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Distributed Control for Distributed Energy Resources: Long-Term Challenges & Lessons Learned

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ABSTRACT Recently, the academic and industrial literature has arrived at 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 paper serves to highlight lessons recently learned from the literature and point to seven open long-term challenges facing the future design of electricity markets. They are: 1.) simultaneously manage the technical & economic performance of the electricity grid 2.) span multiple operations time scales, 3.) enable active demand side resources, 4.) activate the power grid periphery, 5.) promote synergies with interdependent infrastructures, 6.) respect organizational jurisdictions, and 7.) promote resilient self-healing operation. For each challenge, some recent contributions are highlighted and promising directions for future work are identified.

INDEX TERMS Smart grid controls, Variable energy resources, Energy storage, Demand side resources, Electric microgrids, Power systems stakeholders, Electricity market structures

I. 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.

A. POWER GRID EVOLUTION DRIVERS

The first of these drivers is decarbonization. The past few decades have been marked by concern about rising CO_2 emissions. Furthermore, energy importing nations have sought to wean themselves off of coal, oil and natural gas. As a result, many nations have promoted the adoption of local renewable energy sources in order to improve their energy security and 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 instated in many US states to encourage renewable energy generation. For example, the California RPS set out to increase the percentage of renewables in the state to 33% by 2020 and to 50% by 2030 [8]. Of course these measures have led to a significant growth in the amount of variable energy resources (VERs) in the grid with photovoltaic (PV) solar growing by as much as 50% in 2016 alone [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], [11]. 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 [12]–[14].

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 [15]–[17]. 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 [18]–[21].

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 [22], [23]. 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 [23]. In time, this vertically aligned chain became more unbundled to allow for diversified and competitive wholesale prices [23]–[27]. 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 [14], [28]. Empowered consumers cause both physical and economic changes to the electricity grid [12], [28], [29]. 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 [30]. In spite of their potential benefits, many questions remain as to how DSM programs will be implemented to realize these gains [31].

B. CONTRIBUTION

These five drivers cause an evolution of the grid to one that is 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 [32]. In that regard, this paper 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 [31]. The paper also points to several open long-term challenges which require resolution to support distributed energy resources.

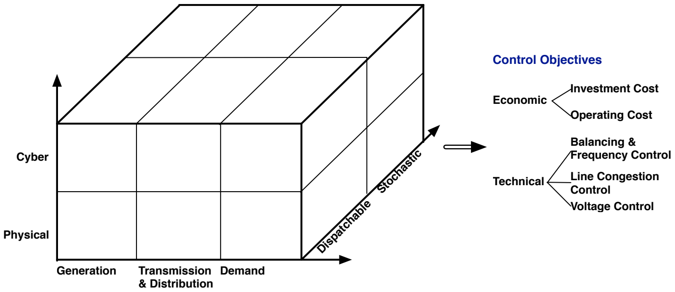


FIGURE 1: The power grid is taken as a cyber-physical system composed of an energy value chain with dispatchable and stochastic elements that must fulfill certain technical and economic objectives "Reproduced from [31] ©Elsevier Apr 1, 2016, used with permission".

C. OUTLINE

To that effect, the rest of the paper is structured in seven open challenges. Section II discusses the need to simultaneously balance the technical and economic performance of the electric grid. Section III recognizes that control actions span multiple operation timescales and asserts the need for holistic assessment methods to capture potential inter-timescale coupling. Section IV argues for active demand side resources, and Section V addresses the need to activate the power grid at the periphery. Section VI discusses the need to promote synergies with interdependent infrastructures, such as electrified transportation, natural gas, district heating and cooling, etc. Section VII addresses the organizational jurisdictions found with the evolving smart grid. Section VIII emphasizes the importance of resilient self-healing operation for the electricity grid. Finally, the paper is brought to a conclusion in Section IX.

II. CHALLENGE I: SIMULTANEOUSLY MANAGE TECHNICAL & ECONOMIC PERFORMANCE

The evolution of the electricity grid will simultaneously impact its technical and economic performance [31] 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. Awareness of the stochastic and dispatchable nature of energy resources is imperative as it provides grid operators the flexibility they require to ensure

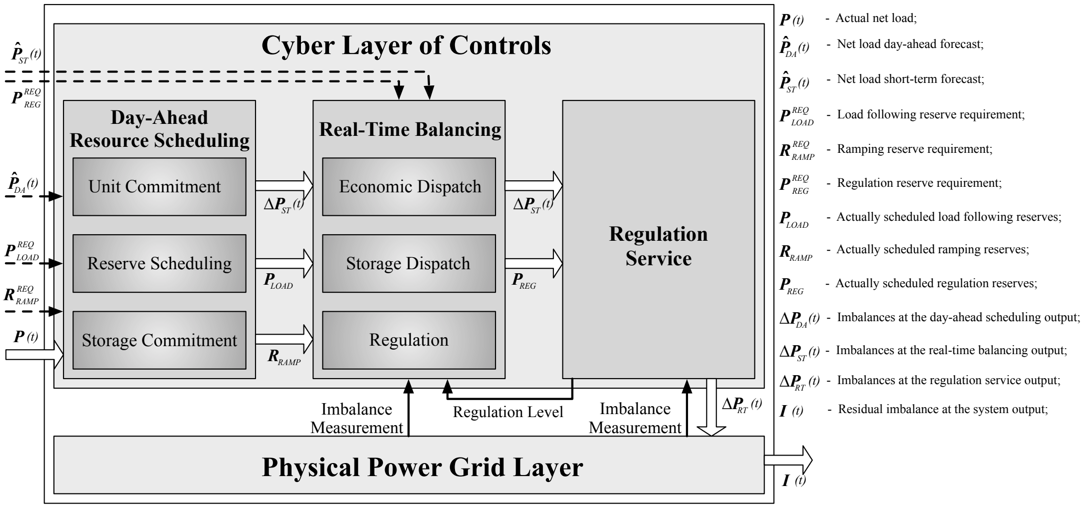


FIGURE 2: A conceptual model of the power grid enterprise control simulator "Adapted from [33] ©IEEE Apr 1, 2015, used with permission".

system stability and reliability especially as more VERs and DSRs are added to the grid. 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 must weigh 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.

Most academic literature on the control of the electricity grid has primarily studied a single resource such as variable energy [34]–[36], energy storage [37]–[39] or demand side resources [12]–[14]. 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 [31]. Additionally, some of these studies have been conducted on specific case studies, making generalization to other cases difficult [40]–[42]. Many integration studies ignore the cost of additional measurement and control technologies [35], [43]–[45]. Similarly, various grid codes impose regulations on renewable energy integration without providing a cost rationalization [34], [35]. 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 [46], [47] despite recent closed-form analytical derivations showing the dependence on both factors [48]. 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 [33], [49]. 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 [33], [49]–[53]. Originally, the concept of enterprise control [54], [55] was developed in the manufacturing sector out of the need for greater agility [56], [57] and flexibility [58]–[60] 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 [61], [62] were developed coalescing in the current ISA-S95 standard [55], [63]. Analogously, recent work on power grids has been proposed to update operation control center architectures [64] and integrate the associated communication architectures [65]. The recent NIST interoperability initiatives further demonstrate the trend towards integrated and holistic approaches to power grid operation [66]. Other works have also proposed decentralized approaches to generation control by combining two or more market layers to achieve economic equilibria [67]–[69]. 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 [69]. These initiatives form the foundation for further and more advanced holistic control of the grid [70]–[75].

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 [37],

[76]–[82]. The enterprise control model described fully in [33] 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 [33], which will significantly reduce the overall system cost. Additionally, the model in [33], [49] 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 [48]–[50], [77], [79], [80], [83]–[85]. More recently, the power grid enterprise control simulation has been used to complete a real-life renewable energy integration study for the region controlled by ISO New England [86], [87].

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 [88], [89]. 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 other 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 [88]. The work in [89] 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. Other works also show that optimal sizing and placement of distributed generation and capacitor banks can largely improve the efficiency of supply and minimize system losses [90]. From recent literature, it is obvious 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 [91]. 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 [31], [92]–[94]. The challenge here is that the taxonomy and definition of operating reserves from one power system geography to the next varies [91]. Furthermore, this taxonomy and definition is often different from the methodological foundations found in the literature [91]. There is even significant differences in the definitions found within the literature itself [91], [95]–[97]. 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 [91]. Recently, Muzhikyan et al have shown closed-form analytical derivations of the required quantities of all three types of operating reserves [48]. 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 [48], [51]. 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 system, 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.

III. 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) [98], [99]. 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 [98], [99]. In the past, these control actions have been studied separately under the assumption that they are independent because of their distinct timescales [31].

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 [100] and wind [101] power spectra shown in Figures 5 and 6. The Federal Energy Regulatory Commission (FERC) has responded to these findings by reducing the minimum time requirement for economic dispatch to 15 minutes [102]. 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 [36]. 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 [103]. 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 [37], [76], [79]–[82]. 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 [104]–[107]. In these approaches [104]–[107] decoupling is achieved through decentralized and distributed controllers, and a steady state equilibria of the system is illustrated. The enterprise control model presented in [33] 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 [33] reveal the power grid's cross-time scale dynamic behavior.

Results from [49] 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 [50]. 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 [49]. An enterprise 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 [31]. This opens up a plethora of practical questions for the emerging theory on hybrid dynamic systems [108]. The formal analysis of such systems would provide direct guidance as the power grid continues to evolve with new control architectures.

IV. 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 [13]. Distributed generation and 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 [39].

Similarly, power systems economics in the distribution system have been structured such that electricity prices paid by consumers are independent of system conditions [22], [25]. 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 [22], [24]. 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 [109]. 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 specialized processors have

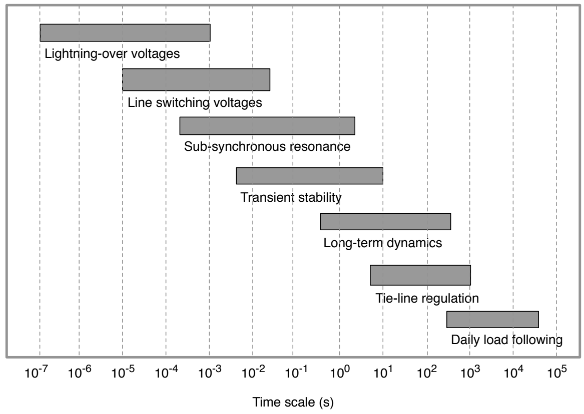


FIGURE 3: Timescales of Physical Power Grid Dynamics "Reproduced from [31] ©Elsevier Apr 1, 2016, used with permission".

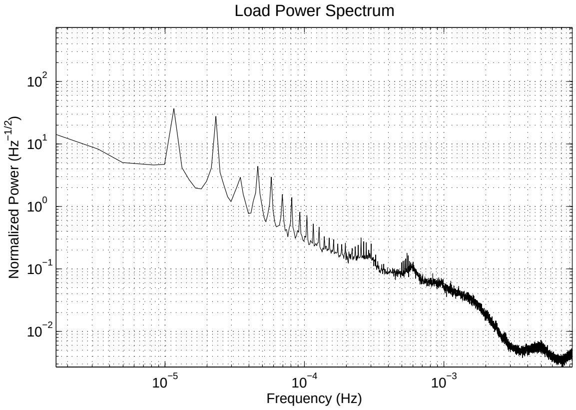


FIGURE 4: Normalized power spectrum of the daily load (Data from Bonneville Power Administration) "Reproduced from [31] ©Elsevier Apr 1, 2016, used with permission".

