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Long-Term Challenges for Future Electricity Markets with Distributed Energy Resources

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Abstract Recently, the academic and industrial literature has arrived to a consensus in which the electric grid evolves to a more intelligent, responsive, dynamic, flexible and adaptive system. This evolution is caused by several drivers including: decarbonization, electrified transportation, deregulation, growing electricity demand, and active consumer participation. Many of these changes will occur at the periphery of the grid; in the radial distribution system and its potentially billions of demand-side resources. Such spatially-distributed energy resources naturally require equally distributed control and electricity market design approaches to enable an increasingly active "smart grid". In that regard, this chapter serves to highlight lessons recently learned from the literature and point to three open long-term challenges facing future design of electricity markets. They are: 1.) simultaneously manage the technical & economic performance of the electricity grid 2.) span multiple operations time scales, and 3.) enable active demand side resources. For each challenge, some recent contributions are highlighted and promising directions for future work are identified.

Keywords Smart grid controls · Variable energy resources · Energy storage · Demand side resources · Electric microgrids · Power systems stakeholders · Electricity market structures

PACS PACS code1 · PACS code2 · more

Mathematics Subject Classification (2010) MSC code1 · MSC code2 · more

1 Introduction

Traditional power systems were built upon the assumption that generation was controlled by a few centralized generation facilities that were designed to serve fairly passive loads [1,2]. This assumption has since controlled the structure of the physical power grid, power systems economics as well as regulatory measures. However, several drivers have emerged to challenge this assumption.

1.1 Power Grid Evolution Drivers

The first of these drivers is decarbonization. With rising concern about CO_2 emissions, many nations have taken major steps to lower their greenhouse gas (GHG) emissions. More specifically, the European Union has vowed to reduce their GHG emissions to 40% of 1990 levels by 2030 [3, 4] and increase their renewable energy portfolio by at least 27% in 2030 [5]. Also, the Paris Agreement signatories have set national goals to combat climate change within their own capabilities [6, 7].The Renewable Portfolio Standard (RPS) and the Mandatory Green Power Option (MGPO) policies have been implemented in many US states to encourage renewable energy generation [8]. For example, the California renewable

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portfolio standard (RPS) set out to increase the percentage of renewables in the state of California to 33% by 2020 [9].

The second driver is rising electricity demand; especially in developing countries. Studies have shown that electricity demand in developing countries will continue to increase steadily by about 4% each year between 2000 and 2030; approximately tripling in that time [10–12]. In order to minimize the need for more generation capacity and its associated investment cost, techniques such as peak shaving and demand side management are imperative [13–15].

The third driver of electrified transportation also supports decarbonization efforts. Electric vehicles offer higher well-to-wheel efficiencies and have zero operational emissions if charged using renewable energy sources [16–18]. However, studies have shown that given the temporal and spatial uncertainty of electric vehicles, a large number of plug-in electric vehicles (PEVs) in one region can potentially affect different aspects of power system operations, including balancing performance, line congestion and system voltages. The grid must, therefore, evolve to accommodate charging schedules and energy needs of PEVs [19–22].

Fourth, deregulation of power markets promises greater social welfare, reduced electricity prices and improved quality of service. Traditionally, power systems have consisted of vertically integrated utilities, from generation to transmission to distribution, each having monopolies over their own geographical region [23, 24]. However, as demand for electricity increased and consumption patterns became more variable, a general interest in reducing reliance on regulation and enhancing market forces to guide investments and operations have developed [24]. In time, this vertically aligned chain became more unbundled to allow for diversified and competitive wholesale prices [24–28]. As the electric power grid continues to evolve, deregulated electricity markets must continue to develop down into the distribution system so as to support these objectives.

Lastly, deregulation measures and the rise of smart grid technologies have empowered consumers to take an active role in managing electricity consumption patterns [15, 29]. Empowered consumers cause both physical and economic changes to the electricity grid [13, 29, 30]. As a result, demand becomes more controllable and capable of responding to dynamic prices and reliability signals. Demand side management (DSM) programs offer several opportunities. These include active balancing operations in the presence of stochastic renewable energy resources, and load shifting so as to reduce new generation capacity requirements and increase the utilization of existing facilities [31]. In spite of their potential benefits, many questions remain as to how DSM programs will be implemented to realize these gains [32].

