SANDIA REPORT

SAND2023-10226
Printed October 2023

Sandia National Laboratories

Energy Storage & Decarbonization Analysis for Energy Regulators — Illinois MISO Zone 4 Case Study

Atri Bera, Tu Nguyen, Cody Newlun, Marissa Ballantine, Walker Olis, Robert Taylor, and Will McNamara

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185
Livermore, California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@osti.gov
Online ordering:	http://www.osti.gov/scitech

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.gov
Online order:	https://classic.ntis.gov/help/order-methods

ABSTRACT

Jurisdictions around the world are enacting and enforcing an increasing number of policies to fight climate change, leading to higher penetration of variable renewable energy (VRE) and energy storage systems (ESSs) in the power grid. One of the biggest challenges associated with this process is the evaluation of the appropriate amount of ESS required to mitigate the variability of the VREs and achieve decarbonization goals of a particular jurisdiction. This report presents methodologies developed and results obtained for determining the minimum amount of ESS required to adequately serve load in a system where fossil fueled generators are being replaced by VREs over the next two decades. This technical analysis is performed by Sandia National Laboratories for the DOE Office of Electricity Energy Storage Program in collaboration with the Illinois Commerce Commission (ICC). The Illinois MISO Zone 4 is used as a case study. Several boundary conditions are investigated in this analysis including capacity adequacy and energy adequacy to determine the quantity of ESS required for MISO Zone 4. Multiple scenarios are designed and evaluated to incorporate the impact of varying capacity values of VREs and on the resource adequacy of the system. Several retirement scenarios involving fossil-fueled assets are also considered. Based on the current plans of new additions and retirements of generating assets, the results of the technical analysis indicate that Illinois MISO Zone 4 will require a significant quantity of ESS to satisfy their electricity demand over the next two decades.

ACKNOWLEDGMENT

The work was supported by the U.S. Department of Energy Office of Electricity Energy Storage program directed by Dr. Imre Gyuk.

The team also thanks the Illinois Commerce Commission for providing data, guidance, and feedback on this report.

AUTHOR CONTRIBUTIONS

Atri Bera led the effort. He contributed to conceptualization, model development, performing simulations, and writing this report.

Tu Nguyen contributed to conceptualization, model development, and writing this report.

Cody Newlun contributed to conceptualization, data collection, and performed a technical review of the report.

Marissa Ballantine contributed to conceptualization, data collection and analysis, and performed a technical review of the report.

Walker Olis contributed to conceptualization and performed a technical review of the report

Robert Taylor contributed to conceptualization.

Will McNamara served as the liaison between Sandia National Laboratories and the Illinois Commerce Commission and provided input regarding best practices in energy storage regulatory policies.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Table 0-1. Nomenclature

Abbreviation	Definition
CF	Capacity Factor
CV	Capacity Value
DOE	Department of Energy
ESS	Energy Storage Systems
ICC	Illinois Commerce Commission
LRZ	Local Resource Zone
MISO	Midcontinent Independent System Operator
RPS	Renewable Portfolio Standards
VRE	Variable Renewable Energy

1. INTRODUCTION

Several U.S. states and territories have adopted aggressive decarbonization mandates and targets in an effort to combat climate change. Figure 1-1 provides the current renewable and clean energy standards in the U.S. (as of November 2022) [11].

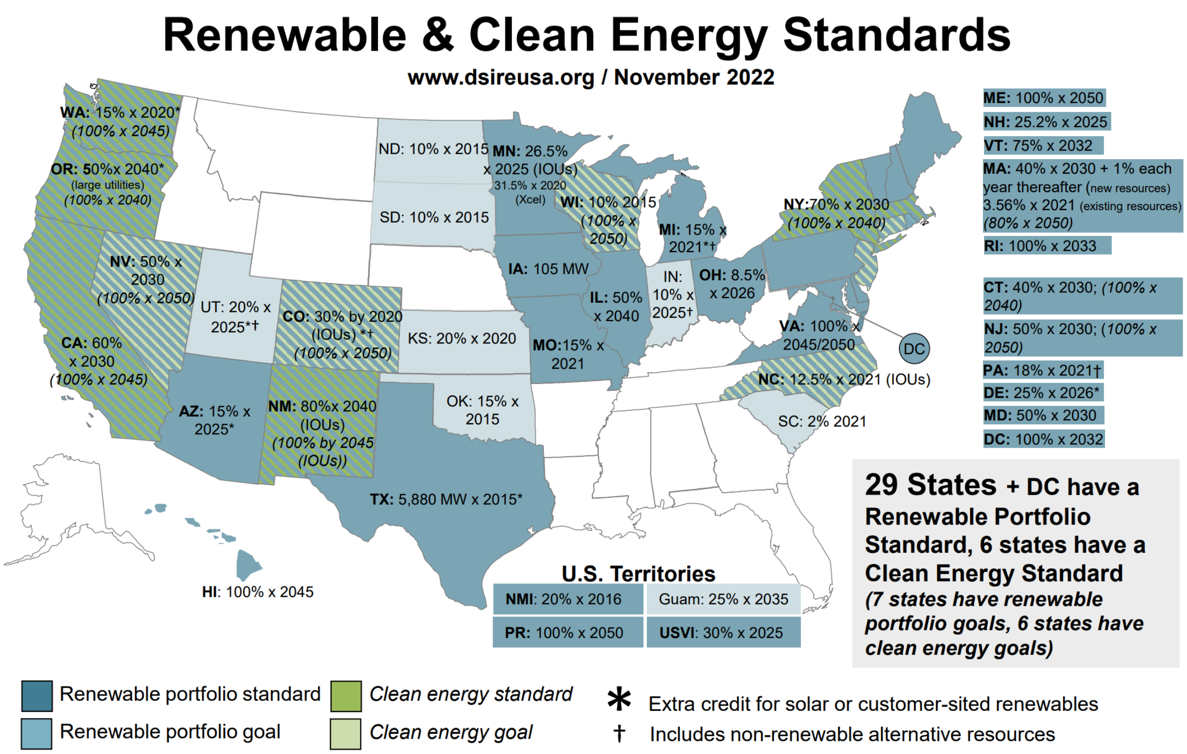

Figure 1-1. Current renewable and clean energy targets in the U.S. and its territories. Figure extracted from [11]

The clean energy targets displayed in Figure 1-1 will require states and territories to significantly expand their respective renewable portfolios. Due to the intermittency of renewable resources and the retirement of fossil-fueled base-load thermal generation, energy storage technologies with ever-longer duration capabilities will be pivotal to maintain reliability in the system.