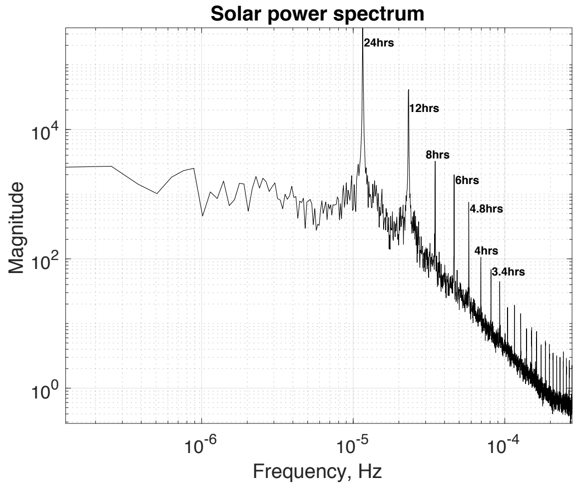


FIGURE 5: Typical Power Spectrum of A Solar PV Panel.

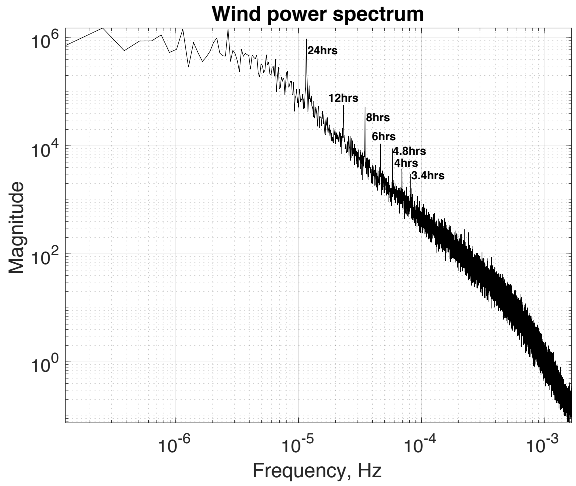


FIGURE 6: Typical Power Spectrum of a Wind Turbine.

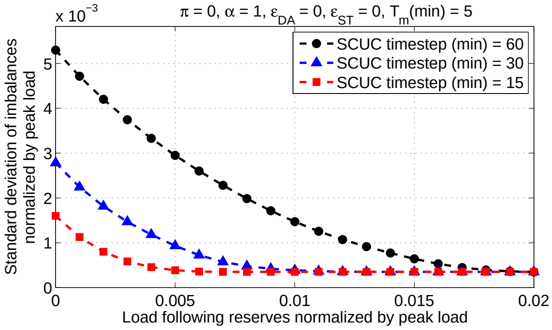


FIGURE 7: The impacts of normalized load following reserves and day-ahead market time step on the normalized standard deviation of power system imbalances "Reproduced from [49] ©IEEE Apr 1, 2015, used with permission".

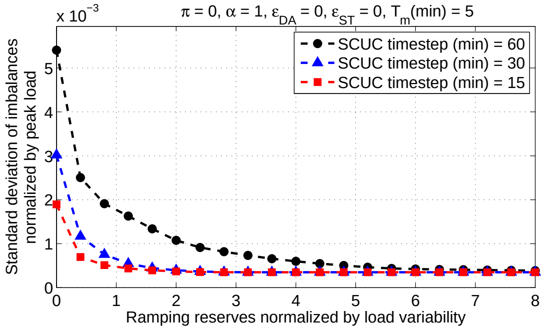


FIGURE 8: The impacts of normalized ramping reserves and day-ahead market time step on the normalized standard deviation of power system imbalances "Reproduced from [49] ©IEEE Apr 1, 2015, used with permission".

the potential to activate demand side resources to participate in the electric system techno-economic decision making [14]. Such technologies promote consumer participation, exploit renewable energy resources, and achieve energy savings [14].

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

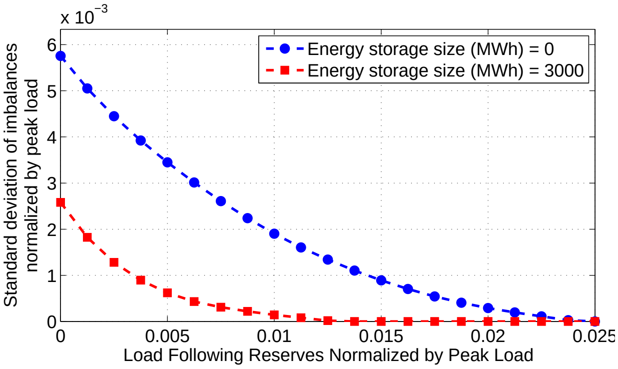


FIGURE 9: The relative trade-offs of utilizing normalized load-following reserves versus energy storage on the normalized standard deviation of imbalances "Reproduced from [50] ©Elsevier Jan 1, 2016, used with permission".

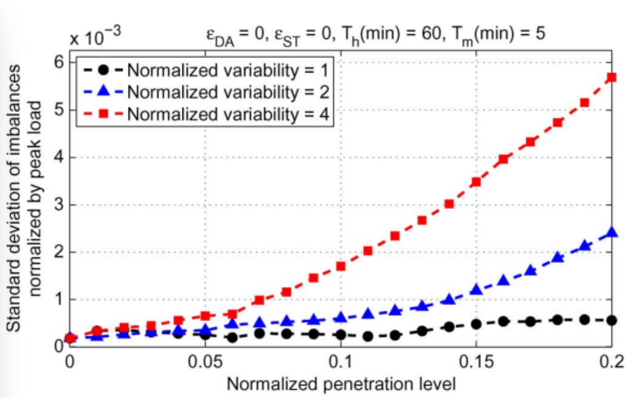
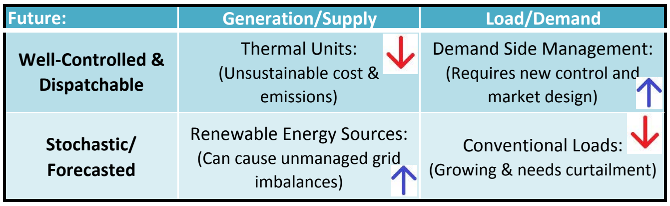


FIGURE 10: Impact of VER variability on power system imbalances "Reproduced from [49] ©IEEE Apr 1, 2015, used with permission".

stochasticity of the generation fleet [31]. In such a case, DSR can be used to reduce demand when solar PV and wind generation unexpectedly drops, to 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 "Reproduced from [31] ©Elsevier Apr 1, 2016, used with permission".

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) [39], [110], [111], and load management programs [112], [113]. 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 [114]. Real-time pricing motivates consumers to purchase power during off peak times in order to reduce their overall energy cost [115]. The concept of real-time pricing (RTP) is, however, still very much under development. Social questions in relation to equity and access still need to be considered and compensation mechanisms must take into account consumers with distributed generation and/or energy storage [39], [111]. Another approach to load management is direct load control (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 [14]. Concerns about consumer privacy have, however, resulted in less participation in DLC programs [110]. Various methods such as probabilistic assessment [116], fuzzy stochastic control [117], game-theoretic [110], [115], and binary particle swarm approaches [112] have been proposed for DLC, RTP programs as well as for optimal power systems control.

More recently, the focus in literature has shifted towards studying the impact of the dynamics introduced by shifting loads, better forecasting techniques, fuel price volatility, and stochastic generation on electricity prices and market stability [67], [68], [75], [118]–[127]. 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 [119], [121], [122] and enhancing the social welfare [75], [124], [126]. While some focus solely on a single layer such as regulation [68], [124], a few DRM techniques combine multiple layers of real-time market control [75]. 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 [67], [68], [118]–[126]. This results in algorithms that fail to acknowledge communication challenges such as latency [75] 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 as in Challenge II.

Considerable attention has been given to 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 [128]–

[130]. 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) [131]. 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 [131]. Unfortunately, it has been determined that consumers are likely to artificially inflate the baseline to increase their compensation [132]. Through a systematic comparison of the academic social welfare and industrial approaches to DSM, Jiang et al. [128], [129] 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 [33], [49], [79], [80].

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" [133]. Many consider the "homeostatic utility control model" proposed by Fred Schweppe in 1980 [134] 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 [135] 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 [136]. 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 [136]. 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 [137]. 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, RTP, time-of-use pricing (TOU), and various pricing tariffs [138] 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 [53].

	Generation	Demand
Dispatchability	• Low – Wind, Solar, Run of River Hydro • Medium – Hydro, Solar CSP • High – Thermal Units	• Low -- Lighting • Medium – HVAC, Commercial buildings • High -- Industrial production
Flexibility/ Ramping (Thermal Energy to Work ratio)	• Low – Nuclear & Coal • Medium – CCGT • High – Hydro, GT, IC	• Low – Chemical, petrochemical, metals • Medium – HVAC, Commercial Buildings, Refrigerators • High – Heaters, kettles, EV battery
Forecastability	• Low – Solar PV • Medium – Wind generation • High – All dispatchable generation	• Low – N/A • Medium – lighting, cooking, hair drying • High – Scheduled Industrial Production
Stability	• Synchronous Generators w/ AVR • Wind Induction Generators w/ low voltage ride through • Solar PV w/ power electronics	• Synchronous motors in HVAC applications • Induction Motor appliances with active harmonic control • EV's w/ power electronic based control
Resilience	• Recovery from generator faults • Intentional switching of generators	• Recovery from load shedding • Intentional switching of loads
	• Intentional and Unintentional Switching of Lines	

TABLE 2: Power grid enterprise control to enable holistic dynamic properties in demand and generation [31].

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 [32]. 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 must find the appropriate balance of physical as well as economic signals.

V. CHALLENGE IV: ACTIVATE THE POWER GRID PERIPHERY

As mentioned in Section IV, the growing penetration of variable energy resources erodes the grid's dispatchability which is only recovered by DSRs. In most cases, these devices are often found at the grid's periphery. Smart grid technologies otherwise known as "the internet of things" are set to cause an explosion in the number of control points on the demand side [13], [14], [109]. Much like the leaves of a tree, these devices are numerous and distributed both spatially and functionally. As such, controlling these devices requires significant scalability and distribution. Furthermore, control architectures must holistically enable dynamic properties such as forecastability, dispatchablity, flexibility, stability and resilience, at the grid periphery [31]. Table 2 shows that demand and generation play a balanced role with regards to these dynamic control properties. Coordinating DSRs at the grid periphery is, therefore, of paramount importance to ensure these dynamic properties.