1.2 Contribution

These five drivers cause an evolution of the grid so as to become more intelligent, responsive, dynamic, flexible, and adaptive. Many of these changes will occur at the grid periphery with the integration of spatially-distributed energy resources; namely distributed generation (e.g solar PV and small-scale wind turbines, and run-of-river hydro turbines) and demand-side resources. These in turn will necessitate their associated distributed control techniques. This work adopts the terms distributed, decentralized, and centralized control as described by Farina [33]. In that regard, this chapter serves to highlight lessons recently learned from the literature. A central theme in these lessons is the need for holistic approaches that integrate multiple layers of control so as to achieve both technical as well as economic objectives [32]. The chapter also points to several open long-term challenges which require resolution to support distributed energy resources.

1.3 Outline

To that effect, the rest of the chapter is structured in three open challenges facing design of electricity markets. Section 2 discusses the need to simultaneously balance the technical and economic performance of the electric grid. Section 3 recognizes that control actions span multiple operation timescales and asserts the need for holistic assessment methods to capture potential inter-timescale coupling. Section 4 argues for active participation of demand side resources. The chapter is brought to a conclusion in Section 5.

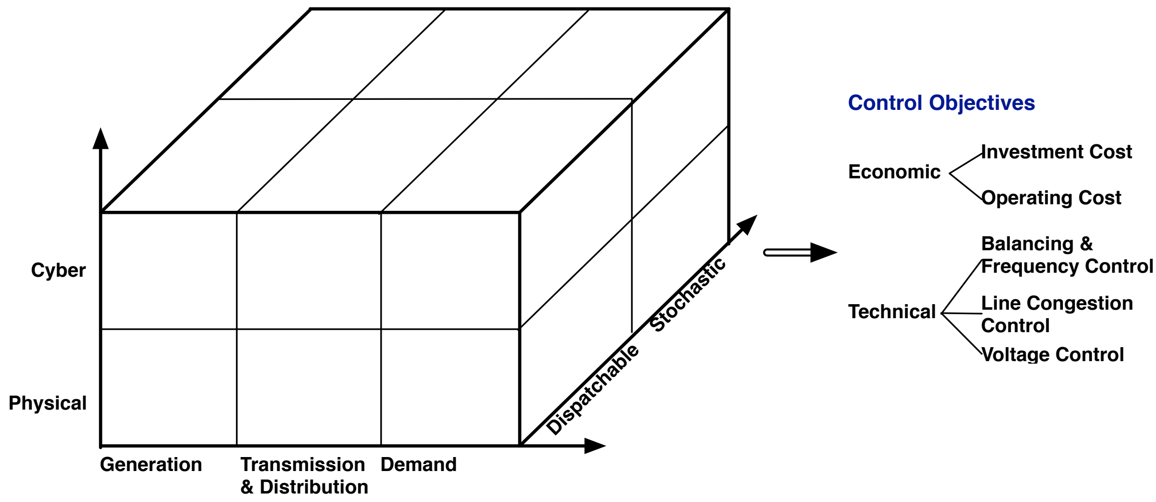

Fig. 1 The power grid is taken as a cyber-physical system composed of an energy value chain with dispatchable and stochastic elements that must fulfill certain technical and economic objectives [32]

2 Challenge I: Simultaneously Manage Technical & Economic Performance

The evolution of the electricity grid will simultaneously impact its technical and economic performance [32] in large part due to the integration of variable energy resources (VERs) and demand side resources (DSRs). Figure 1 presents this argument succinctly. The horizontal axis represents the (physical) generation and demand value chain that is connected through transmission and distribution networks. A second axis recognizes that these resources can be either stochastic or dispatchable. Finally, the vertical axis views the power grid cyber-physically with multiple layers of control decisions, automation and information technologies. Together, this system must achieve both technical and economic control objectives. The technical side includes balancing operations, line congestion prevention and voltage control, while the economic control weighs the investment and operating cost of integrated technologies against their impact on system performance. Thus, each newly added technology should provide measurable improvement to the holistic cost and technical performance. As such, grid control decisions must be assessed holistically to account for the techno-economic trade-offs of its associated layers.