The two market-leading variable renewable energy (VRE) resources—wind and solar—are variable and intermittent in nature. The uncertainty associated with their energy supply negatively affects the reliability of the system, thus risking greater and more frequent load curtailment [12]. This increasing uncertainty has led to the widespread deployment of energy storage systems (ESSs) in the contemporary power grid. ESS are flexible devices with high ramp rates that can help in maintaining a balance between generation and demand in the face of such uncertainty. ESS can be deployed for various applications including frequency regulation, peak shaving, voltage support, energy arbitrage, firming up of renewable resources, and improve system reliability and deferring expensive transmission and distribution capital investments [3]. Due to their fast-acting nature, ESS is a good candidate for quickly generating active power to smooth out the fluctuating nature of the VREs and supply the load, thus improving system reliability.

The DOE Office of Electricity (OE) Energy Storage Program supports efforts for helping energy regulators understand the ESS requirements to adequately serve load as traditional fossil-fueled generators are being widely replaced by uncertain and intermittent VREs. This technical analysis has been performed as part of such efforts in collaboration with the Illinois Commerce Commission (ICC) and using Illinois MISO Zone 4 as a case study. ICC's mission is to ensure adequate, efficient, reliable, environmentally safe and least-cost public utility services at prices which accurately reflect the long-term cost of such services and which are equitable to all citizens. Pursuant to the Illinois Public Utilities Act, Illinois generally relies on competitive markets to ensure resource adequacy and system reliability. As the energy landscape evolves, factors such as planned generation capacity additions and retirements, load growth, and the increasing integration of renewable energy in the resource mix necessitate an assessment of the state's generation capacity. Specifically, to effectively mitigate reliability risks such as outages and disruptions that could impact consumers and businesses, the ICC is seeking to evaluate Illinois's current and future energy landscape. This involves evaluating factors such as retirements of coal/gas power plants, renewable and potentially nuclear capacity expansion, and changes in energy consumption. By examining these factors, the ICC can identify potential generation gaps, where available generation capacity falls short of meeting the projected demand. The ICC is also interested in estimating how much more renewable energy and energy storage it needs to address these gaps.

To support its assessments and decision-making processes in the above tasks, the ICC has established a collaboration with Sandia National Laboratories under the support of the U.S. Department of Energy's Energy Storage Program. This collaborative effort aims to reduce the technical barriers and enhance the ICC's capabilities in evaluating energy storage and energy future scenarios. As part of this collaboration, this technical analysis aims to evaluate the minimum energy storage requirements for Illinois MISO Zone 4 for serving electricity demand in the state reliably, based on the present generating resources and the planned retirements and additions over the next two decades. In particular, this analysis tries to answer the following questions:

1. When could Illinois MISO Zone 4 experience unserved electricity demand within the next two decades and how can the use of energy storage address the gap in electricity generation and demand?

2. How can delays for planned projects and the addition of new unplanned projects impact the gap between electricity generation and demand over the next two decades?

The tasks performed under this technical assessment include the following:

- Evaluating capacity and energy adequacy for Illinois MISO Zone 4 for years 2023 to 2042;

- Evaluating the minimum amount of ESS capacity and energy required by Illinois MISO Zone 4 to achieve capacity and energy adequacy for the years 2023 to 2042;

- Evaluating the additional generating capacity required in the system in case the system lacked sufficient energy to charge the ESS;
- Generating and evaluating multiple scenarios using different potential capacity values (CVs) and capacity factors (CFs) of wind and solar generating resources; and
- Generating and evaluating multiple scenarios considering different potential retirement and addition schedules of the generation fleet.

Some key assumptions of this technical analysis are stated here:

- This work examines Illinois' ability to achieve capacity and/or energy adequacy in MISO Zone 4 through the exclusive use of Illinois MISO Zone 4 resources. While Illinois' ability to achieve capacity and/or energy adequacy is impacted by resources in areas outside Illinois MISO Zone 4 and resources participating in regional energy markets more generally, examination of the impact of resources outside of Illinois MISO Zone 4 is out of scope of this work.
- It is assumed that current nuclear resources in Illinois MISO Zone 4 do not retire on or before 2043 even though current Zero Emission Credits for the resources cease after May of 2027.
- The minimum ESS requirement values were evaluated based on the assumption that capacity and energy adequacy are achieved solely by utilizing ESS and no VREs were installed in addition to the ones already existing in the 2023 unless stated. In practice, additional capacities of VREs might also need to be installed to obtain more economical solutions.
- Several boundary conditions involving the above-mentioned tasks are investigated. These conditions are necessary but not sufficient to achieve capacity and/or energy adequacy. For example, the amount of ESS installations determined in the analyses presented in this work may be necessary to achieve capacity and/or energy adequacy during average operating conditions, but may be insufficient to achieve capacity and/or energy adequacy outside of average operating conditions.
- A detailed hour-by-hour analysis based on optimized system operations was out of scope of this work.
- The scope of work also did not include the calculation of CVs and CFs of generating resources. Historical data and existing literature have been referenced to extract the numbers relevant to the Illinois.

The rest of the report presents the mathematical models, assumptions, case studies, findings, and limitations of the analysis performed.

2. MATHEMATICAL FRAMEWORK

This section describes the mathematical models developed in this work for evaluating the capacity and energy adequacy conditions of a system and for evaluating the minimum ESS sizes required to adequately serve load.

2.1. Capacity Adequacy Condition

A boundary condition has been investigated to determine whether MISO Zone 4 has the minimum amount of installed generation capacity to support the annual peak load. This condition is necessary but not sufficient to achieve capacity adequacy.

