]. These studies show that the hybrid does better than both technologies as a standalone in both cases due to their complementarity. Moreover, the significantly high VRE penetration to the Californian grid may be attributed to high wind resource quality and its diversity as compared to that of Israel. This estimate shows the potential theoretical upper limit that can be achieved if the grid is perfectly flexible in terms of its generator composition and transmission operation. Unfortunately, the grid is not that flexible even though it already has some of the enabling technologies depending on location. The enabling technologies that will increase grid penetration are energy storage, curtailment, transmission interconnection, and demand response (in the form of load shifting). These enabling technologies will be discussed in detail in the following sections.

3.1.2. Handling variability and its impact

On a good solar day, PV varies following a well-known bell-shape pattern, which makes it easier for forecasting as compared to wind. However, on bad weather days clouds could block the solar irradiance to make forecasting challenging. Particularly, moving clouds could overshadow part of PV plants, which will lead to more spiky or flat PV output depending the relative size of the clouds and PV systems as opposed to the smoothly changing PV output profile. Relatively smaller moving cloud (as compared to the corresponding PV system array) over a large array of PV system results in flat peaked PV output. On a typical clear day, PV output increase up to midday when it starts to decrease. On the other hand, electricity demand continuously increases during the day until it peaks in the evening. Electricity grid should respond to the net difference of the two (demand minus PV output), which forms a valley that reaches minimum at mid-day. The power plant managing this variation will have to down ramp until solar noon when it starts doing the opposite. This phenomenon is nothing new to the power system but the ramping rate and range during a given day increases as compared to the pure electromechanical system that manages demand related variability alone. However, occasional ramping requirement can be large enough for existing power system [21,29]. The story for wind is not that different from solar though the reported ramping need is not as much as solar [29]. Data gathered from various grids show that ramping requirements, in most case except times of windstorm, remains in a range that could easily be contained by existing system [6]. Nevertheless, it is worth noting that most of these studies cover smaller VRE penetrations. At such amount of penetration, utilities only need to identify sufficient fast ramping generators, transmission interconnections (that can relief the system at stress time using import or export) and demand response options that can handle the anticipated ramping need. Ramping need can also be ameliorated through proper long-term resource planning, by following planning strategy that emphasizes geographically distributed resource (that lead to smoothing) [21] and encourages the use of wind-solar tandem (which increases resource complementarity) [23,24], depending on local resource quality. However, as VRE penetration to a bulk power system increases ramping, over generation, and related operational challenge could be significant to contain without enabling technologies, such as energy storage, curtailment, and etcetera. Even though demand response could play some role at various amount of VRE penetration, its connection to storage availability needs further clarification.

3.1.3. Uncertainty

The other challenge of large-scale PV penetration is short and long-term uncertainty on PV output. The uncertainty has three sources [30–33], namely: (i) those coming from solar resource measurement and forecasting; (ii) those related to PV module characteristics; (iii) those related to overall system performance. The solar irradiance received at a given location continually varies following complex planetary process, which makes its accurate prediction a bit complex. The accuracy of the measured data also depends on the instrumental error and condition of measurement. For instance, satellite imagery based irradiance data is reported to show normalized root mean square error of about 4% to 8% for monthly and 2% to 6% for annual irradiation values as compared to irradiance measured on ground [30]. Furthermore, accuracy of modelling of module characteristics and overall system performance is compromised by various factors. Researchers often report that the STC rating differs from outdoor measurement at the same condition. As a result, it is not easy to arrive at accurate modelling of PV output and forecasting of same. The ratio of the actual yield to continuous PV output at STC termed as performance ratio (PR) is traditionally used as an indicator to monitor this effect [30]. This PR value continually improved over the years from approximately 50% over 3 decades ago to above 80% at present. Short-term forecasts typically refers to 6–72 hours ahead. A typical 6-hour forecasts use real measured data, and produces a reliable forecast. However, longer than 6 hour a head forecast requires the use of numerical weather modeling tools, which reduces the accuracy of the forecast. The root mean square forecast error exceeds 50% if the forecast deals with time horizon longer than 24 hour a head [30]. In short, forecast accuracy depends on time horizon, region, applied model type, weather condition (especially cloudy/clear day), and etcetera. However, the short-term forecast is a necessary tool to achieve an optimal operation through employment of a more accurate generation-scheduling and controlling mechanism.