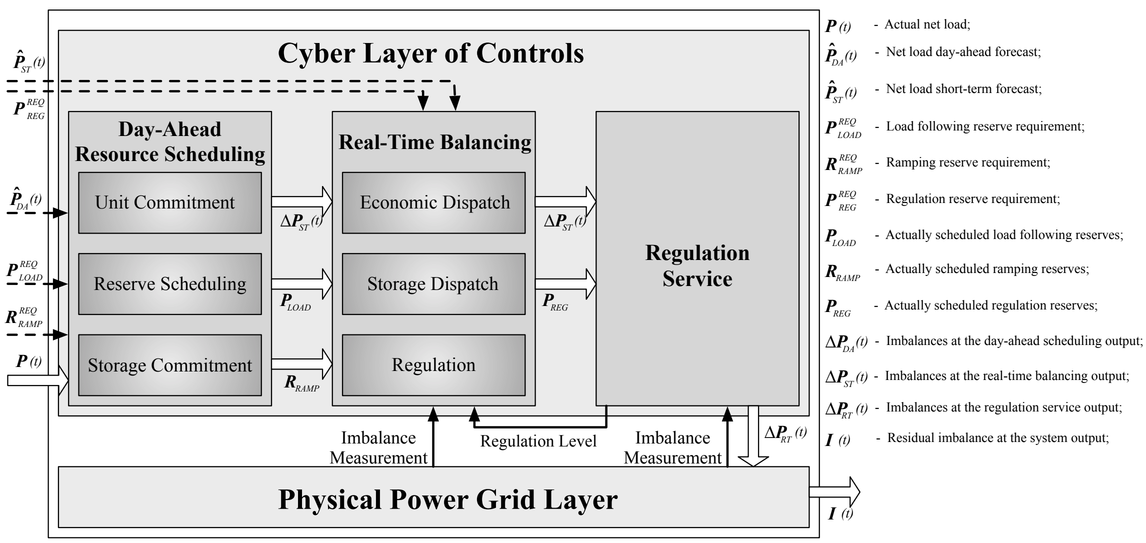

Fig. 2 A conceptual model of the power grid enterprise control simulator [34].

Most academic literature on the control of the electricity grid has primarily studied a single resource layer such as variable energy [35–37], energy storage [38–40] or demand side resources [13–15]. These studies have also focused on a single layer of power system balancing operations, such as security-constrained unit commitment (SCUC) or security-constrained economic dispatch (SCED), thus ignoring potential cost benefits of ancillary services which are drivers of overall system performance [32]. Additionally, some of these studies have been conducted on specific case studies, making generalization to other cases difficult [41–43]. Many integration studies ignore the cost of additional measurement and control technologies. Similarly, various grid codes impose regulations on renewable energy integration without providing a cost rationalization. Furthermore, most studies have been limited to statistical analyses that are yet to be validated by simulations. These statistical analyses are based upon either the net load variability or its forecast error [44, 45] despite recent closed-form analytical derivations showing the dependence on both factors [46]. Lastly, many of the grid control assumptions are based on the experience of system operators. This experience, albeit practically useful, is not guaranteed to remain valid as the grid evolves [34, 47]. Overall, these studies indicate a lack of holistic assessment methods that are necessary to successfully capture the techno-economic benefits of control decisions.

Recent works have proposed the concept of an integrated power grid enterprise control as a means of creating techno-economic synergies and studying their trade-offs [34, 47–51]. Originally, the concept of enterprise control [52, 53] was developed in the manufacturing sector out of the need for greater agility [54, 55] and flexibility [56–58] in response to increased competition, mass-customization and short product life cycles. It's essence is a single simulation that includes the physical production system connected to multiple layers of control, operations, and management at their associated time scales. Over time, a number of integrated enterprise system architectures [59, 60] were developed coalescing in the current ISA-S95 standard [53, 61]. Analogously, recent work on power grids has been proposed to update operation control center architectures [62] and integrate the associated communication architectures [63]. The recent NIST interoperability initiatives further demonstrate the trend towards integrated and holistic approaches to power grid operation [64]. Other works have also proposed decentralized approaches to generation control by combining two or more market layers to achieve economic equilibria [65–67]. One such work presents a distributed optimization-based controller that combines automatic generation control (AGC) layer with the economic dispatch (ED) to achieve economic efficiency in real-time market operations [67]. These initiatives form the foundation for further and more advanced holistic control of the grid [68–73].

In power systems, enterprise control is achieved by creating a single simulation that ties the physical power grid to several layers of control and optimization so as to study the technical and economic performance simultaneously [38, 74–80]. The enterprise control model described fully in [34] holistically addresses three control layers: resource scheduling in the form of a security-constrained unit commitment (SCUC), balancing actions in the form of a security-constrained economic dispatch (SCED) and operator manual actions, and a regulation service in the form of AGC. The enterprise control diagram is shown in Figure 2, where each consecutive layer operates at a smaller timescale, reducing the imbalances with each layer of control. This model has been used to explore the effects of timescale coupling and net load variability on balancing performance and system costs. The results show that reducing day-ahead and real-time market time steps can potentially reduce load following, ramping and regulation reserve requirements [34], which will significantly reduce the overall system cost. Additionally, the model in [34, 47] was used to conduct a series of steady-state simulations to study the impact of integrating variable energy, energy storage, and demand side resources on power system imbalances [46–48, 75, 77, 78, 81–83].

