Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid

Future Grid Thrust Area 3 White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Thrust Area 3 White Paper

Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid

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Power Systems Engineering Research Center

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Executive Summary

The integration of renewable energy resources into the power grid is driven, largely, by environmental regulation aimed at promoting sustainable energy resources and reducing carbon emission resulting from energy use. Price and quantity controls of carbon emissions through taxation and cap and trade policies, along with renewable portfolio standards (RPS) are the primary drivers for massive penetration of renewable energy resources and for electrification of transportation. Both wind and solar photovoltaics are expected to comprise a significant portion of new power generation. However, the operating characteristics of these resources which are strongly influenced by weather patterns have a profound impact on the planning and operation of the power grid.

Renewable energy production is uncertain and cannot be forecasted accurately. Furthermore, it exhibit a highly variable diurnal pattern, hence integrating massive amounts of renewable energy resources into the power grid presents major challenges in terms of the dispatch, reserves, and ramping. The unpredictability of wind power supply which may change rapidly due to cold fronts and wind shifts can cause large deviations from hour-ahead dispatch schedules, as may a moving cloud cover affect supply from solar resources. Such uncertainty and variability exacerbates the need for spinning reserves, non-spinning reserves, regulation and flexible ramp resources in order to mitigate potentially adverse impact on system reliability.

There is a need for research aimed at understanding and quantifying the impact that massive integration of wind and solar power will have on the power system in terms of efficiency, operational reliability, economic consequences and environmental outcomes. We also need to address the design and evaluation of technological and market based approaches to mitigation the adverse impact of such integration. Such analysis should be based on simulation models designed to explore and evaluate technological and market solutions that can facilitate the integration of renewable resources. Specifically, the potential of harnessing the inherent flexibility of certain load types such as heating, cooling and air conditioning (HVAC), PHEV charging and the deployment of distributed and system level storage devices to mitigate the variability and uncertainty of renewable resources. Specific research addressed in this trust area focuses on:

- Mitigation of supply intermittency through mobilization of flexible loads such as smart charging stations for PHEVs that will enable modulation of the charge rate so as to follow renewable resource availability and price signals.
- Computational algorithms that explicitly account for uncertainty and variability of renewable resources and can handle large number of distributed resources.
- Distributed control strategies that will enable “harvesting” of fast load response through minimally disruptive adjustments of large number of thermostatically controlled loads.
- Efficient resource management through market mechanisms based on improved load modeling and incentives.

- Advanced planning, simulation and verification tools that will assure efficiency and reliability in an environment with massive deployment of intermittent resources, distributed generation, storage, demand response and intelligent periphery.

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1 Introduction

The integration of renewable energy resources into the power grid is driven, largely, by environmental regulation aimed at promoting sustainable energy resources and reducing carbon emission resulting from energy use. Price and quantity controls of carbon emissions through taxation and cap and trade policies, along with renewable portfolio standards (RPS) are the primary drivers for massive penetration of renewable energy resources and for electrification of transportation. To reduce greenhouse gas emissions many states have implemented renewable portfolio standards that require a certain percentage of electricity generation to come from renewable sources. Both wind and solar photovoltaics are expected to comprise a significant portion of new renewables. However, the operating characteristic of these resources which are strongly influenced by weather patterns has a profound impact on the planning and operation of the power grid. There are two characteristics of power supply from renewable energy resources which present significant obstacles to their large-scale integration into the power grid. Renewable energy production is uncertain and cannot be forecasted accurately, as illustrated in Figure 3.1 below. Furthermore, it exhibit a highly variable diurnal pattern, as illustrated in Figure 3.2, so that even if perfect forecasts were possible, integrating massive amounts of renewable energy resources into the power grid presents significant challenges in terms of the dispatch, reserves, and ramping requirements [23]. These problems are particularly acute with respect to wind power whose availability is adversely correlated with demand. The unpredictability of wind power supply which may change rapidly due to cold fronts and wind shifts can cause large deviations from hour-ahead dispatch schedules, as may a moving cloud cover affect supply from solar resources. Starting up units to compensate for a sudden shortage in wind power or solar power supply takes time and may necessitate curtailments of load. Furthermore, the need for emergency startups leads to increased emissions, and increased maintenance cost due to added wear on these units. Such emergency startups also disrupt market operations and increase dispatch cost due to the minimum load constraints of these units.

Unanticipated increase in wind power supply is also problematic since it may require shutting down units due to minimum load constraints and over generation. The minute-by-minute and intra-hour variability of wind and solar power generation exacerbates the need for spinning reserve, non-spinning reserve, regulation and flexible ramp resources in order to compensate for the inability to perfectly forecast wind and mitigate potentially adverse impact on system reliability. Since such renewable resources tend to vary rapidly and in great magnitude it becomes necessary to invest in and dispatch fast starting generators with sufficient ramping capabilities and those are typically more expensive to operate. The California Independent System Operator (CAISO) has estimated that meeting a 20% renewable energy integration target will require generators which can ramp twice as fast as existing generators, in order to keep up with the abrupt changes in wind power supply [22][37]. Yet, regardless of the challenges wind and solar power are poised to become mainstream energy sources capable of supplying bulk quantities of power to the electricity grid.

Environmental regulations, aimed at reducing carbon emissions, are setting aggressive targets that will require high levels of renewable penetration. For instance Assembly Bill 32 in California has set goals of cutting back greenhouse gas emissions to 1990 levels by 2012 and the RPS mandates 33% integration of renewable energy in California by 2020. As wind penetration increases the aforementioned challenges may impact system reliability, dispatch efficiency, cost of operation and may even undermine the environmental goals that RPSs, aim to achieve, unless the adverse impact of such penetration can be mitigated through technological innovation.

Studies have placed an estimate of wind integration costs of up to $7/MWh for integration levels between 2.4% to 20% [1]. On the other hand; significant amounts of wind power are spilled by system operators in Denmark, Texas and California. This can happen for reliability reasons during load pickup, in order to avoid oversupply, in the case of abrupt shifts in renewable supply, or at nighttime when other generators need to maintain a minimum output level.

Rather than using existing and new generation units to provide the additional services needed to enable the penetration of renewable resources into the generation mix, it may be more cost-effective and/or environmentally-beneficial to provide these services with alternative technologies, namely energy storage devices (e.g., batteries, flywheels, compressed gas, and pumped hydro) and demand response (DR). In this thrust area we focus on DR for two reasons: First, it has significant potential for near-term deployment and impact. Second it has been identified as a crucial component of the portfolio of energy technologies needed to achieve massive de-carbonization of our energy supply system [6].

