Firm Photovoltaic Power Generation: Overview and Economic Outlook

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Grid-connected photovoltaic electricity production steadily grows at the margin of conventional power generation, but its management becomes more complex. To overcome this challenge, a transformation of variable renewable energy (VRE) resources into firm power generation is proposed. Drawing on insights from the International Energy Agency Photovoltaic Power System Task 16 case studies, it becomes evident that achieving nearly 100% VRE power grids that reliably meet demand year-round can be economically viable through optimal VRE transformation. This transformation involves various traditional methods, e.g., storage, VRE blending, geographical dispersion, and load flexibility. However, overbuilding VRE capacity and controlled curtailment, acting as implicit energy storage, are now seen as essential prerequisites for this transformation. Nevertheless, aligning this vision with the current market rules poses a dilemma as it doesn't necessarily align with VRE producers' interests. This predicament calls for a reconsideration of VRE market regulations. Current designs based on marginal energy production signals do not suffice. Instead, it is advocated for market rules grounded in the capacity of firmly enabled VREs rather than their energy output. Ultimately, the economic model should harmonize with the variability of VRE resources, rather than forcing VRE resources to adapt to existing market structures.

1. Introduction

Solar and wind resources are weather-driven variable renewable energy (VRE) resources that have been growing at the margin of a core of dispatchable and baseload conventional generation. To effectively tap into their massive potential, a main challenge ahead for VREs is to evolve beyond the margin and to eventually displace the underlying conventional generation core. This article is based on the research work undertaken as part of International Energy Agency PV Power System (IEA PVPS) Task 16 collaboration program,[1] where we propose to optimally transform intermittent VREs into firm—i.e., effectively dispatchable—power generation capable of meeting the electricity demand on a 24/365 basis.

The variable-to-firm VRE transformation strategies discussed in this article build upon work initiated by Perez[2] to spell out economically optimal paths to enable ultrahigh VRE penetration, complementing the renewable portfolio or large-scale storage approaches pioneered by others (e.g., refs. [3–7]). The transformation enablers include energy storage, optimum blending of VREs, and other renewable resources (e.g., hydro) when available, geographic dispersion, and supply/demand flexibility. Most importantly, the transformation entails overbuilding and proactively curtailing the VREs—a strategy we term applying implicit storage.[8] This counter-intuitive strategy ensures acceptable total VRE production costs, which include both generation and grid integration cost.

Substantiated by the results of in-depth case studies, the article infers that, almost anywhere on the planet, nearly 100% VRE power grids firmly supplying clean power and meeting demand 24/365 are not only possible but would also be economically viable, if VRE resources are optimally transformed from unconstrained run-of-the-weather to firm generation. VREs are then capable of entirely displacing all conventional sources economically (provided now-emerging grid-forming inverter technology resolves any grid frequency and stability issues resulting from the displacement of conventional rotating power generation).

In effect, this article posits that VRE curtailment, which is absolutely vital to achieving least-cost firm power production, is a prerequisite to the energy transition and lowers its cost significantly. However, this optimum point for society is not at the same point as the optimum for an individual producer or a company today. There is therefore a need to evolve current market remuneration rules, which are not adequate to achieve the optimum (least costs for society). Existing remuneration schemes or power purchase agreements (PPAs) that focus on

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energy remuneration are not appropriate. This is because for firm power, capacity availability becomes more important than energy. The existing market designs based on marginal energy costs and merit order induce price signals that are not adequate to reach the goals of decarbonization that require firm VRE power.

In addition to the conclusion, which is presented at the end, this article consists of two main sections: 1) the following section presents the concept of firm VRE power generation and introduces implicit storage (curtailment) as an economically essential strategy to achieve it. The section also summarizes key results developed as part of IEA PVPS Task 16 and related investigations. 2) Section 3 delves into the issue of the changes in market rules that should occur to foster firm VRE power generation. While we do not pretend to give final answers here, we raise important questions to be addressed as early as possible by market designers and policy makers, arguing that the economic model must fit the physics of the available resources and not vice versa.

2. Firm VRE Power Generation: A Review of IEA PVPS Task 16 Investigations

The authors of this article led the IEA work on firm power generation and recently released a report on this activity.[1] In this report, firm power generation is defined as the capability for an electricity generating resource to meet a given electrical load (e.g., the demand of a power grid) 24 h a day and 365 days a year. Electrical generation on power grids has typically amounted to a blend of firm power-capable conventional resources, with resources such nuclear, large hydro, and coal firmly meeting defined baseload requirements and with dispatchable resources such as thermal natural gas generation (combined cycle and peaking units), dispatchable hydro, supplying variable demand requirements according to their respective time response capabilities. These conventional resources are all capable of meeting their assigned load requirements and thus constitute, by definition, firm power resources.

Wind and solar have immense development potential that could entirely displace environmentally taxing conventional generation.[9] However, these VREs do not meet the firm power criterion. They currently rely on the core of conventional baseload/dispatchable generation and operate at the margin of this core. This is illustrated in the top panel of **Figure 1**. The underlying conventional generation must be managed appropriately to embed the VREs and ensure that demand is always met. As the VRE penetration increases (see the bottom panel of Figure 1), their marginal operation intensifies the dispatchable resources' management burden, e.g., with steeper dispatching ramps, deeper duck curves hence requires larger spinning reserves and a greater accuracy for net-load forecasts.