On the other hand, the long-term yield prediction is important for long term planning. Inter-annual difference of solar irradiance could introduce 3% difference on global horizontal radiation depending on location [30]. Conversion to plane of irradiance and calculating the PV AC output introduces additional forms of losses, such as soiling loss and module degradation, etcetera. This difference introduces another level of difficulty to long term planning of power system because maintaining capacity and energy adequacy is vital for secure and reliable operation of the power system. To avail the appropriate resources for secure and economical operation of the system requires a reliable forecast on this regard too.

3.1.4. System adequacy

System adequacy refers to both generation adequacy (capacity adequacy) and energy adequacy challenges that the system will encounter as PV penetration (VRE penetration in general) increases. Capacity adequacy relates to the availability of sufficient generation capacity to meet the instantaneous load while energy adequacy relates to the availability of sufficient energy to meet the year round energy demand, including the demands during weeks of bad VRE generation. In the start phase of VRE development, when its penetration is very low, none of the two adequacy problem becomes a reason of concern for almost all grids. However, as VRE penetration increases its immediate impact will be to reduce the conventional power plants operating times. This will lead to a reduced revenue for those power plants and as a result lead to their withdrawal from the market and consequently discourages further investment in such power plants without further policy measures. Moreover, as VRE penetration increases the conventional fossil based baseload power plants should be retired fully due to their negative impact on grid flexibility. However, conventional power plants that could provide the required balancing needs will continually be used but its full load hours continually decreases as VRE penetration increases. Under an optimally managed transition, the capacity requirement of the conventional balancing need also decreases with an increase in penetration. In turn, the storage technology, which provides unique balancing capability both at times of PV over generation and low/no PV generation, increases with VRE penetration [20,34–37]. In short, the capacity requirement of these conventional balancing resources depend on VRE penetration, curtailment and storage capacity. The magnitudes of these three parameters were reported to increase simultaneously as detailed in [34]. Both curtailment and storage plays balancing roles of some kind in the future power system. Though the capacity adequacy is to be noticed at initial phases of VRE penetration, as witnessed from reported cases of conventional power plants with insufficient revenue withdrawing from the market as wind capacity increases [5,6], the energy capacity adequacy will be noticed at higher level of VRE penetration. The challenge of energy adequacy becomes an issue as conventional balancing system decreases significantly by handing over part of its role to VRE and storage system in tandem. This may not be a challenge of lack of adequate capacity (as could be seen from Figure 4 and related discussion given below) but a shortage of sufficient stored energy that may happen due to the absence of sufficient VRE generation over consecutive days. If there are enough conventional generators, it may be possible to increase their utilization during this period to save the stored energy or even charge the storage as needed. This could solve possible capacity shortage or energy shortage. In addition, it is also possible to build large seasonal storage to manage such problem. However, at this stage the appropriate planning margin for both type of adequacy is not clear. Despite seasonal variability of the resource itself, inter annual change in VRE production has its own impact on related uncertainty as VRE penetration increases. Estimations may be possible but the complex interaction between each of these varying factors (discussed so far) and their significance in impacting its secure operation, makes understanding the underlying science of their system level interaction compulsorily to do reliable estimations.

3.2. Potential Solutions

The foregoing discussion has summarized key challenges of high VRE penetration, the solution of which requires addressing the challenges with new techniques that will change the way we design and operate the power system. The key design principle of the present system is to make sure that sufficient dispatch-able generators that can maintain the frequency and voltage within the specified range in a least cost way are available. In most cases, these deals with ensuring the real time balance of supply and demand through load following mechanism. In the future system, where the dominant generation resource becomes variable, the design principle should also address the above challenges while achieving efficient use of these resources at all time of the year. As of now, most of our thinking lies in the basic approaches of existing system design. In the following section, we will discuss why this approach should be revisited with new knowledge and theories that could better guide the effort to increase the use of large VRE.

