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Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing

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ABSTRACT

This study has developed metrics to evaluate the impact of intermittent renewable generation on the electric load demand that must be balanced by dispatchable generation resources, allowing examination of the general impacts of accommodating high renewable penetration levels. The metrics focus on the sizing, utilization and coordination of load balancing resources to meet the load demand in time. Insights gained from increasing the renewable penetration level in California as an example indicated the following. The balancing generator fleet displayed low capacity factors at high penetration levels. At penetration levels above 45% with no uninterruptable base load, surplus generation occurred and increased exponentially. The occurrence of daily maximum and minimum load points became increasingly unpredictable, rendering fixed time-of-use electricity pricing inappropriate. Capacities of peaker and base load generator type increased and decreased respectively. Net load variability decreased on the 24-h timescale and increased on all shorter timescales, implying changes in the temporal dispatch of balancing generators. The use of energy management strategies such as energy storage was found to be necessary in order to accommodate high renewable penetration levels with minimal impact. The simple metrics allowed identification of key areas to be addressed in order to accommodate high renewable penetrations.

1. Introduction

Concerns over the increased impact of electric energy use trends on the physical, economic, and political environments have motivated a shift to a low-carbon, renewable-based grid mix. Among the different types of renewable energy sources, wind and solar power have garnered significant public and private attention due to each resource exhibiting a number of desirable characteristics for a contributor to a low-carbon, low-pollutant emission electric grid. Other renewable resources such as dispatchable hydropower and relatively predictable base-loaded geothermal power are also available, however may be limited in potential contributions to the renewable power portfolio in certain regions such as California due to geographic accessibility constraints. Therefore, wind and solar power are expected to be key resources in the construction of a renewable electric power portfolio.

Wind power has recently become the fastest growing renewable energy resource and is projected to lead the growth of the renewable power portfolio in the near term. This growth has been due to the fact that wind power exhibits a number of favorable characteristics, including:

- A low levelized cost of electricity compared to other renewable resources. Wind is already competitive with fossil fuel resources in certain cases, and is projected to undercut the price of coal-fired electricity by 2020 without subsidies [1].
- No need for rare materials. Wind turbines use balsa wood, steel, fiberglass, carbon fiber, permanent magnets and copper. Material constraints have been determined to not be a limiting issue even with substantially increased wind turbine manufacturing [2].
- The existence of multiple, unused high wind potential areas.
- Low life-cycle carbon and pollutant emissions.

Solar power also exhibits a number of favorable characteristics and is expected to comprise a large fraction of the overall electric grid portfolio in the long term. These characteristics include but are not limited to:

- Having the highest theoretical exergy potential. Solar irradiation drives all processes on the planet [3].
- Reasonable resources are geographically accessible to most of the world's countries.
- Zero operating greenhouse gas and criteria pollutant emissions
- Potential for use in distributed generation and green-building applications

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- The cost of solar power has been decreasing with time and is projected to continue doing so [4].

An increased share of wind and solar power presents a key part of a feasible strategy for altering the electric grid mix to reduce or possibly negate the increase in carbon dioxide and criteria pollutant emissions that is expected with increased electricity demand. While wind and solar power exhibit numerous favorable characteristics, these sources also exhibit a number of challenges for integration into the electric grid. One of the key obstacles to the widespread use of wind and solar power is the fact that both rely on intermittent driving forces that are independent of load demand or electric grid control.

In order to ensure the reliable delivery of electricity to all end users, the amount of electric power generation must be equal to the magnitude of the electric load demand, accounting for losses for all time. The electric load demand is variable on different timescales from microseconds to years. To cope with this variability, utilities currently interconnect many loads over wide service areas to increase the number of generators serving such a load to reduce the influence of faster timescale variations on the aggregate load demand that the generator fleet must balance. System operators manage the transmission system, ensuring that power is always flowing in the correct direction to serve loads as needed. Electric generators of different types are dispatched in real time according to parameters such as marginal cost of operation, minimum operating time, maximum power, grid congestion constraints, and other mechanisms to meet the load demand at every single time instant.

The projected introduction of high penetration levels of wind and solar power into the electric grid mix introduces a degree of uncertainty and variability into the electric power generation component. The power profile of wind and solar power installations are governed by meteorological and geographic factors, and therefore are generally difficult to dispatch under the control of electric grid operators while maintaining the robustness of electricity services.

In order to enforce that the load is balanced in a robust manner at all times, the North American Electric Reliability Corporation (NERC) sets standards for the operation of the electric grid that balancing authorities must meet. These standards are designed to allow the electric grid system to reliably provide electric power through day-to-day events as well as large scale contingencies. The details of such standards can be obtained from NERC. While NERC determines and enforces that all of the balancing authorities must comply with the reliability standards, it does not control or determine specifically how a given balancing authority must meet those standards. Therefore, balancing authorities that have jurisdiction over different areas tend to employ different methods for meeting these standards. These methods generally follow a certain structure and are tailored to take advantage of the energy resources available within their region. A typical balancing structure employed by a balancing authority contains three predominant categories within which electric power produced by generators on the grid can be classified:

1. *Bulk energy*: The energy delivered by generators in this category is scheduled ahead of time to meet the predicted load profile and energy demand.
2. *Regulation*: The power capacity of generators in this category is provided to compensate for variations and uncertainties in the load demand in “real-time”, since the load demand cannot be predicted exactly beforehand.
3. *Spinning reserve*: The power capacity of generators in this category is used to provide a generation reserve to compensate for contingency conditions on the grid.

With this general structure, power plants (generators) are allowed to bid into the markets represented by each category. Generators which bid into a given market are generally classified into three categories based on their operational characteristics:

Base-load: Base loaded generators provide bulk energy services to meet the predicted load demand. The energy expected to be obtained from such generators is set ahead of time, because these systems require many hours to come online are not required to exhibit any significant ramping or turndown capability. Generators that fall into this category tend to operate for very long time periods and typically encompass large-scale power plants that exhibit high efficiencies, low operating costs and use nuclear or coal fuel.

Load-following: In the bulk energy market, load following generators provide energy to meet daily and hourly variations in the predicted electric load demand above the portion that is met by base-load generators. To provide regulation services, such generators are capable of ramping over short timescales to follow variations in the load demand. To provide spinning reserve services, such generators are capable of operating with reasonable efficiencies and emissions output at part-load conditions. Due to these requirements, such generators tend to operate for periods of time ranging from diurnal operation to multiple days or weeks.

Peaker: Peaking generators provide energy when load-following capacity and flexibility are insufficient to meet the load while maintaining regulation and reserve margins. Due to these operational characteristics, peaking generator types generally operate for the duration of a load peak, typically less than a few hours and provide very little spinning reserve capacity. Such generators must have a shorter minimum operating time than load-following and base-load units, since these generators must turn on and off as needed.

The increased variability and uncertainty associated with integrating large amounts of renewable resources into the electric grid will therefore have implications for the required capacity of the different generator types required to maintain the robustness of the electric grid. To be capable of meeting the variation in the electric load demand with large amounts of intermittent renewable resources at all times with the same level of robustness as the current system, the transmission system and dispatchable generators will be required to respond to more severe power fluctuations. Equipment and control strategies with the capability for handling these fluctuations must be implemented. The required capability of such systems and control strategies is a subject of current research and debate, however understanding the nature of the problem – the effect of renewable resources on the effective load demand – may provide valuable insight toward answering this question.

Solar and wind power installations typically require a large capital investment, which is offset by the harnessing of energy without continuous fuel input once the installation is operating. Therefore, it is generally desired to maximize the power output from installed solar and wind generators to lower the levelized cost of electricity. This is intrinsically different than many conventional generator types such as combustion turbines, which require a relatively low capital investment with higher fuel and operating cost. Due to this mechanism, electric grid utilities are generally required to purchase and deliver electricity obtained by renewable resources to consumers, regardless of the variability associated with the renewable power profile.

Further, the inability to manage renewable generation variations can limit higher penetrations. Such limits are currently being reached in European countries that deployed significant wind and/or solar renewable generation [5]. For example countries such as Denmark often experience periods of simultaneous high wind power output and low load demand, during which electricity obtained from wind resources must be sold at very low prices to neighboring countries that can utilize the excess electricity, and the strong import/export relationship between Denmark and neighboring countries with dispatchable resources is used to manage 70% of wind variability [6], a condition which is not applicable to every country at present. Therefore, load balancing issues present an obstacle for the installation of wind resources since many countries require internal methods for managing variability.

2. Background

Due to the increased attention to large scale integration of renewable resources in recent years, various studies on the impacts of integration large amounts of renewable resources into power systems at a variety of scales have been studied from different perspectives, using a variety of different metrics.

Milligan and the NREL Western Wind and Solar Integration (NREL-WWSI) [7] project have investigated on the effect of the holistic integration of wind and solar resources on electric grid operations up to renewable penetration levels of 35%. Utilizing modeled wind and solar data as presented in Appendix A, the study discovered that coordination between different balancing areas is necessary to reach a renewable penetration level of 35% or higher. The aggregation of wind and solar sites was found to aid in mitigating the impacts of large renewable power fluctuations, and the operational impacts of renewable resource integration did not differ significantly between the use of local, low-quality resources and remote, high quality resources. Exports of power from the study footprint area which covers a large portion of the southwestern United States were found to decrease as the renewable penetration of the receiving area increased.

Ostergaard [8] presented use of a multi-criteria optimization analysis for demonstrating the sensitivity of energy system design with renewable resources to the prioritization of different optimization criteria using the EnergyPLAN software. Examples of optimization criteria included whether the system operated in non-islanding or islanding mode, reserve capacity requirement, import/export use, fossil fuel use, renewable penetration level, carbon dioxide emissions, and various components of energy-related costs. The analysis was applied to the integration of heat pumps and wind power in Western Denmark using well defined cases as an example, and it was discovered that the prioritization of different optimization criteria yielded very different ‘optimal’ system configurations. In addition, there have been a number of further efforts that have focused on the optimization of the renewable resource mix for different types of systems based on prioritization of certain criteria [9–11].

Lund [12] performed an analysis using the EnergyPLAN software to determine the optimal combinations of solar photovoltaics, wind power, and wave power to be integrated into a Danish power supply with a high degree of combined heat and power penetration. Hourly data for wind, solar, and wave power were obtained for the year 2001 from various sources. The main metric used for evaluation was the amount of excess renewable generation present, and the search for combinations of the aforementioned resources were conducted to minimize the amount of excess renewable generation present by taking advantage of synergies between the different renewable resources present in Denmark. It was shown that the large scale integration of individual renewable energy resources imposed a large amount of excess power generation. To minimize the amount of excess power generation, it was concluded that wind power should produce 50% of the total energy obtained from the renewable mix, and the complementing combination of solar photovoltaic and wave power is dependent on the total renewable penetration level. If the penetration level is below 20%, the optimal contributions were found to be 40% solar photovoltaic and 10% wave power. If the penetration level is above 80%, the optimal combination was found to be 20% solar photovoltaic and 30% wave power. Further, it was concluded that the mixture of different renewable resources alone would not eliminate the onset of excess power generation, and while it was a supplement to potential solutions, other strategies would need to be utilized to integrate large amounts of renewable resources without excess power generation. Lund [13] also further used the EnergyPLAN model to conduct an energy flow analysis to discuss the issues and perspectives regarding reaching a 100% renewable penetration level in Denmark, focusing on wind, solar, wave, and biomass power. It was concluded that from an energy flow perspective, the attainment of this goal is possible since the necessary renewable energy sources are present and is contingent on the development and implementation of technologies such as combined heat and power, heat pumps, hydrogen storage for frequency regulation and production of fuel for transportation in combination with savings and efficiency improvements.