If the objective is to displace the underlying conventional generation, VREs must evolve beyond the margin. They must be transformed from intermittent to firm, i.e., be capable of meeting demand 24/365 on their own. Such a transformation is possible with a portfolio of enabling strategies and technologies, which we term firm power enablers or transformation enablers. The IEA report[1] lists the following conventional and well-known transformation enablers: 1) energy storage, which absorbs generation when it exceeds demand and releases it when it falls short of demand; 2) optimum blending of VREs and other renewables (e.g., photovoltaic [PV], wind, and hydro) that often exhibit complementary diurnal or seasonal generation profiles;[10] 3) geographic dispersion, which reduces VREs' inherent variability;[11] and 4) load flexibility achieved either on the demand-side via customer-side demand response, or on the supply-side, by keeping a fraction of dispatchable thermal-generation operational, thus modulating the demand seen by the VREs.[12] (Note that this supply-side flexible generation could be 100% renewable if renewable fuels such as e-fuels are applied).

On top of those conventional enablers, a rich collection of recent research works have jointly advocated that the

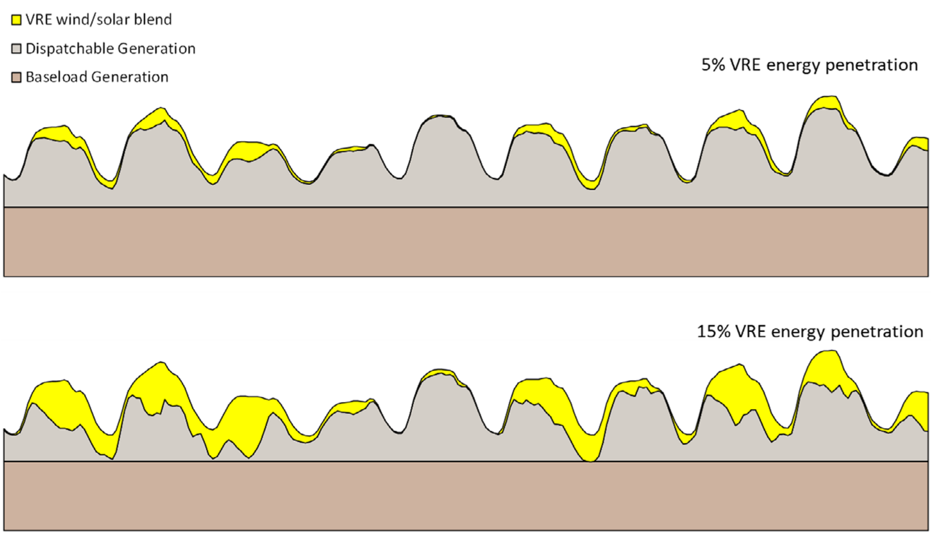

Figure 1. Illustrating variable renewable energy (VRE) generation operating at the margin of a core of conventional power generation at low- and medium-grid-penetration levels. (Note that the load is New York City's, hypothetically served by baseload generation (50%) and dispatchable generation (50%) in the absence of VREs. The VRE resource consists of a simulated time/site specific load–coincident blend of 50%/50% wind/solar generation.

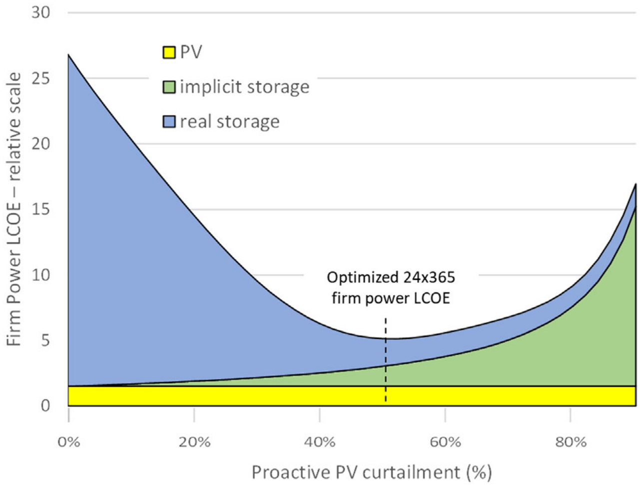

Figure 2. Respective contributions of photovoltaic (PV), storage, and implicit storage (PV overbuild) to the cost of firm power as a function of proactive PV curtailment. The storage-alone option (zero curtailment) is significantly more expensive than an optimized real/implicit storage configuration. Reproduced with permission.[1] Copyright 2023, IEA PVPS Task 16.

variable-to-firm transformation must also entail overbuilding and proactively curtailing the VREs (or applying implicit storage), which is the most important but a counter-intuitive enabler. **Figure 2** illustrates the influence of implicit storage in achieving low-cost firm power generation in the case of PV.

Before interpreting Figure 2, which is vital to the understanding of firm power generation, the optimization problem that underpins the lowest-cost firm power should be understood. Clearly, all aforementioned firm power enablers have specific costs and operational specs (e.g., the cost of grid strengthening associated with geographic dispersion). Their optimal blending determines the most effective and lowest cost firm VRE configuration for a particular location/region. The economic factors and technical characteristics shaping this optimization problem include the following[1]: 1) the CapEx (capital cost) and OpEx (operational cost) of the considered VREs, 2) the CapEx and OpEx of the considered storage technologies, 3) the CapEx and OpEx of demand and/or supply-side flexibility, 4) the CapEx and OpEx of grid strengthening, 5) the considered electrical demand profile, and 6) the generation profile of the considered VRE resources.