VER volatility has increased the urgency in securing resources to provide ancillary services and ensuring proper compensation for such services. To that end, recent works have explored various ways of engaging distributed energy resources and deferrable loads in the provision of ancillary services [84, 85]. The former introduces the concept of intelligent decentralized control architecture which takes advantage of the flexibility of loads to provide ancillary services during peak hours, VER volatility or various contingencies. Unlike other approaches, this work introduces intelligent deferrable loads that employ randomization and localized decision-making to minimize communication congestion. The control protocol minimizes information exchange between loads and balancing authorities by allowing local control loops at the load level. This architecture helps address the privacy concerns and communication constraints that arise from automatic control of loads used in the provision of ancillary services [84]. The work in [85] proposes a real-time charging and discharging controller for electric vehicles that permits tracking of the AGC signal whilst exploring the effects of look-ahead through model-predictive control (MPC). These two frameworks recognize the need to engage demand-side resources in market operations. It is evident that new control architectures that are able to respond quickly to real-time changes in grid operations as well as promote autonomous and decentralized decision-making must be advanced. Naturally, market structures that would enable participation of and proper compensation for such services are necessary.

Perhaps one of the greatest challenges in the techno-economic assessment of power systems with large quantities of variable energy, energy storage, and demand side resources is the quantitative determination of operating reserves. Power system energy resources are fundamentally constrained resources. Therefore, the degree to which they can provide spare capacity of various types is integral to their ability to respond to net load variability and forecast error away from scheduled set points. Such spare capacity has real economic value. And so for decades electricity markets have incentivized generators to provide several types of operating reserves; be they in normal or contingency operation [86]. Consequently, the focus of most renewable (i.e variable) energy integration studies has been on estimating the required quantities of operating reserves as the grid's energy portfolio changes [32, 87–89]. The challenge here is that the taxonomy and definition of operating reserves from one power system geography to the next varies [86]. Furthermore, this taxonomy and definition is often different from the methodological foundations found in the literature [86]. There is even significant differences in the definitions found within the literature itself [86, 90–92]. Nevertheless, the literature is converging towards a consensus view that variable energy integration requires the assessment of three types of normal operating reserves: load following, ramping, and regulation [86]. Recently, Muzhikyan et al have shown closed-form analytical derivations of the required quantities of all three types of operating reserves [46]. This work recognizes that the required quantities of operating reserves depends on endogenous characteristics of the electricity market design as well as exogeneous temporal and spatial characteristics of the net load [46, 49]. This work may prove fundamental as the methodologies of renewable energy integration studies advance to account for more holistic aspects of the grid's techno-economic operation.

As the power grid continues to evolve in the coming years, it is essential that its evolution continues to be assessed techno-economically. While the above works have developed holistic assessment methodologies for today's power systems, new technologies be they physical energy resources or control technologies will continue to be introduced. In essence, the integration of each new technology should be assessed for its overall technical and economic impact. Furthermore, these integration decisions will need to be rigorously framed so as to meet these mixed objectives and their associated trade-offs. In many cases, the technical integration question will have to be considered in the context of an evolving control architecture and stakeholder jurisdictions.

3 Challenge II: Span Multiple Operations Time Scales

As illustrated in Figure 3, power system control phenomena overlap in timescales. Traditionally, power systems literature have broken these phenomena into a hierarchical control structure namely primary, secondary, and tertiary control. Primary control ($10 - 0.1$Hz) performs dynamic stability analyses and generator output adjustments by implementation of automatic generator control (AGC), and automatic voltage regulators (AVR) [93, 94]. Secondary control, acts in the minutes timescale, and provides set points for automatic control actions for primary control. It also involves operator manual actions to ensure secure and stable performance as fast as possible. Tertiary control, which happens in tens of minutes to hours timescale, performs economic optimization to minimize the cost of generation to meet demand subject to generator capacity and line limits [93, 94]. In the past, these control actions have been studied separately under the assumption that they are independent because of their distinct timescales [32].

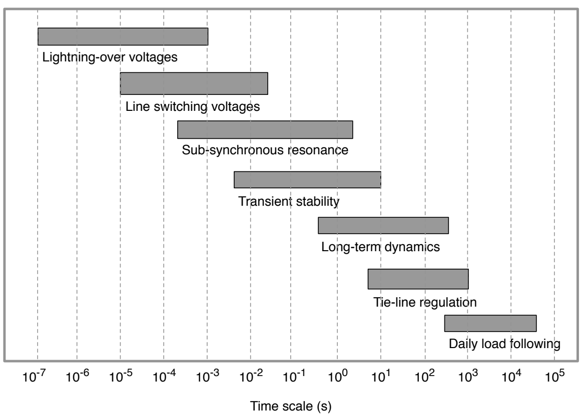

Fig. 3 Timescales of Physical Power Grid Dynamics [95].