There is a need for research aimed at understanding and quantifying the impact that massive integration of wind and solar power will have on the power system in terms of efficiency, operational reliability, economic consequences and environmental outcomes. We also need to address the design and evaluation of technological and market based approaches to mitigation the adverse impact of such integration. Such analysis should be based on simulation models designed to explore and evaluate technological and market solutions that can facilitate the integration of renewable resources. Specifically, the potential of harnessing the inherent flexibility of certain load types such as heating, cooling and air conditioning (HVAC), Plug in electric vehicle (PHEV) charging and the deployment of distributed and system level storage devices to mitigate the variability and uncertainty of renewable resources.

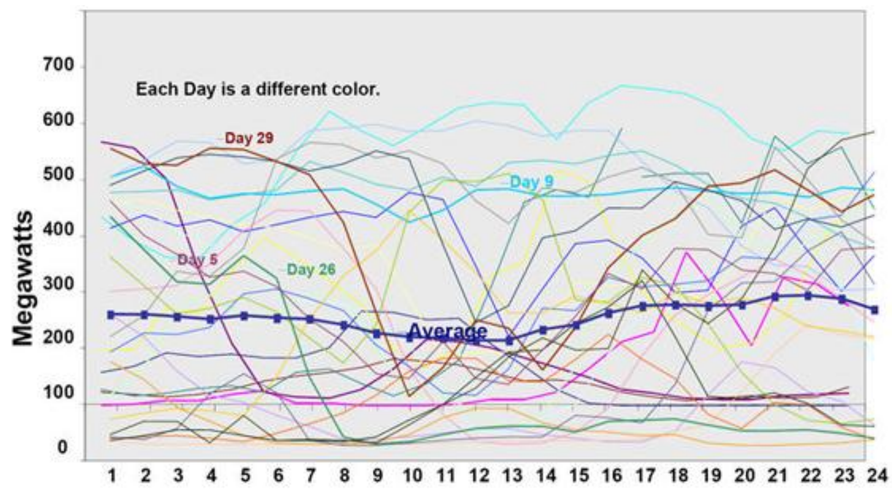

Figure 3.1: Hour to Hour Daily Variations of a Wind Farm's Output Around a Steady Average

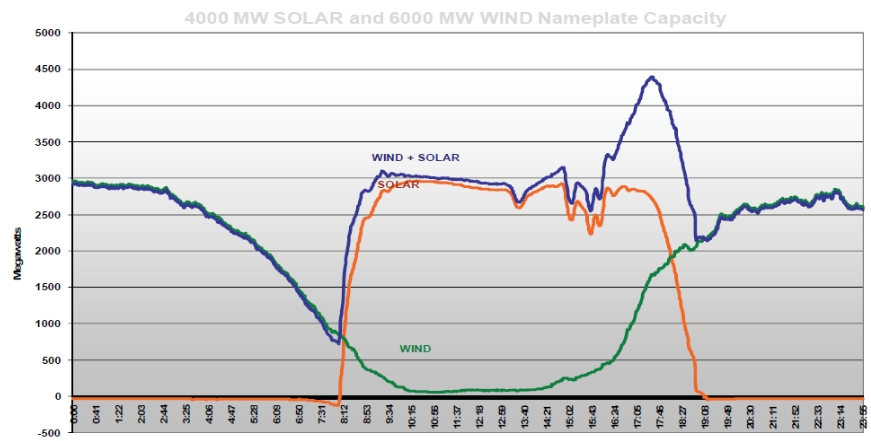

Figure 3.2: Increased Ramp Requirement Due to Renewables Diurnal Variability

2 The Opportunities and the Challenges

Supporting high levels of renewable penetration may degrade system reliability, and increase electricity costs or undermine the environmental objectives of the renewables, due to inefficient resource use. Averting such adverse consequences requires the harnessing of smart metering and IT-based, load control technologies that will enable mobilization of implicit storage capability embedded in flexible loads. Furthermore, new business models need to be developed for commercial entities that will aggregate flexible loads at the retail level to provide wholesale load response products that can meet or mitigate the increased need for reserves.

2.1 New Opportunities/Technologies

The various tasks under this thrust area addresses the aforementioned challenges by exploring concrete control and market based mechanisms for exploiting load flexibility and new enabling technologies. The scope of these tasks also includes the development of optimization and simulation tools that will explicitly account for uncertainty in planning and operation and enable performance assessment of the proposed solutions in a future grid environment.

The primary enabling technology for pervasive mobilization of demand response is an IT infrastructure including smart meters and load control devices that will enable monitoring and control of flexible loads. Such control may involve a portfolio of complimentary approaches targeted for different load types and system operation needs. Following are some examples which are further explored in the research tasks of this trust area:

- Distributed control strategies and appropriate hardware will enable “harvesting” of fast load response through minimally disruptive adjustments of large number of thermostatically controlled loads.
- Massive deployment of mart charging stations for PHEVs will enable modulation of the charge rate so as to follow a price signal, renewables availability or provide V2G services.
- Efficient resource management through improved computational algorithms that explicitly account for uncertainty and variability of renewable resources and can handle large number of distributed resources.
- Autonomous load response agents that will enable implementation of an “intelligent periphery” in the future grid
- Advanced planning, simulation and verification tools that will assure efficiency and reliability in an environment with massive deployment of intermittent resources, distributed generation, storage, demand response and intelligent periphery.

3 The Research Issues

3.1 Task 1: Direct and Telemetric Coupling of Renewable Energy Resources with Flexible Loads

Scope and Methodology

This task focuses on exploiting demand side flexibility as a hedge against supply uncertainty caused by the inherent intermittency of renewable energy resources. Much of the effort to improve demand response and energy efficiency has focused on conservation rather than on exploiting demand side flexibility. Yet, across the full spectrum of residential, commercial and industrial consumption, a significant proportion of the power that we generate is supplied to loads which are time flexible, i.e., deferrable for a few minutes or hours at little or no cost. Such loads include HVAC, electric vehicle charging, refrigeration, home appliances. Furthermore such flexibility is enhanced by technologies such as storage, heat pumps and micro-combined heat and power systems (CHPs).

These time flexible demand side resources could adapt their energy consumption according to the fluctuation of renewable power supply in order to buffer its variability and enable large scale integration of renewable energy without significant impacts on grid operations. Demand side flexibility has the potential of mitigating the variability and uncertainty of renewable resources, thus suppressing their integration costs so as to make them competitive with traditional fossil fuel generators. Load control through direct physical or telemetric coupling of renewable generators with deferrable loads can provide means of mitigating the adverse effect of intermittency in renewables energy resources. Such an approach can be implemented with existing technology, is compatible with existing power systems and power market operations and is aligned with existing economic incentives.

From a resource adequacy perspective, direct coupling will enhance the capacity value of wind and solar resources by effectively reducing the net load and volatility apparent to the system operator. Such capacity value accrues above and beyond the energy value of the intermittent resources. Alternatively such incremental value can be captured through economic coupling via load response to real time prices and load participation in ancillary services markets.