Let the annual peak load in the system be L_{peak} MW for a certain year. Let there be n types of generating resources in the system, the maximum capacity of the i^{th} resource being $P_i^{\max}$ MW that particular year. Let the CV[1] of the i^{th} resource be CV_i. Then, to satisfy the capacity adequacy requirement, the following relationship must hold true:

$$\sum_{i=1}^{n} P_i^{\max} \times CV_i \geq L_{\text{peak}} \tag{2.1}$$

It should be noted that the L.H.S of (2.1) represents the minimum capacity required in the system to satisfy the peak demand. If the installed capacity is lower than this quantity, then the system is guaranteed to experience outages. However, only having the minimum amount might not always be sufficient to avoid load curtailment due to unforeseen outages of system equipment or differences in forecasted and actual VRE generation. Determining the exact amount of generating capacity required to serve the annual peak and/or the hourly demand requires extensive hour-by-hour simulation and is out of scope of this report.

2.2. Energy Adequacy Condition

A second boundary condition is investigated to determine whether the generating resources in MISO Zone 4 are capable of generating sufficient energy in a year to serve the total demand energy in that year. This condition is also necessary but not sufficient to achieve energy adequacy.

[1]The capacity value of a resource can be defined as the fraction of its maximum capacity that it can be expected to contribute toward serving the load during the highest load or highest risk hours during a year [6].

Let the total load energy for a certain year be L_{total} MWh. Then the following condition must hold for the energy adequacy condition to be satisfied:

$$\sum_{i=1}^{n} P_i^{\max} \times CF_i \times 8760 \geq L_{\text{total}} \tag{2.2}$$

where CF_i is the CF[2] of the i^{th} generating resource and 8760 is the number of hours in a non-leap year. Similar to (2.1), the L.H.S. of (2.2) represents the minimum energy required to satisfy the load at all hours of the year. If the energy generated is lower than this quantity, then the system is guaranteed to experience outages. In practice, more energy will likely be required than the minimum to meet the load due to unforeseen outages of system equipment or differences in forecasted and actual VRE generation. System planners including utilities generally include reserve products in their planning process to account for these shortages, including spinning and non-spinning reserves and plan for peak loads that exceeds expectations by including reserve margins when identifying capacity requirements [1].

2.3. ESS Sizing Methodology

This section discusses the methodology used to determine the amount of ESS required by the system to ensure capacity and energy adequacy. For this analysis, it is assumed that only ESS is used to bridge the gap between generation and load and no additional generating resources are used. Several scenarios involving the latter are evaluated in a later section.

2.3.1. ESS Power Rating

The minimum power rating of the ESS required each year to ensure capacity adequacy is determined based on the difference between the total CV of the system and the peak load for that year. From (2.1), the minimum power rating of the ESS required, P_{ESS} can be calculated as follows.

$$P_{\text{ESS}} = L_{\text{peak}} - \sum_{i=1}^{n} P_i^{\max} \times CV_i \tag{2.3}$$

The above equation is valid when the peak load for a year is greater than the total CV of the system. Otherwise, it is assumed that the installed capacity of the system is adequate to serve the peak demand without the need of any additional ESS.

[2]The capacity factor of a resource can be defined as the ratio of actual electrical energy output over a given period of time to the theoretical maximum electrical energy output over that period.

2.3.2. ESS Energy Capacity

The minimum required energy capacity of the ESS required each year is determined based on the number of hours for which the system load is greater than the total CV of the generating fleet in the system. Let h be the number of hours for which the system load is higher than the generation for that hour. Let P_j be the difference between the load and generation for hour j. Therefore, the minimum energy capacity of the ESS required to achieve energy adequacy, E_{ESS}, can be calculated as follows.

$$E_{\text{ESS}} = h \times \sum_{j=1}^{h} P_j \tag{2.4}$$

2.3.3. ESS Charging Energy

As a part of the ESS sizing process, it is also investigated whether the system will possess sufficient energy to charge the ESS once it is discharged to serve the load. Let A_1 be the total energy discharge required from the ESS, A_2 be the energy available for charging, η be the round-trip efficiency of the ESS, Σ_{load} be the total load energy for the year, and Σ_{gen} be the total energy generated in a year. Then, the relationship between the above-mentioned variables can be quantified as follows.

$$\Sigma_{\text{load}} + A_2 = \Sigma_{\text{gen}} + A_1 \tag{2.5}$$

Now, for the system to have sufficient charging energy, the following must be true:

$$A_2 \geq \eta \times A_1 \tag{2.6}$$

In case multiple ESS technologies with different round-trip efficiencies are used, (2.6) can be rewritten as follows.

$$A_2 \geq A_1 \times (\sum_{k=1}^{m} \frac{w_k}{\eta_k}) \tag{2.7}$$

where m is the number of ESS technologies being used, w_k is the proportion of technology k in the system, and η_k is the efficiency of technology k. If the condition stated in the above equation is not satisfied, then the system will not have sufficient energy to charge the ESS. In that case, adding ESS alone will not be able to help the system achieve resource adequacy and additional generation will be required.

3. CASE STUDIES & RESULTS

3.1. Capacity Adequacy

Fig. 3-1 illustrates the comparison between the total capacity value of the installed generating resources in Illinois MISO Zone 4 with the three MISO load futures F1, F2, and F3 [8] for the years 2023 to 2042. A brief description of these futures is provided here: Future 1 assumes that demand and energy growth are driven by existing economic factors, with small increases in EV adoption, resulting in an annual energy growth rate of 0.5%. Future 2 assumes an increase in electrification, driving an approximate 1.1% annual energy growth rate. Future 3 introduces a larger electrification scenario, driving an approximate 1.7% annual energy growth rate. For more details on the MISO futures, the readers can refer to [8]. It can be observed that the generating fleet will be unable to meet the annual peak as early as 2024 for future F3, while for F1 and F2, this will occur 2027 onward. A base case is presented in Fig. 3-1 with the CVs of wind and solar assumed to be 15.5% and 50%, respectively [9]. The CVs of all other resources considered here are reported in the Appendix.