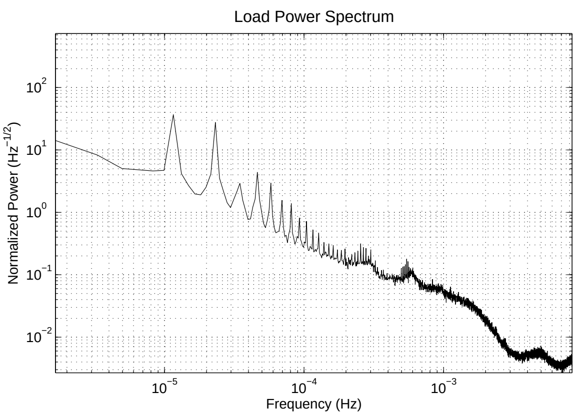

Fig. 4 Normalized power spectrum of the daily load (Data from Bonneville Power Administration) [32] [96].

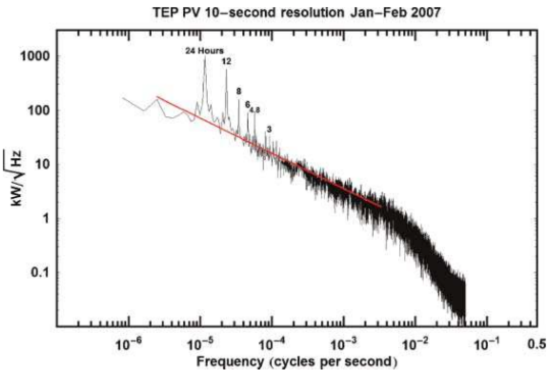

Fig. 5 Typical Power Spectrum of A Solar PV Panel [97].

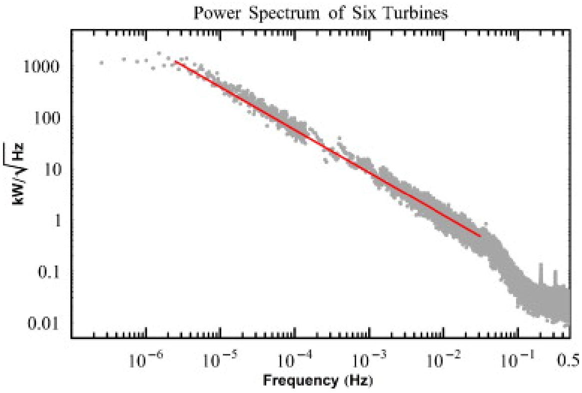

Fig. 6 Typical Power Spectrum of a Wind Turbine [98].

However, a study of the load power spectrum, shown in Figure 4, exhibits variations across a wide range of frequencies. Similarly, multi-timescale dynamics are observed in the solar photovoltaic [97] and wind [98] power spectra shown in Figures 5 and 6. The Federal Energy Regulation Committee (FERC) has responded to these findings by reducing the minimum time requirement for economic dispatch to 15 minutes [99]. Several Independent System Operators (ISO) have further reduced their dispatch time to only 5 minutes. A recent study has shown that due to VER integration, the frequency of manual operator actions with regards to curtailment has increased significantly [37]. Furthermore, it has been shown that the probability of infeasible real-time dispatches is likely to increase in the absence of exact profile distributions for stochastic resources [100]. In summary, the integration of VER introduces dynamics at all control time scales and consequently challenges the separation of primary, secondary and tertiary control phenomena.

Academic studies have illustrated the impacts of cross-timescale variability on power system balance and operating cost [38, 74, 77–80]. Lately, optimization-based approaches that seek to capture the time-scale coupling of primary, secondary, and tertiary control of power networks with controllable loads have been introduced [101–104]. In these approaches [101–104] decoupling is achieved through decentralized and distributed controllers, and a steady state equilibria of the system is illustrated. The enterprise control model presented in [34] integrates primary, secondary, and tertiary control layers into a holistic dynamic simulation to capture the inter-timescale coupling within these three layers. The simulations in [34] reveal the power grid's cross-time scale dynamic behavior.

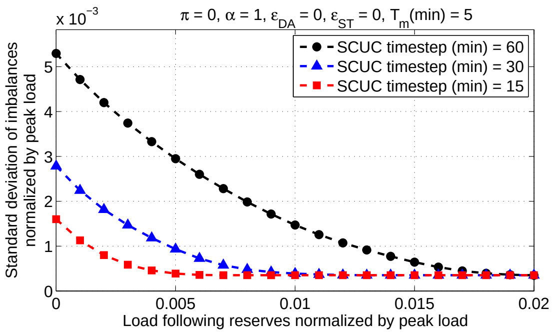

Fig. 7 The impacts of normalized load following reserves and day-ahead market time step on the normalized standard deviation of power system imbalances [47].