The proposed coupling approach is based on a paradigm change which is premised on redefining flexible load as an amount of energy that has to be provided within a specified time frame as opposed to the traditional characterization of load as a demand for power over time. To advance such a paradigm change research needs to focuses on devising optimal strategies for the use of contracted renewable resources supplemented by spot electricity purchased from the grid to serve flexible loads. In addition, business models must be explored for serving such loads or for aggregating load flexibility in order to provide whole sale balancing energy and reserves.

To assess the efficacy of the direct coupling approach it needs to be compared to alternative option for exploiting load response and load flexibility. Figure 3.3 attempts to illustrate the range of such alternatives from the point of view of centralization level. At one extreme we consider an idealized benchmark system where the system operator has complete information about the flexibility of each resource and can optimally dispatch every supply and demand side resource. At the other extreme load flexibility is conveyed through an aggregate price responsive demand function, whereas renewable resources are bidding into the real-time market and price is used for adjusting the consumption patterns of demand [4][14][16][36]. Flexible and inflexible consumers participate in the market through demand bids. When there is an increase in renewable supply, the market price of power drops and flexible consumers increase their consumption. Conversely, a shortage in renewable supply results in higher market prices and elicits a reduction in flexible demand. This approach requires that consumers be exposed to real-time pricing and assumes that they are capable of optimizing demand on a real-time basis. Moreover, demand bids fail to convey the inter-temporal dependencies of deferrable demand and the non-convexities of generator operating costs. This can result in demand peaks during periods of low real-time prices as well as excessive startups and minimum load costs for generators [35].

The coupling of renewable generation with deferrable demand into a virtual resource that appears controllable and predictable to the system operator, is an intermediate solution designed to overcome the drawbacks of price-based demand response. In this approach we assume that an aggregator serves flexible consumers primarily through renewable energy assets, relying to a limited extent on the real-time market. The reasoning is that the flexible portion of the electricity market can absorb the unpredictable and uncontrollable fluctuation of renewable power supply without experiencing deterioration in quality of service. The setup is similar to dynamic scheduling [14], whereby demand and supply resources in different control areas pair their schedules in order to produce a zero net output to the remaining system. Such scheduling is implemented in the ERCOT market in Texas. The coupling of resources allows the virtual resource to override the market, thereby overcoming the need to expose deferrable consumers to real-time pricing. Instead, coupling merely assumes real-time pricing at the wholesale/aggregator level, which is consistent with current electricity market operations. Moreover, deferrable loads communicate basic needs to the aggregator (e.g. ‘charge my vehicle by 6 a.m.’, or ‘keep the building within this temperature band’), and rely on the aggregator to fulfill these requests. This transfers the intelligence of the system from the consumer to the aggregator level, much like how aggregators operate currently. Through coupling, the amount of information that can be communicated within the virtual resource between renewable suppliers and deferrable loads is much greater relative to the use of real-time pricing.

The drawback of the coupling approach is that it forgoes some of the efficiency gains obtained through markets. For instance, direct coupling would allocate renewable energy to a flexible load that may value that energy below the prevailing spot price. Furthermore direct coupling may not be able to exploit the geographical diversification of renewable energy from different locations.

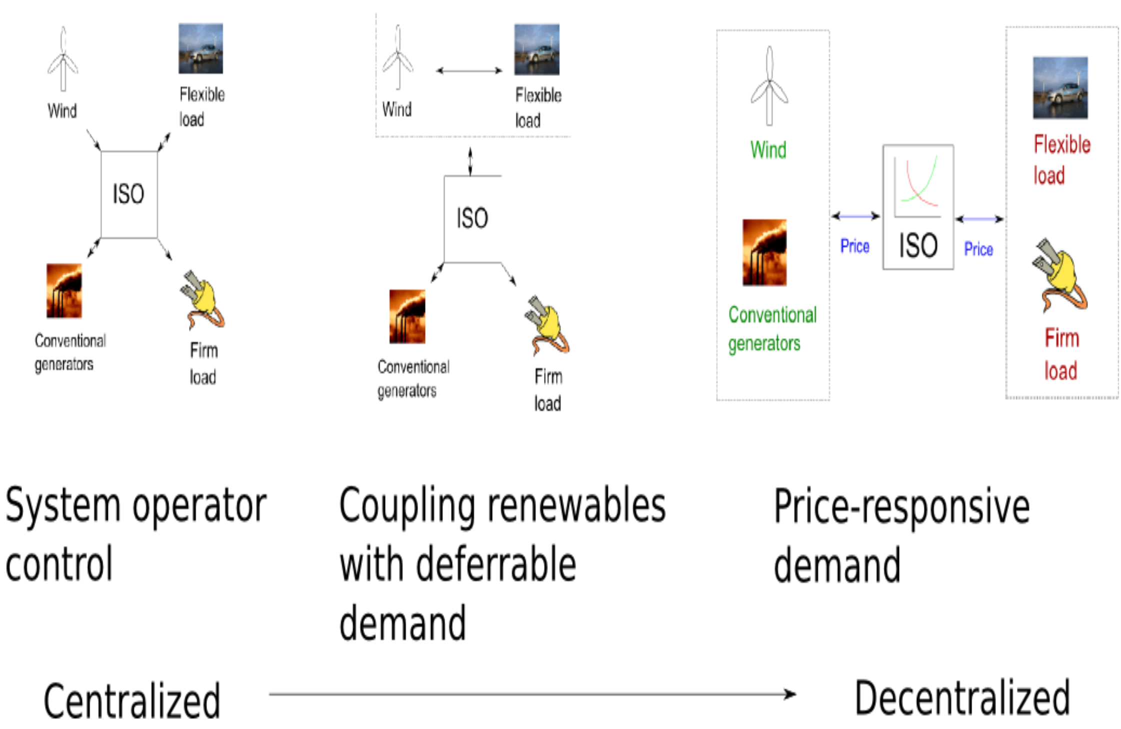

Figure 3.3: The Spectrum of Demand Response Paradigms According to the Degree of Centralization

A primary goal of this task is to assess the merit of the proposed coupling approach in comparison with the two extreme paradigms depicted in Figure 3.3. Such comparison requires a simulation framework that explicitly accounts for uncertainty and accurately represents the balancing actions of the rest of the system. Clearly load response will be more valuable in a system dominated by inflexible generation resources such as nuclear power plants than in a system dominated by hydro resources. A unit commitment model is appropriate for representing the technical constraints associated with bulk generation. In order to deal with uncertainty, such as demand and renewable supply fluctuations as well as generator and transmission failures, system operators currently impose ad hoc reserve requirements to unit commitment models [36]. These requirements commit excess generation capacity above and beyond what is required for serving forecast demand, in order to protect the system against unpredictable fluctuations in firm demand and renewable supply. These constraints are based on ad-hoc heuristic rules and operator experience. Unfortunately, such rules may be inadequately for a future grid with increased amounts and sources of uncertainty due to integration of renewable energy and demand response resources. There is a need for more sophisticated and consistent techniques for determining the economically optimal amount of reserves that are necessary for operating the system reliably. Stochastic unit commitment models explicitly account for the sources of uncertainty in the system and attempt to ensure reliable operation at minimum cost. As a result, stochastic unit commitment models have recently attracted significant attention [9][26][31][33][37][40].