A report by the California Energy Commission [5] conducted a review of international experience with the integration of intermittent renewable energy resources onto grid-scale power systems, focusing on lessons learned that could aid in the integration of renewable energy resources into the California electric grid. This report focused primarily on wind power due to the large installed capacity of wind farms throughout the world compared to solar power. It was discovered that transmission system operators in Europe tended to implement very strict control strategies for the management of wind power, including ramp rate limits, the required ability to provide frequency control, and wind power curtailment strategies. A restructuring of the ancillary service provisions was found to be necessary at higher renewable penetration levels. Issues were also reported in New Zealand regarding the onset of very high ramp rates and curtailment due to the presence of a base load in the power system. A diverse array of strategies including wind forecasting and demand response has been implemented to accommodate wind power, however the specific strategies utilized vary by region and country. It was also suggested by various studies that the implementation of wind turbine performance controls and the sharing of reserves or energy imbalances between multiple control areas allowed more robust management of increasing amounts of variable generation.

Additional integration reports and studies have been conducted focusing explicitly on wind power [14–17]. Wind power has been the focus of many integration studies due to its large grid-tied capacity worldwide and its higher degree of unpredictability. An outline of technical challenges presented by the integration of wind power into the electric power system was presented by Georgilakis [18]. It was discovered that the variable nature of wind power could pose challenges for the dispatch and allocation of reserve resources, using the reserve capacity requirement as the main metric and indicating that for a wind penetration level of 10%, the reserve capacity increase is on the order of 2–10%. The variable nature of wind power also has implications for the costs associated with its integration into the current market structure, indicating that operating cost impacts are small at low penetration levels and moderate at higher penetration levels (10% or higher). Variation in wind power output also poses issues for the power quality of electricity on the transmission system, causing voltage dips, frequency variations and low power factors, possibly undermining the ability of the electric grid to provide the levels of reliability required by end users. Economic transmission planning has also been deemed a challenge. Finally, the onset of wind power curtailment due to excess power generation without complementary energy management strategies or strong interconnections with other control areas was discovered to be a challenge. Similar types of challenges were also identified by a variety of other wind integration studies [17,19,20].

However, there have been some integration studies for large scale solar power. Denholm [21] analyzed the impacts of large scale solar photovoltaic deployment on generators on the electric grid, also primarily using the amount of curtailed renewable energy as the main metric for quantification. It was concluded that due to the large reliance of the current generator fleet on base-loaded generators, large amounts of electricity generated by solar power would have to be rejected by the electric power system when the solar penetration level reaches about 15%. To accommodate the large scale deployment of solar photovoltaics, it was concluded that an increased degree of generator flexibility brought about by decreased reliance on base-loaded generators could allow solar penetration levels to reach 20–30% before the onset of curtailment for solar power. The use of energy management strategies such as energy storage, demand response controls of end use appliances or linkage with the transportation sector in terms of plug-in hybrids or hydrogen production could be used to allow the solar penetration level to be increased further.

While many studies have quantified and evaluated a particular aspect or issue regarding the integration of intermittent renewable resources on the electric grid, there still remains many effects of the large scale integration of renewable resources on the power system that are yet to be quantified and evaluated. Quantification and evaluation of these challenges is difficult due to the complexity of the mechanisms governing the operation of load balancing elements in a given electric system, and the variation between systems. This study therefore seeks to present an array of suitable metrics which can be quickly calculated for quantifying and evaluating, at a general level, the different impacts of the use the large scale integration of renewable resources into a load balancing system without requiring the specific details of load balancing element operation such as market mechanisms. The aim of these metrics is to demonstrate the level of information that can be obtained about the impact of a system modification without outright modeling of the specific mechanisms governing load balancing system. These metrics will then be specifically applied to the utility grid of the state of California to serve as a case study to identifying the types of challenges for utility-grid load balancing that be potentially faced when reaching very high renewable penetration levels, such that an indication of how the capabilities of load balancing elements need to be improved in order to accommodate these high renewable penetration levels. It is important to note, however, that the integration analysis carried out in this study will focus on load balancing and energy management. This analysis will use the developed metrics to demonstrate issues for load balancing elements in the electric grid that arise due to the dynamic character of load demand and power producing elements. Issues that manifest for transmission system operation are not examined explicitly in this study, and are subjects for future work.

3. Metrics of quantification

In order to accurately determine the effect of integrating large amounts of renewable resources into a load-balancing electric system, a range of relevant metrics must be established which quantify the different manners by which the integration of renewables will affect the design and operation of load-balancing elements such that dispatchable generators will meet the electric demand within the system at all times. Once developed, these metrics can be applied to any scale of electric system with a load demand and primary generators, and can also be used to compare the design and operation requirements of different system configurations. The significance of each metric discussed herein.

3.1. The net load signal

The majority of the analysis focuses on the characteristics of the “net load” power, which is the load that dispatchable generators will have to meet in time and is defined as follows:

$$P_{NL} = P_{Load} - P_{Ren} \tag{1}$$

Where P_{Load} is the total electric load demand at a single instant and P_{Ren} is the corresponding total renewable power generation that is actually delivered to meet the load at that time, after the effects of power curtailment and losses, if applicable, have been accounted for.

On the utility grid, the net load signal represents the power profile that generators in the electric system in combination with any auxiliary technologies must be able to meet at all times and follow dynamically in order to ensure that the total power generation is always matched to the load demand. The properties of this signal have direct implications for the required temporal behavior of electric generators in a system such as the utility grid. The generators which are tasked with meeting the net load power are called “balance generators”. Since this particular study does not incorporate any auxiliary technologies such as energy storage, the balance generators are the primary load-balancing element that must meet the effective load demand in this case. Therefore, all of the metrics presented as follows are properties of the net load signal that pertain to a different aspect of balance generator fleet behavior or design. This signal has the same significance for any scale of internally balanced system, where the load demand of the system is met mostly by energy resources internal to the system. Such a system will be referred to as a ‘balanced’ system.

The proposed metrics can be applied to different measured signals of the system to obtain different types of information depending on the type of system that these metrics are applied to. A list of the proposed metrics is presented as follows.

3.1.1. Parameters of the net load signal

- Maximum Net Load Value
- Minimum Net Load Value
- Net Load Value Range
- Net Load Capacity Factor

3.1.2. Surplus generation metrics

- Surplus Renewable Fraction

3.1.3. Occurrence and duration metrics

- Load Duration Curves
- Daily Occurrence of Maximum and Minimum Net Load Values
- Generator Duration Counts

3.1.4. Frequency-based metrics

- Power Spectral Density.

The significance of each metric for self-balancing and non-self-balancing systems is presented as follows.

3.2. Parameters of the net load signal

Some information about the design and management of load-balancing systems can be garnered by simply examining the parameters of the net load signal. The particular parameters considered and their significance to load balancing is as follows:

Maximum net load: This is the maximum value of the balance signal over the time period considered.

- The maximum net load value indicates the minimum balance generator fleet rated power capacity that is required to meet the load demand of the system.

For a balanced system, the balance generator fleet must be sized to provide at least this amount of power even if only for one time instant throughout the time period considered to prevent outages. This generator fleet size does not take into account the additional margins for safety and reliability. However, the inclusion of these margins serves only to increase the required generator fleet size, and therefore the metric indicates a minimum required generator fleet capacity.

Minimum net load: This is the minimum value of the net load signal.

- The minimum net load value indicates the fraction of the balance generator fleet capacity that must be capable of shutting off or operating at significant part load.

For a balanced system, this signifies the most extreme part-load condition that the balance generator fleet must be capable of operating at. On a large scale system, multiple generators within the fleet must be shut off to meet this load point. A low minimum net load value indicates that a larger fraction of the fleet must be capable of shutting off, and a value of zero indicates that the entire fleet may need to exhibit that capability unless alternative measures such as premature curtailment of renewable power are taken. On a small scale, a single generator or handful of generators will most likely be called to operate at part load.

Net load range: This is the difference between the maximum and minimum of the balance signal.

- The net load range indicates the fraction of the balance generator fleet capacity that must be dispatchable and therefore is one measure of required fleet flexibility.

For a balanced system, this quantity has implications for the required degree of flexibility, as the balance generator fleet must be capable of spanning all load points within this range and this amount of installed capacity must be flexible (i.e. capable of regularly changing power level). A larger net load range will require that the balance generator fleet be capable of cycling a larger fraction of its generators for at least one start and stop cycle, indicating the need for increased flexibility.

Net load capacity factor: The balance capacity factor is defined as the ratio of the average balance power to the maximum balance power.

- The net load capacity factor measures the utilization of the installed balance generator fleet assets.

For a self-balancing system, this quantity gives an indication of how much of the total installed capacity of the balance generators is typically used over a given time period. Generator cost is directly related to this metric, since capital investment must eventually be recovered by revenue garnered by producing and delivering power. A large maximum net load indicates a large installed capacity and therefore a large capital investment, while the average net load is indicative of the typical power delivered and is therefore tied to the financial return on the investment. High capacity factor values are preferable, since this indicates that the installed assets are being fully or mostly utilized for the intended purpose.

3.3. Surplus generation metrics

Surplus renewable generation (%): This is the fraction of the available renewable energy that cannot be used to immediately serve the load of the system in question.

- The surplus renewable generation measures the extent of utilization of the installed renewable energy resources.

The obtained renewable energy that cannot be used to serve the load of the system in question due to the presence of excess power in the absence of sufficient demand must be transmitted to another balancing area, stored, or curtailed. In the case of curtailment, a high surplus renewable fraction indicates wasting of the potential to generate renewable power. The significance of this metric is the same for all scales of load balancing systems. Low values are preferable, as that indicates that the installed renewable resources are utilized to the highest extent possible within the system that such resources were installed to serve.

3.4. Occurrence and duration metrics

Load duration curve: This metric displays the amount of time that the net load power is equal to or above a particular value. This gives a sense of how much of the generation capacity of system equipment is utilized for different fractions of the time period considered.

- In a self-balancing system, this metric displays the required part-load operation of the balance generator fleet, the distribution of how often the fleet operates above a fraction of its rated capacity, and how these characteristics change with different system configurations.