Smart grid technologies cause the electricity grid to evolve from a more centrally structured system to a large decentralized cyber-physical one. Millions or even billions of autonomous, interacting components at the grid's periphery have to be monitored and coordinated in real-time or near real-time [139]. The ongoing consensus in academic literature is that decentralized control architectures with distributed decision making would provide more flexibility, scalability and extensibility than centralized solutions [140]. Solutions that implement multi-criteria optimizations to ensure alignment between local and global system objectives are especially necessary to guarantee grid interoperability [140] despite decentralization [141]. Multi-agent systems (MAS) have been proposed as a key enabler of highly decentralized decision making [142]–[147], and their effectiveness at addressing decentralized systems has been demonstrated in several application domains [148]–[150].

MAS architectures have several key features including modularity, scalability, reconfigurability, and robustness that when taken together enable the realization of decentralized systems. The modularity of these systems is particularly significant to the integration of demand side resources as new elements can be added without the need to stop, reconfigure, or reprogram [140]. MAS systems enable semi-autonomous behavior by agents that ensures stability and resiliency as the loss of an agent does not impact the entire system. As a result of these characteristics, smart grid components can be monitored and controlled without compromising the stability of the entire system [140]. For example, the MAS architecture developed in [145] uses a reconfigurable MATLAB dynamic stability simulator coupled to JADE, a Java based mobile agent platform, to study the coordination of multiple microgrids and asserts the ability of MAS to maintain the resiliency of an infrastructure with actively switching microgrids. [151] observes that multi-agent architectures designed for power systems control must enable changes in structures as well as dynamic properties to assure holistic techno-economic assessment.

While MAS architectures appear as the leading technology to achieve distributed control behavior at the grid periphery, their adoption is ultimately governed by the evolution of the electricity infrastructure. This architecture can only be developed to the extent that smart grids devices are adopted in the electricity grid. Unfortunately, the physical grid infrastructure is still not ready to fully accommodate smart grid technologies. Physical devices integrated into the grid must adhere to the local grid code and be supported by price signals that incentivize demand-side behavior. Additionally, MAS must successfully demonstrate comparable global behavior as centralized solutions. Agents must be able to respond to stochastic events in the grid and coordinate control decisions in real-time. In that regard, decentralized algorithms must be cost-optimal while maintaining physical stability and synchronization [152]. This would require high level as well as low level coordination of agent groups [109] in real-time. Control structures must account for both time scale variations and any associated delays. Networked communication and its associated latencies [153]–[156] exacerbate this challenge given the large amounts of data and devices involved. Furthermore, algorithms must converge quickly and arrive at consensus solutions [155]. These factors emphasize the need for scalable distributed algorithms that spread across multiple control layers as well as timescales.

VI. CHALLENGE V: PROMOTE SYNERGIES IN INTERDEPENDENT INFRASTRUCTURES

The evolution of the electric power grid will bring about more stringent techno-economic performance requirements. As previously discussed in Section IV, demand side resources must recognize not just the price incentives that may arise from demand side management programs but also the utility gained from the consumption of electricity. Meanwhile, on the supply side, power generation will have to ensure that they are responsive to a grid that operates both dynamically and flexibly. Said differently, the evolved electric power grid will no longer be operated in isolation and instead must account for the infrastructures and services to which it connects [157]. These include electrified transportation [18], [19], [158], [159], energy-water nexus [160]–[166], district heating and cooling (DHC) [167]–[169], industrial energy management [170]–[172], and natural gas supply [173], [174].

First, electrified transportation has emerged as a key infrastructure for efficiency improvement and decarbonization of the transportation system [17], [175]. However, the short ranges and long charging times lead to congestion and increased wait time at charging stations. Most works have attempted to mitigate the challenges of stationary charging through advanced control such as coordinated charging [176]–[178], vehicle-to-grid stabilization [179]–[184], and charging queue management [185], [186]. Some studies have shown that both seasonal and traffic conditions affect the charging rates and power grid performance thus strengthening the need for a holistic approach [187]. These works have acknowledged the coupling of the two networks–transportation and electricity–and have emphasized the need to holistically assess the impacts of electrified transportation.

To that effect, several recent works have sought to study the two infrastructures together as a transportation-electricity nexus (TEN) enhanced by an Intelligent Transportation Energy Systems that maintain temporal and spatial awareness for drivers, traffic controllers, as well as power system operators [18], [158], [159]. An earlier implementation of a TEN was a Berlin-based study implemented on a multi-agent transportation simulator (MATSim) [19]. Later, a full scale study for the the city of Abu Dhabi was conducted using the Clean Mobility Simulator [18]. The former demonstrated a reduction in vehicle induced peak load to less than 17% of its original value through the use of a smart scheduler and a behavioral balance that incorporates individual, traffic and power system behaviors. The latter work takes a holistic approach to study the relative impacts of the nexus and asserts the significance of holistic assessment methods in mitigating the negative effects of electric vehicle integration in either infrastructure. Farid [159] signaled that an intelligent transportation energy system can serve to modify vehicle dispatch and route choice and manage queues and wait times. In general, [18], [158], [159], [188] have demonstrated that an intelligent transportation-energy nexus leads to savings in investment, operation, and time for individual EV owners; thus strengthening the case for a TEN.

Second, the demand and supply of electricity and water are inherently coupled. It is estimated that up to 18% [160]of electricity goes into water and wastewater treatment and transportation while in the United States, 45% of water withdrawals go into cooling thermal power plants [189]. As the population grows, the demand for both electricity and water is expected to grow as well. This growth is further complicated by effects of climate change that have led to a distortion of available freshwater reserves [165]. Due to this coupling, scarcity or losses in either system are bound to affect both infrastructures [165]; motivating the need for synergistic savings. Consequently, a holistic system-of-systems approach is necessary to capture the techno-economic benefits of this nexus.

Several works have recognized the need to develop synergies for the energy-water-nexus [161]–[164], [190]–[192]. One work found that renewable energy integration reduces CO_2 emissions as well as water withdrawals [193]. Another showed that water storage in the potable water distribution can alleviate balancing constraints in the electric power grid [194]. Such synergies may be integrated within an engineering systems methodology to study the nexus holistically [165], [195], [196]. A SysML reference architecture for the energy water nexus allows the study of couplings between the two systems and provides further opportunities in improving the holistic assessment of the nexus [165]. Later, a bond graph model [195] showed the flows of matter and energy between the electricity, water, and wastewater systems as outlined in the reference architecture [165]. This work lays out a mathematical framework for integrating disparate parts of the energy-water nexus [195]. The nexus could potentially allow process shifting whereby energy-intensive water supply options are shifted to periods of low electricity demand, and water could be used as a storage element to aid in smoothing the demand curve [165], [194]. Future work in this area might explore multi-agent system approaches to promote decentralized, semi-autonomous decision-making for the nexus.

Third, production systems consume up to 33% of the electricity produced [197]. These systems are also responsible for about 36% of CO_2 emissions [198]. As concerns about global emissions continue to grow, most industrial facilities are adopting energy efficient practices in their operations [199]–[202]. Going further, dynamic energy management can be viewed as a form of demand side management for grid-balancing applications [170]. As seen in Table 2, production facilities bear great potential for demand side management as they serve as controllable loads to help counteract the intermittency of VERs [170]–[172]. In return for their participation in DSM, industrial facilities might require certain services such as high quality electricity [170]. This implies an interdependency between the electricity and production system.

Fourth, district heating and cooling (DHC) systems compete with the electric power grid with respect to these two critical functions. A natural question is not just when to use one system versus the other but also how they may be co-operated. In some systems, the cogeneration of heat and power further couple these thermal and electrical energy systems [167]–[169]. Furthermore, the utilization of heat from surplus industrial sources, waste-to-energy facilities, geothermal wells, and solar thermal plants has the potential to significantly enhance energy efficiency measures. Considering the energy balance in both infrastructures simultaneously can also minimize overall emissions [168].

Lastly, on the fuel supply side, natural gas resources play a key role in stabilizing the electricity grid [173], [174]. Gas turbines provide fast ramping capabilities to help manage the intermittency of VERs. Additionally, gas fired generating plants are also less carbon-intensive than coal and oil fired facilities. The natural gas supply, however, is limited by pipeline capacity, relatively fixed price contracts, and priority accorded to household heating [174]. These factors necessitate the integrated study of natural gas and power systems networks particularly as the latter evolves to a more dynamic operating mode.

These works demonstrate the growing interdependence of these infrastructures. The design, planning and operation of these infrastructures especially in the presence of potentially conflicting and/or competing stakeholders is a major and relatively open challenge. In this regard, it is important to recognize that many infrastructures (namely transportation, production supply chains, and water) have the potential to serve as DSRs and therefore contribute to the associated challenge in Section IV. For example, industrial facilities have long provided emergency demand response [171], [172] while water storage [194], [203] has helped alleviate the intermittency of VERs. These grid supporting activities exist on the supply side as well. For instance, natural gas and oil supply power plants, water feeds both thermal power and hydro plants, and wastewater treatment plants can produce

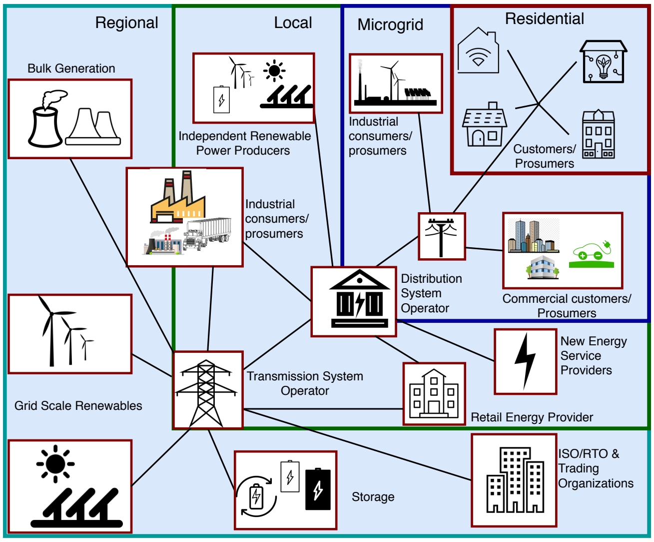


FIGURE 11: Organizational jurisdictions of various power system's stakeholders. (Adapted from Grid Wise Architecture Council) [208].

electricity from the biogas that they produce. Meanwhile, it is equally important to recognize that these infrastructures are energy carriers in their own right and have their own performance goals. Natural gas, coal, oil, transportation, water and DHC, can all be viewed energetically to support new multi-modal energy management solutions. In light of these interdependencies, the conventional power grid architecture needs to be revisited as it evolves towards a "smart grid" with new integrated decisions in both planning and operation.

VII. CHALLENGE VI: RESPECT ORGANIZATIONAL JURISDICTIONS

The development of a new smart grid architecture naturally brings about new jurisdictional challenges for electric power stakeholders. Within this new architecture, the role of the utility at the heart of the distribution system will evolve as 1) more demand side resources become active and 2) the distribution system adopts market based structures like distribution system operators (DSOs) [204]–[206] and transactive energy [133], [135], [137], [138], [207].