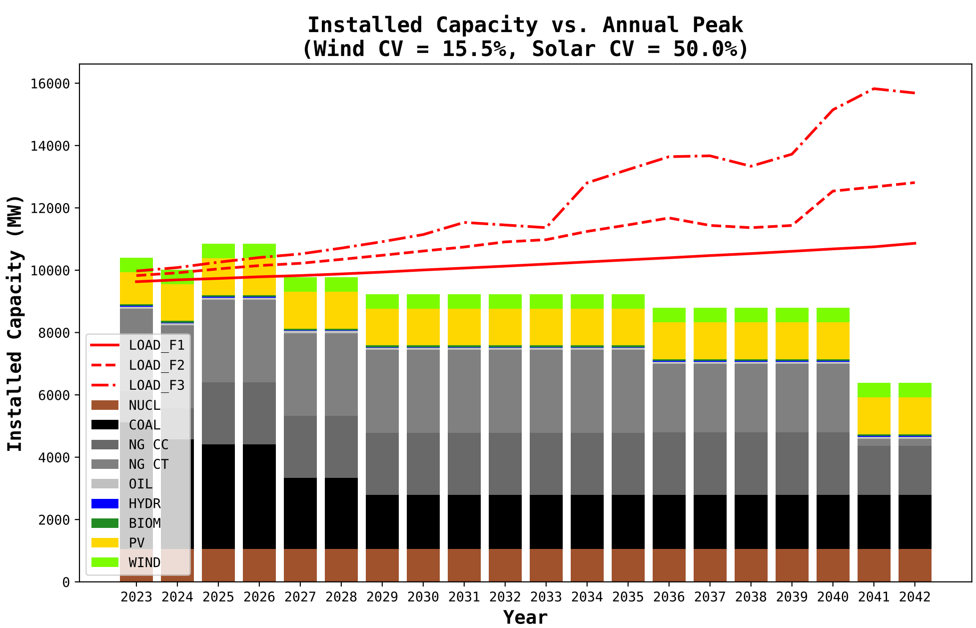

Figure 3-1. A comparison between the total capacity value of the installed resources and the peak demand.

Several scenarios are developed by varying the CVs of wind and solar resources and the capacity adequacy of the system is investigated for each scenario. The CVs of the conventional resources are left unchanged since those depend on their outage rates and and have historically been more predictable (although recent storms suggest this may warrant additional investigation in future analyses[10]). A wide range of wind and solar CVs are considered [7, 5]. For wind, CVs ranging from 10%–40% are considered while for solar the range of CV considered is 50%–80%. The results of the scenario analysis are presented in Fig. 3-2.

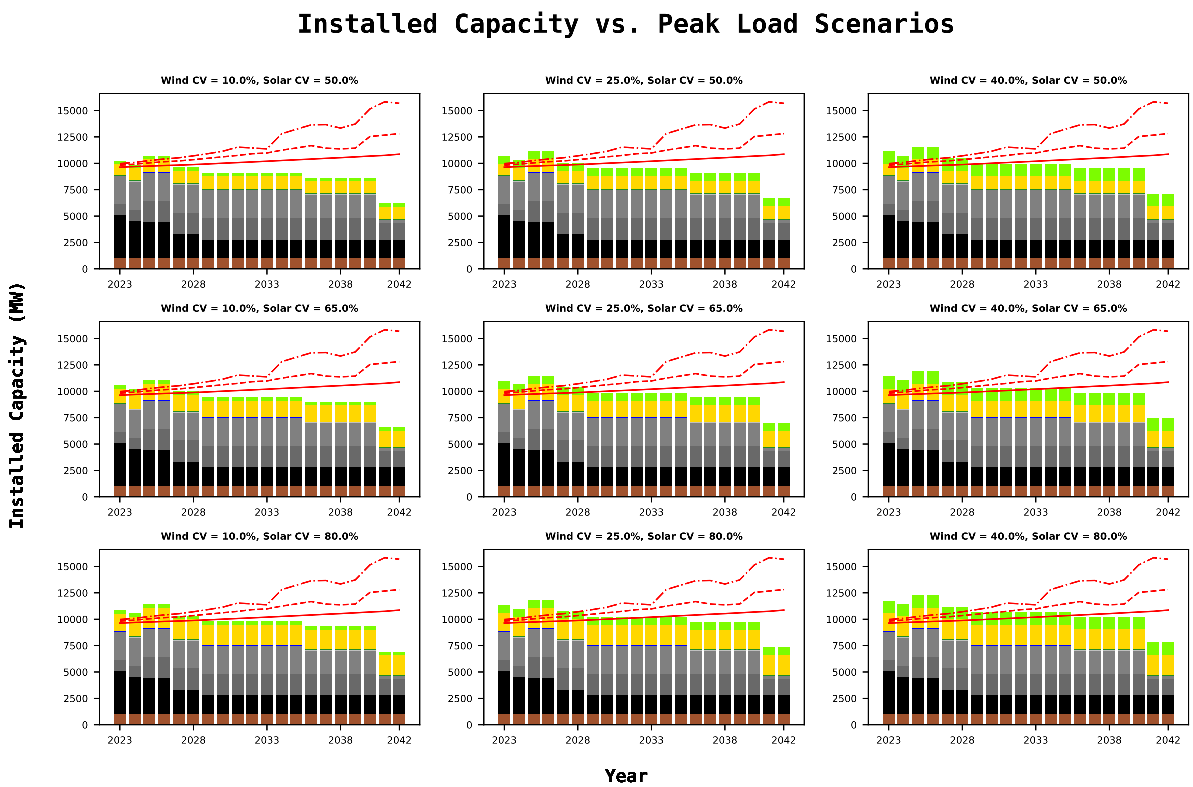

Figure 3-2. Capacity adequacy scenarios for different capacity values of wind and solar resources.

The subplot on the top left corner denotes the worst case scenario with wind and solar CVs assumed to be 10% and 50% respectively. It can be observed that for this case, the system will be unable to serve the annual peak load as early as 2024 for future F3, while for F1 and F2, this will occur 2027 onward. **It should be noted that this is also the most likely scenario for Illinois MISO Zone 4 since the CVs of wind and solar resources used for this case is very similar to the numbers assigned to LRZ4 of MISO [9].** The calculation of actual CVs from historical data was out of scope of this work.