The improved performance of stochastic unit commitment comes at a computational cost. Firstly, it is necessary to reduce the representation of uncertainty in the system in terms of a few representative and appropriately weighted scenarios that guide the model to the optimal selection of reserves [11][13][12], however, such problems are still computationally challenging. Even for moderately sized systems, as few as 12 scenarios of uncertainty are enough to stall commercial optimization solvers due to the large scale of the resulting mixed integer linear program. For this reason, various special-purpose decomposition algorithms have been proposed in the literature [8][31][38] that can be used for breaking the problem down to smaller sub-problems, each sub-problem representing a single realization of uncertainty. As part of the research of this task we have developed scenario selection and decomposition algorithms that handle renewable supply uncertainty and element failures in a transmission constrained network [32][33] and we have demonstrated the superior performance of these algorithms relative to common system operator practice.

Stochastic optimization is also used at the retail load level in developing algorithms for smart use of renewable energy in combination with conventional power purchased from the spot market to serve flexible loads at minimum cost. Smart charging of PHEV batteries is an example of such an application. Efficient aggregation of such intelligent loads requires the development of business models that will provide the correct incentives and control strategies for a fleet of flexible loads that can bridge the gap between retail level load flexibility and wholesale market operation. Again stochastic dynamic optimization is the methodology of choice for determining such control strategies and for evaluating the efficacy of alternative load response aggregation methods.

Expected Results

- Comparison of fixed operating reserve rules vs. stochastic unit commitment under probabilistic wind scenarios and development of a stochastic dynamic programming algorithm for serving flexible load using uncertain wind resources and spot energy.
- Developing optimal strategies for direct coupling of flexible load with wind resources in the context of a competitive electricity market and a business model for aggregating flexible loads to provide ancillary service and balancing energy in the whole sale market.
- Simulation based comparison of direct coupling of wind and flexible load vs. centralized market approach based on price signals and load response.

- Design of a smart charging algorithm for PHEV batteries that optimizes the use of coupled wind power and spot market energy procurement.

3.2 Task 2: Mitigating Renewables Intermittency through Non-disruptive Distributed Load Control

Scope and Methodology

One generally thinks of large industrial loads and commercial buildings as the best candidates for traditional DR programs because these customers consume large amounts of electricity and, subsequently, are able to curtail a substantial amount of power when a DR event is called. Moreover, it is simpler for the utility or aggregator to interact with a small number of large customers than a large number of small customers. However, there are several benefits to using aggregations of small residential loads to provide power system services. Specifically, these loads (1) can provide more reliable responses in aggregate than small numbers of large loads [6][19]; (2) are spatially distributed; (3) employ simple local controls, which both facilitates faster responsiveness [6] and makes them easy to model for state estimation and control purposes [19][24]; and (4) display continuous, not discrete, control responses in aggregate as opposed to large loads which generally employ DR strategies such as stepping down industrial processes, HVAC loads, or lighting [25].

Thermostatically controlled loads (TCLs), such as air conditioners, electric water heaters, electric heaters, and refrigerators, have perhaps the most potential of all types of residential loads. TCLs operate within a hysteretic ON/OFF temperature dead-band. Adjusting TCL temperature within the dead-band adjusts the thermal energy stored in the TCL – much like a battery stores chemical energy – without a noticeable effect on end-use function [4]. Therefore, carefully designed load control schemes should allow us to control TCLs to track a desired trajectory (e.g., market signal or automatic generation control signal) while still performing their stated function. The goal of this task is to understand the ability of populations of TCLs to provide power systems services, while still providing the heating and cooling services requested by the user. Additionally, we aim to understand how existing and future grid information technology infrastructure constraints our ability to control TCL populations. Lastly, we plan to quantify the size of the TCL resource, costs, and revenue potential.

The research needed to accomplish the above goals is as follows:

1. **Development of new TCL population models**. High-fidelity, reduced-form models are important for predicting TCL population behavoir and designing both state estimators and controllers. While most previous work has assumed TCL parameter homogeneity, we aim to explicitly model heterogeneity. Additionally, we aim to develop models that in cannonical forms ammenable to common controls and state estimation frameworks.
2. **Development of effective control strategies that preserve end-use function while delivering systemic benefits.** The goal of the controller is to follow a regulation or load following signal, while ensuring that each TCL provides the heat or cool required by the user. One way of ensuring that the user's needs are satisfied is to

ensure that the TCL never operates outside of the user-defined dead-band. Based on the information available to the controller and tracking requirements, it is possible to design various types of controllers, e.g., proportional, predictive, optimal.

3. **Analysis of the ability of TCLs to provide power systems services as a function of the information available for system identification, state estimation, and control**. The information available to the central controller offline and in real time affects our ability to estimate the model, estimate the states, and control the system. For example, if information is available from the local level (Figure 3.3) offline but not in real time, it is possible to create a good model of the system, but we must use semi-global information to estimate the evolving state. In general, if less information is available, the TCL population tracking performance degrades. We aim to compare TCL performance, under a variety of sensing and communications scenarios, to the performance of generators, which traditionally provide power system services. Given policy objectives, this comparison will allow one to determine the minimum amount of infrastructure required for direct load control of TCLs.

4. **Analysis of the TCL resource potential, costs, and revenue potential. Key to understanding if and how TCLs could provide power systems services, is quantifying**:

   a. The total resource potential, i.e. how much power and energy capacity a population of TCLs has to offer to the market;

   b. The costs associated with DR-enabling infrastructure, deployment, and DR program operations; and

   c. The potential revenues from participation in existing/new energy and ancillary services markets, and/or through 'energy storage' and price arbitrage.

   These quantities will help us understand if TCLs are competitive with generators and energy storage devices that may provide services to the grid. To perform this analysis, we must consider current and future TCL penetration levels and costs, and TCL load shapes, which vary through the year. Additionally, we need to develop optimal control strategies that maximize revenues.

Expected Results

- Modeling and control results will lead to algorithms and approaches that can be used in pilot projects, which will eventually be used to ground-truth the simulation-based analysis.
- Understanding how the amount and type of information available affects our ability to control to TCLs to follow signals will help system operators decide what infrastructure needs to be in place to collect/transmit information to achieve acceptable performance.
- Technical results along with results from the resource, cost, and revenue analyses will allow us to directly compare the capabilities and costs/benefits of TCLs to those of generators and energy storage devices.