3.2.1. Grid flexibility and enhance transmission network

Grid flexibility is a measure of the capability of the bulk power system to respond to any kind of fluctuations in the system. This capability also refers to the ability of conventional generators to perform the required load following as VRE penetration increases. If a given power system has the ability to ramp its generators 100% down to zero in response to fluctuations that grid has 100% flexibility. In reality most power systems have some typical baseload power plants that should be continuously operated. As a result, power system flexibility is lower than 1. In section 3.1.1, we have seen that grid matching of VRE stays limited even for 100% grid flexibility. Thus, it is clear that grid penetration of VRE becomes even lower for lower grid flexibility. The use of storage can increase VRE penetration but grid flexibility will still limit its capability. Because addition of energy storage technology does not directly mean an increase in grid flexibility even if it increases system balancing capability. If the baseload power plants are sourced from polluting fossil sources, these power plants have to be replaced by more flexible generators in the short term and with energy storage and VRE tandem in a long term. This will allow reaching to higher VRE penetration in gradual step.

The other factor that can limit energy penetration of VRE will be transmission bottle neck. Transmission bottle neck occurs in one of the following two cases: (i) absence of sufficient transmission capacity to transport energy generated by remotely sited VRE sources to appropriate consumption center; and (ii) when VRE resource is built in a load area that also depends on transportation of energy generated by baseload power plants. This could lead to transmission congestion that limits VRE transport at a time of high VRE generation. The potential solutions are increasing flexible transmission interconnection, address grid flexibility and increase use of geographically distributed resources. Distributing resources need to be understood in two forms: (i) those which are directly connected to customer at low voltage distribution level; (ii) those which are geographically distributed across the wider network rather than concentrating VRE power farms into few load areas with best resources. In a study performed to identify optimal situation for increasing VRE penetration to the state of California electricity grid, high penetration was reported without the need to increase transmission connection between load areas beyond what is required to meet the electricity demand of that year [20]. This is because the VRE resources are well distributed at various part of the state. Customer level distributed generation has also a potential to reduce transmission interconnection need, however the level of total maximum distributed generator capacity to be built in a given feeder must be defined to avoid potential system disturbance that might be caused by such a system. Overall, the question of interest is how to change these parameters in an optimal way during our transition and build the necessary enabling tools and policies for its optimal long-term operation and use. The improvement in any parameter should be motivated by the need to increase system wide VRE penetration, not to achieve high VRE penetration at smaller spot inside a large system. Currently, most of our tools focus on building the best resources without paying attention to long-term system implication.

3.2.2. Energy storage

The role of energy storage and its required size depends on grid flexibility, storage system design (selected energy to power ratio), VRE penetration, curtailment, scheduling strategy, and may be on non-storage demand response mechanism [20,34–38]. In a series of studies performed on Israeli grid, system designing accuracy that conforms to the seasonal and diurnal variability of PV output and demand profile is essential to arrive at a system that can optimally match PV to the local electricity demand [21,27,23,35,36,39]. Moreover, the studies show that storage power and energy capacity choice depends on grid flexibility, targeted VRE penetration and assumed curtailment. These studies shows that multiple mix of these parameters could lead to same amount of VRE penetration. The choice of the appropriate mix should be defined based on a variety of multi-criteria system designing and policy rules that needs to be developed as more knowledge is gained about the future energy systems. However, the key lessons from these studies are:

(1) Appropriate sizing of storage power and energy capacities should be followed based on the seasonal and diurnal interaction of the VRE output and demand profile. The essence of this statement dictates not only about the importance of appropriate choice of the two storage properties but also deals with the choice of proper storage hybrid and their optimal use. The above requirement stretches far beyond the simplistic approach that we follow to design storage in the current system (where storage is designed for some typical service), which requires the understanding of holistic use of various storage technologies and their combined effect to deliver the needed service. In addition, it is very important to achieve an optimal use of the storage resources to increase grid penetration.