For a self-balancing system, the distribution of balance generator operation can be identified: whether the balance generator fleet operates with most of its generators on or off for a defined fraction of the time period considered. High balance power relative to the maximum capacity for a long period of time indicates low turndown and high utilization, while low net load power relative to the maximum capacity indicates the opposite. A load duration curve with a continuous shape indicates that the balance generator fleet operates across a spectrum of load points, while a shape with distinct steps indicates that the balance generator fleet typically operates at discrete load points. This metric has implications for the dispatch of generators within the balance generator fleet, and insight into the progression of the required part-load operation with renewable penetration level can be obtained.

Daily occurrence of max. and min. net load: This metric indicates the hour of each day in which the daily maximum and minimum balance values occur for a given system configuration.

- For self-balancing systems, this metric gives insight into the typical periods of grid congestion which can be used for determining electric rate structures.
- This metric also allows one to assess the compatibility of a given system with auxiliary energy management technologies.

Examining this quantity at different renewable penetration levels also has implications for the compatibility of a given renewable mix with other auxiliary technologies such as electric vehicle charging or thermal energy storage, which preferably charge during periods of minimum load.

Generator capacity by type: The distribution of generator capacity by type is a metric that allows one to estimate the respective capacities of peaker, load-following, and base-loaded power plants in the balance generator fleet based on the duration of generator operation based on the length of time that a balance generator unit is operating.

- For a self-balancing system, this metric gives an estimation of the respective fractions of balance generator types (peaker, load-following or base-load) that will be required to meet the load demand and the change in the mix required for different system configurations. Changes in this mix have implications for balance generator fleet efficiency and emissions.
- The provided estimation does not explicitly model spinning reserve or other margins and market bidding operations.
- In order to use and interpret the significance of this metric correctly, the balance generator fleet must be assumed to be comprised of equal capacity generator units and a reasonable correspondence between generator type and duration must be known.

The development and calculation of the metric is presented as follows:

The balance generator fleet is assumed to be composed of equal capacity generators, and the diversity of the balance generator fleet is not captured. The generator duration counts are obtained by examining the net load signal at different given power levels which are increased by equal increments from zero. The increment magnitude is equal to the assumed capacity of the individual generators composing the balance generator fleet. At each power level, the periods of generator operation (start and stop) at or above that power level are located and each of their duration recorded. A graphical representation of the process is presented in Fig. 1:

At each power level, the distribution of the duration of generator operation (t_1, etc…) is sorted into a histogram based on categories of generator operation periods that correspond to typical peaker, load following, and base load power plant operation. The ratio between the number of counts in each category and the total number of counts for this particular power level (generator) is calculated. The capacity of the generator is then divided among the categories according to this distribution. For example, if the assumed generator size is 10 MW and a particular generator has half of its operation periods fall into the peaker category and half into the load following category, this generator contributes 5 MW to the total peaker capacity and 5 MW to the total load following capacity.

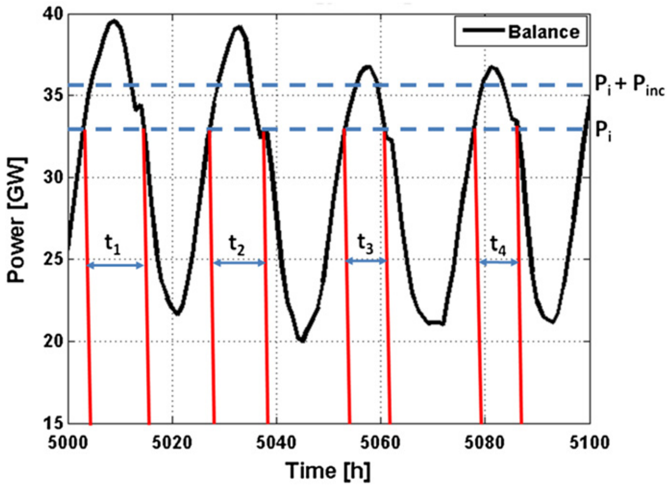

Fig. 1. Example of extracting generator duration counts.

The process is then repeated for successive power levels until all levels up to the maximum net load value are examined. At this point, the total contributions of each generator to the peaker, load-following, and base-load categories are then added together, and an estimation of the total capacities of each type of power plant is obtained.

For this study, the assumed generator size is 10 MW and the generator operation periods are categorized into ranges which correspond to different types of electric generators according to the following as presented in Table 1:

These categories are not strict rules for the dispatch of different generator types, since such rules vary with market operations and regional load balancing entities. Rather, these categories are a reasonable but loose representation of the typical average duration period of a specific type of electric generator based on an examination of actual generator dispatch from Federal Energy Regulatory Commission in the year 2000 for the state of California [22]. Also note that the generator duration counts does not take into account the requirements for spinning reserve and other margins that would contribute strongly to the generator type portfolio, and therefore is not exactly representative of the dispatch of generator types in time, but rather gives an indication of trends. Exact modeling of the generator dispatch in time is beyond the scope of this work.

For example, if the capacity corresponding to shorter-duration generator types increases for a fixed maximum balance fleet capacity, this implies that the balance generator fleet will have to be composed of increased fractions of peaker and load-following units, as this indicates that balance generator units will tend to only be in operation for shorter time periods. This also indicates that the relative capacity of base loaded power plants will need to be decreased to accommodate for the new characteristics of the net load signal. A shift in the balance generator type mix in this manner could have strong implications for the overall emissions and efficiency of the balance generator fleet. While real systems are composed of generators with a diverse array of capabilities, resolution of such would require specific spatial and temporal data for every power plant within a given system, the properties of which would vary from location to location. Therefore, to obtain a general sense of how the balance generator composition by service type behaves, the use of equal capacity generators is sufficient.

3.5. Frequency spectrum metrics

Power spectral density (PSD): This is a frequency domain measure that quantifies the relative magnitude of typical variations in the net load signal as a function of oscillation timescale

Table 1
Average generator duration periods per cycle.

Category	Duration period length	Classification	Typical generator types
1	≤5 h	Peaker	Natural-gas brayton cycle Reciprocating engines
2	6–168 h	Load-following	Natural-gas combined cycle Natural-gas rankine cycle Natural-gas brayton cycle
3	169 + h	Base-load	Nuclear rankine cycle Coal-powered rankine cycle Gasified coal-powered combined cycle

(frequency), with important frequencies registering as ‘peaks’ in the spectrum. Large peaks correspond to high magnitude fluctuations and vice versa. This measure sheds insight into how the magnitude and frequency of commonly experienced signal fluctuations change with renewable penetration level.

- In a self-balancing system, this metric gives an indication of the dispatch of units in the balance generator fleet in time and timescales of variation of balance generator units.

For a self-balancing system, this metric highlights implications for the dispatch of generators of the balance generator fleet in time. For example, large peaks in the spectrum occurring at higher frequencies indicate that the net load signal typically exhibits high magnitude fluctuations on a fairly fast timescale, therefore a large capacity of balance generators would have to be dispatched on this timescale to balance such fluctuations. An increase in the magnitude of a PSD peak corresponding to a short timescale with renewable penetration level would indicate that higher capacities of fast-cycling generators would need to be installed to accommodate net load fluctuations.

4. Case study: effect of high renewable penetration on the electric grid in California

This section applies metrics presented prior to the electric system of the state of California to determine implications for the design and operation of dispatchable generators within the utility grid with increased renewable penetration. It is important to emphasize that in this study the balance generator fleet is assumed to operate without any uninterruptable base load such that a wide range of impacts can be identified.

The details of the utilized wind and solar data, as well as the renewable deployment curve for determining the renewable resource mix for each renewable penetration level are available in Appendix A. To obtain solar power output from irradiation and weather data, this model uses a first-principles model developed by Tarroja [23].

4.1. *Behavior of the Net Load Statistics*

Utilizing the renewable mix described previously, the relevant statistical properties of the net load signal behave as presented in Fig. 2:

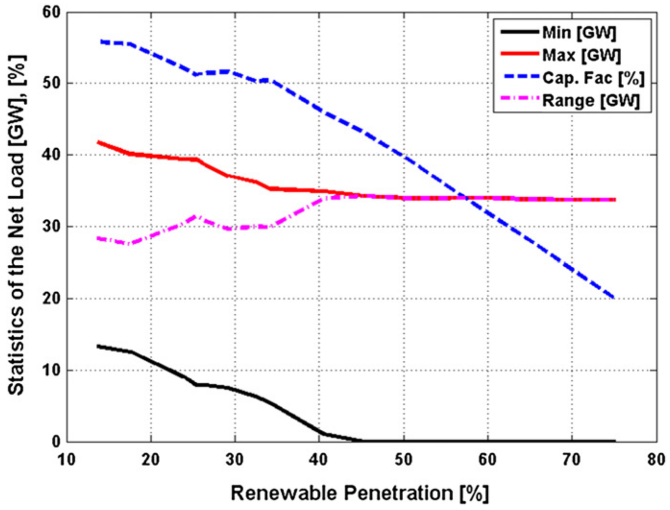

Fig. 2. Net load Statistics: diverse renewable scenario.

As renewable penetration level is increased, the maximum net load decreases slightly at lower renewable penetration levels after which it remains relatively constant. The maximum net load decreases from 41.73 GW at the 13% penetration level to 34.89 GW at the 40% level, and remains relatively constant to about 33.77 GW at the 75% level. The decrease in the maximum net load at lower renewable penetration levels is primarily due to the presence of solar power and increases in non-intermittent renewables. Solar power occurs during periods of peak or near-peak loads and tends to decrease the maximum net load to a limited extent. The occurrence of solar power peaks during the daytime decreases the noon to 1 pm load peak at lower solar capacities by leveling the load during that time to a limited extent. As solar power increases, however, the time of maximum net load shifts toward the late afternoon during the second load peak, caused by citizens arriving home from work and utilizing residential appliances, where solar power is generally low or zero and therefore cannot affect this peak. In addition, the onset of high wind power in this region tends to be in the late night and early morning hours after the second load peak has passed, and wind power also tends to be low during this late afternoon period. This trend is especially prevalent in the summer season when loads tend to be highest. Therefore, after the non-intermittent renewables are no longer increased in capacity and wind and solar power become the primary means for increasing renewable penetration level, the maximum net load may not be affected significantly.

This result implies that without energy storage or some form of demand response to level the maximum load, the maximum installed capacity of the balance generator fleet must remain relatively constant even though the energy obtained by such generators will be decreased. The balance generator fleet will be required to have a large capacity, and the installation of renewable resources alone will not decrease this capacity appreciably due to a high reliance on intermittent renewables. This result also implies that the assumption that an increase in solar power will reduce the peak net load power on a one-to-one basis is faulty and should not be used.