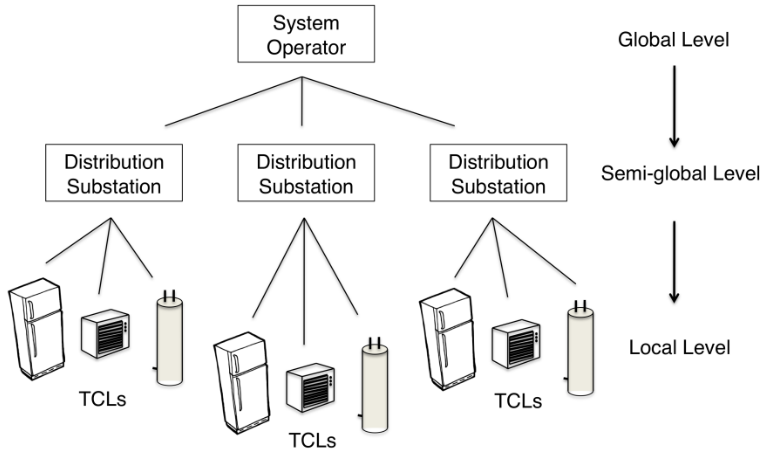

Figure 3.4: Physical Levels of the Power System

3.3 Task 3: Planning and Market Design for Using Dispatchable Loads to Meet Renewable Portfolio Standards and Emissions Reduction Targets

Scope and Methodology

This task complements Tasks 3.1, 3.2 and 3.4 by focusing on the effects of deferrable demand on environmental quality as well as on system costs and the integration of renewable sources of generation. The types of deferrable demand considered go beyond thermostatically controlled loads and beyond current types of market-based interruptible load that entails some inconvenience for customers. In effect, deferrable demand separates the purchase of electric energy from the delivery of energy services, and with these capabilities, customers are not inconvenienced. The types of deferrable demand investigated are 1) Plug-in Electric Vehicles (PEV), by managing their charging and discharging profiles [41], and 2) HVAC systems in buildings using thermal storage to augment standard space conditioning systems [30].

Climate change and urban air pollution are two major environmental problems that have important implications on the power sector through environmental regulations. The direct damage caused by emissions from power plants, such as SO_2, NO_X, fine particulates and heavy metals can be treated as external costs to generating power from fossil fuels. Many states have set up RPS and emission reduction targets for the power sector to mitigate climate change and improve air quality. For example, New York State has adopted a goal of obtaining 30 percent of its electricity from renewable sources by 2015; six Northeastern states are committed to developing strategies for reducing NO_X emissions on High Electric Demand Days (HEDD) by 134.9 tons/day to achieve ozone air quality attainment in the region.

We envision that aggregating PEV and thermal storage will provide a cost-effective way to 1) increase the penetration of renewable energy, by mitigating the inherent variability of these sources, 2) reduce criteria emissions and improve urban air quality, and 3) lower total system costs [28]. In particular, intelligent PEV charging/discharging can provide ramping services to mitigate wind variability. Wide deployment of thermal storage can shift substantial amounts of peak load from the daytime, when ozone is formed photo-chemically, to nighttime, when NO_X emissions are less likely to increase ozone formation. The specific objectives in this task are to 1) develop a unifying framework to characterize the two types of deferrable demand, 2) determine the engineering and economic feasibility of aggregating deferrable demand to facilitate the provision of systems services by aggregators, and 3) design the market characteristics that provide the correct incentives for managing the system services provided by aggregators.

This task's objectives will be pursued and demonstrated through analyses and simulations conducted on a 36-bus reduction of the Northeast Power Coordinating Council (NPCC) network developed at Carnegie Mellon University. This test network has been further developed by Cornell researchers to incorporate the costs and the emission rates of CO_2, SO_2 and NO_x for over 600 generators. The model also incorporates a realistic representation of the stochastic characteristics of wind generation from 16 sites in the Northeast. The analysis uses a Cornell implementation (SuperOPF) of stochastic multi-period Security Constrained Optimal Power Flow (SCOPF), which determines the amount of conventional generating capacity needed to maintain system reliability endogenously, as well as, the amount of potential wind generation dispatched and how deferrable demand is managed. Preliminary results show that deferrable demand is an effective way to 1) flatten the daily pattern of system load, 2) reduce the wholesale cost of electric energy purchased for customers, 3) reduce the amount of installed generating capacity needed for System Adequacy, 4) increase the amount of wind dispatched, and 5) provide ramping services to mitigate wind variability [29]. We anticipate that deferrable demand also reduces total emissions from power plants and the associated costs of damage when the environmental analysis has been completed.

The elements of this research are as follows.

1. **Identify the needs for different types of systems services.** First, we will analyze the historical data of generation, loads, and requirements for frequency regulation and generation/load following. For wind energy, we foresee that the requirements for systems services will depend on the inherent variability of wind speeds as well as mismatches between forecasts and actual realizations. Statistical analyses of wind speeds will be conducted using data from NREL (EWITS) to characterize the patterns of the variability and forecasting mismatches. Next we will estimate the future needs for frequency regulation and generation/load following under different renewable penetration levels and emission targets. We will construct a range of future scenarios from business-as-usual, to 20% wind by 2030, to aggressive 80% carbon emission reduction by 2050. We will also refer to the regional RPS and the planning documents from NYISO and ISO-NE regarding their projections of the future generation mix.
2. **Examine the engineering/economic feasibility of aggregating dispatchable loads.** Our general approach is to examine the current/projected development of PEV and HVAC technologies, and to evaluate the engineering feasibility for energy aggregators to provide system services at different timescales. This will involve conducting power systems simulations to quantify the effectiveness of the services provided, and designing market products that help reduce the system variability of generation from high penetrations of wind to improve the overall reliability of the

electric delivery system. Our initial technology assessment indicates that a large aggregation of PEV batteries have the potential for ramping services, and that an energy aggregator of buildings with both ice batteries and AC units is able to shift a large portion of the HVAC load from day to night, and to provide load-following by dispatching AC on/off, temperature settings, and ice-making commands to a large number of customers.

3. **Evaluate the performance of a unified market for multi-timescale systems services.** We will test a unified market in which the rates of payments are based on the timescales of the systems services and power provided. Our criteria for evaluating such a market are:
   - ***a.*** System operators will be rewarded with economically efficient ways to meet high penetrations of renewables and emission reduction targets;
   - ***b.*** Aggregators will be rewarded by financial payments for providing systems services;
   - ***c.*** Dispatchable load owners will be rewarded by lower costs for their energy services.

Expected Results

- New market products for incorporating deferrable demand
- Evaluation and recommendations on how to improve current market designs and environmental quality
- Assessment of whether or under what conditions it makes sense to aggregate deferrable demand to provide systems services.