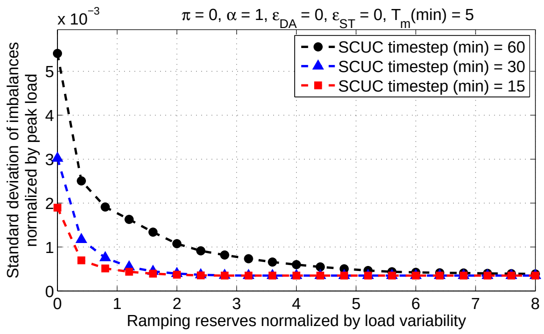

Fig. 8 The impacts of normalized ramping reserves and day-ahead market time step on the normalized standard deviation of power system imbalances [47].

Results from [47] demonstrate that system imbalances are significantly reduced when the time scale of the real-time market is reduced from 60 to 15 minutes. Additionally, the overall load-following and ramping reserve requirements are decreased as seen in Figures 7 and 8. A study of the relative merits of energy storage reserves in the balancing operations and resource layer of control shows that energy storage is effective at balancing high net-load variability and small day-ahead market time-step [48]. Figure 9 shows that integrating storage reduces the overall system imbalances and the amount of load following reserve requirements. Figure 10 illustrates that the system with a higher normalized variability and greater penetration of renewables will experience greater system imbalances [47]. An enterprise

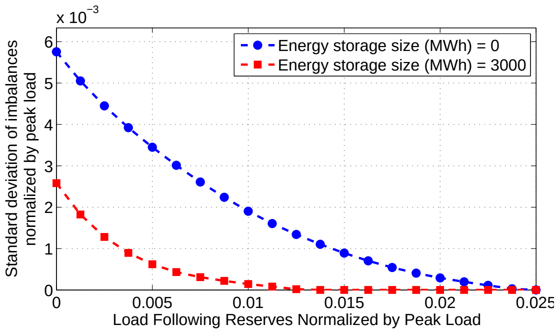

Fig. 9 The relative trade-offs of utilizing normalized load-following reserves versus energy storage on the normalized standard deviation of imbalances [48].

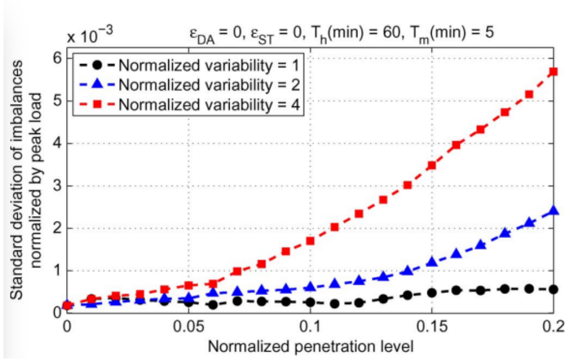

Fig. 10 Impact of VER variability on power system imbalances [47].

control model demonstrates the time scale coupling of various power system phenomena, and asserts the benefits of cross-layer coupling in the holistic assessment of techno-economic trade-offs.

Multi-timescale dynamics that are introduced by VERs and DSRs imply multilayer control approaches. The challenge with a multilayer approach is that each layer of control affects the overall life-cycle properties of the system. In this context, the dispatchability, flexibility, stability, forecastability, and resilience of the power system would need to be studied from a multilayer and not just a single layer perspective [32]. This opens up a plethora of practical questions for the emerging theory on hybrid dynamic systems [105]. The formal analysis of such systems would provide direct guidance as the power grid continues to evolve with new control architectures.

4 Challenge III: Enable Active Demand Side Resources

As mentioned in the introduction, the electricity grid has traditionally operated under the paradigm that generation exists to follow the exogenous variability in consumer demand [2]. This has had a significant impact on the design of grid infrastructure in that generation capacity must be sized for peak demand irrespective of how infrequently that capacity is required over the course of the year [14]. Distributed generation and demand side resources (DSRs), as actively controlled energy resources, have the potential to reduce the need for generation capacity expansion. Their presence, however, causes the potential for upstream flows from the power grid periphery towards the centralized transmission system. This possibility violates another long-held assumption in the power grid where the transmission system is organized in a meshed fashion while the distribution system is organized in a radial fashion allowing power to flow outwards in one direction [1, 2]. Instead, distributed generation and DSRs are set to challenge this structural assumption requiring a meshed topology on the demand side too [40].