(2) Storage size increase initially leads to significant increase in PV penetration, however, the fast increase stops after it reaches some threshold where it starts to level off. The point of the leveling off (inflection

point) depends on grid flexibility. Further increase of storage capacity beyond these threshold has small benefit in increasing grid penetration of PV. Thus, other mechanisms, such as curtailment, demand response, and proper forecasting and scheduling strategies could help arriving to higher penetration without the need to further increase storage capacity [35,36]. With the mix of these strategies, it was shown that the required storage capacity is less than daily average demand of the local grid suffices to achieve VRE penetration of approximately 90% of the annual demand [35,36].

Similar analysis performed using the state of California grid data set using a more diverse resource arrives at the same findings [20,24]. Moreover, it was clearly shown that regions with diverse resources could benefit from wind solar complementarity and achieve same penetration with lower storage capacity as compared to regions with less diverse resources. A recent techno-economic modeling result performed using Israeli grid data set has arrived at the same results while providing some new insights [34]. The new lessons are: (i) VRE penetration, curtailment and storage simultaneously increases in certain fashion during our transition to high renewable grids; (ii) the techno economic performance of specific storage technology depends on the link between these three parameters; (iii) accordingly storage were classified as diurnal and seasonal storage based on their potential application (see (v)); (iv) The VRE penetration and storage capacity need follows similar trend as the one found in the above studies [20,24,35,36] however the point of inflection at same grid flexibility was found to depend on curtailment policy. This result also shows that for 100% flexible grid, a storage with capacity of about daily average demand suffices to reach to approximately 90% annual VRE penetration. (v) More importantly, the inflection points were useful to classify storage technologies depending on their roles before and after that inflection point. Storage technologies that play a significant role before the inflection point are classified as diurnal storage, but storage technologies that join the systems with a massive capacity above the inflection point are called seasonal storage. The inflection point is also the point where these seasonal storage technologies start to play significant roles depending on the curtailment policy. Note that some storage technologies has a characteristics that makes them suitable for both diurnal and seasonal application. Regardless of the curtailment policy, it can be concluded that a diurnal storage technology deployment monotonically increases with VRE penetration until it reaches approximately 90% of the annual demand. The reported relationships are a consequence of the achievement of an optimal matching between VRE output and load profile under given constraints throughout the transition period. This shows that in order to take advantage of this relationship and make an effective transition to 100% RE, planners should follow paths that would gradually increase the flexibility of the existing energy system while increasing energy storage capacity in the system. These findings strongly points towards the need for better theoretical framework to understand the future system. Present studies are based on parametrization that simplify several technical details. Even if they are already providing valuable lessons, this makes them short of determining important designing and operational rules. For example, in Solomon et al. 2014 [20], it was reported that storage energy and power capacity changes from one point in the network to the other. This suggests the required specific technology and its location in the network may vary depending on storage design representation. The optimal identification of such a requirement requires, among several other things, a more advanced model than most of the models that are currently utilized. Alternatively, simplifying parametrization should be developed based on better knowledge of the system level science.