The minimum net load starts at about 13.51 GW at the 13% RE level and decreases in a fairly linear manner with renewable penetration level to zero at the 45% penetration level. The decrease in the minimum net load at lower renewable penetration levels is primarily due to the large presence of wind power production, which produces near-peak values during the late night and early morning hours when loads are the lowest. Since increasing wind power is the primary method for increasing renewable penetration level at the low end, the minimum net load is decreased significantly. The net load range increases from 28.38 GW at the 13% penetration level to the magnitude of the maximum net load by the 45% penetration level, exhibiting only a small decrease from the 25% to the 28% penetration level due to an increase in solar power during that race which decreases the maximum net load.

This result implies that at renewable penetration levels near 45% without energy management strategies, if it is desirable to absorb as much of the obtained renewable energy as possible, the balance generator fleet may need to be capable of shutting off completely for periods throughout the year, and will also need to be capable of operating at any load point between 0% and 100% of its cumulative rated capacity. Operation of the balance generators in this manner also has implications for the reliability and degradation of combustion turbines due to frequent starting and stopping of operation. Alternatively, renewable power generation may have to be actively curtailed to prevent the balance generator fleet from decreasing power output below a certain level or maintain certain reserve margins and prevent excessive wear on combustion turbines.

Finally, the net load capacity factor is shown to decrease from about 56% initially to about 19% by the 75% renewable penetration level. The initial decrease at lower renewable penetration levels (below 33%) is slight, since the maximum net load is still decreasing due to solar power and non-intermittent renewables while the average net load decreases linearly with penetration level. Once the maximum net load begins to remain constant, however, the net load capacity factor still decreases in a linear manner since the average net load is still decreasing. By the 75% penetration level, balance generators only provide about 19% of the energy that the fleet is capable of providing, indicating a very low utilization of these assets.

This result implies that in order to accommodate large amounts of renewable power, the balance generators must have a large capacity which will not be utilized very often, even with a diverse portfolio of renewables. This type of supporting infrastructure can be very expensive since a large capital cost will be imposed by installing a high capacity system, but the return on investment will be very low since only relatively small amounts of energy are sold to the consumers.

4.2. *Behavior of the surplus generation metrics*

As increasingly large capacities of renewable power are installed on the electric grid, periods of peak renewable generation begin to cause periods of zero net load. The change in the surplus renewable generation with renewable penetration level is presented in Fig. 3:

Since there is no renewable over-generation before the 45% penetration level, the surplus renewable fraction is essentially zero before this level. Once over-generation starts to occur, the surplus renewable generation starts to increase in an exponential manner. Wind power primarily, and solar power strictly, exhibits peak power generation only during certain times of the day. Therefore, to increase the renewable penetration level further using wind and solar power, capacity must be scaled up such that that even periods of off-peak wind and solar power generation are contributing to substantial reductions in the net load signal. As wind and solar capacity is scaled up, however, the magnitude of the peak power output of such systems increases in tandem. This is especially prevalent at high renewable penetration levels. This causes hours of near-peak wind and solar power generation to cause periods of over-generation in addition to periods of peak generation, and therefore exponentially more energy is not used to serve the system load. By the 75% penetration level, about 19.22% of the total energy available from the renewable mix is not utilized within the system.

This result implies that without a means to dispatch loads, a fairly significant amount of renewable energy obtained may be wasted, consistent with the findings of Lund [12,24]. This may decrease the value proposition for renewable power installations at higher penetration levels, since such installations are characteristic of high capital costs and benefit financially from delivering large amounts of energy.

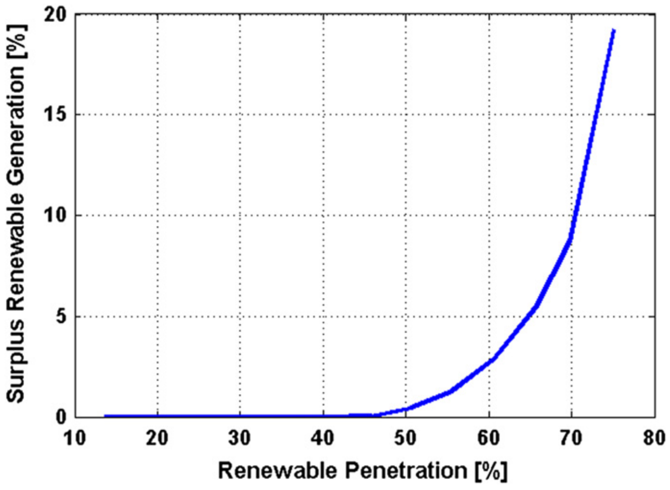

Fig. 3. Surplus renewable generation: diverse renewable scenario.

4.3. *Behavior of the occurrence and duration metrics*

4.3.1. *Load duration curves*

The progression of the load duration curves with increasing renewable penetration level is presented in Fig. 4:

As the renewable penetration level increases, the load duration curves show relatively uniform decreases in net load levels for lower renewable penetration levels (pre-over generation). This trend is primarily due to the presence of both wind and solar power in the renewable mix – solar power primarily decreases loads during the daytime whereas wind power generally decreases loads during the night time, and occasionally in the daytime as well. Therefore, the entire time spectrum of the load throughout the day is affected by renewable generation and all net load levels are decreased in duration. Once over-generation sets in, the decrease in net load levels begins to increase at an accelerated rate. As displayed by the load duration curves and curtailment metrics, the downtime increases as renewable penetration level is increased and the onset of curtailment is shown to occur between the 33% and 50% penetration level, which was determined to be 45% by the previous metric.

With the current electric grid mix, which is about 16% in the state of California, no over-generation exists since the current renewable penetration level is very small, and the fluctuations caused by renewable power generation are essentially noise in the system. Under this case, the balance generator fleet operates at or above 23 GW or 54% of maximum capacity for at least half of the year, and the net load levels do not drop below 13 GW as signified by the statistics. This is the part-load operation requirement of the current balancing generator fleet. At lower renewable penetration levels (below 33%), the shape of the load duration curve is maintained, indicating that the part-load requirements are relatively unchanged.

Above the 33% penetration level, renewable power fluctuations become noticeable in the system and the shape of the load duration curve begins to change, with an increase in the hours of low net load levels relative to the maximum net load for that case. The

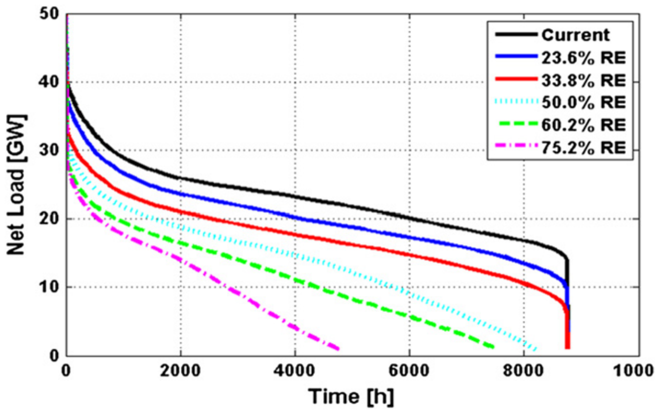

Fig. 4. Load duration curves: diverse renewable portfolio.

balance generator fleet in these cases will be required to operate at significantly decreased part-load levels as well as a large maximum capacity level. By the 75% renewable penetration level, the balance generator fleet only operates above 3.5 GW or 9.8% of maximum capacity for half of the year. These results imply that without energy management technologies and strategies, the integration of increasing amounts of renewables will impose significant part-load operation requirements and turndown periods on the balance generator fleet. The balance generator fleet in this case will be required to operate for most of the year with the majority of its generators shut off, indicative of the implications presented by examining the net load capacity factor. For the periods when the balance generators are in operation, the generator fleet will have to be capable of operating across the entire spectrum of load points with equal frequency, requiring flexibility in the dispatch of the balance generators.

4.3.2. *Daily occurrence of min. and max. net load*

A scatter plot which displays the magnitude of the minimum net load value and the occurrence of such value for the year 2005 at renewable penetration levels of a) 13%, b) 33%, c) 50%, and d) 75% is displayed in Fig. 5:

At low renewable penetration levels, the minimum load primarily occurs during the early morning hours, between 11 pm and 5 am. As the renewable penetration level is increased, the daily minimum load point starts to occur across multiple hours of the day. By the 33% renewable penetration level, the minimum power magnitude decreases primarily due to wind power and a large amount of occurrences remain between 11 pm and 5 am. However, some minimum load points start to occur during the daytime, between 11 am and 5 pm, which corresponds to the effect of solar power peaks occurring simultaneously with atypical wind power generation. By the 50% level, minimum load points span all magnitudes and tend to occur across almost all hours of the day throughout the year, and by the 75% penetration level, significant over-generation reduces the minimum load point magnitude to zero and tends to occur across all hours of the day.

This behavior implies that with increased renewable penetration, it will become increasingly difficult to predict the daily occurrence of minimum load. Primarily, this has implications for the use of a fixed schedule for time-of-use electricity pricing, where electricity is generally cheaper during periods of low load. The use of such a pricing scheme would not be appropriate once large amounts of renewable power are integrated into the electric grid due to the demonstrated unpredictability of the minimum load period. A possible alternative is the use of an electricity price signal that adjusts in real-time depending on the behavior of renewable generators.

The unpredictability of the occurrence of minimum load also has implications for the use of or interface with auxiliary technologies. For example, thermal energy storage is used to displace cooling loads toward off-peak hours, primarily the night time, to save on electricity costs and ease grid congestion. However, with increased renewables, the minimum load period may not always occur during the night time, and the system would have to adjust in real-time in order to serve its intended purpose.