The introduction of distributed energy resources (be they demand or generation) incentivizes new market participants and multilateral relationships between residences, businesses, microgrids, and distribution system operators. These relationships are summarized in Figure 11. To begin with, transparent energy prices through transactive energy platforms enable consumers of all sizes to participate in producing, buying, and selling electricity. Due to distributed generation (DG) some consumers may wish to become prosumers, not just as DSR participants but also as microgrids.

At the residential layer, consumers will participate in demand response programs to reduce overall energy costs as they buy energy from multiple sources based on cost, value, and demand. At the household level, DSRs will impose further control demands such as consumer privacy which must be addressed within control infrastructures. The second layer of stakeholder jurisdiction is characterized by authorities whose responsibility is to promote advanced automation and control–from substations and wires to homes, buildings, cars, and appliances. This layer also incorporates active and flexible microgrids that enhance local and regional resilience. The third layer of stakeholder jurisdiction is composed of independent power producers, industrial consumers and producers, and retail energy providers. This layer provides newer and wider data exchange and unlocks opportunities for new services to consumers at the distribution layer. Finally, the fourth layer includes all grid scale energy producers (renewable and traditional), storage, and RTO/ISO trading organizations. Coordinated and increased interoperability between these jurisdictional layers is highly necessary to prevent conflicts of interest. The inter-connectivity of these stakeholder jurisdictions motivates the need for greater clarity in existing power grid stakeholders structure in the presence of quickly growing roles and responsibilities.

As seen in Figure 11, power systems stakeholder roles and jurisdictions are highly interconnected. Neither can function properly without the other. Hence a lack of coordination at any individual layer could potentially pose efficiency and reliability challenges at the grid level. The control infrastructures that support power systems decision-making must always respect these legal boundaries. Naturally, this imposes more constraints on the degree of distribution/centralization of control infrastructures as well as the nature and quantities of the data that can be exchanged within these layers.

Finally, the engagement of other infrastructures in the grid's energy management system brings about additional jurisdictional challenges. The water, transportation, and industrial supply chain system all have the potential to enhance the electricity grid operation as mentioned in Section VI. Their operational entities and stakeholders are new to the grid, hence control solutions must respect these jurisdictional boundaries as well. These factors emphasize the importance of holistic enterprise control in addressing interoperability of various electric grid jurisdictions.

VIII. CHALLENGE VII: PROMOTE RESILIENT SELF-HEALING OPERATION

The successful integration of VERs and DSRs requires the grid to accept actively and readily switching microgrids. The transformation of the grid from one that is topologically fixed to one that is composed of actively switching microgrids suggests the need for system resiliency. Resiliency, is a property where healthy regions of the grid continue to function while disrupted and perturbed regions return to normal operation [70], [71], [73], [209]. The ability of microgrids to continue to operate while connected or disconnected from the main power grid [38], [210]–[212] is significant to achieving system resiliency. However, DSRs and VERs have introduced numerous control points that span multiple timescales in microgrids [109]. These control points require holistic enterprise control assessment where all layers of control are analyzed [31]. Naturally, control and coordination of microgrids has followed the hierarchical primary, secondary, and tertiary control of the conventional power grid with a few modifications suited to the unique features of microgrids [38], [210]–[212]. Unfortunately, most of these studies are often centralized and fail to account for the resilient system behavior when microgrids disconnect from and reconnect to the grid [213]. Additionally, these studies have neglected interactions between multiple microgrids [214]. There is a need for distributed and resilient control algorithms to ensure the stability of actively switching microgrids.

Recent works have prescribed resilient control systems built upon the concept of open, distributed, and interoperable architectures [215]–[218] that are based on a cyber-physical power grid structure [213]. Multi-agent systems have also been suggested as possible architectures for resilient self healing behaviour [216], [217]. An analysis of multi-agent system design principles for resilient self-healing behavior is provided based on axiomatic design of large flexible engineering systems. This study also carries out an assessment of current MAS implementations to determine compliance with these design principles. Only one MAS platform [145], [219] demonstrated complete compliance with the required design principles. The work in [145], [219] illustrated resilient self-healing behavior in microgrids towards both load ramping, and load variability. Future work must also aim to account for techno-economic trade-offs in microgrid control and coordination and guarantee the stability of switching behavior.

IX. 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.

REFERENCES

[1] A. Von Meier, Electric power systems: a conceptual introduction. John Wiley & Sons, 2006.

[2] P. Schavemaker, L. Van der Sluis, and Books24x7 Inc., Electrical power system essentials. Chichester, England ; Hoboken, NJ: Wiley, 2008. [Online]. Available: http://www.loc.gov/catdir/enhancements/fy0810/2008007359-d.htmlhttp://www.loc.gov/catdir/enhancements/fy0810/2008007359-t.html

[3] E. Commission, "A Roadmap for moving to a competitive low carbon economy in 2050," European Commission, Brussel, 2011.

[4] M. Haller, S. Ludig, and N. Bauer, "Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generationnamics of renewable generation," Energy Policy, vol. 47, pp. 282–290, August 2012.

[5] T. Ackermann, E. M. Carlini, B. Ernst, F. Groome, A. Orths, J. O'Sullivan, M. de la Torre Rodriguez, and V. Silva, "Integrating variable renewables in Europe: current status and recent extreme events," IEEE Power and Energy Magazine, vol. 13, no. 6, pp. 67–77, 2015.

[6] J. Rogelj, M. Den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, and M. Meinshausen, "Paris Agreement climate proposals need a boost to keep warming well below 2 C," Nature, vol. 534, no. 7609, pp. 631–639, 2016.

[7] W. Obergassel, C. Arens, L. Hermwille, N. Kreibich, F. Mersmann, H. E. Ott, and H. Wang-Helmreich, "Phoenix from the Ashes—An Analysis of the Paris Agreement to the United Nations Framework Convention on Climate Change," Wuppertal Institute for Climate, Environment and Energy, vol. 27, no. 6, pp. 243–262, 2015.

[8] C. P. U. Commission et al., "California renewables portfolio standard (RPS)," URL: http://www.energy.ca.gov/portfolio/ [cited Dec. 12, 2017], 2017.

[9] IEA, "Renewables 2017: Analysis and Forecasts to 2022," International Energy Agency, Tech. Rep., 2017.

[10] ——, "World Energy Outlook, Energy and Air Pollution," International Energy Agency, Paris France, Tech. Rep., 2016.

[11] F. Birol et al., "World energy outlook 2010," International Energy Agency, vol. 1, 2010.

[12] C. W. Gellings, "The concept of demand-side management for electric utilities," Proceedings of the IEEE, vol. 73, no. 10, pp. 1468–1470, 1985.

[13] P. Palensky and D. Dietrich, "Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads," Industrial Informatics, IEEE Transactions on, vol. 7, no. 3, pp. 381–388, 2011.

[14] P. Siano, "Demand response and smart grids—a survey," Renewable and Sustainable Energy Reviews, vol. 30, pp. 461–478, Feb 2014.

[15] G. Pasaoglu, M. Honselaar, and C. Thiel, "Potential vehicle fleet co2 reductions and cost implications for various vehicle technology deployment scenarios in europe," Energy Policy, vol. 40, pp. 404–421, Jan 2012.

[16] T. Litman, "Comprehensive Evaluation of Transport Energy Conservation and Emission Reduction Policies Victoria Transport Policy Institute," Victoria, BC, 2012.

[17] D. Anair and A. Mahmassani, "State of charge: Electric vehicles' global warming emissions and fuel-cost savings across the United States," Union of Concerned Scientists, 2012.

[18] R. Al Junaibi, A. Viswanath, and A. M. Farid, "Technical feasibility assessment of electric vehicles: An Abu Dhabi example," in 2013 International Conference on Connected Vehicles and Expo (ICCVE). IEEE, 2013, pp. 410–417.

[19] M. D. Galus, "Agent-based modeling and simulation of large scale electric mobility in power systems," Ph.D. dissertation, ETH Zurich, 2012.

[20] A. M. Farid, "A Hybrid Dynamic System Model for Multi-Modal Transportation Electrification," IEEE Transactions on Control System Technology, vol. PP, no. 99, pp. 1–12, 2016. [Online]. Available: http://dx.doi.org/10.1109/TCST.2016.2579602

[21] ——, "Electrified transportation system performance: Conventional vs. online electric vehicles," in Electrification of Ground Transportation Systems for Environment and Energy Conservation (in press), N. P. Suh and D. H. Cho, Eds. Berlin, Heidelberg: Springer, 2016, ch. 22, pp. 1–25. [Online]. Available: http://amfarid.scripts.mit.edu/resources/Books/TES-BC05.pdf

[22] S. Stoft, Power System Economics: Designing Markets for Electricity, 1st ed. Wiley-IEEE Press, 2002.

[23] W. W. Hogan, "Electricity Whole-sale Market Design in a Low-Carbon Future," in Harnessing renewable energy in electric power systems : theory, practice, policy. Washington, DC: RFF Press, 2010, pp. 113–136.

[24] ——, "Multiple Market-Clearing Prices, Electricity Market Design and Price Manipulation," The Electricity Journal, vol. 25, no. 4, pp. 18–32,

May 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1040619012000917

[25] A. Garcia, L. Mili, and J. Momoh, "Modeling electricity markets: A brief introduction," 2008.

[26] D. Kirschen and G. Strbac, Fundamentals of power system economics. West Sussex, England: Wiley Online Library, 2004.

[27] M. Shahidehpour, H. Yamin, and Z. Y. Li, Market Operations in Electric Power Systems. New York, New York, USA: New York: Wiley, 2002.

[28] M. H. Albadi and E. F. El-Saadany, "A summary of demand response in electricity markets," Electric Power Systems Research, vol. 78, no. 11, pp. 1989–1996, 2008.

[29] S. Breukers, E. Heiskanen, B. Brohmann, R. Mourik, and C. Feenstra, "Connecting research to practice to improve energy demand-side management (dsm)," Energy, vol. 36, no. 4, pp. 2176–2185, Apr 2011.

[30] G. Strbac, "Demand side management: Benefits and challenges," Energy Policy, vol. 36, no. 12, pp. 4419–4426, Dec 2008.

[31] A. M. Farid, B. Jiang, A. Muzhikyan, and K. Youcef-Toumi, "The Need for Holistic Enterprise Control Assessment Methods for the Future Electricity Grid," Renewable & Sustainable Energy Reviews, vol. 56, no. 1, pp. 669–685, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.rser.2015.11.007

[32] M. Farina and G. F. Trecate, "Decentralized and distributed control," in EECI-HYCON2 Graduate School on Control 2012, 2012.

[33] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "An Enterprise Control Assessment Method for Variable Energy Resource Induced Power System Imbalances Part 1: Methodology," IEEE Transactions on Industrial Electronics, vol. 62, no. 4, pp. 2448–2458, 2015. [Online]. Available: http://dx.doi.org/10.1109/TIE.2015.2395391

[34] M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," Renewable and Sustainable Energy Reviews, vol. 16, no. 6, pp. 3876–3890, Aug 2012.