3.2.3. Curtailment

The energy curtailment that is being reported by present day utilities are mainly caused by low flexibility of the dispatched generators (commonly known as grid flexibility) and transmission congestion. This is because the simplest way to increase grid penetration of VRE is to curtail energy at times of high VRE generation to improve the demand matching at other time of the year for any grid flexibility. In previous studies, it was shown that curtailing approximately 5% of the annual VRE penetration increases grid penetration of PV from 17,4% to 29% to the Israeli grid [27] and 20% to 31% to the ERCOT Texas grid [28]. The role of curtailment was also evaluated together with use of storage. According to studies in [36] and [20], it was reported that allowing curtailment increases the use of a given storage to increase VRE penetration to the Israeli and California grid, respectively. In other word, if we allow sufficient curtailment, we can arrive at higher penetration with a storage capacity significantly lower than what is required without curtailment. The Israeli and Californian grid studies show that by allowing 20% total VRE energy loss (the loss due to energy storage efficiency plus curtailment), a storage energy capacity lower than the corresponding daily average demand suffices to reach to approximately 90% annual VRE penetration. Energy curtailment has also shown additional benefit of reducing the balancing requirement that comes from conventional power plants, often termed as backup [24,39]. Note that the term 'balancing' and 'backup' capacity were used by different groups to refer to the same thing; i.e. any generation resources available to fill in the shortfalls of the VRE generators and storage.

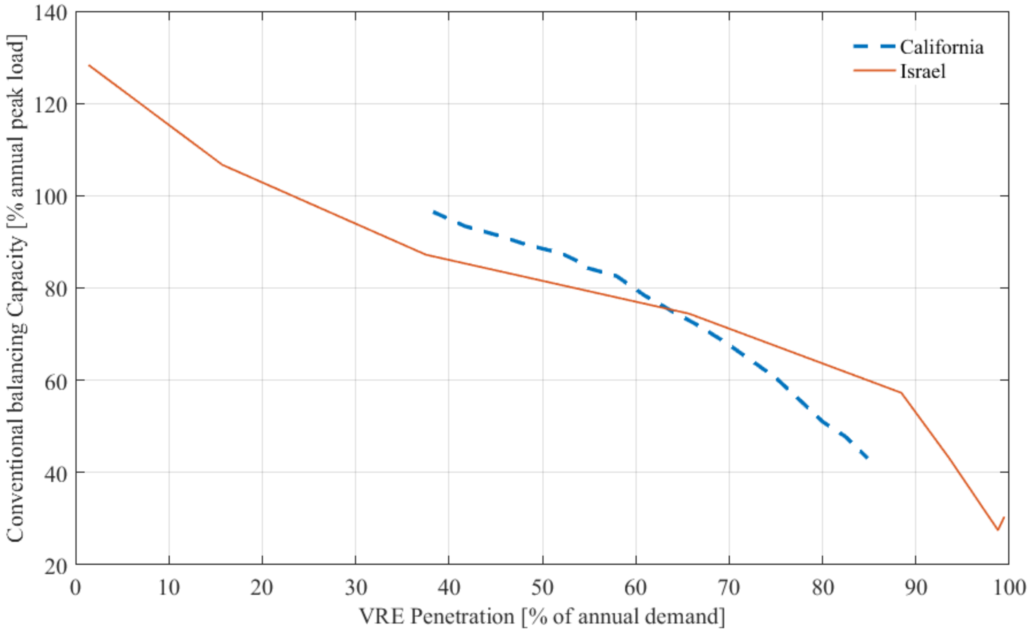

Figure 3. Relation of conventional capacity and VRE penetration for Californian [20] and Israeli grid (see basecase scenario [34]). The data were produced using different models and under different conditions but due to technical reasons shows the same trend. The data for California corresponds to total storage capacity of 186 GWh/22GW, the variation occurs as curtailment changes. But the Israeli grid study allows varying both curtailment and storage capacity simultaneously as VRE penetration increases.