The subplot on the bottom right corner denotes the best case scenario with wind and solar CVs assumed to be 40% and 80% respectively. For this case, the system will be able to serve peak load until 2028 for future F3, 2030 for F2, and 2035 for F1. However, it should be noted that this scenario is unlikely for the Illinois MISO Zone 4 since the CVs assigned by MISO for the state is much lower than those assumed for this case.

3.2. Energy Adequacy

Fig. 3-3 illustrates the comparison between the total energy that can be generated by the installed resources in Illinois MISO Zone 4 with the total load energy of the three futures F1, F2, and F3 for the years 2023 to 2042. A base case is presented in Fig. 3-3 with the CFs of wind and solar assumed to be 30% and 25%, respectively [4]. The CFs of all other resources considered here are reported in the Appendix. From the results, it can be observed that for F3, the total energy generation will fall short of the total load energy 2040 onward while for F1 and F2, this will occur for the first time in 2041. It should be noted that this the most likely case for Illinois, MISO Zone 4 since the CFs considered for this case are the same as that considered by the ICC [4]. The calculation of actual CFs from historical data was out of scope of this work.

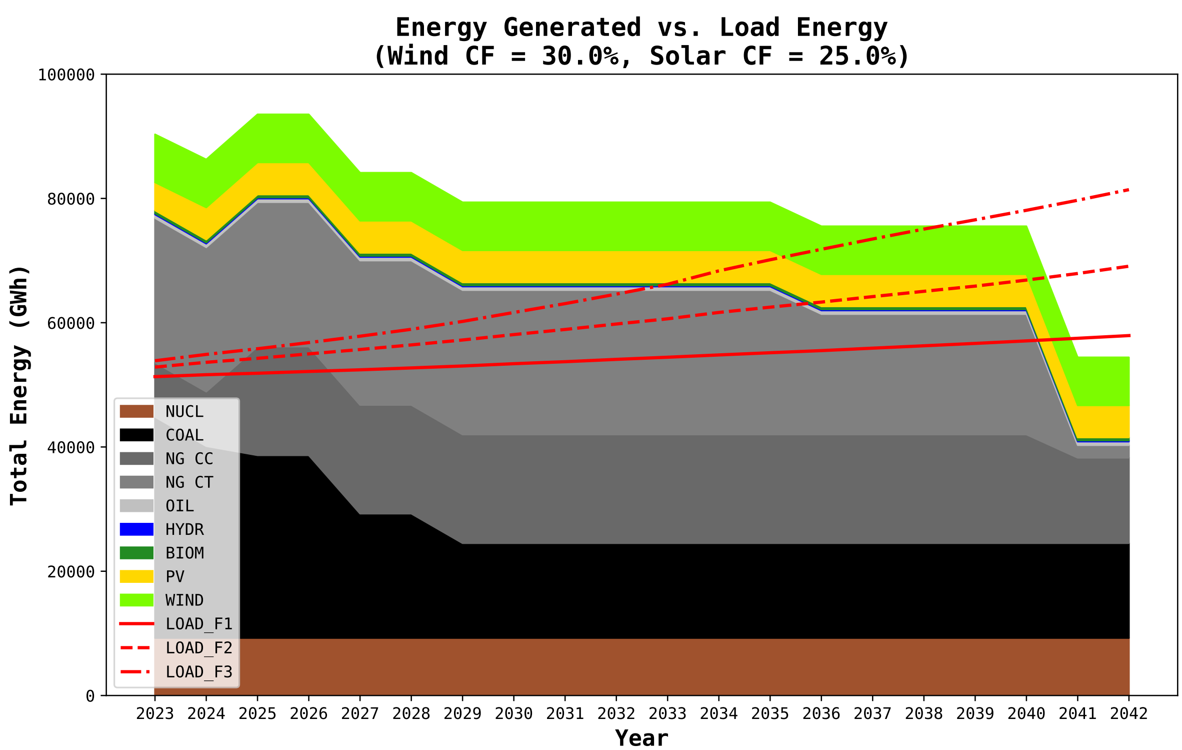

Figure 3-3. A comparison between the yearly energy generation capability of the system and the total yearly load energy.

Several scenarios are developed by varying the CFs of wind and solar resources and the energy adequacy of the system is investigated for each scenario. The CFs of the conventional resources are left unchanged since those depend on their outage rates and are more predictable. For wind, CFs ranging from 25%–30% are considered while for solar the range of CF considered is 20%–30%. The results of the scenario analysis are presented in Fig. 3-3.

The subplot on the top left corner denotes the worst case scenario with wind and solar CFs assumed to be 25% and 20% respectively. It can be observed that for F3, the total energy generation will fall short of the total load energy 2038 onward while for F1 and F2, this will occur for the first time in 2041.

The subplot on the bottom right corner denotes the best case scenario with wind and solar CFs assumed to be 35% and 30% respectively. It can be observed that for F1, F2, and F3, the total energy generation will fall short of the total load energy 2041 onward.