3.4 Task 4: Probabilistic Simulation of Power Systems with Integrated Renewable, Demand Response and Storage Resources

Scope and Methodology

As discussed earlier, the variability and intermittent nature of renewable resources creates an acute need for practical planning and operations tools to study and to quantify the effects of the integration of such resources into the grid. This task addresses this need through the development of a computationally efficient probabilistic simulation tool. In addition, in the operations arena, we aim to provide analytically based results that are useful for updating schedules with the latest information and forecasts. The quantification of the economic, environmental and reliability impacts in the simulation approach is carried out for varying levels of wind, solar and demand response penetration with the explicit representation of the uncertainty in the variability/intermittency nature of renewable generation at multiple sites, the impacts of payback of load curtailments and the load and availability of conventional generation. As the transmission grid is also represented, these sources of uncertainty have direct impacts on the transmission-constrained day-ahead market outcomes. The simulation studies will be useful to investigate the impacts of the deepening penetration of renewable, demand and storage resources on the key variable effects that are assessed in planning and policy analysis studies, and to answer a wide array of "what if" questions.

In the operations domain, we develop a framework to assess the system's operational reliability and operational costs under different reserves policies and under a range of renewable penetration levels. A key element of this framework is to quantify, through off-line studies, how sensitive are certain dynamic variables, and how they might deviate outside performance requirements due to the uncontrolled variability of renewable resources. These sensitivity studies allow the construction of trade-off surfaces between economics and operational reliability, which may lead to some generalizations for specific systems. Indeed, such an investigation can allow the determination of reserves requirements dynamically. From the investigation, we select the maximum value of the reserves that we may view as corresponding to worst-case conditions. These reserves requirements can then be used in the formulation of the unit commitment problem, the solution of which will provide operators with a robust solution that includes the variability and intermittency effects. The effective application of robust optimization which represents a contending alternative to stochastic optimization is a critical part of the work.

In the planning domain, a unified modeling framework will be created, which represents, with the appropriate level of detail, the supply- and demand-side resources, the transmission grid, the market clearing operations, the market structure and operating policies, as well as the various sources of uncertainty. The framework serves as an analytical basis for developing a comprehensive simulation tool for power system planning, economic/environmental/reliability evaluation and policy analysis for longer-term studies. The tool will be useful to determine the most effective way to integrate renewable, demand and storage resources into the system and market clearing operations by quantifying their impacts on the market performance, generation dispatch, transmission usage and congestion, emissions, and system reliability. Such quantification is also very useful in investment decisions, regulatory filings and policy formulation and analysis. Our investigations will provide practical insights into the significant role played by these resources in the efficient utilization of generation and transmission assets, and in the increased competition in the electricity markets to bring about lower prices to consumers.

The proposed simulation approach aims to emulate the behavior, over longer-term periods, of power systems with integrated intermittent sources of energy, demand response resources and utility-scale storage units. We identify multiple issues associated with the development of such a tool. One of the main concerns is to develop a probabilistic simulation tool that is both computationally tractable and capable of incorporating the representation of time-dependent resources, including the transmission grid utilization and its impacts on the day-ahead hourly market outcomes. Such an endeavor requires major modifications of conventional probabilistic production costing tools [2] [3] [15] that, typically, cannot represent the transmission network and the time dependencies of certain resources, such as wind and solar. In order to incorporate such time-dependent elements, a major challenge is to set up a unified framework that can accommodate both the probabilistic aspects of the simulation and the time dependencies of the incorporated elements.

The production costing and reliability assessment, with the representation of the transmission network incorporated, is a key driver for moving away from the analytical procedure in the conventional probabilistic simulation approach. In addition, the needs for the explicit consideration of the correlated behavior of load and the time-dependent elements, and the availability of supply resources, lead to the idea of the development of a stochastic simulation approach that, via multiple experiments, i.e., samples of outcomes of interest, can emulate power system operations over a longer period of time [10]. We investigate appropriate stochastic models for representing the inherent intermittency and variability in wind and solar power outputs patterns and their correlation with the system loads over time. These models provide useable approximations to the underlying probability distributions that are used in the random sampling in the simulation. Specifically, the random samples of the wind and solar power outputs with the associated loads are inputs in the emulation of power system operations to determine the transmission-constrained day-ahead hourly market outcomes and corresponding dispatch levels of the controllable generating sources. The selection of the smallest indecomposable unit of time in the simulation work is made to balance the needs of adequate detail in the representation of time-varying phenomena and the computational burden of the approach.

Special attention is paid to the representation of active demand response resources (*ADRR*s) and utility-scale storage units, in addition to the conventional and wind and solar renewable resources. An associated challenge with this representation is the extension of the clearing of the transmission-constrained hourly day-ahead markets (*DAM*s) with appropriate modifications that incorporate the impacts of the added resources. For instance, in the case of *ADRR*s, the modifications involve keeping track of *ADRR* curtailment offers and the attendant payback effects, if any. The incorporation of the load shifts resulting from the curtailment actions clearly impact the overall economics and so are explicitly represented in the modified formulation of the hourly *DAM* clearing, with the associated transmission impacts [21]. The incorporation of utility-scale storage units brings additional specific requirements as storage operations occur across multiple hours and thus they impact, and are impacted by, the hourly *DAM* outcomes. Indeed, a storage unit can be, at any point in time, either a generator, a load or idle. Moreover, a storage unit may only act as a generator once it has been charged – having acted as a load in some of the preceding hours. Thus, we model such strong time-dependencies and represent a storage unit’s participation in the hourly *DAM*s as a load bidder for charging purposes and as an electricity supplier for discharging purposes. This is done while accounting for the available resources at those specific times, including intermittent resources, *ADRR*s and other storage units.