Similarly, power systems economics in the distribution system have been structured such that electricity prices paid by consumers are independent of system conditions [23, 26]. Those consumers that connect directly to transmission system have been wholesale market price takers up until only recently. Consequently, radical changes in consumer demand that result in more expensive generation do not affect the prices paid by consumers [23,25]. Furthermore, system operators have traditionally had minimal control over the load size, often resorting to blunt solutions such as emergency load shedding, and blackouts in the most extreme situations [106]. However, as the new smart grid infrastructure is deployed, demand side resources will play a significant role in ensuring grid stability. Consumer participation favors load flexibility and peak shifting hence promoting grid reliability. Sensors, communication systems, automated metering, intelligent devices and ad specialized processors have the potential to activate demand side resources to participate in the electric system techno-economic decision making [15]. Such technologies promote consumer participation, exploit renewable energy resources, and achieve energy savings [15].

Coordinated control of the demand side is also key to the successful integration of VERs. As seen in Figure 1, the introduction of variable renewable energy resources erodes the dispatchability of the grid introduced by thermal power generation. DSM restores the grid's dispatchability thereby enhancing reliability and flexibility amidst the increased stochasticity of the generation fleet [32]. In such a case, DSR can be used to reduce demand when solar PV and wind generation unexpectedly drops, meet the associated ramp profile, and even act as an ancillary service that responds to short term frequency and voltage deviations.

Future:	Generation/Supply	Load/Demand
Well-Controlled & Dispatchable	Thermal Units: (Unsustainable cost & emissions) ↓	Demand Side Management: (Requires new control and market design) ↑
Stochastic/ Forecasted	Renewable Energy Sources: (Can cause unmanaged grid imbalances) ↑	Conventional Loads: (Growing & needs curtailment) ↓

Table 1 Demand and generation portfolio of the future grid. [32].

DSM programs take several forms but have the common feature of market-based price signals that aim to reduce electricity consumption. DSM programs include energy efficiency, demand response (DR) [40, 107, 108], and load management programs [109, 110]. Load management programs are designed to reduce consumption or shift it to off-peak hours. Peak shifting is accomplished through real-time pricing schemes whereby the energy price grows with the aggregated load for a given period [111]. Real-time pricing motivates consumers to purchase power during off peak times in order to reduce their overall energy cost [112]. The concept of real-time pricing (RTP) is, however, still very much under development. Social questions in relation to equity and access need to be considered and compensation mechanisms must address consumers with distributed generation and/or energy storage [40, 108]. Another approach to load management is direct load management (DLC). DLC is based on an agreement between utilities and consumers whereby consumers agree to let utilities remotely control the energy consumption of some of their appliances such as lighting and thermal comfort equipment [15]. Concerns about consumer privacy have, however, resulted in less participation in DLC programs [107]. Various methods such as dynamic programming [113], fuzzy logic [114], game-theoretic [107, 112], and binary particle swarm approaches [109] have been proposed for DLC and RTP programs.

More recently, the focus in literature has shifted towards studying the impact of the dynamics introduced by shifting loads, fuel price volatility, and stochastic generation on electricity prices and market stability [65, 66, 73, 115–123]. The concept of dynamic real-time markets (DRM) refers to market structures that are setup so as to enable active VER and DR participation and coordination in real-time or near real-time. In this market model, demand-side participants are price-setters rather than price-takers. To ensure real-time or near real-time coordination, extensive, flexible, and distributed communication channels capable of handling the large amounts of data generated and provide feedback in real-time are imperative. DRM approaches tend to be geared towards the overall stability of the wholesale electricity markets [116, 118, 119] and enhancing the social welfare [73, 121, 123]. While some focus solely on a single layer such as regulation [66, 121], a few DRM techniques combine multiple layers of real-time market control [73]. It is however important to note that a significant number of these approaches have neglected to define the communication layer or rather assumed a perfect communication network [65, 66, 115–123]. This results in algorithms that fail to acknowledge communication challenges such as latency [73] that affect the resiliency of DRM structures. Naturally, this emerging diversity of DSM approaches need to be rigorously assessed; be it techno-economically as in Challenge I, or across multi-time scales in Challenge II.