Insofar as electricity is concerned, its cost is commonly gauged in terms of the levelized cost of electricity (LCOE), which measures lifetime costs (CapEx + OpEx) divided by energy production. The LCOE, which is represented on the ordinate of Figure 2, is foremost the sum of LCOEs of the considered VREs, storage, and, as applicable, any allowable flexible resources capable of modifying the load seen by the VREs. The LCOE of individual enabler is further a function of the proactive PV curtailment percentage. More specifically, the LCOE of unconstrained PV, which is represented in yellow, does not change with proactive PV curtailment percentage; the LCOE of real storage (i.e., batteries) drops as the PV curtailment percentage increases; and the LCOE of implicit storage (i.e., overbuilt PV) rises as the PV curtailment percentage increases.

In the case of Figure 2, the minimum-LCOE "sweet spot" is achieved at about 50% proactive PV curtailment; this percentage would differ from one case to another. In practice, for a given power grid, this optimum point is determined empirically from time-coincident, multiyear hourly time series of demand and VRE generation, by scanning the costs/curtailment solution space of an operational firm power system configuration such as shown in **Figure 3**. Hourly resolution should be sufficient in most cases since configurations optimized to handle major multiday VRE deficits [e.g., cloudy winters] will include considerably more energy storage than needed to handle any short-term fluctuations). Short-term fluctuations and spike are of course a specification concern for equipment design so it always operates properly, but not for firm power system optimization.[10] This optimization can be done either iteratively by choosing the most appropriate actions of each hour,[2] or by mathematical programming—depending on the battery model, the optimization can be written into a mixed-integer linear program or a bilinear program.[13] Note that this type of operational configuration and the determination of an optimum operating point has been well known to the designers/operators of islanded remote PV/wind systems.[14] It is extended here to the utility-scale operation of local/regional power grids.

IEA Task 16 investigated two types firm power generation for VREs: 1) firm power generation at high renewable penetration, which is concerned with meeting the entire demand of a power grid, or a significant fraction thereof, i.e., displacing the underlying conventional dispatchable generation core as discussed earlier; and 2) firm power support, which is an "entry level" firm power generation that addresses easier-to-meet firm load targets, such as day-ahead VRE production forecasts, or net-load imbalances, as pathway to begin operationalizing firm power.[15,16] The remaining part of this section focuses on reviewing selected high renewable penetration investigations most directly relevant to energy transition focus of this article.

2.1. Firm Power Study Minnesota

One of the first case studies to explicitly identify curtailment as the key enabler of VRE firm power at the least possible cost was produced by Perez et al.[12] for the State of Minnesota. Its results demonstrated prospective (2050) firm power production cost targets well below 50 $ MWh^{-1} with a 45% wind and 55% PV blend. This study concluded with a recommendation that, to achieve this lowest cost firm generation potential, proactive curtailment strategies should inform future transactional PV remuneration systems; hence, since PV remuneration systems depend on regulations, that proactive curtailment strategies should inform the latter—a topic we approach in Section 3.

2.2. Firm Power Study MISO

The Minnesota case study was extended to the entire Midcontinent Independent System Operator (MISO) that spans 10 electrical regions from the Gulf of Mexico to Canada.[17] This study confirmed and expanded on the Minnesota findings: firm 100% wind/solar power could be achieved at near or below 50 $ MWh^{-1} when considering future (2050) utility-scale costs

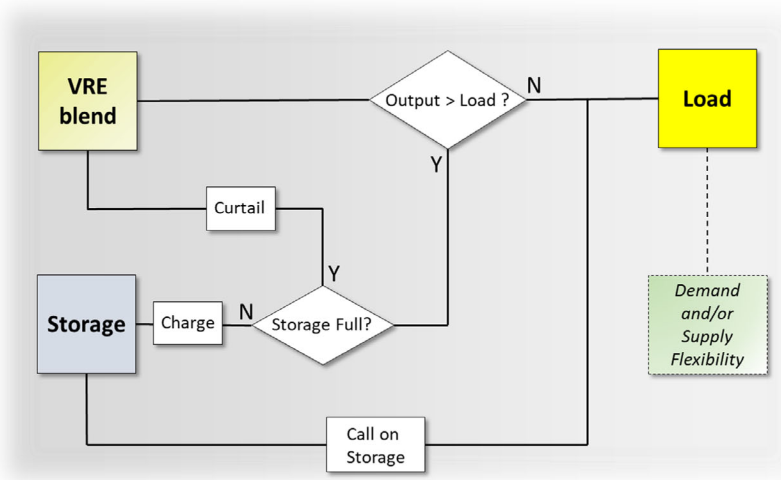

Figure 3. Operational algorithm of a VRE resource system including storage, implicit storage (dynamic curtailment), and supply/demand–side load demand modifiers.

for PV, wind, and battery storage. This study investigated the impact of both continental geographical dispersion and flexibility on the cost of firm power. Regarding geographical distribution, it concluded that the economic gains from interconnecting individual electrical regions was modest, even when taking a "copper plate" approach, i.e., not accounting for transmission buildup necessary to distribute wind/PV MISO-wide. Each electrical region could operate independently islanded at 100% VRE with only a small (≈10%) firm power premium compared to the entire MISO territory. Consistent regional VRE regional islanding conclusions were subsequently drawn by refs. [18,19] for many other locations. **Figure 4** illustrates the 100% wind/PV firm power LCOE for each MISO region operating independently (no transmission interconnection between regions). The figure also conveys the optimum least-cost PV/wind blend in each region. Note that this blend is generally PV dominant in all but the windiest regions. Regarding flexibility, the study showed that retaining 5% dispatchable (natural gas) energy generation (i.e., 95% VRE) could reduce firm power LCOEs by 15%–20% compared to pure wind/solar configurations.