In this paper, we will use the term "balancing", however note that we extend the meaning to include storage power capacity as well in connection with Figure 4. Figure 3 shows how renewable energy curtailment increase leads to a reduced conventional balancing capacity need while increasing grid penetration. The figure shows that using the 186 GWh/22 GW storage, which at 20% total energy loss achieves grid penetration of approximately 85% of the annual demand, the corresponding conventional balancing capacity was reduced to 59% of the peak demand. For the study of the Israeli grid, the model allows simultaneous changing of both parameters (curtailment and storage capacity) with VRE penetration. The decrease in conventional balancing capacity is a result of combined effect. Note that the total energy loss (total loss) stands for the loss due to curtailment plus loss due to storage efficiency. Out of the 20% total energy loss, the loss due to storage efficiency is about 8% and 3% of the total renewable generation for the Israeli and California grid, respectively. A decrease in curtailment could lead to an increase in the energy storage size and vice versa, but the best option is to find the optimal condition by considering various constraints. At high level of penetration, storage technology can also serve for balancing in addition to conventional capacities. Even if VRE generates depending on whether, it can also be controlled to reduce or increase its output in response to a change in demand so that balancing need can be reduced during operation. For example, Tracking PV technologies are well suited for such application because part of the tracking PV power plant can be turned away from the sun to reduce its output at the time of over generation. These segments could be turned back to the sun if the demand exceeds generation in the subsequent hours. Wind power plants are already performing such activities depending on market. But the use of such technique requires proficient forecasting and scheduling during system operation. But a precondition for that is designing a flexible system anticipating various operational scenarios at the time of planning. The balancing role of storage should be intuitionally clear. As a result of an increase in storage with VRE penetration, it can be understood that its power capacity also increases. Consequently, the composite balancing capacity increases as VRE penetration increases. Figure 4 presents these relationships using the data of one scenario presented in [34] to clarify this. The figure shows that the conventional balancing capacity decreases as storage power capacity increases together with curtailment. Consequently the aggregate of the two increases.

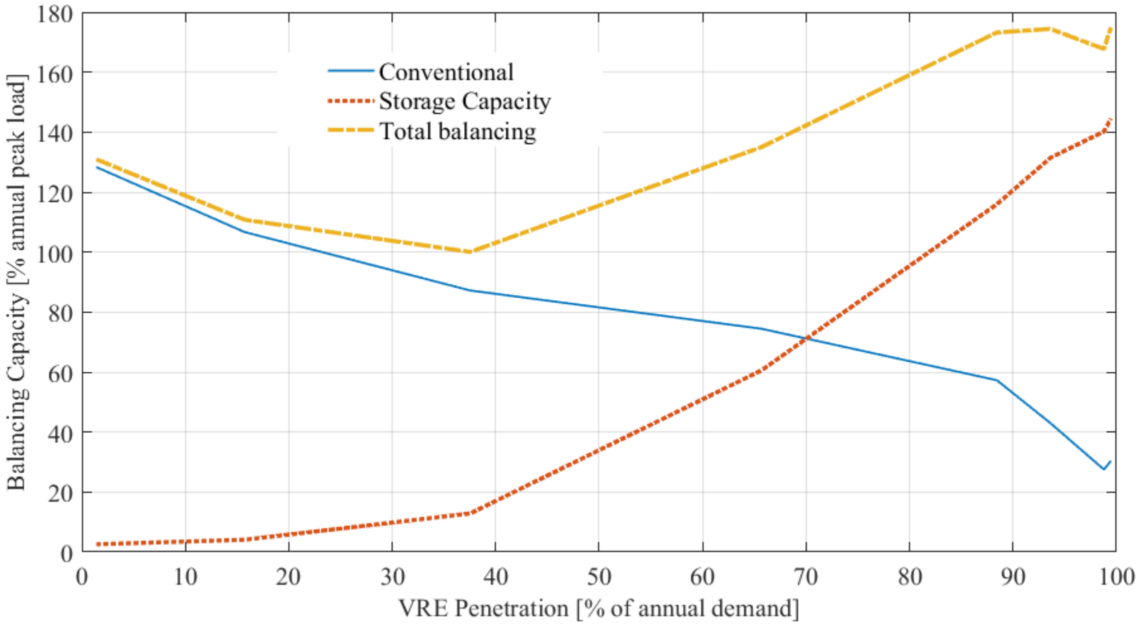

Figure 4. Balancing capacity changes with VRE penetration for Israeli grid (see base case scenario [34]).