A scatter plot which displays the magnitude of the maximum net load value and the occurrence of such value for the year 2005 at renewable penetration levels of a) 13%, b) 33%, c) 50%, and d) 75% is displayed in Fig. 6:

With a low renewable penetration level, the peak load strictly occurs during the daytime hours between 10 am and 8 pm. The load

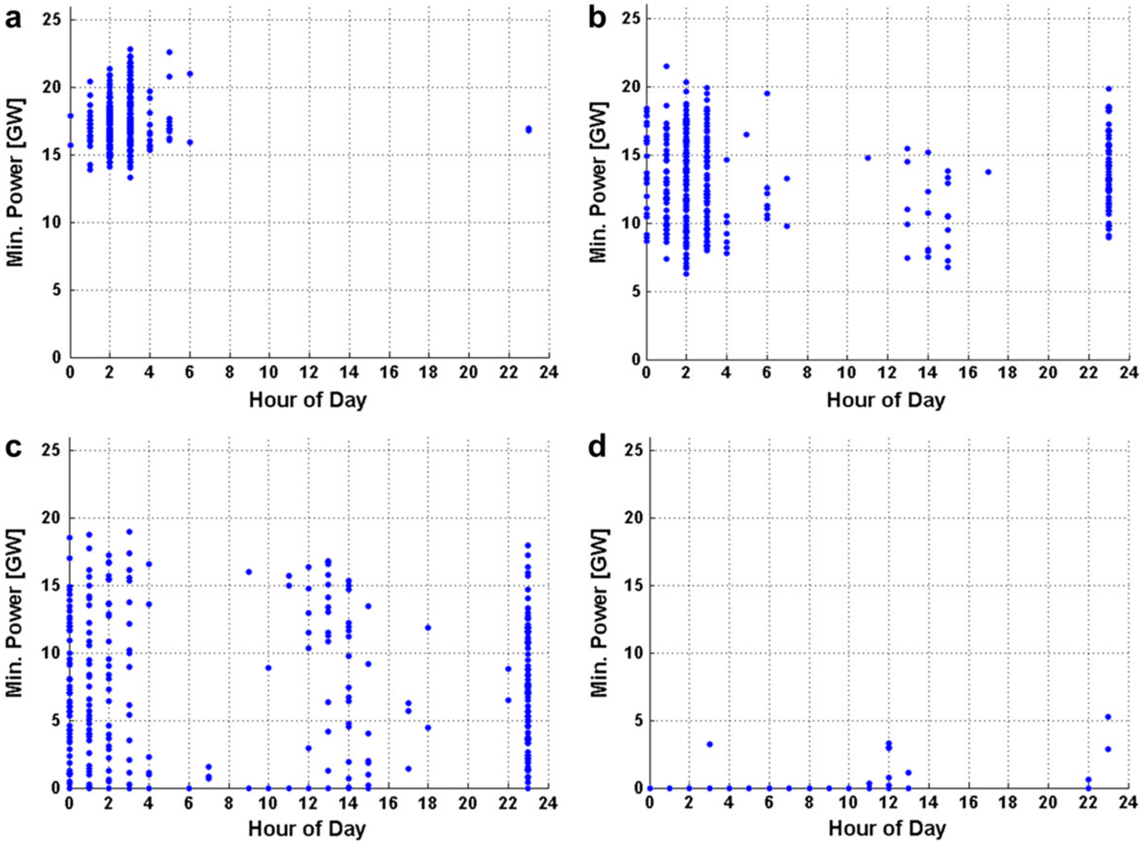

Fig. 5. Value and occurrence of minimum net load Value: a) 13% RE, b) 33% RE, c) 50% RE, d) 75% RE.

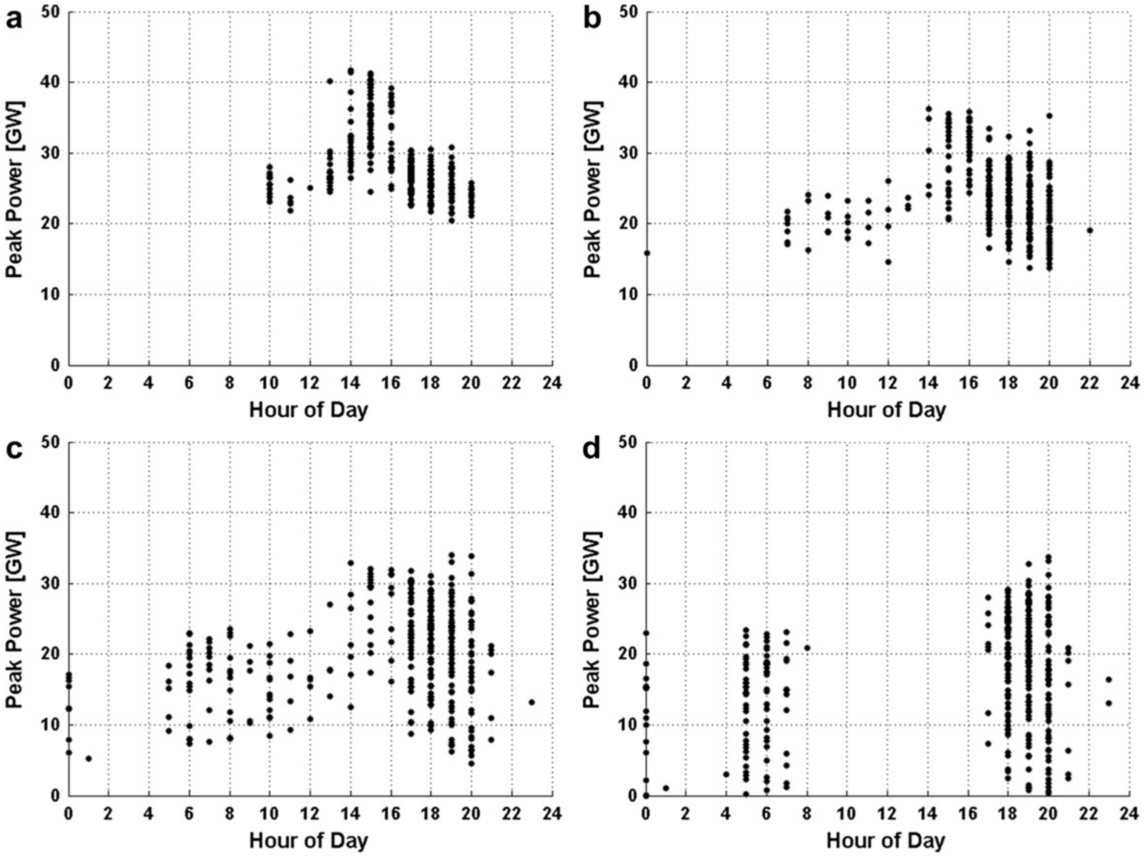

Fig. 6. Value and occurrence of maximum net load Value: a) 13% RE, b) 33% RE, c) 50% RE, d) 75% RE.

profile in this region generally exhibits two local load peaks, a daytime peak slightly after noontime which corresponds to the electricity demand of the business and industrial sectors, and a peak between 5pm and 8pm which corresponds to the increase in residential load due to the majority of citizens returning home and activating their home appliances and lights. The larger of these two peaks during the day will correspond to the maximum load peak.

As the renewable penetration level is increased to 33%, the magnitude of the maximum load points is slightly decreased and these points tend to span a larger range of times throughout the day. The concentration of maximum load points between 5 pm and 8 pm is slightly increased while the concentration between 11 am and 3 pm is slightly decreased. This is due to the onset of solar power partially negating the daytime load peak. Since the time duration of solar power does not expand to the early evening hours, and peak wind power in this region tends to occur during the late night/early morning hours, the residential load peak takes precedence as the period of maximum load.

A further increase in the renewable penetration level to 50% exacerbates this trend. At this level, maximum load points are shown to occur across almost all hours of the day, with the majority falling between 5 am and 9 pm. Stronger concentrations of maximum load points are still present during the time of the residential load peak between 5 pm and 8 pm, however a significant amount of the maximum load points occur outside of this time period. The resource mix at the 50% renewable penetration level contains slightly more than double the installed wind capacity of the 33% case, which is primarily responsible for the trend displayed herein. Since wind power does not have a strict time duration for occurrence, low to moderate amounts of wind power can occur during off-peak hours. As the wind capacity is significantly increased, the low amounts of wind power that occasionally occur during off-peak hours, such as during the time of the residential load peak, contribute to decreasing the magnitude of the load during the 5 pm–8 pm time window. This shifts the daily time of maximum load to the early daytime hours, when there is generally no wind power in this region and solar power has not yet reached its peak.

At the 75% renewable penetration level, the points of maximum load tend to occur in two distinct periods: 4 am–7 am and 5 pm–9 pm, as opposed to the relatively continuous spectrum exhibited by the 33% and 50% cases. This behavior is primarily due to the extremely large amounts of solar power that are present in the resource mix for the 75% case. At this level, the solar capacity is so large that solar power completely serves (and occasionally overpowers) the portion of the load that occurs during the daytime, and the points of maximum load are shifted toward times when solar power is virtually non-existent. Whether the load peak occurs in the early evening or mid morning hours depends on the magnitude of off-peak wind generation relative to the load at those times for each day.

This behavior implies that near and mid-term increases in the renewable penetration level will introduce a large amount of uncertainty into predicting when the maximum load point occurs throughout any given day. With the deployment curve used in this analysis and the characteristics of renewable power generation and load profiles from the state of California, the maximum load points only occur within predictable windows at either very low or very high renewable penetration levels. In between those levels, the maximum load point can occur essentially across a wide range of hours out of the day.

In the same manner as the shift of minimum load times, the shift of the occurrence of maximum load times has many implications for fixed schedule time-of-use electricity pricing. Electricity is generally more costly during periods of high load, and the current time-of-use pricing schedule is based around this precept. However, with increased renewables, the occurrence of maximum load periods become less predictable, and the use of a fixed time-of-use pricing schedule may not be appropriate.

Also similar to the implications of the shift of minimum load times, the shift in maximum load periods has implications for interfacing with different technologies such as energy storage or electric vehicles. Since many technologies may currently be used to control and mitigate excessive congestion on the electric grid, these technologies will have to be used in conjunction with each other to render the periods of maximum and minimum loads relatively predictable, or be capable of responding in real time to daily changes in the occurrence of maximum and minimum load times.

4.3.3. Generator capacity by type

The estimation of the capacities of different generator types at renewable penetration levels between 13% and 75% is displayed in Fig. 7, bounded by the maximum net load value as indicated by the solid black line:

As the renewable penetration level is increased, the total capacity of base-load generator types steadily decreases, the total capacity of load-following generator types remains fairly constant, while the fraction of peaker generator types significantly increases. The decrease in the base load capacity with increasing renewable penetration level follows closely the trend of the decreasing minimum net load level with increasing renewable penetration discussed prior. At the 13% renewable penetration level, the base load power plant capacity is estimated to be 14.6 GW, which is very close to the 13.51 GW minimum net load value. These two values are not equal since the base-load category includes generators which will operate for longer than 169 h but not necessarily for the entire year. This value decreases to 1.13 GW by the 45% penetration level, and to zero by the 75% penetration level. The load following generator capacity remains fairly constant, starting at 10.8 GW at the 13% penetration level, rising as high as 14.6 GW by the 45% penetration level, dropping to near its initial value at 10.6 GW at the 70% level, and decreasing to 8.5 GW at the 75% level. The peaker generator capacity, however, monotonically increases with renewable penetration level. At the 13% renewable penetration level, the peaker capacity is estimated to be about 16.2 GW, and increases steadily to 25.1 GW by the 75% penetration level.

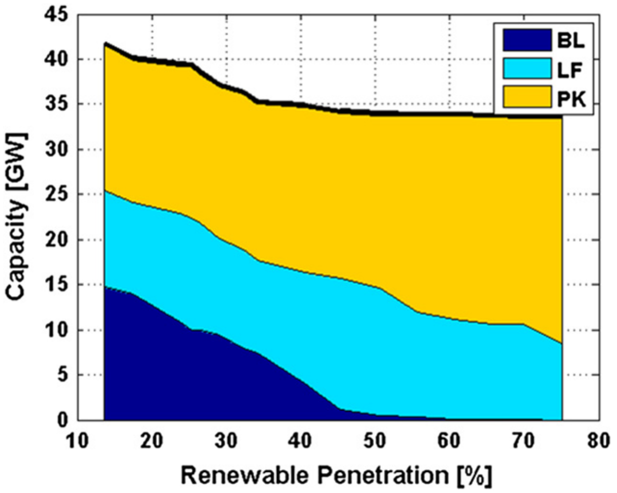

Fig. 7. Estimation of generator type capacities for renewable penetration levels between 13% and 75%. BL: Base Load, LF: Load-Following, PK: Peaker.