[35] F. Diaz-Gonzalez, M. Hau, A. Sumper, O. Gomis-Bellmunt, and F. Díaz-gonzález, "Participation of wind power plants in system frequency control : Review of grid code requirements and control methods," Renewable and Sustainable Energy Reviews, vol. 34, pp. 551–564, 2014.

[36] M. Wolter, "Reducing the curtailment amount of renewable energy using efficiency-based allocation," in Mathworks Energy and Utilities Virtual Conference, 2012, pp. 1–2.

[37] K. Heussen, S. Koch, A. Ulbig, and G. Andersson, "Unified system-level modeling of intermittent renewable energy sources and energy storage for power system operation," Systems Journal, IEEE, vol. 6, no. 1, pp. 140–151, March 2012.

[38] J. M. Guerrero, P. C. Loh, T.-L. Lee, and M. Chandorkar, "Advanced Control Architectures for Intelligent Microgrids-Part II: Power Quality, Energy Storage, and AC/DC Microgrids," Industrial Electronics, IEEE Transactions on, vol. 60, no. 4, pp. 1263–1270, 2013.

[39] I. Atzeni, L. G. Ordóñez, G. Scutari, D. P. Palomar, and J. R. Fonollosa, "Demand-side management via distributed energy generation and storage optimization," IEEE Transactions on Smart Grid, vol. 4, no. 2, pp. 866–876, 2013.

[40] M. Albadi and E. El-Saadany, "Comparative study on impacts of wind profiles on thermal units scheduling costs," IET Renewable Power Generation, vol. 5, no. 1, p. 26, 2011.

[41] T. Aigner, S. Jaehnert, G. L. Doorman, and T. Gjengedal, "The effect of large-scale wind power on system balancing in northern europe," IEEE Trans. Sustain. Energy, vol. 3, no. 4, pp. 751–759, Oct 2012.

[42] A. Robitaille, I. Kamwa, A. H. Oussedik, M. de Montigny, N. Menemenlis, M. Huneault, A. Forcione, R. Mailhot, J. Bourret, and L. Bernier, "Preliminary impacts of wind power integration in the hydro-quebec system," Wind Engineering, vol. 36, no. 1, pp. 35–52, Feb 2012.

[43] F. Rodriguez-Bobada, A. R. Rodrigues, A. Cena, and E. Giraut, "Study of wind energy penetration in the Iberian peninsula," Red Electrica de Espana, Madrid, Spain, Tech. Rep., 2006.

[44] U. Axelsson, R. Murray, V. Neimane, and ELFORSK, "4000 MW wind power in Sweden Impact on regulation and reserve requirements," Elforsk, Tech. Rep., 2005.

[45] G. Strbac, A. Shakoor, M. Black, D. Pudjianto, and T. Bopp, "Impact of wind generation on the operation and development of the uk electricity systems," Electric Power Systems Research, vol. 77, no. 9, pp. 1214–1227, Jul 2007.

[46] K. Bruninx and E. Delarue, "A statistical description of the error on wind power forecasts for probabilistic reserve sizing," IEEE transactions on Sustainable Energy, vol. 5, no. 3, pp. 995–1002, 2014.

[47] H. Holttinen, M. Milligan, B. Kirby, T. Acker, V. Neimane, and T. Molinski, "Using Standard Deviation as a Measure of Increased Operational Reserve Requirement for Wind Power," Wind Engineering, vol. 32, no. 4, pp. 355–377, 2008. [Online]. Available: citeulike-article-id:8373954http://dx.doi.org/10.1260/0309-524X.32.4.355

[48] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "An A Priori Analytical Method for Determination of Operating Reserves Requirements," International Journal of Energy and Power Systems, vol. 86, no. 3, pp. 1–11, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.ijepes.2016.09.005

[49] ——, "An Enterprise Control Assessment Method for Variable Energy Resource Induced Power System Imbalances Part 2: Results," IEEE Transactions on Industrial Electronics, vol. 62, no. 4, pp. 2459 – 2467, 2015. [Online]. Available: http://dx.doi.org/10.1109/TIE.2015.2395380

[50] ——, "Relative Merits of Load Following Reserves and Energy Storage Market Integration Towards Power System Imbalances," International Journal of Electrical Power and Energy Systems, vol. 74, no. 1, pp. 222–229, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.ijepes.2015.07.013

[51] A. Muzhikyan, A. M. Farid, and T. Mezher, "The Impact of Wind Power Geographical Smoothing on Operating Reserve Requirements," in IEEE American Control Conference, Boston, MA, USA, 2016, pp. 1–6. [Online]. Available: http://dx.doi.org/10.1109/ACC.2016.7526593

[52] B. Jiang, A. M. Farid, and K. Youcef-Toumi, "A comparison of day-ahead wholesale market: Social welfare vs industrial demand side management," in IEEE International Conference on Industrial Technology, Sevilla, Spain, 2015, pp. 1–7. [Online]. Available: http://dx.doi.org/10.1109/ICIT.2015.7125502

[53] ——, "Demand side management in a day-ahead wholesale market a comparison of industrial and social welfare approaches," Applied Energy, vol. 156, no. 1, pp. 642–654, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2015.07.014

[54] P. G. Martin, "The need for enterprise control: Automation engineers improve business performance," InTech Magazine, vol. Nov/Dec, pp. 1–5, November/December 2012. [Online]. Available: https://ww2.isa.org/standards-publications/isa-publications/intech-magazine/2012/december/cover-story-the-need-for-enterprise-control/

[55] ANSI-ISA, "Enterprise Control System Integration Part 3: Activity Models of Manufacturing Operations Management," The International Society of Automation, Tech. Rep., 2005.

[56] L. M. Sanchez and R. Nagi, "A review of agile manufacturing systems," International Journal of Production Research, vol. 39, no. 16, pp. 3561–3600, Jan 2001.

[57] A. Gunasekaran, "Agile manufacturing: enablers and an implementation framework," International Journal of Production Research, vol. 36, no. 5, pp. 1223–1247, 1998.

[58] R. Beach, A. P. Muhlemann, D. H. R. Price, A. Paterson, and J. A. Sharp, "Review of manufacturing flexibility," European Journal of Operational Research, vol. 122, no. 1, pp. 41–57, 2000. [Online]. Available: http://dx.doi.org/10.1016/S0377-2217(99)00062-4

[59] A. De Toni and S. Tonchia, "Manufacturing Flexibility: a literature review," International Journal of Production Research, vol. 36, no. 6, pp. 1587–1617, 1998.

[60] H. J. Pels, J. C. Wortmann, and A. J. R. Zwegers, "Flexibility in manufacturing: an architectural point of view," Computers in Industry, vol. 33, no. 2-3, pp. 271–283, 1997.

[61] T. J. Williams, G. A. Rathwell, and H. Li, A Handbook on Master Planning and Implementation for Enterprise Integration Programs. Purdue University Institute for Interdisciplinary Engineering Studies, 2001.

[62] K. Kosanke, F. Vernadat, and M. Zelm, "Cimosa: Enterprise engineering and integration," Computers in Industry, vol. 40, no. 2-3, pp. 83–87, 1999.

[63] ANSI-ISA, Enterprise-Control System Integration Part 1: Models and Terminology. Instrument Society of America, 2000, no. July.

[64] F. F. Wu, K. Moslehi, and A. Bose, "Power System Control Centers: Past, Present, and Future," Proceedings of the IEEE, vol. 93, no. 11, pp. 1890–1908, 2005.

[65] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, "A survey on smart grid communication infrastructures: Motivations, requirements and challenges," IEEE Communications Surveys & Tutorials, vol. 15, no. 1, pp. 5–20, 2013.

[66] Anonymous, "NIST Framework and Roadmap for Smart Grid Interoperability Standards Release 1.0: NIST Special Publication 1108," Office of the National Coordinator for Smart Grid Interoperability, National Institute of Standards and Technology, United States Department of Com-