2.3. Firm Power Study Switzerland

The Firm PV Power Generation in Switzerland (FIPPS) project applied the approach developed for MISO to the context of Switzerland.[20,21] This context is characterized by a highly seasonal PV resource, little wind development potential, and a large, sophisticated hydropower resource including pumped hydro storage and long-term one-way storage systems. The main objective was to assess the cost of operating the Swiss power grid with a large contribution from firm PV, while at the same time growing demand by 30% to accommodate planned transportation and building electrification, and entirely phasing out nuclear power that currently accounts for 30% of the grid's energy. Several supply-side flexibility scenarios accounting for 5%–10% of energy generation to complement hydropower and PV were considered, including interconnectivity with (i.e., import from) the European grid and dispatchable thermal generation powered

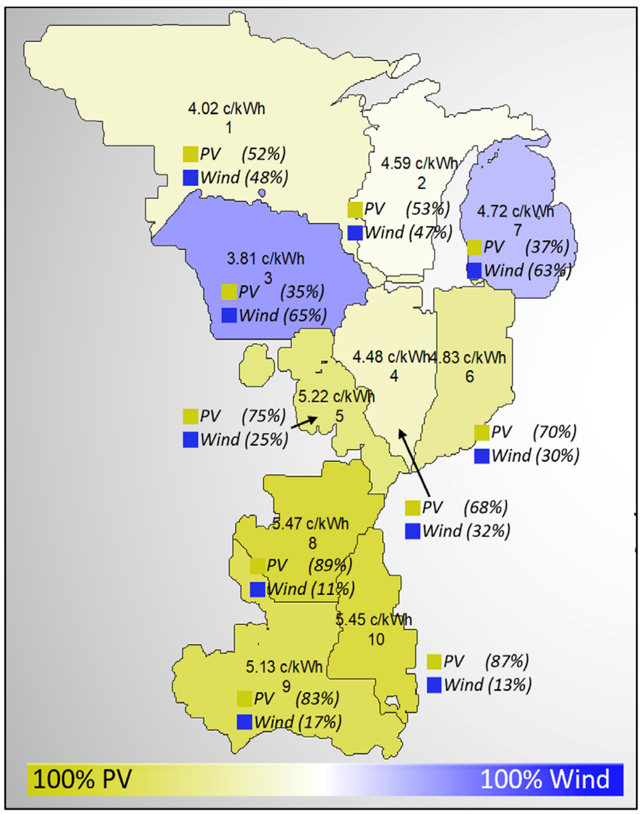

Figure 4. Optimum distribution of PV and wind and resulting firm power levelized cost of electricity (LCOE) in each of Midcontinent Independent System Operator (MISO)'s electrical load resource zones. These numbers correspond to 2050 utility-scale technology cost assumptions.

by either conventional natural gas, biogas or 100% greenhouse-gas-free e-fuels. Considering 2050 utility-scale PV and battery-storage systems, all scenarios yielded firm power electricity production costs ranging from 5.5 to 6.5 ¢ kWh^{-1}. Considering more expensive small-scale user-sited PV/storage systems, the firm electricity price range increased to 7–8.5 ¢ kWh^{-1}. As was observed for MISO, operating Switzerland autonomously without interconnection to the European grid only resulted in a small firm power premium of ≈0.2 ¢ kWh^{-1}. Another important result of the FIPPS study is the observation that a small energy fraction (10%) of fully renewable dispatchable e-fuel thermal generation, while it is several (5+) times more expensive than conventional natural gas, can play an essential catalyst role by providing flexibility and keeping the overall production costs acceptable. Indeed, in the most extreme considered scenario—an autonomous, 100% renewable grid with firm PV, hydro, and 10% flexible e-fuels—the overall cost of power production would be kept below 6.5 ¢ kWh^{-1} for utility-scale systems. **Figure 5** illustrates the evolution of seasonal energy dispatching on the Swiss power grid from the current nuclear/hydro configuration to this 100% renewable and autonomous Switzerland scenario. Importantly, all considered scenarios require curtailment to achieve acceptable power production costs that would have been 1.5–4 times higher by operating the PV resource without implicit storage.