These trends tend to occur due to the increased variability that the increased amount of intermittent renewable capacity has on the effective load demand (net load power) and the nature of such variability. In general, these trends indicate that as more renewable resources are added to the power generation portfolio, the balance generators which meet the effective load demand will be required to operate and provide power for shorter periods. This behavior is due to the fact that the renewable resources that will have to be relied upon for increasing the renewable penetration level to high percentages tend to exhibit power profiles with large power output peaks that occur within short time windows, and these peaks occur regularly on a diurnal cycle.

Solar power, for example, provides high power during the daytime and zero power at nighttime, with steep ramp rates during transitionary periods in the early morning or early evening. Combined with the diurnal variability of the load demand, this behavior creates low net load power periods during the daytime when the raw load demand is usually high in addition to the low net load power period in the early morning hours when the raw load demand is generally low. Therefore the daily time of relatively high net load power is restricted to times of high load and low solar power, occurring in the early evening hours during the residential load peak. The duration of this peak, however, is relatively short (less than 6 h), and the steep drop off in solar power output preceding this period indicates that the generators which must meet this peak must start up quickly. These factors combine to increase the peaker generator capacity. In addition, very high solar power output during the daytime decreases the net load power below the original minimum value, interrupting the duration periods of base-load generator types and displacing such types with peaker and load follower generator types.

Wind power has a similar effect. In this region, wind power tends to peak at nighttime when the raw load demand is generally low, interrupting the operation of base load power plants and displacing such capacity with shorter-duration generator types. In addition, wind power tends to exhibit more frequent, short term fluctuations in power output compared to solar power. In a power generation portfolio containing high wind power capacities, fluctuations will be significant enough to correspond to multiple generators starting up and shutting down for the duration of such fluctuations. Since wind power peaks during points of originally low load, however, wind power generation does not typically interact with periods of high load demand similar to solar power, and therefore does not significantly change the shape of the net load power signal. The result is that wind power displaces base load capacity with primarily load following capacity.

The combination of wind and solar power compounds these effects since each resource tends to affect different time periods of the day. The combination of these resources disrupts base-loaded generator operation during multiple points throughout the course of a single day in a manner that is generally repeatable every 24 h and contributes to increases to further increases in peaker capacity. This combination also causes the load following fraction to remain fairly constant with renewable penetration. The presence of wind power displaces base load capacity with primarily load following capacity, while the presence of solar power displaces base load capacity with peaker capacity. Since the combination of both resources interrupts net load power generation at multiple points within the day, however, balance generators that would normally operate in a load-following manner due to the effects of wind power are interrupted by the presence of solar power. This causes load following capacity to be displaced with peaker capacity. Therefore, load following capacity is increased by wind power but decreased by solar power when installed in combination with the former. The net result is for the load following capacity to remain relatively constant. The small variation in load following capacity with renewable penetration is characteristic of the respective capacities of wind and solar power. When wind power capacity outweighs solar power capacity, the load following capacity increases slightly, while the opposite shows a decrease.

This result has strong implications for the design and operation of the balance generator fleet and identifies a key challenge that must be addressed with energy management strategies in order to accommodate high renewable penetration levels. The increased variability in the effective load demand will not accommodate generator types with minimum operation times such as nuclear power plants and coal-powered combined cycle power plants, which require long time periods to start up and shut down. Base load power plants generally provide the cheapest electricity rates due to exhibiting high plant capacity factors indicating good return on capital investment. In addition, base load power plants also tend to exhibit higher efficiencies, since the lack of required ramping capability allows these plants to operate at or near design power, more complex system configurations for recovering energy to be implemented and since the scale of such plants are typically very large, this minimizes heat losses due or other losses in turbine components. Base loaded power plants also exhibit lower criteria pollutant emissions (NOx, SOx, particulates, etc…) relative to the majority of load following and peaker power plants due to the large scale of such plants allowing predominantly on-design-point operation and the implementation of pollutant cleanup equipment such as selective catalytic reduction. While load following power plants can be configured to provide comparable high efficiencies and low emissions to typical base-loaded power plants with only slight increases in electricity cost, peaker plants generally cannot be. The quick ramping capabilities required of a peaker plant or general short-duration generator type do not allow much flexibility for energy recuperation components since such components slow the response of the system. Peaker plants by definition tend to frequently operate at part load where efficiency suffers in heat engines and emissions tend to increase significantly. Therefore, the decrease in base load capacity and increase in peaker capacity implies that without energy management strategies, the average efficiency of the balance generator fleet may be decreased at higher renewable penetration levels, and the criteria pollutant emissions of the fleet is likely to increase.

It is important to note, however, that this result estimates the respective capacity of generator types, not the energy obtained from each type. At high renewable penetration levels, it may be possible that a majority of the energy used to serve the load demand may be obtained from high efficiency load following plants and not peaker plants, therefore the effects of decreased efficiency and higher criteria pollutants emissions will still be present but may not be as pronounced to the same extent as the capacity numbers imply. To address those issues directly requires an examination of the dispatch and operation of each generator type in time taking into account all relevant margins, and modeling of the generator fleet and dispatch in time is beyond the scope of this work, but is a subject on ongoing and future work within our group. However, the elimination of the base load generator fraction and the need to maintain a large peaker capacity with a low capacity factor still poses significant technical challenges and will most likely increase the cost of electricity.

4.4. Behavior of the net load power spectral density

The progression of the shape of the net load power spectral density with increasing wind penetration level is presented in Fig. 8. Note that the renewable power data used in this analysis are spatially dispersed to the extent possible across the respective resource potential areas of California, and already takes into account the reduction in power variability due to the spatial dispersion of wind and solar resources. The limits of this effect are explored by Tarroja [25,26] and Ostergaard [27].

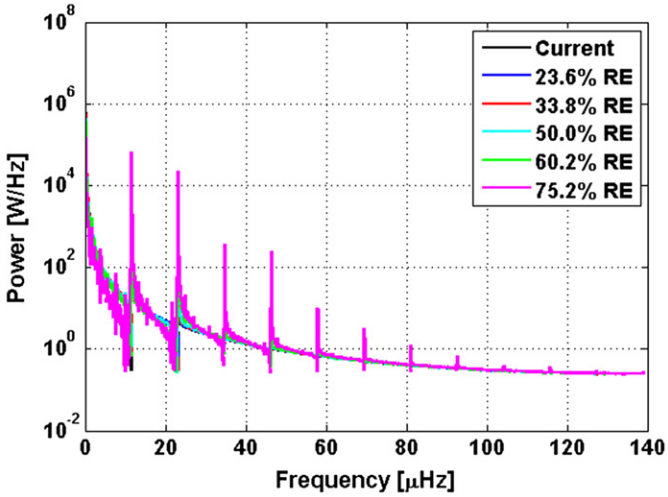

Fig. 8. Power spectral density: diverse renewable scenario.

The change in the magnitude of the peaks of the power spectral density (PSD) with increasing renewable penetration is difficult to determine from examining the PSD directly since the frequencies at which peaks occur do not shift with renewable penetration in this case and on these timescales. Therefore, for this section, changes in variability are directly analyzed in terms of the progression of the PSD peaks.

As the total renewable power portfolio becomes composed of a larger fraction of wind and solar power, the frequency spectrum of the net load signal will begin to exhibit peaks that correspond to the dominant fraction. Therefore, in order to examine variability, the magnitude of the PSD peaks at frequencies corresponding to 24, 12, 8, and 6 h timescales are examined as a function of renewable penetration, presented in Fig. 9:

For renewable penetration levels below 25%, the 24-h variability remains relatively constant after which it decreases to a local minimum at the 33% level. The constant region for the 24-h variability is mainly caused by the fact that according to the deployment curve used, at lower renewable penetration levels the renewable mix is largely composed of non-intermittent renewables, and compared to the fluctuations in the load signal, the fluctuations in intermittent renewable power output at these levels are very small.

The 12-h variability increases steadily due to the presence of a combination of wind and solar power. Wind in this region and solar power affect different times of the day typically, and the periods of peak output from wind and solar farms tend to be out of phase by approximately 12 h, therefore introducing 12-h variability into the net load signal. Large quantities of wind and solar power begin to be added at the 25% penetration level. Wind power primarily peaks during the night hours and solar power strictly peaks during the daytime hours. With a mix of wind power and solar power, the total renewable generation profile often exhibits two peaks in the diurnal profile corresponding to wind and solar peaks, approximately 12 h apart. As the power portfolio becomes increasingly composed of these resources, the magnitude of this variability increases. In the net load signal, these wind and solar power peaks manifest themselves as valleys. In addition, this effect serves to significantly decrease the 24-h variability, eliminating the daytime peak and nighttime valley of typical load behavior and

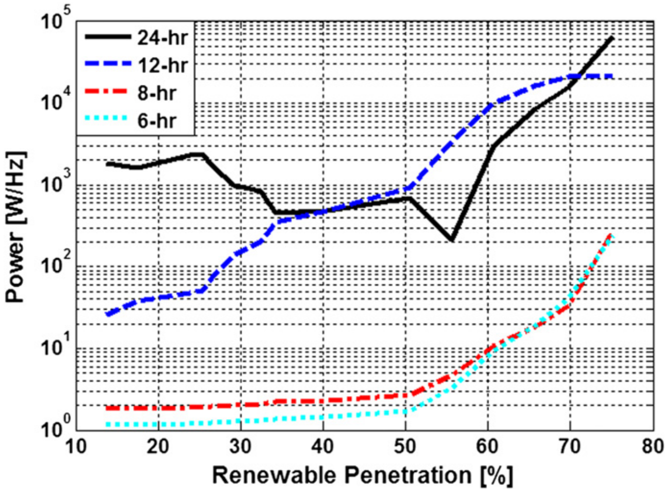

Fig. 9. Progression of PSD peaks: diverse renewable portfolio.

replacing it with net load valleys at the noon to 1pm time period and the late night/early morning hours corresponding to wind and solar power peaks, and net load peaks during the morning and late afternoon hours approximately 12 h apart. A time-series snapshot of this effect is presented for the 50% penetration level case in Fig. 10:

This effect has its strongest influence when the installed wind and solar capacities are equal or near equal. Note that in the progression of the PSD peaks, the 24-h variability reaches its lowest values and the 12-h variability exhibits the sharpest increase when approaching the 33% and 55% penetration level. These penetration levels correspond to renewable power mixes which contain equal or near equal wind and solar power capacities with the deployment curve used in this analysis. In this case, the magnitude of the wind and solar power peaks (and therefore net load valleys) are often near equal, creating a very strong 12-h sine wave component in the net load signal. The decrease in the 24-h variability at the 55% penetration level is the largest since wind and solar power are larger components of the power portfolio compared to the 33% level. When these capacities are not equal, a 24-h component is still strongly present due to the differences in the magnitude of wind and solar peaks, which occurs on a 24-h timescale but is nearly eliminated when wind and solar capacities are equal.