merce, Washington D.C., Tech. Rep. NIST Special Special Publication 1108, 2010.
[67] G. Wang, A. Kowli, M. Negrete-Pincetic, E. Shafieepoorfard, and S. Meyn, "A control theorist's perspective on dynamic competitive equilibria in electricity markets," IFAC Proceedings Volumes, vol. 44, no. 1, pp. 4933–4938, 2011.
[68] D. J. Shiltz, M. Cvetković, and A. M. Annaswamy, "An integrated dynamic market mechanism for real-time markets and frequency regulation," IEEE Transactions on Sustainable Energy, vol. 7, no. 2, pp. 875–885, 2016.
[69] N. Li, C. Zhao, and L. Chen, "Connecting automatic generation control and economic dispatch from an optimization view," IEEE Transactions on Control of Network Systems, vol. 3, no. 3, pp. 254–264, 2016.
[70] M. Amin, "Toward self-healing energy infrastructure systems," Computer Applications in Power, IEEE, vol. 14, no. 1, pp. 20–28, 2001.
[71] ——, "Toward a self-healing energy infrastructure," in Power Engineering Society General Meeting, ser. 2006 IEEE Power Engineering Society General Meeting. Montreal, Canada: IEEE, 2006, pp. 7 pp. BN — 1 4244 0493 2.
[72] ——, "Challenges in reliability, security, efficiency, and resilience of energy infrastructure: Toward smart self-healing electric power grid," in BT - 2008 IEEE Power and Energy Society General Meeting, 20-24 July 2008, ser. 2008 IEEE Power Energy Society General Meeting. Pittsburgh, PA, USA: IEEE, Jul 2008, pp. 1–5.
[73] S. M. Amin, "Smart grid overview issues and opportunities. advances and challenges in sensing modeling simulation optimization and control," European Journal of Control, vol. 17, no. 5-6, pp. 547–567, 2011.
[74] S. D. J. McArthur, P. C. Taylor, G. W. Ault, J. E. King, D. Athanasiadis, V. D. Alimisis, and M. Czaplewski, "The autonomic power system - network operation and control beyond smart grids," 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), pp. 1–7, Oct 2012.
[75] P. Wood, D. Shiltz, T. R. Nudell, A. Hussain, and A. M. Annaswamy, "A framework for evaluating the resilience of dynamic real-time market mechanisms," IEEE Transactions on Smart Grid, vol. 7, no. 6, pp. 2904–2912, 2016.
[76] A. Bejestani, A. Annaswamy, and T. Samad, "A hierarchical transactive control architecture for renewables integration in smart grids: Analytical modeling and stability," Smart Grid, IEEE Transactions on, vol. 5, no. 4, pp. 2054–2065, July 2014.
[77] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "Variable Energy Resource Induced Power System Imbalance as Mitigated by Real-Time Markets and Operator Actions," in 3rd MIT-MI Joint Workshop on the Reliability of Power System Operation & Control in the Presence of Increasing Penetration of Variable Energy Sources, Abu Dhabi, UAE, 2012, pp. 1–6.
[78] A. Muzhikyan, A. M. Farid, and K. Y. Toumi, "Variable Energy Resource Induced Power System Imbalances," in 5th MIT-MI Joint Workshop on the Reliability of Power System Operation & Control in the Presence of Increasing Penetration of Variable Energy Sources, Abu Dhabi, UAE, 2013, pp. 1–41.
[79] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "Variable Energy Resource Induced Power System Imbalances: A Generalized Assessment Approach," in IEEE Conference on Technologies for Sustainability, Portland, Oregon, 2013, pp. 1–8. [Online]. Available: http://dx.doi.org.libproxy.mit.edu/10.1109/SusTech.2013.6617329
[80] ——, "Variable Energy Resource Induced Power System Imbalances: Mitigation by Increased System Flexibility, Spinning Reserves and Regulation," in IEEE Conference on Technologies for Sustainability, Portland, Oregon, 2013, pp. 1–7. [Online]. Available: http://dx.doi.org.libproxy.mit.edu/10.1109/SusTech.2013.6617292
[81] E. Ela and M. O'Malley, "Studying the variability and uncertainty impacts of variable generation at multiple timescales," Power Systems, IEEE Transactions on, vol. 27, no. 3, pp. 1324–1333, 2012.
[82] A. Kiani and A. M. Annaswamy, "A Hierarchical Transactive Control Architecture for Renewables Integration in Smart Grids," 51st IEEE Conference on Decision and Control, 2012.
[83] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "An Enhanced Method for Determination of the Ramping Reserves," in IEEE American Control Conference, Los Angeles, CA, USA, 2015, pp. 1–8. [Online]. Available: http://dx.doi.org/10.1109/ACC.2015.7170863
[84] ——, "An Enhanced Method for Determination of the Regulation Reserves," in IEEE American Control Conference, Los Angeles, CA, USA, 2015, pp. 1–8. [Online]. Available: http://dx.doi.org/10.1109/ACC.2015.7170866
[85] ——, "An Enhanced Method for the Determination of Load Following Reserves," in American Control Conference, 2014, Portland, Oregon, 2014, pp. 1–8. [Online]. Available: http://dx.doi.org/10.1109/ACC.2014.6859254
[86] A. M. Farid, "2017 iso new england system operational analysis and renewable energy integration study (soares): Study methodology," in ISO New England Planning Advisory Committee, Westborough, MA, 2017.
[87] S. O. Muhanji, A. Muzhikyan, Z. Berzolla, and M. Farid, Amro, "2017 iso new england system operational analysis and renewable energy integration study: Project methodology report," Laboratory for Intelligent Integrated Networks of Engineering Systems, Tech. Rep., 2017.
[88] S. P. Meyn, P. Barooah, A. Bušić, Y. Chen, and J. Ehren, "Ancillary service to the grid using intelligent deferrable loads," IEEE Transactions on Automatic Control, vol. 60, no. 11, pp. 2847–2862, 2015.
[89] G. Wenzel, M. Negrete-Pincetic, D. E. Olivares, J. MacDonald, and D. S. Callaway, "Real-time charging strategies for an electric vehicle aggregator to provide ancillary services," IEEE Transactions on Smart Grid, 2017.
[90] M. Eskandari Nasab, I. Maleksaeedi, M. Mohammadi, and N. Ghadimi, "A new multiobjective allocator of capacitor banks and distributed generations using a new investigated differential evolution," Complexity, vol. 19, no. 5, pp. 40–54, 2014.
[91] H. Holttinen, M. Milligan, E. Ela, N. Menemenlis, J. Dobschinski, B. Rawn, R. J. Bessa, D. Flynn, E. Gomez-Lazaro, and N. K. Detlefsen, "Methodologies to determine operating reserves due to increased wind power," IEEE Trans. Sustain. Energy, vol. 3, no. 4, pp. 713–723, Oct 2012.
[92] A. S. Brouwer, M. van den Broek, A. Seebregts, and A. Faaij, "Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems , and how these can be modeled," Renewable and Sustainable Energy Reviews, vol. 33, pp. 443–466, 2014.
[93] H. Holttinen, M. O. Malley, J. Dillon, and D. Flynn, "Recommendations for wind integration studies – IEA task 25," International Energy Agency, Helsinki, Tech. Rep., 2012.
[94] H. Holttinen, A. Orths, H. Abilgaard, F. van Hulle, J. Kiviluoma, B. Lange, M. OMalley, D. Flynn, A. Keane, J. Dillon, E. M. Carlini, J. O. Tande, A. Estanquiro, E. G. Lazaro, L. Soder, M. Milligan, C. Smith, and C. Clark, "Iea wind export group report on recommended practices wind integration studies," International Energy Agency, Paris, France, Tech. Rep., 2013.
[95] E. Ela, M. Milligan, and B. Kirby, "Operating reserves and variable generation," Contract, vol. 303, no. August, pp. 275–3000, 2011.
[96] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, "A survey of frequency and voltage control ancillary services—part i: Technical features," IEEE Transactions on power systems, vol. 22, no. 1, pp. 350–357, 2007.
[97] CIGRE, "Ancillary services: An overview of international practices technical brochure 435," CIGRE Working Group C5.06, Tech. Rep., October 2010.
[98] A. J. Wood and B. F. Wollenberg, Power generation, operation, and control, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2014.
[99] A. G. Expósito, A. Gomez-Exposito, A. J. Conejo, and C. Canizares, Electric energy systems: analysis and operation. CRC Press, 2016.
[100] A. E. Curtright and J. Apt, "The character of power output from utility-scale photovoltaic systems," Progress in Photovoltaics: Research and Applications, no. September 2007, pp. 241–247, 2008.
[101] J. Apt and A. Curtright, "The spectrum of power from utility-scale wind farms and solar photovoltaic arrays," Carnegie Mellon Electricity Industry Center Working Paper, Pittsburgh, PA, United states, Tech. Rep., 2007.
[102] Federal Energy Regulatory Commission, "Order No. 764," FERC, Tech. Rep., 2012.
[103] W. Wei, N. Li, J. Wang, and S. Mei, "Estimating the probability of infeasible real-time dispatch without exact distributions of stochastic wind generations," IEEE Transactions on Power Systems, vol. 31, no. 6, pp. 5022–5032, 2016.
[104] X. Zhang and A. Papachristodoulou, "Distributed dynamic feedback control for smart power networks with tree topology," in American Control Conference (ACC), 2014. IEEE, 2014, pp. 1156–1161.
[105] H. Zhang, J. Zhou, N. Fang, R. Zhang, and Y. Zhang, "Daily hydrothermal scheduling with economic emission using simulated annealing tech-

nique based multi-objective cultural differential evolution approach," Energy, vol. 50, no. 0, pp. 24–37, feb 2013.

[106] A. Jokic, "Price-based optimal control of electrical power systems," 2007.

[107] J. Zhang, S. Nabavi, A. Chakrabortty, and Y. Xin, "Convergence Analysis of ADMM-Based Power System Mode Estimation Under Asynchronous Wide-Area Communication Delays," 2015.

[108] J. Lunze and F. Lamnabhi-Lagarrigue, Handbook of hybrid systems control : theory, tools, applications. Cambridge, UK ; New York: Cambridge University Press, 2009.

[109] A. M. Annaswamy, M. Amin, C. DeMarco, T. Samad, J. Aho, G. Arnold, A. Buckspan, A. Cadena, D. Callaway, E. Camacho, A. Caramanis, A. Chakrabortty, A. Chakraborty, J. Chow, M. Dahleh, A. D. Dominguez-Garcia, D. Dotta, A. M. Farid, P. Flikkema, D. Gayme, S. Genc, M. G. I. Fisa, I. Hiskens, P. Houpt, G. Hug, P. Khargonekar, H. Khurana, A. Kiani, S. Low, J. McDonald, E. Mojica-Nava, A. L. Motto, L. Pao, A. Parisio, A. Pinder, M. Polis, M. Roozbehani, Z. Qu, N. Quijano, and J. Stoustrup, "IEEE Vision for Smart Grid Controls: 2030 and Beyond," IEEE, Tech. Rep., 2013.

[110] A.-H. Mohsenian-Rad, V. W. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid," IEEE Transactions on Smart Grid, vol. 1, no. 3, pp. 320–331, 2010.

[111] Z. Baharlouei, M. Hashemi, H. Narimani, and H. Mohsenian-Rad, "Achieving optimality and fairness in autonomous demand response: Benchmarks and billing mechanisms," IEEE Transactions on Smart Grid, vol. 4, no. 2, pp. 968–975, 2013.

[112] M. A. A. Pedrasa, T. D. Spooner, and I. F. MacGill, "Scheduling of demand side resources using binary particle swarm optimization," IEEE Transactions on Power Systems, vol. 24, no. 3, pp. 1173–1181, 2009.

[113] B. Ramanathan and V. Vittal, "A framework for evaluation of advanced direct load control with minimum disruption," IEEE Trans. Power Syst., vol. 23, no. 4, pp. 1681–1688, Nov 2008.

[114] P. Samadi, A.-H. Mohsenian-Rad, R. Schober, V. W. Wong, and J. Jatskevich, "Optimal real-time pricing algorithm based on utility maximization for smart grid," in Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on. IEEE, 2010, pp. 415–420.

[115] H. Chen, Y. Li, R. H. Louie, and B. Vucetic, "Autonomous demand side management based on energy consumption scheduling and instantaneous load billing: An aggregative game approach," IEEE Transactions on Smart Grid, vol. 5, no. 4, pp. 1744–1754, 2014.

[116] A. Noruzi, T. Banki, O. Abedinia, and N. Ghadimi, "A new method for probabilistic assessments in power systems, combining monte carlo and stochastic-algebraic methods," Complexity, vol. 21, no. 2, pp. 100–110, 2015.

[117] I. Ahmadian, O. Abedinia, and N. Ghadimi, "Fuzzy stochastic long-term model with consideration of uncertainties for deployment of distributed energy resources using interactive honey bee mating optimization," Frontiers in Energy, vol. 8, no. 4, pp. 412–425, 2014.

[118] J. Hansen, J. Knudsen, A. Kiani, A. M. Annaswamy, and J. Stoustrup, "A dynamic market mechanism for markets with shiftable demand response," Proceeding of the 19th IFAC World Congress, 2014.

[119] A. K. Bejestani and A. Annaswamy, "A dynamic mechanism for wholesale energy market: Stability and robustness," IEEE Transactions on Smart Grid, vol. 5, no. 6, pp. 2877–2888, 2014.

[120] Z. Almahmoud, J. Crandall, K. Elbassioni, T. T. Nguyen, and M. Roozbehani, "Dynamic pricing in smart grids under thresholding policies: Algorithms and heuristics," arXiv preprint arXiv:1610.07559, 2016.

[121] D. P. Zhou, M. Roozbehani, M. A. Dahleh, and C. J. Tomlin, "Stability analysis of wholesale electricity markets under dynamic consumption models and real-time pricing," in American Control Conference (ACC), 2017. IEEE, 2017, pp. 2048–2053.

[122] A. Kiani and A. M. Annaswamy, "Wholesale Energy Market in a Smart Grid: Dynamic Modeling and Stability," 50th IEEE Conference on Decision and Control, 2011.

[123] S. Jenkins, A. Annaswamy, J. Hansen, and J. Knudsen, "A dynamic model of the combined electricity and natural gas markets," in Innovative Smart Grid Technologies Conference (ISGT), 2015 IEEE Power & Energy Society. IEEE, 2015, pp. 1–5.