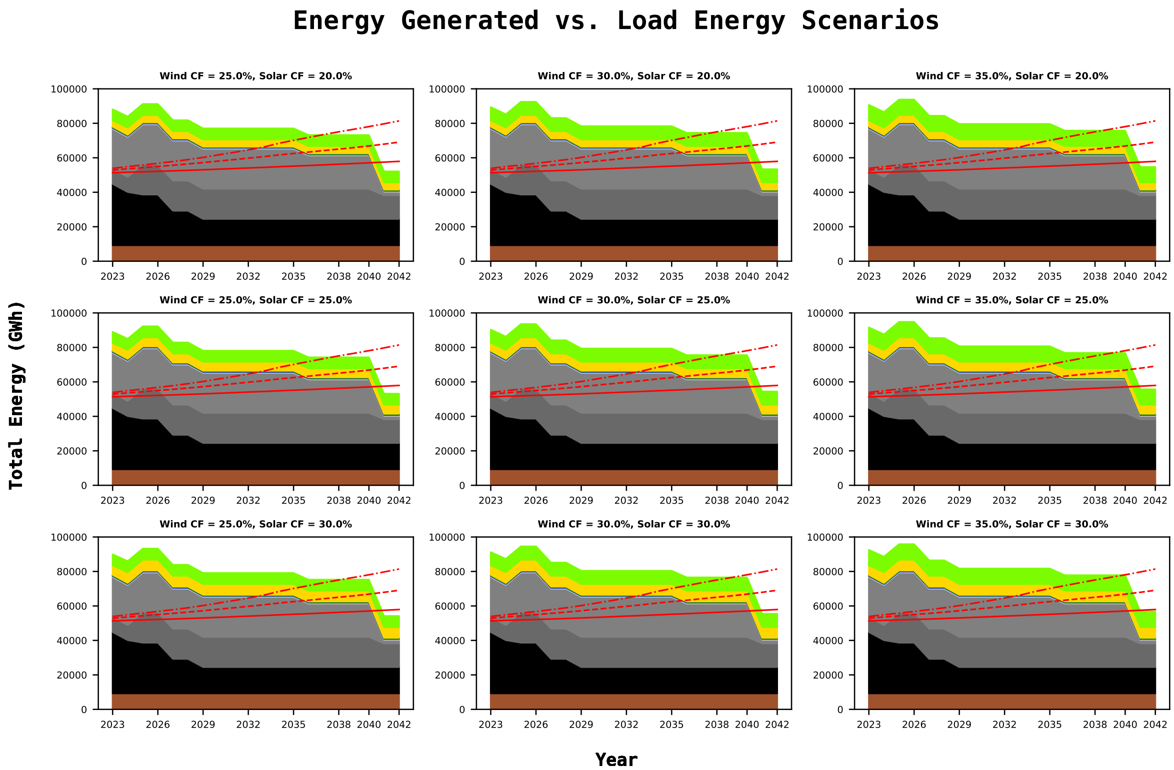

Figure 3-4. Energy adequacy scenarios by considering different capacity factors for wind and solar resources.

The key conclusion that can be drawn from the adequacy analysis is that while the system will fall short of serving the annual peak as early as 2024, the total energy generation will be adequate till 2040 for most scenarios. This is not unusual however, since the system experiences high demand only for a small percentage of hours every year while the demand for the rest of the hours remain well below that level, thus reducing the total annual load energy required.

3.3. Energy Storage Required

The quantity of ESS required for each scenario is calculated using the methodology outlined in Section 2.3.1 and 2.3.2. The results are presented here as follows.

3.3.1. Power Rating

The minimum power rating of the ESS required for the three futures F1, F2, and F3 are illustrated in figures 3-5, 3-6, and 3-7 respectively. As mentioned in Section 2.3.1, this minimum power rating of the ESS for each year is calculated based on the difference between the annual peak and the total capacity value of the installed generating assets for that year.

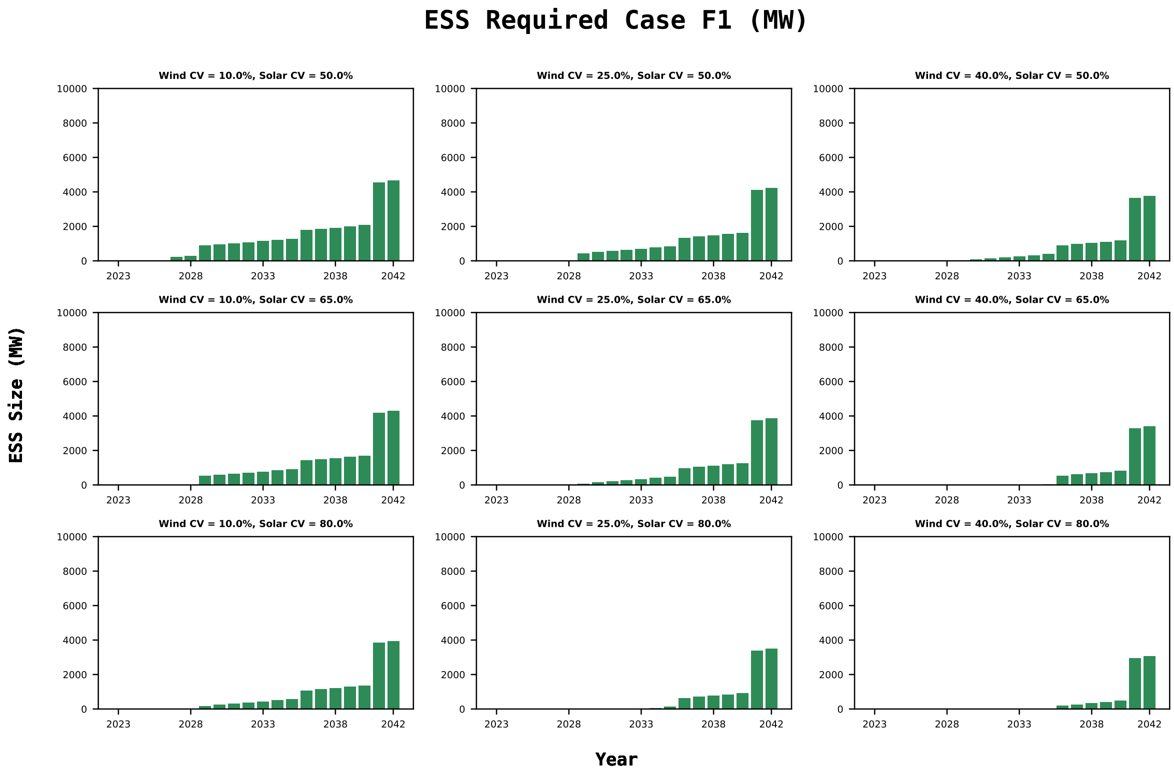

Figure 3-5. Minimum power rating of energy storage required for Future F1.

From the results, it can observed that the ESS requirements for each year are coherent with the results presented in Section 3.1. For instance, in Figure 3-2, we see that for the worst case scenario, the system will be unable to serve the annual peak load for the first time in 2027 for future F1. Hence, it is only logical that the system will require ESS in the year 2027 for the first time to serve the annual peak, which is reflected in the top left subplot of Figure 3-5.