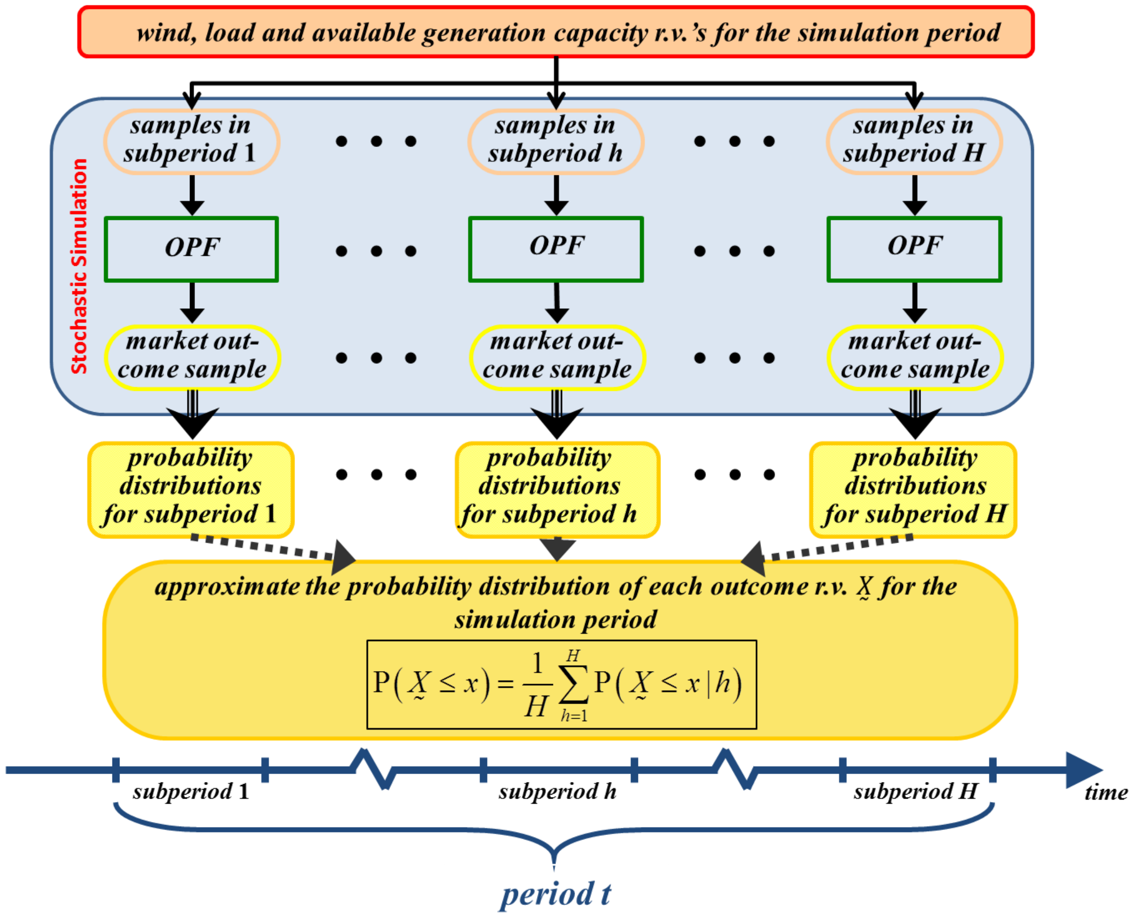

Figure 3.5: Basic Elements of the Stochastic Simulation

The need for computational tractability leads to the selection of multiple representative weeks rather than the simulation of each week by itself. Since many weeks present similar conditions in terms of load, wind and solar patterns and conventional unit availabilities, we take advantage of this situation in reducing the total number of weeks simulated. In this way, we capture the bulk power system operations over time with, typically, 16 rather than 52 simulated weeks, taking into account various phenomena, including seasonality and maintenance scheduling. We are intimately involved at this stage on the development of additional schemes for speeding up the overall calculations. We are generalizing the concepts to develop a scheme for selecting such representative weeks in different systems. An additional avenue of pursuit for improving the computational tractability of the simulation approach is the use of variance reduction techniques to reduce the number of samples necessary to ensure statistical reliability [20]. We need to adapt variance reduction techniques to the large-scale load-resource system with the various inter-dependencies among the resources, bearing in mind that the simulation uses serially correlated observations, particularly with the time dependencies in the storage unit operations. Results on these aspects will be reported at a future date.

4 The Future Grid

The large-scale integration of renewable energy sources in power systems aimed to address environmental concerns is largely inhibited by the fact that these resources fluctuate randomly and mostly beyond human control. The mobilization of flexible demand side resources such as heating and cooling, refrigeration, water pumping, electric vehicle charging, can contribute significantly to alleviate the technical challenges that arise from balancing system operations around fluctuating renewable resources. Such resources can act as virtual storage devices by adapting their consumption level to the availability of renewable supplies (wind and solar) and complementing actual storage and distributed generation resources (e.g. micro CHPs). Harnessing the capability of large number of distributed supply and demand resources can contribute to economic efficiency of the power grid by alleviating the need for investment in backup reserves without compromising reliability. The proliferation of information technologies such as smart meters, load control devices, and PMUs in the future grid will provides the infrastructure for monitoring and control of massively distributed dispatchable assets. Furthermore such infrastructure will enable an "intelligent periphery" in the power grid and empower customer choice of reliability levels by transforming local reliability and supply adequacy from a public good to a private good.

Traditionally the system operator ensures that online supplies will be sufficient to serve the load given load forecast uncertainty, supply fluctuations and possible contingencies, by deploying reserves. Simplistically, we think of reserve deployment as a two stage decision process as depicted in Figure 3.6. Slow reserves must be committed in stage 1 (day ahead) although their output level can be adjusted to a limited extent in the second stage when load and renewable resource supply are revealed. Flexible reserves, on the other hand, such as quick start CT and demand side resources can be started and adjusted as a recourse action in response to short term fluctuations of load and renewables. In the future grid the first stage reserve deployment decision will be optimized by explicitly accounting for the second stage uncertainties using stochastic unit commitment methods that can incorporate load dispatchability into the portfolio of resource options as discussed in Section 3.1.

However, the ability to treat loads as dispatchable and the proliferation of distributed resources and storage devices increases the number of dispatch decisions by two or three orders of magnitudes as compared to the number of generators being dispatched today by system operators. In addition the increased uncertainty and variability associated with massive penetration of renewables requires explicit consideration of uncertainty in the planning, operation and verification of the power system through consideration of multiple probabilistic supply scenarios and network contingencies. These tasks are further complicated by considering topology control options which can co-optimize short term grid configuration to improve economic efficiency and respond to contingencies. In sum, the scale and uncertainty consideration of optimal commitment and dispatch problems with massive integration of renewables, massive mobilization of distributed supply and demand assets and including topology control, present unprecedented computational challenges that cannot be tackled by traditional mathematical formulation and conventional software and hardware.