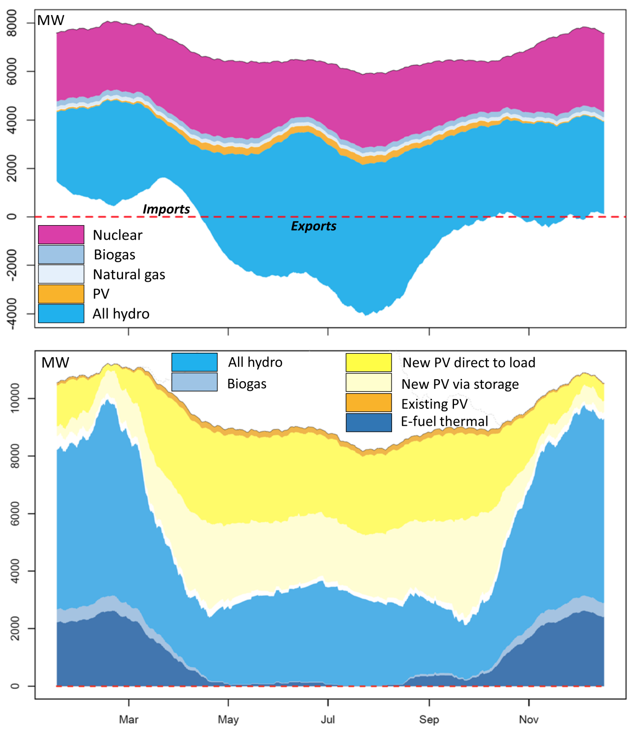

Figure 5. Annual dispatch of Swiss based on supply-side resources. The top graph represents current conditions for the year 2020 (the top line of the stacked graph represents the total load on the Swiss grid). The bottom graph represents the annual dispatch of resources for the 100% renewable, autonomous power grid scenario including PV, hydro, and dispatchable thermal generation (e-fuels and biogas). Note that the daily generation data points underlying these graphs have been smoothed using a 15-day running mean to facilitate visualization.

2.4. Firm Power Study Italy

In the study entitled Italian Protocol for Massive Solar Integration,[22] Pierro et al. applied the concept of optimum VRE curtailment to sketch out a gradual, systematic transition from current power generation conditions to a future (2060) 92% renewable configuration dominated by PV (48%), with 18% wind and 26% hydro. This future configuration retains 8% flexible thermal generation from natural gas, while noting the possibility of its eventual replacement by clean e-fuels. With 8% of built-in supply-side flexibility, the optimum VRE curtailment level was determined to be about 25%. One of the strengths of this study is that it keeps the bottom-line electricity production cost on the Italian grid nearly equal to its present cost of less than 50 € MWh^{-1} for every phase of the transition between current and future conditions, accounting for VRE and storage cost evolution over time, integrating their growth into existing government plans for the initial years, and gradually transitioning from run-of-the-weather (aka dump) PV and wind into firm, optimally curtailed PV and wind initially addressing the "entry level" easier-to-meet firm VRE and net-load forecast targets. The Italian Protocol transition is illustrated in **Figure 6**.

2.5. Firm Power Study La Reunion

The firm power study for the Reunion Island's power grid[23] focused on PV-only and considered multiple firm load targets ranging from "entry level" firm forecasts, to ultrahigh penetration, meeting 100% of the island's demand 24/365 (intermediate targets included meeting the loads of the commercial sector, or displacing diesel power generation). **Figure 7** reports the LCOE of firm power PV for each scenario as a function of penetration and total investment CapEx. Importantly, unlike the previous studies, economic results for La Reunion consider current (circa 2019) small-to-medium scale costs for PV and storage. For this reason, the LCOE cost 100% PV firm power scenario amounts to 35 ¢ kWh^{-1}, noting that this is already roughly equivalent to the cost of generating power on the island today with a mix of imported coal, hydro, natural gas, and biomass (future PV/storage technology costs could reduce this amount by a substantial factor). As for the Italian, Swiss, and US investigations, implicit storage is central to achieving these costs which otherwise would be severalfold higher.

2.6. Firm Power Study Europe

Van Eldik[1,24] applied a similar approach to evaluate firm VRE power generation across the European continent (EU + 10 neighboring countries). This study analyzes what the optimal share of solar PV, and wind power (onshore and offshore) is in combination with lithium-ion battery and hydrogen storage to guarantee firm power across the continent. The study takes into account the existing bidding zones/balancing areas across the continent, and the existing transmission constraints between these zones. Results are quantified in terms of LCOE premium relative to unconstrained VRE generation, based on near future (2030) technology cost estimates. They are fully consistent with the previous investigations, yielding optimum curtailment levels of ≈50% and

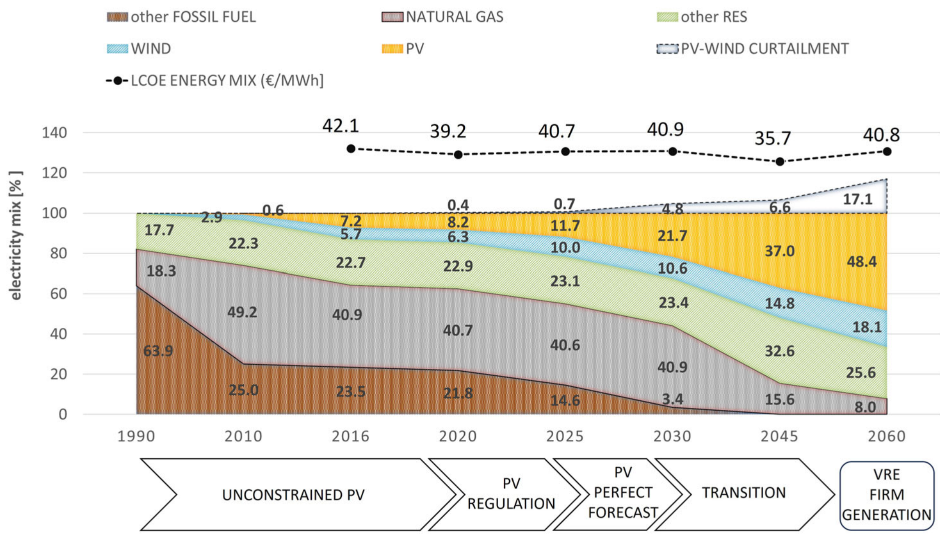

Figure 6. Evolution of firm-electricity-generation mix and cost through the transition. Taking advantage of the existing dispatchable hydroelectric and geothermal and biofuel power plants in Italy, the study demonstrates that it will be economically feasible to reach fully predictable (perfectly forecasted) solar production by 2030 and firm power generation by 2060 with a renewable penetration of 92%.