Considerable attention has been given DSM programs in the context of load scheduling in the day-ahead market or load shifting in the real-time energy markets. In the electric power industry, these programs are implemented through optimization algorithms that aim to minimize the overall generation cost given capacity and ramping constraints [124–126]. Demand units are represented in the wholesale energy market through curtailment service providers (CSP) who bid through independent system providers (ISO) or reliability transmission organizations (RTO) [127]. The CSP has an estimated baseline consumption–consumption without demand response–from which load reductions can be measured. Load reductions that are accepted by the bidding process are expected to commit and are compensated based on their bidding price as compared to the Locational Marginal Pricing (LMP), and retail rates [127]. Unfortunately, it has been determined that consumers are likely to artificially inflate the baseline to increase their compensation [128]. Through a systematic comparison of the academic social welfare and industrial approaches to DSM, Jiang et al. [124, 125] illustrated that inaccurate baselines in industrial DSM could potentially lead to higher systems costs, wrong dispatch levels, and unachievable social welfare. Furthermore, more recent studies have shown that inflated baselines could result in more control requirements in subsequent layers of enterprise control [34, 47, 77, 78].

One emerging concept for demand side management is called “Transactive Energy” and it is used to refer to “techniques for managing generation, consumption or flow of electric power within the electric power system through the use of economic or market based constructs while considering grid reliability constructs” [129]. Many consider the “homeostatic utility control model” proposed by Fred Schweppe in 1980 [130] as the intellectual inspiration for transactive energy (control). Transactive energy techniques can be implemented on a localized level such as residential demand response, or on a generation to consumption level. A transactive energy project by the Pacific Northwest National Laboratories (PNNL) studied the effect of two way communication between generation and distributed DSRs on energy balance, line congestion, and real-time prices [131] in the Olympic Peninsula in Washington State. This demonstration tested the GridWise transactive energy architecture on 100 homes in the region. This demo has since been extended to 5 states, 11 utilities, the Bonnerville Power Administration (BPA), two universities, and multiple companies [132]. In this demonstration, they were able to test the performance of the control architecture on various system instabilities such as power outages, wind fluctuations, and transmission incidences such as line outages [132]. Another approach, the Transactive Energy Market Information Exchange (TeMIX), applies decentralized decision-making and control techniques at the grid periphery to allow direct interaction between consumer devices and distribution grid devices [133]. This project enables smart grid services that can quickly respond to the high penetration of variable energy resources, PEVs, and energy storage. Transactive energy platforms are enhanced by the concept of dynamic pricing and tariffs [134] which provide a trading experience for electricity markets that almost mimics the stock market. Finally, transactive energy approaches eliminate the need for demand response baselines and have the potential to avoid many of the associated negative impacts [51].

As demand side management develops, rigorous assessment becomes an important challenge. In that regard, holistic assessment must be techno-economic as in Challenge I, and cross multiple time scales as in Challenge II. Furthermore, in discussing demand side management, it is important to recognize that the (economic) utility of consumed electricity is different depending on its purpose. For example, a kWh of electricity used in space heating is not equivalent to a kWh of electricity used in making silicon wafers. The later provides much greater value to its consumers; and consequently their willingness to pay for that kWh would be quite different. To that effect, modeling the economic utility of electricity consumption is of paramount importance as it represents a large trade-off with price-incentives in DSM schemes. Therefore, it will become increasingly important to revise the utility models of demand-side participants so that they more closely reflect the reality. Such an approach may quickly overwhelm the practical constraints of centralized market-designs and instead may require distributed decision-making approaches. Distributed control architectures offer a middle-ground between decentralized and centralized architectures. Like decentralized architectures they have multiple controllers acting on a physical system but add coordination between controllers so as to achieve performance similar to or equal to centralized architectures [33]. Finally, it is important to recognize that while market-based approaches may result in economic efficiency, they may not guarantee physical life cycle properties. Approaches that too closely resemble the stock market must recognize that financial markets do not necessarily exhibit stable behavior. Consequently, DSM programs find the appropriate balance of physical as well as economic signals.

5 Conclusion and Future Work

In conclusion, this work identified several long-term drivers which together cause the introduction of distributed energy resources at the grid’s periphery. This, in turn, poses significant long-term challenges. Power grid assessment must be increasingly holistic considering technical and economic trade-offs as well as variations that span multiple layers. Such techniques demand multi-layer approaches that represent hybrid dynamic phenomena which are difficult to design formally. Demand side resources (DSRs) are also expected to play a significant role in promoting grid reliability. Utility modeling as well as multi-layered, scalable, and distributed control algorithms will enhance the integration of DSRs. Moving forward, power systems design and operation must adapt to the changing needs and interests of new and old stakeholders; be they in the electric power grid or in interdependent infrastructures. Finally, the newly evolved “smart grid” must ultimately demonstrate resilient self-healing operation which will likely be enabled by distributed control and/or multi-agent systems. This work has highlighted some of the recent contributions with respect to these areas and identified areas where many challenges still remain.

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