Also, as observed from figures 3-1 and 3-2, the annual peaks for futures F1, F2, and F3 are in ascending order. Hence, from figures 3-5, 3-6, and 3-6 we see that the ESS requirements for cases F1, F2, and F3 are also in ascending order.

3.3.2. Energy Capacity

The minimum ESS energy capacities required for all scenarios are calculated based on the methodology presented in Section 2.3.2. Some of the results are illustrated in this section while the rest of

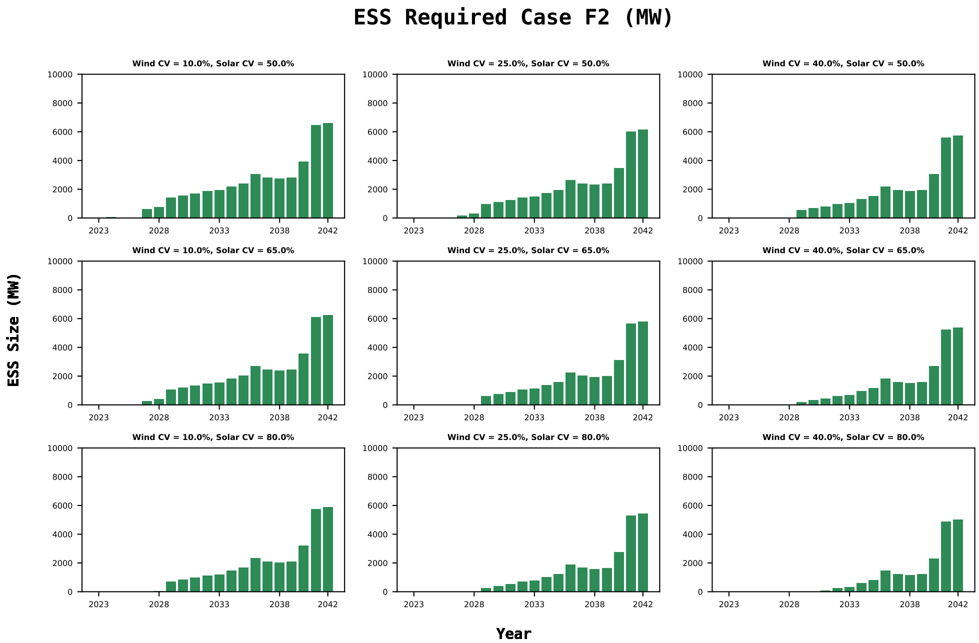

Figure 3-6. Minimum power rating of energy storage required for Future F2.

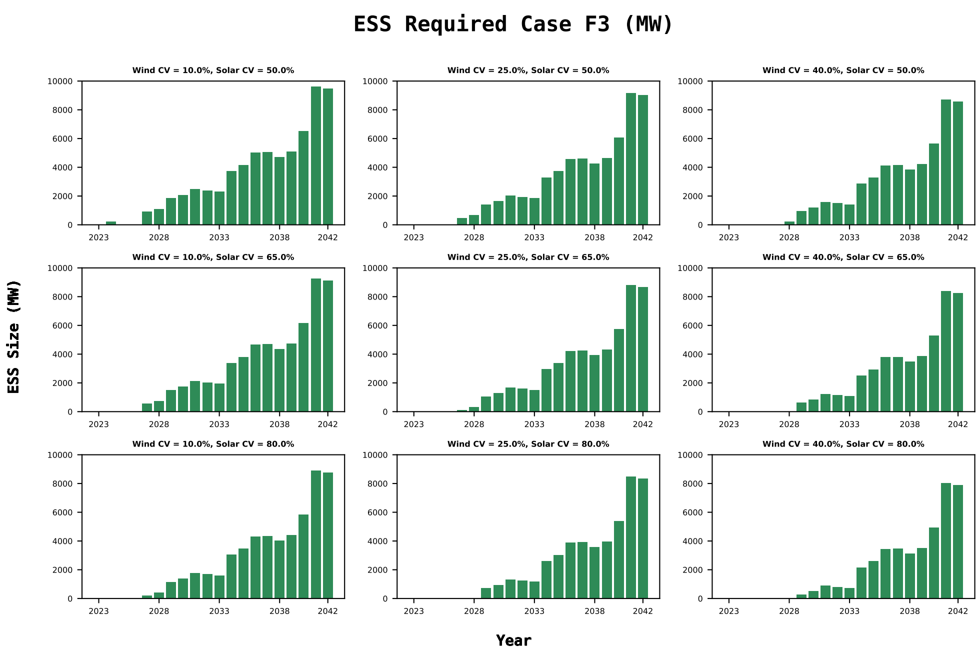

Figure 3-7. Minimum power rating of energy storage required for Future F3.