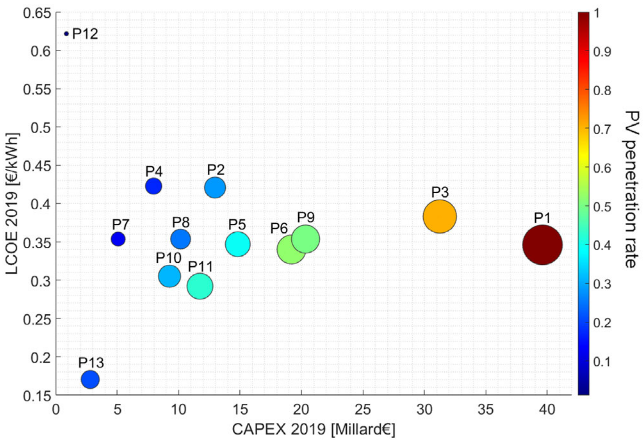

Figure 7. LCOE of firm power based upon 2019 PV/storage costs. The P1 scenario corresponds to 100% firm power PV penetration. (Other intermediate firm load target scenarios include P2-substituting diesel plants, P3-subsituting coal plants, P4-supplying cooling demand, P5-supplying the tertiary sector, P6-supplying tertiary and industrial sectors, P7–P9-supplying constant load at 50, 100, and 200 MW, P10-meeting a trapezoidal day-time load peaking at 300 MW, P11-meeting 100% demand during daytime only, P12-meeting evening peak demand only, and P13-meeting firm day-ahead solar forecasts). Reproduced with permission.[1] Copyright 2023, IEA PVPS Task 16.

a premium of 4.5 with batteries as means of storage, and ≈30% curtailment/3.5 premium when applying a battery/hydrogen-storage blend. Firm power premiums would be 3–5 times higher without implicit storage.

2.7. Firm Power Study Northeastern China

In a recent article addressing data, methods, and models involved in the determination of optimum firm solar power solutions, Yang et al.[25] presented a case study for a single power plant operating in the city of Harbin, in northern China. The study's main contribution is twofold. First is that it proposed a mathematical programming viewpoint on the optimization of firm kilowatt premium, which is not just faster than the original iterative approach but also guarantees the obtainment of global optimal solution. Second is that it considered various sources of uncertainty, such as PV/battery modeling uncertainty and interannual solar resource uncertainty, which may affect the optimization results. In the case study, the levels of optimum curtailment (40%–45%), of premium with respect to unconstrained generation (3.9–4.2), and of reduction of this premium compared to a system operating without implicit storage (3–5), are fully consistent with all previous studies. In absolute economic terms, the study concluded that, with current utility-scale CapEx and OpEx for PV and storage (833 $ kW^{-1} and 137 $ kWh^{-1}, respectively), firm power LCOE is still considered as too high to be competitive with existing dispatchable resources at ≈22 ¢ kWh^{-1}, but that firm VRE power could fetch below 5 ¢ kWh^{-1} when considering expected future costs—an arguably encouraging result for single-plant, pure PV generation in northeastern China.

3. Result Implications: Need for New VRE Market Rules

The case studies summarized in the previous section cover a wide range of VRE resources and electrical demand conditions. The consistency of their findings suggests that 100% renewable power grids dominated by firm PV and wind are not only possible but would also be economically reasonable. Several observations stand out in particular: 1) in all cases, implicit storage (curtailment) is key to achieving economically optimal 24/365 solutions by a considerable margin. 2) Large geographical scale interconnection only has a modest economic impact. This is because in most cases, firm power can be generated/delivered locally with an appropriate mix of nearly collocated resources at a reasonable premium. 3) Long-term energy storage is not indispensable. This is because implicit storage can reduce the quantity of physical storage considerably, in most cases to less than 10 h worth of installed VRE capacity. 4) Applying thermal energy generation (e.g., combined cycle) to provide a level of supply-side flexibility with 100% renewable synthetic e-fuels, although several times more expensive than conventional fuels-powered thermal generation, is very effective with a minimal impact on the overall electricity cost bottom line. This renewable supply-side flexibility reduces the amount of VRE oversizing, reduces the amount of storage, and acts as a fail-safe insurance against any possible extreme solar/wind droughts.

These observations tend to go contrary to the current thinking underlying renewable planning and deployments (e.g., refs. [13,26–29]). Coincidently, these key enablers of least-cost, long-term ultrahigh VRE penetration are not monetizable under current energy market rules.