[124] M. J. Garcia, T. R. Nudell, and A. M. Annaswamy, "A dynamic regulation market mechanism for improved financial settlements in wholesale electricity markets," in American Control Conference (ACC), 2017. IEEE, 2017, pp. 1425–1430.

[125] Q. Huang, M. Roozbehani, and M. A. Dahleh, "Efficiency-risk tradeoffs in electricity markets with dynamic demand response," IEEE Transactions on Smart Grid, vol. 6, no. 1, pp. 279–290, 2015.

[126] J. Knudsen, J. Hansen, and A. M. Annaswamy, "A dynamic market mechanism for the integration of renewables and demand response," IEEE Transactions on Control Systems Technology, vol. 24, no. 3, pp. 940–955, 2016.

[127] Y. Liu, W. Wang, and N. Ghadimi, "Electricity load forecasting by an improved forecast engine for building level consumers," Energy, vol. 139, pp. 18–30, 2017.

[128] B. Jiang, A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "Demand Side Management in Power Grid Enterprise Control – A Comparison of Industrial and Social Welfare Approaches," Applied Energy, vol. 187, pp. 833–846, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2016.10.096

[129] ——, "Impacts of industrial baseline errors in demand side management enabled enterprise control," in IECON 2015 – 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 2015, pp. 1–6. [Online]. Available: http://dx.doi.org/10.1109/IECON.2015.7392637

[130] B. Jiang, A. M. Farid, and K. Youcef-Toumi, "Impacts of industrial baseline errors on demand side management in day-ahead wholesale markets," in Proceedings of the ASME Power & Energy 2015: Energy Solutions for Sustainable Future, San Diego, CA, 2015, pp. 1–7. [Online]. Available: http://engineering.dartmouth.edu/liines/resources/Conferences/SPG-C45.pdf

[131] R. Walawalkar, S. Fernands, N. Thakur, and K. R. Chevva, "Evolution and current status of demand response (DR) in electricity markets: Insights from PJM and NYISO," Energy, vol. 35, no. 4, pp. 1553–1560, 2010.

[132] H.-p. Chao, "Demand response in wholesale electricity markets: the choice of customer baseline," Journal of Regulatory Economics, vol. 39, no. 1, pp. 68–88, 2011.

[133] Council, Gridwise Architecture, "Transactive Energy," URL: http://www.gridwiseac.org/about/transactive_energy.aspx [cited: 18 Feb. 2017], 2016.

[134] F. C. Schweppe, R. D. Tabors, J. L. Kirtley, H. R. Outhred, F. H. Pickel, and A. J. Cox, "Homeostatic utility control," IEEE Transactions on Power Apparatus and Systems, vol. PAS-99, no. 3, pp. 1151–1163, May 1980.

[135] D. Hammerstrom, R. Ambrosio, J. Brous, T. Carlon, D. Ghassin, J. DeSteese, R. Guttromson, G. Horst, O. Järregren, R. Kajfasz et al., "Pacific Northwest GridWise TM Testbed Demonstration Projects, Volume I: The Olympic Peninsula Project," 2007.

[136] R. Melton, "Pacific northwest smart grid demonstration project technology performance report volume 1: Technology performance," Pacific Northwest National Laboratory (PNNL), Richland, WA (United States), Tech. Rep., 2015.

[137] E. G. Cazalet, "Temix: a foundation for transactive energy in a smart grid world," in Grid-Interop Forum, 2010.

[138] D. Hammerstrom, T. Oliver, R. Melton, and R. Ambrosio, "Standardization of a hierarchical transactive control system," Grid Interop, vol. 9, p. 2009, 2009.

[139] V. C. Güngör, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid and smart homes: Key players and pilot projects," IEEE Industrial Electronics Magazine, vol. 6, no. 4, pp. 18–34, 2012.

[140] P. Vrba, V. Marik, P. Siano, P. Leitao, G. Zhabelova, V. Vyatkin, and T. Strasser, "A review of agent and service-oriented concepts applied to intelligent energy systems," Industrial Informatics, IEEE Transactions on, vol. 10, no. 3, pp. 1890–1903, Aug 2014.

[141] J. K. Kok, C. J. Warmer, and I. G. Kamphuis, "Powermatcher : Multiagent control in the electricity infrastructure," in AAMAS 2005 – 4th International joint conference on Autonomous Agents and MultiAgent Systems, Utrecht, July 2005, 2005, pp. 75–82.

[142] A. A. Hamad and E. F. El-Saadany, "Multi-agent supervisory control for optimal economic dispatch in DC microgrids," Sustainable Cities and Society, 2016.

[143] S. D. J. McArthur, E. M. Davidson, V. M. Catterson, A. L. Dimeas, N. D. Hatziargyriou, F. Ponci, and T. Funabashi, "Multi-Agent Systems for Power Engineering Applications; Part II: Technologies, Standards, and Tools for Building Multi-agent Systems," Power Systems, IEEE Transactions on, vol. 22, no. 4, pp. 1753–1759, 2007.

[144] ——, "Multi-Agent Systems for Power Engineering Applications; Part I: Concepts, Approaches, and Technical Challenges," Power Systems, IEEE Transactions on, vol. 22, no. 4, pp. 1743–1752, 2007.

[145] S. Rivera, A. M. Farid, and K. Youcef-Toumi, "A Multi-Agent System Coordination Approach for Resilient Self-Healing Operation of Multiple Microgrids," Industrial Agents: Emerging Applications of Software Agents in Industry. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1–20, 2014.
[146] J. Queiroz, P. Leitão, and A. Dias, "A Multi-Agent System for Micro Grids Energy Production Management Supported by Predictive Data Analysis," DSIE| 16, p. 151, 2016.
[147] M. Merdan, A. Prostejovsky, I. Hegny, W. Lepuschitz, F. Andrén, and T. Strasser, "Power Distribution Control Using Multi-Agent Systems," in Recent Advances in Robotics and Automation. Springer, 2013, pp. 323–333.
[148] P. Leitao, V. Marik, and P. Vrba, "Past, present, and future of industrial agent applications," Industrial Informatics, IEEE Transactions on, vol. 9, no. 4, pp. 2360–2372, Nov 2013.
[149] P. Vrba, P. Tichy, V. Marik, K. H. Hall, R. J. Staron, F. P. Maturana, and P. Kadera, "Rockwell automation's holonic and multiagent control systems compendium," Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on, vol. 41, no. 1, pp. 14–30, 2011.
[150] M. Pěchouček and V. Mařík, "Industrial deployment of multi-agent technologies: review and selected case studies," Autonomous Agents and Multi-Agent Systems, vol. 17, no. 3, pp. 397–431, 2008.
[151] A. M. Farid, "Multi-agent system design principles for resilient coordination & control of future power systems," Intelligent Industrial Systems, vol. 1, no. 3, pp. 255–269, 2015.
[152] A. Arenas, A. Diaz-Guilera, J. Kurths, Y. Moreno, and C. Zhou, "Synchronization in complex networks," Physics Reports, vol. 469, no. 3, pp. 93–153, Dec. 2008. [Online]. Available: http://dx.doi.org/10.1016/j.physrep.2008.09.002
[153] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "A survey on smart grid potential applications and communication requirements," IEEE Transactions on Industrial Informatics, vol. 9, no. 1, pp. 28–42, 2013.
[154] V. C. Güngör, D. Sahin, T. Kocak, S. Ergüt, C. Buccella, S. Member, C. Cecati, G. P. Hancke, and S. Member, "Smart grid technologies : Communication technologies and standards," IEEE Transactions on Industrial Informatics, vol. 7, no. 4, pp. 529–539, 2011.
[155] D. Henry and J. Emmanuel Ramirez-Marquez, "Generic metrics and quantitative approaches for system resilience as a function of time," Reliability Engineering and System Safety, vol. 99, pp. 114–122, Mar 2012.
[156] D. Sharma, A. Trivedi, D. Srinivasan, and L. Thillainathan, "Multi-agent modeling for solving profit based unit commitment problem," Applied Soft Computing Journal, vol. 13, no. 8, pp. 3751–3761, 2013. [Online]. Available: http://dx.doi.org/10.1016/j.asoc.2013.04.001
[157] M. Amin, "System-of-systems approach," in Intelligent Monitoring, Control, and Security of Critical Infrastructure Systems. Berlin, Heidelberg: Springer, 2015, pp. 317–354.
[158] A. M. Farid, "A Hybrid Dynamic System Model for Multimodal Transportation Electrification," IEEE Transactions on Control Systems Technology, 2016.
[159] A. Farid, "Electrified transportation system performance: Conventional vs. online electric vehicles," Electrification of Ground Transportation Systems for Environment and Energy Conservation, pp. 1–25, 2015.
[160] G. Olsson, Water and energy: threats and opportunities. IWA publishing, 2015.
[161] K. Hussey and J. Pittock, "The energy–water nexus: managing the links between energy and water for a sustainable future," Ecology and Society, vol. 17, no. 1, 2012.
[162] J. Macknick, R. Newmark, G. Heath, and K. C. Hallett, "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature," Environmental Research Letters, vol. 7, no. 4, p. 045802, Dec 2012.
[163] D. Yergin and C. Frei, "Energy Vision Update 2009. Thirsty Energy: Water and Energy in the 21st Century," in Geneva, World Economic Forum/Cambridge Energy Research Association, 2009.
[164] L. Park and K. Croyle, "Californias water-energy nexus: Pathways to implementation," GEI Consultants, Inc, Tech. Rep., 2012.
[165] W. N. Lubega and A. M. Farid, "A reference system architecture for the energy–water nexus," IEEE Systems Journal, vol. 10, no. 1, pp. 106–116, 2016.
[166] USDOE, "The water-energy nexus: Challenges and opportunities," United States Department of Energy, Tech. Rep., 2014.
[167] M. A. Rosen, M. N. Le, and I. Dincer, "Efficiency analysis of a cogeneration and district energy system," Applied thermal engineering, vol. 25, no. 1, pp. 147–159, 2005.
[168] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, and B. V. Mathiesen, "4th generation district heating (4gdh): Integrating smart thermal grids into future sustainable energy systems," Energy, vol. 68, pp. 1–11, 2014.
[169] H. Lund, B. Möller, B. V. Mathiesen, and A. Dyrelund, "The role of district heating in future renewable energy systems," Energy, vol. 35, no. 3, pp. 1381–1390, 2010.
[170] W. C. Schoonenberg and A. M. Farid, "A dynamic production model for industrial systems energy management," in Systems, Man, and Cybernetics (SMC), 2015 IEEE International Conference on. IEEE, 2015, pp. 1–7.
[171] M. Starke, D. Letto, N. Alkadi, R. George, B. Johnson, K. Dowling, and S. Khan, "Demand-side response from industrial loads," in 2013 NSTI Nanotechnology Conference and Expo, ser. Technical Proceedings of the 2013 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2013, vol. 2. Oak Ridge National Laboratory, Oak Ridge, TN 37831, United StatesENBALA Power Networks, Toronto, ON, M5H 2V6, CanadaUniversity of Tennessee, Knoxville, United StatesUniversity of Texas, Austin, United States: Nano Science and Technology Institute, 2013, pp. 758–761.
[172] S. Emec, M. Kuschke, M. Chemnitz, and K. Strunz, "Potential for demand side management in automotive manufacturing," IEEE PES ISGT Europe 2013, pp. 1–5, Oct 2013.
[173] M. Shahidehpour and Z. Li, Elecitricity market Economics. New York: John Wiley and Sons, 2005.
[174] K. Li and C. Lai, "Adaptive–impulsive synchronization of uncertain complex dynamical networks," Physics Letters A, vol. 372, no. 10, pp. 1601–1606, Mar 2008.
[175] W. Su, H. Rahimi-eichi, W. Zeng, and M.-y. Chow, "A Survey on the Electrification of Transportation in a Smart Grid Environment," IEEE Transactions on Industrial Informatics, vol. 8, no. 1, pp. 1–10, 2012.
[176] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid," IEEE Trans. Power Syst., vol. 25, no. 1, pp. 371–380, Feb 2010.
[177] E. Sortomme, M. M. Hindi, S. D. J. MacPherson, and S. S. Venkata, "Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses," IEEE Transactions on Smart Grid, vol. 2, no. 1, pp. 198–205, Mar 2011.
[178] M. F. Shaaban, M. Ismail, E. F. El-Saadany, and W. Zhuang, "Real-time PEV charging/discharging coordination in smart distribution systems," IEEE Transactions on Smart Grid, vol. 5, no. 4, pp. 1797–1807, 2014.
[179] B. K. Sovacool and R. F. Hirsh, "Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (phevs) and a vehicle-to-grid (v2g) transition," Energy Policy, vol. 37, no. 3, pp. 1095–1103, Mar 2009.
[180] E. Sortomme and M. A. El-Sharkawi, "Optimal Scheduling of Vehicle-to-Grid Energy and Ancillary Services," Smart Grid, IEEE Transactions on, vol. 3, no. 1, pp. 351–359, 2012.
[181] M. D. Galus, M. Zima, and G. Andersson, "On integration of plug-in hybrid electric vehicles into existing power system structures," Energy Policy, vol. 38, no. 11, pp. 6736–6745, Nov 2010.
[182] M. D. Galus, S. Koch, and G. Andersson, "Provision of load frequency control by phevs, controllable loads, and a cogeneration unit," IEEE Trans. Ind. Electron., vol. 58, no. 10, pp. 4568–4582, Oct 2011.
[183] F. Mwasilu, J. J. Justo, E.-k. Kim, T. D. Do, and J.-w. Jung, "Electric vehicles and smart grid interaction : A review on vehicle to grid and renewable energy sources integration," Renewable and Sustainable Energy Reviews, vol. 34, pp. 501–516, 2014.
[184] H. Lund and W. Kempton, "Integration of renewable energy into the transport and electricity sectors through v2g," Energy Policy, vol. 36, no. 9, pp. 3578–3587, Sep 2008.
[185] S. H. Low, "A duality model of tcp and queue management algorithms," IEEE/ACM Transactions on Networking, vol. 11, no. 4, pp. 525–536, 2003.
[186] D. Charypar and K. Nagel, "An event-driven queue-based traffic flow microsimulation," pp. 1–29, 2007.
[187] H. Akbari and X. Fernando, "Futuristic model of Electric Vehicle charging queues," in Signal Processing and Integrated Networks (SPIN), 2016 3rd International Conference on. IEEE, 2016, pp. 789–794.
[188] T. J. van der Wardt and A. M. Farid, "A hybrid dynamic system assessment methodology for multi-modal transportation-electrification,"