Confirmation of this trend was discovered by examining an isolated case where only wind and solar power are integrated into the load profile of the South Coast Air Basin in equal increments at every penetration level, up to peak capacities of 15,000 MW for each resource and a cumulative total of 30,000 MW. Such a case yielded the PSD peak progression presented in Fig. 11:

When wind and solar capacities are equal or near equal, the 24-h variability is decreased for large capacity ranges of wind and solar power while the 12-h variability sharply increases monotonically. Note that in this isolated case, the 24-h variability reaches a minimum at 40% penetration level and begins to increase afterwards, a trend which is reflected in the diverse renewable portfolio case from the 55% penetration level and higher. This effect is mainly due to the onset of over-generation.

Above the 55% penetration level in the diverse renewable portfolio case, the 24-h variability begins to increase sharply while the 12-h variability begins to decrease the rate at which it increases before saturating at very high renewable penetration levels. This effect is due to the onset of over-generation which starts to occur on a 24-h timescale due to the reliance on solar power for increasing the renewable penetration level at the high end. The effect of shifting the 24-h variability to 12-h variability is limited due to the fact that the net load valleys have a minimum value below which its magnitude cannot be decreased. In parallel, the net load peaks are also limited, since times of zero or near zero simultaneous wind and solar generation do not affect the net load peaks. Therefore, the amplitude of the 12-h sine wave component of the net load signal is limited, and the magnitude of the 12-h variability can only increase to a certain point. The onset of renewable power over-generation then becomes a major determining factor of net load variability and causes the behavior of the PSD peaks above the 55% penetration level. At the high penetration levels, solar power is relied on to be the primary component for increasing renewable penetration and the capacity of solar is greatly increased over the capacity of wind power in these cases. The capacity of solar power at these levels is subsequently large enough to single-handedly cause over-generation during periods of peak solar power generation, introducing periods of zero net load which occur in tandem with solar power on a 24-h timescale. A time-series snapshot of this effect for the 75% renewable penetration level is presented in Fig. 12:

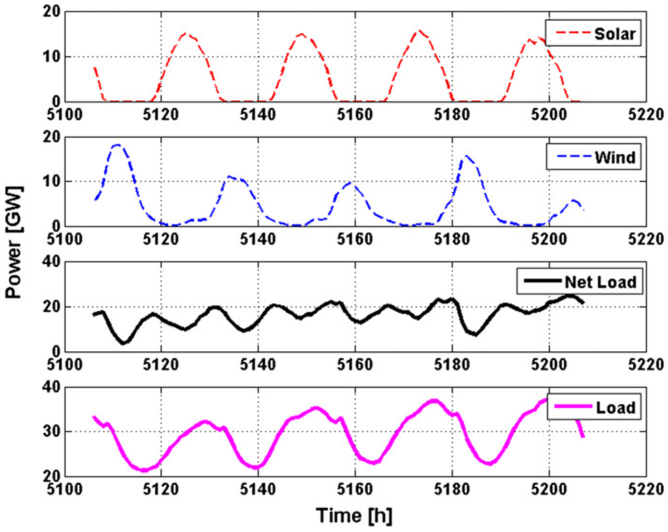

Fig. 10. Shift from 24-h net load variability to 12-h balance variability.

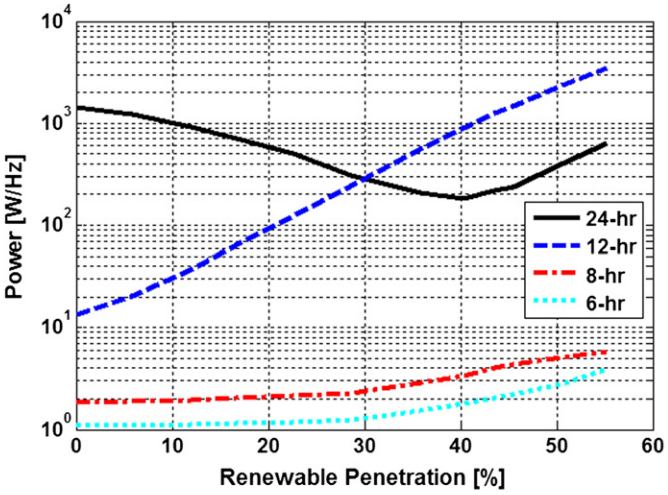

Fig. 11. Progression of PSD peaks: 50/50 wind and solar isolated case.

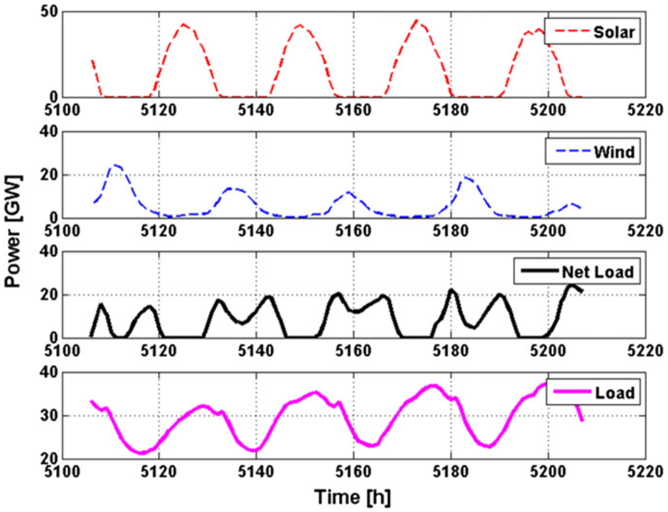

Fig. 12. 24-h timescale over-generation: diverse renewable portfolio.

The larger amounts of solar capacity that are utilized at the high penetration levels allow the onset of curtailment even during periods of relatively low solar power generation (such as the winter time), causing the sharp increase in 24-h variability.

Finally, the variability components on the shorter timescales of 8 h and 6 h increase monotonically with renewable penetration in this case. As more intermittent renewable generation is implemented into the power portfolio, the small magnitude fluctuations which occur on faster timescales due to cloud passes or changes in the prevailing wind become an increasingly large contributor to the altering the net load signal. Therefore, the magnitude of the variability on these timescales increases.

Overall, these results imply that in order to accommodate the highly dynamic behavior of intermittent renewable power generation, the balance generator fleet will need to be managed and prepared for dispatching large generation capacity on a 12-h timescale instead of a 24-h timescale at low to moderate renewable penetrations, and for dispatching such capacity on both a 12 and 24-h timescale at higher renewable penetrations. The integration of intermittent renewable resources requires that the balance generator fleet be flexible and capable of responding to large power variations across a range of timescales. Building this capability into the balance generator fleet may require the introduction of new generator operation and dispatch strategies taking into account these effects as well as those described by the other metrics prior. In addition, the balance generator fleet will need to be prepared for dispatching larger generation capacities on faster timescales.

5. Summary and conclusions

This study presented an array of metrics based on the properties of the effective load demand (net load) that must be met by dispatchable generators that evaluated and quantified a wide array of effects at a general level that the large scale integration of renewable resources would have on the design and operation of load-balancing elements of a given system without the outright modeling of the governing mechanisms of the load balancing system. This set of metrics was applied to examine the impacts of the integration of a diverse portfolio of renewable resources on the operation and design of the dispatchable generator fleet without the presence of auxiliary energy management strategies in the state of California from a bulk load management perspective as a demonstration of its capabilities. The approach identified a number of challenges that must be addressed, and it was determined that the integration of renewable resources to reach high renewable penetration levels could impose severe challenges for the balance generator fleet and implied costs of installing and operating such a fleet *without energy management strategies*. A summary of the study is as follows:

1. The balance generator fleet will be subject to large periods of part-load operation.
2. Low net load capacity factors imply that capacity in large excess of what is used will need to be installed on the grid, indicating high capital costs with low rates of financial return due to a minimal amount of energy being obtained from such generators.
3. The onset of non-zero surplus renewable generation at high renewable penetration levels prevents the utilization of all of the energy obtained from renewable resources. In addition, large amounts of energy may be wasted at the high renewable penetration levels.
4. The onset of non-zero surplus renewable generation requires that a strategy to potentially turn off the balance generator fleet may need to be developed, potentially introducing frequent periods of downtime and start-stop cycling. In the presence of base loaded generators, non-zero surplus renewable generation will occur at lower penetration levels or base loaded capacity will have to be reduced, albeit at higher penetration levels than either wind or solar integration alone.
5. The integration of large amounts of renewable resources render the occurrence of the daily maximum and minimum load points more unpredictable, rendering the use of a fixed schedule for time-of-use electricity pricing inappropriate.
6. The large scale integration of renewable resources will require an increase in the capacity of peaker generator types and a decrease in that of base-loaded generator types for the effective load demand to be met at higher renewable penetration levels based on an estimation of minimum generator operation time.
7. The dynamic behavior of intermittent renewable resources such and wind and solar will require that the balance generator fleet be capable of dispatching larger generation capacities on faster timescales, most notably the 12-h timescale as opposed to a 24-h timescale.
8. To reach very high renewable penetration levels in the California electric grid without significant impact to the design, operation and management of balance generators, energy management strategies must be implemented to complement large capacities of intermittent renewable energy resources.

Further implications of these challenges are as follows:

- Frequent operation at severe part-load levels has the potential to decrease the efficiency of the balance generator fleet unless balance generators are designed to accommodate such operation, and gives rise to low asset utilization as exhibited by low net load capacity factors.
- Nonzero surplus renewable generation may decrease the value proposition of renewable resources, especially of types that have very high capital costs (such as solar power).
- Shutting off the balance generator fleet may increase degradation rates of combustion turbine components, or alternatively, renewable power may have to be curtailed prematurely to allow the balance generator fleet to maintain contingency margins.
- The unpredictability of daily minimum and maximum load points at increased renewable penetration levels may require

changes in the operation of auxiliary technologies to serve their intended purpose.
- The shift in the generator type mix may cause the cost of electricity and criteria pollutant emissions increase, while balance generator fleet efficiency may decrease.

It is important to note that these challenges were identified in the absence of an uninterruptible base load, that is, the entirety of the balance generator fleet was assumed to be flexible. The modern balance generator fleet does not currently exhibit this capability: namely, base loaded generators which cannot be turned down to operate at part load are a significant contributor to the current electric generator fleet. The presence of a non-zero uninterruptable base-load value exacerbates these identified challenges further. The overall primary conclusion of the case study is as follows: For the state of California and similar areas, there is a strong need for the development and implementation of a suitable portfolio of energy management technologies and strategies to mitigate these challenges to the extent possible and allow higher renewable penetration levels to be reached. Energy management technologies such as demand response, energy storage, and other types of dispatchable loads will be required to allow high renewable penetration levels to be reached without significant impacts on the operation of the balance generator fleet, and this is a clear topic for future work.