3.1. Inadequacy of Current VRE Market Rules

The current rules governing renewable deployments lead to VRE output maximization and curtailment avoidance. This is largely true at all scales from user-sited to utility-scale. The fundamental reason is that renewable production is valued in terms of energy produced. Since the energy value is determined by markets that have been designed for conventional dispatchable generation, renewables are valued at the margin against the conventional generation they would replace. This necessarily implies the fact that they are not valued in terms of the service they could deliver to the power grid independently of the conventional generation they must displace. The merit-order effect setting prices on energy markets and determined by the bidding of generating units[30] is perfectly suited for fuel-based dispatchable/conventional resources, but ill-suited to the physical characteristics of VREs that are controlled by seasons and the weather.

Keeping this marginal system unchanged will keep renewable in a marginal position, notwithstanding stressing the markets with harder to predict net-loads (e.g., see ref. [31]), negative net-loads, steeper ramps, imposing limits on VRE deployments, imposing unplanned reactive curtailments, and considerably reducing the value of new VRE entrants, rapidly reaching the limits of what the systems can take. Applying storage for self-consumption (small scale) and time-of-day shifting or evening peak shaving (larger scale) are attempts to stretch the marginal system to keep it going for a while longer, but these schemes are still marginal in essence and intraday in thinking, while the issue is, and the solutions must be non-marginal and 24/365.

3.2. Possible New VRE Market Rules

In view of the inadequacy of the present-day VRE market rules, it is thought that effective market rules that can catalyze the forming of 100% VRE grids should 1) value firm VRE power generation, 2) reflect the physical characteristics of the VREs, and 3) recognize that optimum firm power results from the concerted operation of several resources that cannot be treated independently (e.g., wind + storage + PV).

An effective approach would be to remunerate an optimal ensemble of resources in terms of deployed capacities needed to insure least-cost firm power generation and apportion this remuneration to each resource in the ensemble. An example of such possible remuneration is illustrated in **Figure 8** (a zoomed view of Figure 2), for the simple case of PV and storage (real and implicit): The installed capacity of the ensemble that can deliver the lowest 24/365 energy LCOE is remunerated terms of this installed capacity regardless of energy produced at any point in time. In this example, the overall remuneration is distributed between PV and storage proportionally to their contribution to this least cost configuration. The PV fraction fully accounts for the reality that part of the output will be curtailed proactively. As a critical part of this ensemble capacity remuneration scheme, PV/storage operators would let the grid operators manage both curtailment and storage charge/discharge. Note that the optimal resource blend, hence the distribution capacity remuneration between resources, could evolve over time for new systems to reflect the evolving cost balance between the considered VRE and storage technologies.

The additional inclusion of wind into the aforementioned simple remuneration system should be straightforward, with a fraction of the overall capacity remuneration commensurate to its contribution, also implying that grid operators would control operational wind curtailment as needed from a grid operation standpoint.

For flexible dispatchable resources, however, a distinct remuneration system based on energy could be maintained, since their contribution would be linked to the amount of conventional fuel or e-fuel, with an agreed-upon cost per energy unit. Note that this energy cost assumption for dispatchable was used in the FIPPS study presented earlier. Nonetheless, method for setting and thus pricing the amount of flexible resource in a VRE-dominant grid may differ from today's forecast-error-based method as used by US transmission system operator (TSO) PJM and other grid operators.

Most importantly, these new VRE/storage remuneration systems would be most effective if implemented outside of, and in parallel to existing (merit-order) energy markets for dispatchable resources, into markets analogous to existing capacity markets.[32] Incidentally, the pressures on existing merit-order energy markets would be considerably relieved by injecting firm,

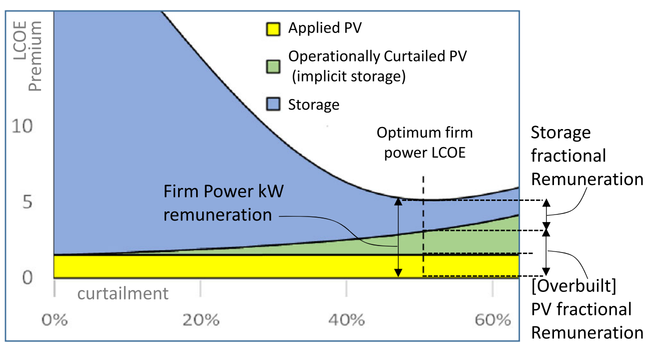

Figure 8. Example of a possible firm power remuneration system in the simplified case of PV/real/implicit storage configuration.

load-shaped VRE power into the grids instead of the current unconstrained power with its variability, peaks, ramps, and droughts.

3.3. Importance of Timing

Market rules facilitating the deployment of firm power VRE configurations should be implemented as early as possible. Indeed, the incorporation of a growing base of long-term contracted, unconstrained marginal VRE generation could make the task of future firm power solutions commensurately more expensive. In **Figure 9**, we quantitatively illustrate this possibly considerable economic impact for MISO's electrical regions no. 7 corresponding to the State of Michigan. The assumptions underlying this figure include the following: 1) a transition from the current energy generation mix to 100% VREs by 2040; 2) at 100% VRE penetration, power generation must be firm (by definition); 3) the cost of firming unconstrained VREs corresponds to the LCOE at zero curtailment in Figure 1; 4) the cost of firming optimized VRE systems corresponds to the LCOE at the sweet spot in Figure 1; 5) the growth of VREs from current level to 2040 is assumed to be exponential until 2030 and linear after that; and 6) the deployment of optimal firm VREs only begins when enabling market rules are implemented (the x-axis represents the onset of such enabling market rules).