Energies, vol. 10, no. 5, p. 653, 2017. [Online]. Available: http://dx.doi.org/10.3390/en10050653

[189] E. Mielke, L. D. Anadon, and V. Narayanamurti, "Water consumption of energy resource extraction, processing, and conversion," Belfer Center for Science and International Affairs, 2010.

[190] A. S. Stillwell, D. C. Hoppock, and M. E. Webber, "Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus," Sustainability, vol. 2, no. 4, pp. 945–962, 2010.

[191] A. Siddiqi and L. D. Anadon, "The water–energy nexus in middle east and north africa," Energy Policy, vol. 39, no. 8, pp. 4529–4540, Aug 2011.

[192] A. M. Farid, W. N. Lubega, and W. Hickman, "Opportunities for Energy-Water Nexus Management in the Middle East and North Africa," Elementa, vol. 4, no. 134, pp. 1–17, 2016. [Online]. Available: http://dx.doi.org/10.12952/journal.elementa.000134

[193] W. Hickman, A. Muzhikyan, and A. M. Farid, "The Synergistic Role of Renewable Energy Integration into the Unit Commitment of the Energy Water Nexus," Renewable Energy, vol. 108, pp. 220–229, 2017. [Online]. Available: https://dx.doi.org/10.1016/j.renene.2017.02.063

[194] A. Santhosh, A. M. Farid, and K. Youcef-Toumi, "The Impact of Storage Facility Capacity and Ramping Capabilities on the Supply Side of the Energy-Water Nexus," Energy, vol. 66, no. 1, pp. 1–10, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.energy.2014.01.031

[195] W. N. Lubega and A. M. Farid, "Quantitative engineering systems modeling and analysis of the energy–water nexus," Applied Energy, vol. 135, pp. 142–157, 2014.

[196] H. Abdulla and A. M. Farid, "Extending the energy-water nexus reference architecture to the sustainable development of agriculture, industry & commerce," in First IEEE International Smart Cities Conference, Guadalajara, Mexico, 2015, pp. 1–7. [Online]. Available: http://dx.doi.org/10.1109/ISC2.2015.7366166

[197] A. Bruzzone, D. Anghinolfi, M. Paolucci, and F. Tonelli, "Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops," CIRP Annals-Manufacturing Technology, vol. 61, no. 1, pp. 459–462, 2012.

[198] E. Efficiency, "Tracking Industrial Energy Efficiency and CO2 Emissions," International Energy Agency, vol. 34, no. 2, pp. 1–12, 2007.

[199] A. Giret, D. Trentesaux, and V. Prabhu, "Sustainability in manufacturing operations scheduling: A state of the art review," Journal of Manufacturing Systems, vol. 37, pp. 126–140, 2015.

[200] G. May, M. Taisch, and D. Kelly, "Enhanced energy management in manufacturing through systems integration," Vienna, Austria, 2013, pp. 7525 – 7530, decision support tools;High energy consumption;Information and Communication Technologies;Key performance indicators;Management concerns;Monitor and control;Monitoring and control;Performance indicators;. [Online]. Available: http://dx.doi.org/10.1109/IECON.2013.6700386

[201] M. Schulze, H. Nehler, M. Ottosson, and P. Thollander, "Energy management in industry–a systematic review of previous findings and an integrative conceptual framework," Journal of Cleaner Production, vol. 112, pp. 3692–3708, 2016.

[202] S. Thiede, Energy efficiency in manufacturing systems. Springer Science & Business Media, 2012.

[203] R. Jiang, J. Wang, and Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," IEEE Transactions on Power Systems, vol. 27, no. 2, pp. 800–810, 2012.

[204] P. van den Oosterkamp, P. Koutstaal, A. Van der Welle, J. De Joode, J. Lenstra, K. Van Hussen, and R. Haffner, "The role of DSOs in a Smart Grid environment," Final Report project Ecorys and ECN for DG ENER, 2014.

[205] S. Ruester, I. J. PÉREZ-ARRIAGA, S. Schwenen, C. Batlle, and J.-M. Glachant, "From distribution networks to smart distribution systems: Rethinking the regulation of European electricity DSOs," Utilities Policy 31 (2014), Tech. Rep., 2013.

[206] O. Zinaman, M. Miller, A. Adil, D. Arent, J. Cochran, R. Vora, S. Aggarwal, M. Bipath, C. Linvill, A. David et al., "Power Systems of the Future," The Electricity Journal, vol. 28, no. 2, pp. 113–126, 2015.

[207] G. Horst et al., "Pacific Northwest GridWise TM Testbed Demonstration Projects Part II. Grid Friendly TM Appliance Project," Gridwise Architecture Council, Tech. Rep., 2007.

[208] Gridwise Architecture Council, "Transactive Energy Inforgraphic," URL:http://www.gridwiseac.org/pdfs/te_infographics [cited: Feb 19 2017], 2016.

[209] S. M. Amin and M. Amin, "Smart grid security, privacy, and resilient architectures: Opportunities and challenges BT - 2012 IEEE Power \& Energy Society General Meeting. New Energy Horizons - Opportunities and Challenges, 22-26 July 2012," in IEEE Computer Applications in Power, ser. IEEE Comput. Appl. Power (USA), vol. 14, no. 1. EPRI, Palo Alto, CA, USA: IEEE, Jan. 2012, pp. 20–28. [Online]. Available: http://dx.doi.org/10.1109/67.893351http://dx.doi.org/10.1109/PESGM.2012.6345767

[210] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," IEEE Transactions on Smart Grid, vol. 3, no. 4, pp. 1963–1976, Dec 2012.

[211] J. M. Guerrero, M. Chandorkar, T.-L. Lee, and P. C. Loh, "Advanced control architectures for intelligent microgrids – part i: Decentralized and hierarchical control," IEEE Trans. Ind. Electron., vol. 60, no. 4, pp. 1254–1262, Apr 2013.

[212] R. Majumder, "Some aspects of stability in microgrids," IEEE Trans. Power Syst., vol. 28, no. 3, pp. 3243–3252, Aug 2013.

[213] A. M. Farid, "Intelligent transportation-energy systems: Abu dhabi feasibility study," in Gulf Traffic Conference, Dubai, UAE, 2014, pp. 1–32.

[214] R. H. Lasseter, "Smart distribution: Coupled microgrids," Proceedings of the IEEE, vol. 99, no. 6, pp. 1074–1082, Jun 2011.

[215] M. D. Ilic, "From hierarchical to open access electric power systems," Proceedings of the IEEE, vol. 95, no. 5, pp. 1060–1084, may 2007.

[216] C. Rieger and Q. Zhu, "A hierarchical multi-agent dynamical system architecture for resilient control systems," 2013 6th International Symposium on Resilient Control Systems (ISRCS), pp. 6–12, Aug 2013.

[217] C. G. Rieger, K. L. Moore, and T. L. Baldwin, "Resilient control systems," 2013.

[218] A. Vaccaro, M. Popov, D. Villacci, and V. Terzija, "An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication, and Verification," Proceedings of the IEEE, vol. 99, no. 1, pp. 119–132, Jan. 2011. [Online]. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=5638117&contentType=Journals+&+Magazines&searchField=Search_All&queryText=microgrids+communication

[219] S. Rivera, A. M. Farid, and K. Youcef-Toumi, "A multi-agent system coordination approach for resilient self-healing operation of multiple microgrids," Industrial Agents: Emerging Applications of Software Agents in Industry, pp. 1–20, 2014.

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