In addition, the additional issues that arise due to constraints on transmission and distribution system operation were not accounted for in this study, but also need to be solved to allow attainment of high renewable penetration levels and a suitable set of technologies to manage voltage and other relevant parameters must also be implemented in that sector in tandem to bypass obstacles that currently limit renewable energy penetration on the electric grid.

Overall, this study presented a set of metrics based on the properties of the effective load demand which can be calculated for any electric system. The use of these metrics allowed a wide array of general but quantifiable insight about the implied requirements of the design and operation of load balancing elements of the electric system to be obtained with relatively limited information. The ease of calculation of these metrics allows quick comparison of the effect of renewable penetration on different electric systems and, as a result, serves as an initial tool to optimize the renewable portfolio for an electric system with a load demand of a different character. These metrics can be extended to apply to any scale of electric system, from buildings to entire grid-balancing areas, and requires only an effective load demand (net load) signal and knowledge of the constraints of the load-balancing elements of the system.

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Appendix A. Utilized data and renewable deployment curve

For the case study in this analysis, the metrics are applied to the electric grid of the state of California. Therefore, appropriate spatially and temporally resolved wind and solar power data along with temporally resolved load data were obtained from the following databases.

A.1. Wind and solar data origins

A spatially and temporally resolved wind speed and power dataset was developed by the NREL Western Wind and Solar Integration Project (NREL-WWSI) [28]. The dataset provides wind speed and potential power output at a 10-min resolution for potential wind sites across the United States for the years of 2004 through 2006 with a spatial resolution of 2 km by 2 km areas. Each square kilometer area of the study is assumed to contain ten 3-MW wind turbines. Details of the dataset compilation are presented in the report presented by the 3TIER Corporation [29]. The electric power output and effective wind speed from each of these areas were determined using a mesoscale model developed by 3TIER Corporation. The performance curve for the Vestas V90 3.0 MW turbine was used to determine the wind power output potential of each block.

The interface to the NREL database is presented in Figure A.1 for the Tehachapi Region in Southern California. Each wind turbine icon or colored dot on the map is representative of one 2 km by 2 km block. The icon colors represent the effective capacity factor of each block at a height of 100 m as shown in Table A.1.

Table A.1
Legend for NREL wind potential map capacity factors

Icon Color	Wind potential capacity factor
Blue	<25%
Green	25–30%
Yellow	30–35%
Orange	35–40%
Red	>40%

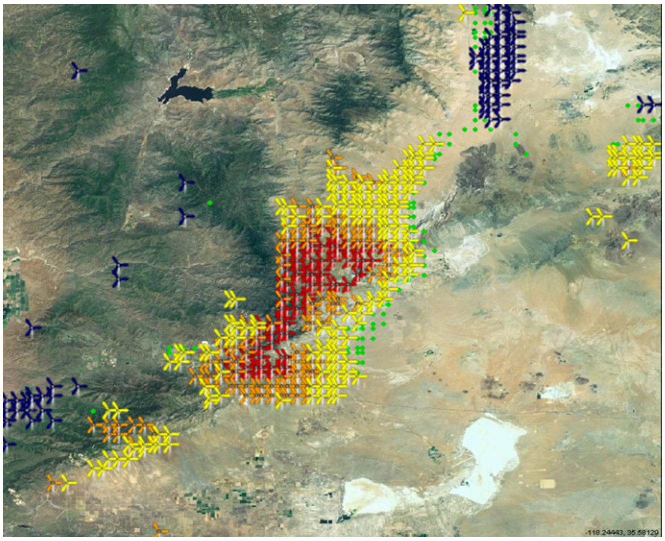

Fig. A.1. NREL Wind Farm Potential Map in the Tehachapi region of Southern California.

For the current study, the wind potential region in the Tehachapi region in California is examined due to its high wind potential [30], regional proximity to major population centers in the southern California region, as well as its potential to support a large capacity of wind power generation. Data from the NREL model were obtained and uploaded into an SQL data server, where it was extracted by applying SQL database queries. One example of such a query was used to effectively calculate the sum of the power output from every turbine block confined to a user-specified set of spatial coordinates (latitude and longitude). This approach allows the user to obtain wind power data for different sizes of wind farms within the potential map or for the entire potential map itself. Wind power data were also obtained for different geographical regions, allowing the evaluation of wind power characteristics as a function of regional dispersion. In addition, simple mathematical operations such as calculating the mean and standard deviation of each wind turbine block were also implemented using an SQL query. Note that due to the nature of the source data, the effect of wind turbine shadowing is not captured.

For assessing the effect of the integration of solar resources on the effective load demand, a solar irradiation dataset is used such that it is measured from a region consistent with that of the load and wind power data for the Southern California region. Solar power production is modeled by utilizing irradiation data obtained from the National Solar Radiation Database (NSRDB) [31] developed by NREL as inputs to first-principles-based models of solar photovoltaic panels. The dataset includes the different components of irradiation (direct, diffuse) and is converted into an effective total (in-plane) irradiation, after which it is fed to a first-principles solar photovoltaic model described by Tarroja [23]. Data from the NSRDB are available for most sites from 1991 through 2005. The database contains hourly-resolved irradiation measurements from a variety of sites spread throughout the U.S, as shown in Figure A.2:

This particular study uses solar irradiation data from a spatially diverse array of sites, as located across Southern California as shown.

A.2. Load data origins

This particular analysis uses the load demand of the entire state of California as the load profile to be served. A dataset for the aggregated load demand as reported by the three major investor-owned utilities (Southern California Edison, Pacific Gas & Electric, and San Diego Gas & Electric) to the California Independent System Operator (CAISO) was obtained for the year 2005. While a multitude of smaller utility entities exist within California, these three major utilities account for the vast majority of the electric demand within the state. This dataset has a 1-h resolution and spans the entire year. Wind and solar data were obtained for the same time period, and the wind dataset was converted to a 1-h resolution to match the load data. This was found to be reasonable given that the scale of the spatial diversity of the wind resources and the scale of the system are sufficiently large such that very fast timescale fluctuations in wind power are very small compared to the longer timescale fluctuations. For this particular analysis, it is assumed that there exists no base load, that is, the balance generator fleet is assumed to be completely flexible and no non-zero power level is required to be maintained at all times.

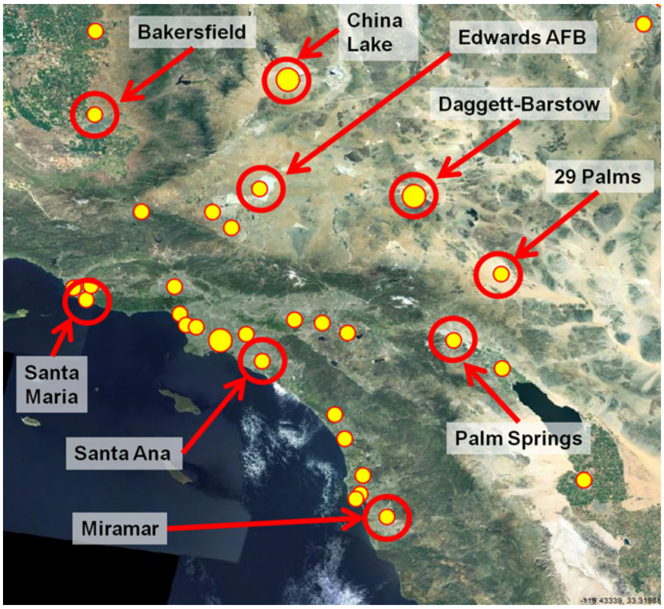

Fig. A.2. Location of NSRDB solar irradiation measurements (Yellow).

A.3. Renewable Deployment curve

The properties of the renewable power generation profile and therefore the effective load demand profile will depend on the mix of renewable resources used to serve the load demand at any given renewable penetration level. As a state, California has set a renewable portfolio standard goal for reaching a 33% renewable penetration level on the statewide system by the year 2020. As a result, a number of studies have been carried out to determine the feasible deployment of different renewable resources between the current time and the target year, taking into account planning, policy, permitting, and transmission construction issues. To develop the first part of the deployment curve used in this analysis, renewable resource capacities and capacity factors specified by the reference case roadmap in the 33% RPS Implementation Preliminary Report [32] are used as inputs to the renewable power generation module to define renewable penetration levels up to 33% in this study. Above the 33% renewable penetration level, the deployment of renewable resources was projected based on capacity limitations presented by the NREL WWSI [28] and the following assumptions:

1. Wind power is sourced primarily from the Southern California Region. This is based on data displayed in the NREL WWSI [28] which seems to indicate that the majority of the state's wind power potential is based in this region.
2. Wind power is assumed to be cheaper than solar power in the near term, until most high wind areas have been utilized. Therefore, wind power will be used to increase the renewable penetration level until it nears its capacity limit, after which solar power will become the primary means of increasing the penetration level.
3. Small Hydro, Biomass, Biogas, and Geothermal are not assumed to increase in capacity beyond their amounts at the 33% renewable penetration level. This assumption is based on capacity limitations for each of these individual resources.
4. Solar power becomes cost competitive by the time relatively high renewable penetration levels are reached (50% +), and the solar portfolio is assumed to be comprised of 70% desert azimuth tracking PV systems and 30% coastal fixed PV systems.

Combining all of these factors produces the deployment curve presented in Figure A.3, and this curve is used as the basis for this analysis.

After the 33% penetration level, cases are evaluated at the 40%, 45%, 50%, 55%, 60%, 65%, 70% and 75% penetration levels.

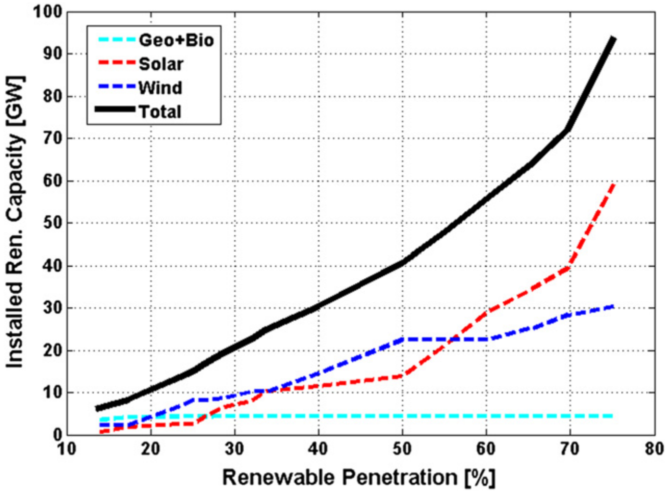

Fig. A.3. Renewable deployment projection based on assumptions.

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