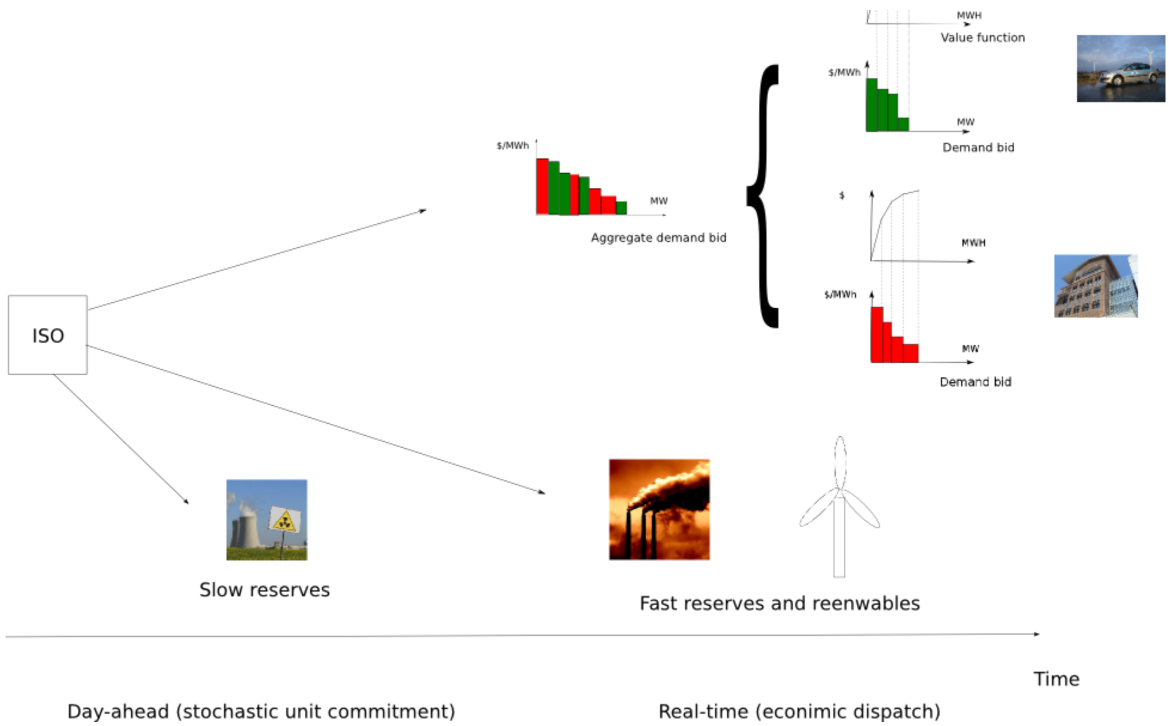

Figure 3.6: Two Stage Reserves Deployment

New mathematical formulations and computational tools employing high performance computing (HPC) capability will be needed to address resource planning, operation and verification tasks in a time frame and accuracy suitable for electricity grid operation. But, even with such new tools it is unrealistic to expect that the system operator will issue dispatch instructions to hundreds of thousands of resource. Hence, system operations and electricity markets will have to rely on various forms of resource aggregation methods and supporting business models that will facilitate the pooling of retail level resources into wholesale market products. Such resource pooling at the retail level by traditional load serving entities or through innovative third party aggregators will be facilitated by the proliferation of IT which will provide visibility and controllability of loads down to the appliance level along with distribution level supply resources such as distributed storage, solar panels, micro CHP etc.

Traditional utilities can implement load response aggregation by offering retail customers real time price options that will induce load response and reflect such forecasted response through their wholesale procurement bids in the day ahead or real time balancing market. More targeted load response aggregation such as electric vehicle charging may be offered by dedicated utilities such as Better Place (http://www.betterplace.com/). Such entities will be in a position to deploy smart charging stations at homes businesses and public location that will control charging of EV/PHEV so as to meet transportation needs while minimizing energy cost and providing V2G services. These entities may also contract directly with renewable resources as discussed in Section 3.1, and adjust their consumption so as to offset supply volatility, hence reducing the variability and uncertainty of such resources to the ISO.

Another form of load response aggregation may take the form of contracted control of massive numbers of thermostats by a utility or third party aggregator to produce an AGC equivalent product allowing load following through small non-disruptive adjustments of the thermostats set points, as described in Section 3.2. Cycling of air conditioners is another form of such non-disruptive load control that can be used to provide wholesale ancillary service.

We are already witnessing significant proliferation of various business models for load aggregation by companies like Enernoc (http://www.enernoc.com/) and ViridityEnergy (http://viridityenergy.com/) who offer to large industrial customers, commercial buildings, educational campuses and other large users, ways of optimizing their energy use and capture wholesale price savings.

From a wholesale market perspective system operators are being challenged to maintain adequate reserves that are needed to meet the increased variability and uncertainty of supply due to growing penetration of intermittent renewable resources. In order to take advantage of the expending spectrum of demand side resources discussed above, system operators will need to upgrade their operating procedures through improved mathematical formulations and computational capabilities. At the same time new market products are needed that better reflect the physical response capabilities of demand side and distributed resources. The markets for these products need to provide the correct incentives for flexible resources to reveal their physical characteristics and respond to market signals in way that benefits the system. New mechanisms for procuring and remunerating performance of Regulation developed in response to FERC order 755, and new flexible ramping products being considered by the California ISO, are examples of the market reforms designed to respond to the above challenges. The design and evaluation of such market mechanisms is addressed in Section 3.3.

The benefits of the above vision where demand response, distributed resources and intelligent grid periphery plays a key role in mitigating the obstacles to massive deployment of renewable resources cannot be realized unless this vision is reflected in the planning of the future grid infrastructure. Such planning requires new advanced tools including stochastic optimization, simulation models and verification techniques that can account for the complexity and uncertainty in future scenarios reflecting load growth, load response capability, technological innovation such as storage and electrification of transportation, etc. Such a model is described in Section 3.4 which outlines a comprehensive analysis tool for assessing the behavior of the future grid over longer-term periods. The envisioned tool allows the computation of various metrics of interest that quantify the economics, reliability and environmental impacts of power system operations over such periods [10][21].

5 Conclusions

The drive to decarburization of our energy supply due to environmental concerns will result in massive penetration of renewable resources into the electricity supply infrastructure along with the electrification of the transportation sector. These changes create challenges due to the intermittent nature of renewable resources and opportunities for mass proliferation of IT technologies into the future electricity infrastructure in order to mitigate these challenges [18]. This paper is premised on the proposition that the traditional approach of mitigating supply and demand uncertainty through procurement of reserves from conventional generation resources is not sustainable and uneconomical in an environment with massive penetration of renewable resources. Short of a disruptive breakthrough in cheap storage technology that will make the synchronicity constraints in the power grid obsolete, the only viable alternative to mitigate the intermittency of renewable resources is massive deployment of technologies that will mobilize demand side flexibility and distributed resources. Such deployment requires research and innovation in several areas detailed in Section 3. These include load control strategies and aggregation of many flexible loads, new business models to incentivize demand response, new market mechanisms and products for integrating load response into ISO operations. At the planning level, new optimization tools and simulation models are required that will account for supply uncertainty, demand side flexibility and intelligent periphery in generation and transmission expansion decisions and in the evaluation of economic, performance and environmental metrics. Finally, the vast number of resources that will need to be coordinated in the future grid, the supply and demand uncertainty and the large amount of data that will become available through the proliferation of IT infrastructure necessitates a new generation of models and algorithms that will require high performance computing (HPC) capability. In developing such tools we should anticipate that HPC capabilities that are currently only available at supercomputing facilities will become ubiquitous in the future grid.

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