In summary, effective system design depends on our understanding of the interaction between these and other varying factors. The penetration-curtailment-storage nexus reported in [34] provides important fundamental lessons that needs to be understood along with several other issues. Because that interlink, which shows that the three should simultaneously increase in some way, resulted due to a physical bound created by the matching characteristics of PV output and demand profile.

3.2.4. Demand response

Demand response is a process of controlling electricity demand by sending a demand adjust command order to consumers of any type by grid operator. The idea was primarily conceived to shift load from expensive peak demand time to cheap off-peak periods to reduce average cost of electricity. Currently, the idea is expanded as a tool to contain VRE variability in order to increase its penetration. This is to be implemented by taking quick adjustment to electricity load to cope with frequency regulation demand. Moreover, to increase VRE penetration the shift should move loads to time of high VRE generation. The role of demand response, in the form of demand shift, to increase PV penetration was studied in [38,40]. The study shows that shifting some portion of the electricity demand to time of peak solar generation could increase PV penetration to electricity grid. But there were no sufficient evidence that the loads could practically be shifted on year round bases to effect meaningful PV penetration using load shift. However, demand response application to shift customer away from peak demand time and encourage demand side participation in reserve service is currently on progress. Regardless of its obvious benefits for frequency regulation, it is difficult to practically quantify its contribution to increase grid penetration of VRE as of now.

The foregoing discussion shows the importance of understanding the interaction of several factors to design future energy system that can fulfil the possible optimal and efficient operation to be achieved based on the anticipated generation resource, local demand profile and potential technical solutions available to solve the challenging task of matching the VRE output to electricity demand. As amount of VRE penetration changes, the role and importance of one technology, such as storage technology choice [34] and demand response role [37], may change. Moreover, an increased use of some of the technical solutions reduces the need for other solution [37]. A closer look at the corresponding quantitative data suggests the presence of physical link between most of these factors. Understanding these factors could provide a unifying theoretical framework that could give the base for developing future system design rules. Such rules could bring agreements on way of guiding the research in the area, which needs harmonizing to realize comparability between results of various group. On top of that their role has an associated seasonality. As a result, designing should follow multi-criteria rules that is cognizant of the future operational challenges and the sustainability that we aspire to achieve.

4. Conclusions

Over the past decade, PV industry has achieved a rapid capacity addition as compared to any other energy technology. The increase, which is driven by spectacular technology cost decline, is expected to continue at a faster rate. Together with this exciting news also comes a significant system level technical challenge that should be addressed as VRE penetration increases. This paper presents the analysis of literature data in order to clarify system requirement for large PV penetration. Despite the large capacity increase observed during the past decade, energy penetration achieved by PV remains too low because of the variability and diffuse nature of the solar resources. In addition, adding large capacity to achieve high PV penetration should address the following technical limits, namely: matching, variability, uncertainty and system adequacy. To overcome these challenges, several enabling techniques, such as energy storage, curtailment, transmission interconnection, demand response, resource complementarities, increased grid flexibility, improved forecasting, geographic distribution of generation resources, were among the most discussed by various researcher. A closer look at some systematic studies shows that developing theoretical framework for the future system is the best way to guide the smooth development of an effective and secure system. This argument is based on the observation that (i) the role and importance of one technology, for instance specific storage technology and demand response, may change as VRE penetration increases; (ii) the increase in use of one application decreases the importance of the other; (iii) the use of some of the discussed solution may depend on level of penetration as they also depend on season. Thus, it is important to design the system based on a criteria formulated with the understanding of system level science or theoretical framework.

In short, the design of the future energy system should not be seen as a simple question of arriving at a least cost option that can provide a low carbon energy future. This is due to the lack of unifying rules regarding system design and several simplification that are employed in economic models. However future design rules should enforce criteria's suitable for arriving at a sustainable option for economic development while also building a system with effective reliability and security. This could be done in effective way if we create a scientific framework based on system level understanding of our resources.

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Conflict of interest

The author declares no conflict of interest.

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