Of course, this example represents an extreme case where long-term unconstrained generation contracts at all scales (from user-sited to utility-scale) could never be renegotiated into firm power contracts, but it illustrates the economic impact of the issue and conveys that the sooner effective firm power enabling market rules are put in place the easier and less costly the energy transition will be.

3.4. Getting from Here to There

The results presented in Section 2 show that nearly 100% VRE power grids will operate very economically at the 2040–2050 horizon when applying future technology costs. However, some of studies (e.g., those for La Reunion and China) point out that, when applying current costs, firm VRE power-generation numbers are considerably higher (35 ¢ kWh^{-1} in La Reunion, 22 ¢ kWh^{-1} in Harbin, China). For this and the timing reason discussed earlier, it would therefore be effective to subsidize firm power deployment early on, so firm deployments can start right away with firm power LCOEs commensurate with current wholesale market prices. The application of such subsidies could follow a standard business plan model (e.g., see ref. [33]): operating in the red during priming time before crossing in the black for profit-making time. Initial subsidies—representing the societal investment—would eventually be compensated for by long-lasting future gains (least-cost clean energy for generations). Note that such initial subsidies would not have to be unreasonably large and could consist in a large part of properly reapportioned existing subsidies to foster optimum firm power deployments. For instance, the US 30% federal tax credit and rapid depreciation schedules[34] amount by themselves to an effective current technology cost reduction of ≈45% for PV. Importantly, the firm power-generation numbers presented in Section 2 assume unsubsidized, before-tax prices, so for the sake of illustrative example, applying current US-sized subsidies to the aforementioned Reunion and Harbin cases would bring their firm LCOEs down to respectively 19 and 12 ¢ kWh^{-1}, i.e., well below current generation for La Reunion, and much closer to current market prices in China.

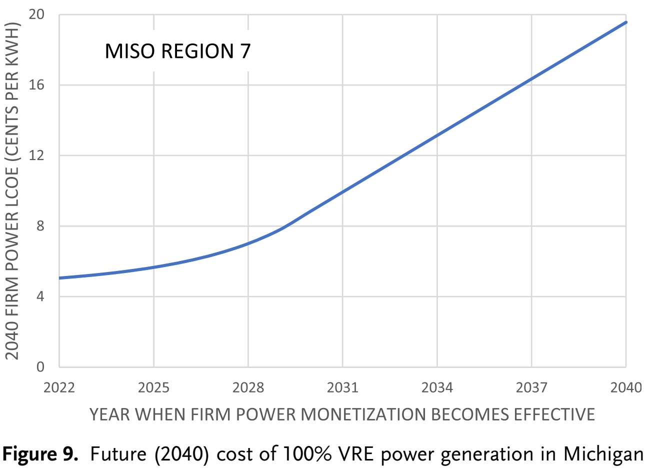

Figure 9. Future (2040) cost of 100% VRE power generation in Michigan as a function of the onset of firm power enabling market rules.

4. Conclusion

We have shown that the concept of firm power generation—transforming unconstrained run-of-the-weather VREs into load-shape generating resources by applying the optimum balance between explicit and implicit storage—is economically effective in many regions of the world. The optimum VRE/storage balance varies depending on the VRE resource characteristics and the load requirements—for instance very high latitudes, or increasingly winter peaking loads from building electrification should yield higher storage and wind balance versus solar. Overarchingly, this optimum balance is a function the relative costs of PV, wind, and storage. In all cases, significant shares of PV and/or wind need to be optimally curtailed to achieve acceptably low-firm power-generation costs. Operational VRE curtailment is therefore a prerequisite for the energy transition and lowers its costs significantly.

The case studies we presented also suggest 1) that optimally combining implicit and explicit storage can mitigate requirement for major long distance transmission buildup—we observe that firm power can be generated within smaller regions at a minor firm power premium, 2) that very long-duration storage buildup is not essential, and 3) that a small amount of thermal generation, even if powered by expensive 100% renewable synthetic fuels replacing current fossil fuels, would be very effective and provide a fail-safe insurance against any VRE supply drought.

The big question is how to achieve this optimum when starting from the existing paradigm underlying VRE deployments. Current remuneration vehicles and market regulations do not support the needed change. Continuing with current market remuneration schemes, where a large share of the VRE revenues is linked to energy production is likely to lead to increased markets stress and costly energy systems. There is a pressing need to find new solutions supporting the change to firm power generation because later the system is changed the costlier the transition would be. Some suggestions have been described in this article: in principle, the VRE/storage remuneration should be switched from energy accounting to installed capacity accounting. This implies that VRE production should not be part of the current marginal energy cost-based market, but part of new capacity markets. Regulators and grid operators should take the lead by defining optimal capacities for VREs, curtailments, and storage, and encourage their ensemble remuneration in terms of available capacity to meet demand. This would involve defining new regulations for TSOs and DSOs since they would need to operationally manage controls for VRE curtailment and storage.

Changes in the market design will—as always—induce resistance. Curtailment will lower the income for individual PV or wind producers; their optimum is at zero curtailment. PPA arrangements based on energy produced will not work without changes. It will be important to take this into account to get still enough incentives to strongly grow VREs.

Grid operators will need new regulations not easy to achieve and they will gain additional power, to be overviewed effectively.

There is a clear and imperative need to investigate and answer the questions regarding development of efficient VRE electricity market models supporting robust, firm renewable power electric grid operations.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

dispatchabilities, high penetrations, photovoltaics (PVs), power grids

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