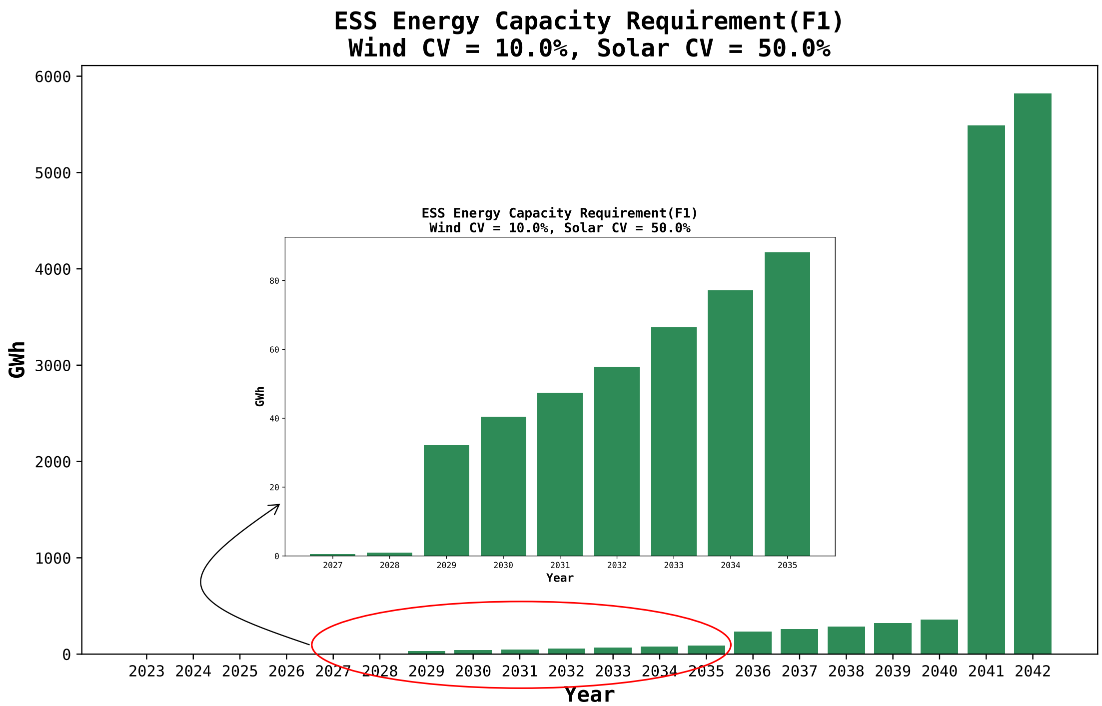

Figure 3-8. Energy capacity required for worst case of F1

the results are reported in the Appendix.

Figure 3-8 presents the results for the worst case scenario for future F1. As mentioned in Section 3.1, this is also the most likely scenario for Illinois MISO Zone 4. It can be observed from the results that ESS energy requirement increases steadily from 2027 and grows exponentially in the years 2041 and 2041.

Figure 3-9 presents the results for the best case scenario for future F1. Results show that for this case, the ESS energy requirement is much lower than the previous case due to the high CVs of the VREs. A steady increase can be seen from year 2036 to 2040 and an exponential growth can be seen for years 2041 and 2042.

For both cases presented here, we see a very high ESS energy requirement for the years 2041 and 2042. There are two major factors behind this phenomenon, the primary one being the retirement of a large fleet of natural-gas fueled combustion turbines. The other factor is that the total load energy surpasses the total potential annual electricity generation in these two years. Thus the system has to rely on ESS to supply a large amount of load. Which raises the following question: will there be sufficient energy generated by the system to charge the ESS? This is explored in the following section.

3.3.3. ESS Charging Energy Requirement

As mentioned in Section 2.3.3, the system might not possess sufficient energy to charge the ESS once it is discharged to serve to load. The condition presented in (2.7) must be satisfied to ensure

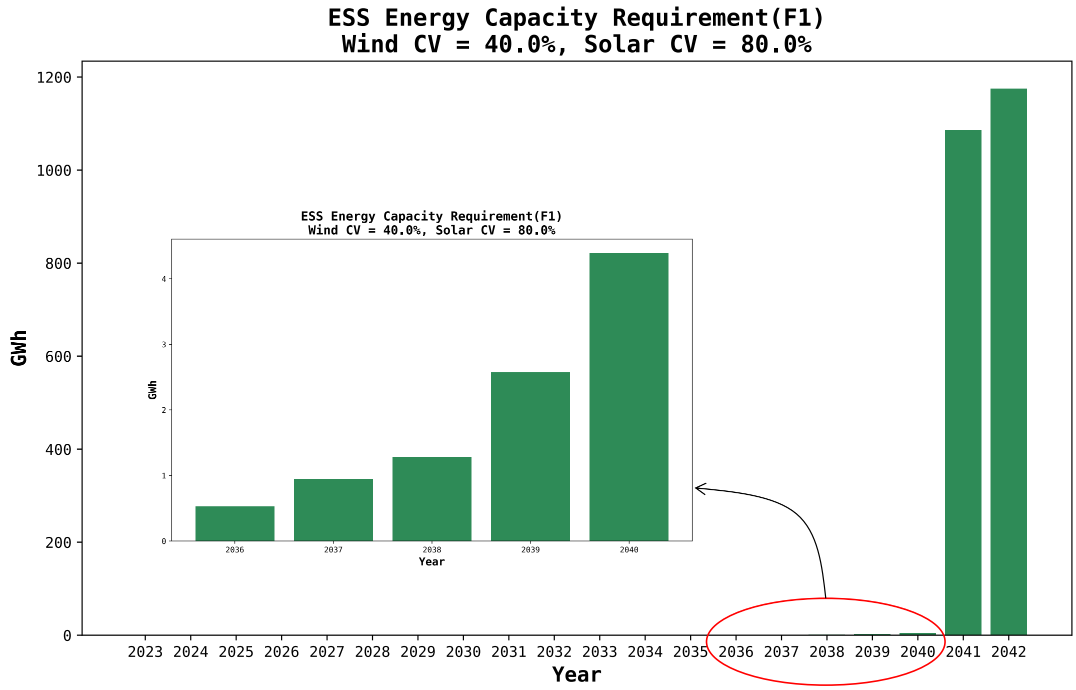

Figure 3-9. Energy capacity required for best case of F1

Table 3-1. ESS Parameters

Technology	Parameter	Value
Long Duration	w_1	0.6
(e.g. Hydrogen)	η_1	0.4
Medium Duration	w_2	0.2
(e.g. Pumped Hydro)	η_2	0.75
Short Duration	w_3	0.2
(e.g. Li-ion)	η_3	0.95

that there is enough charging energy.

Figure 3-10 shows the results for Case F1 where the L.H.S. and R.H.S are compared. For this case, it is assumed that there are three types of ESS technologies in the system, that is, long duration, medium duration, and short duration. Table 3-1 shows the proportions and efficiencies of the ESS technologies assumed. It should be noted that this is a fictitious scenario and the proportion and efficiencies of ESS technologies in a future system will be different.

It can be observed from the results that for years 2023 to 2040, the system will have sufficient energy to charge the ESS. However, for years 2041 and 2042, the system will fail to achieve resource adequacy with the use of ESS alone. Additional generating resources will need to be installed for these years.

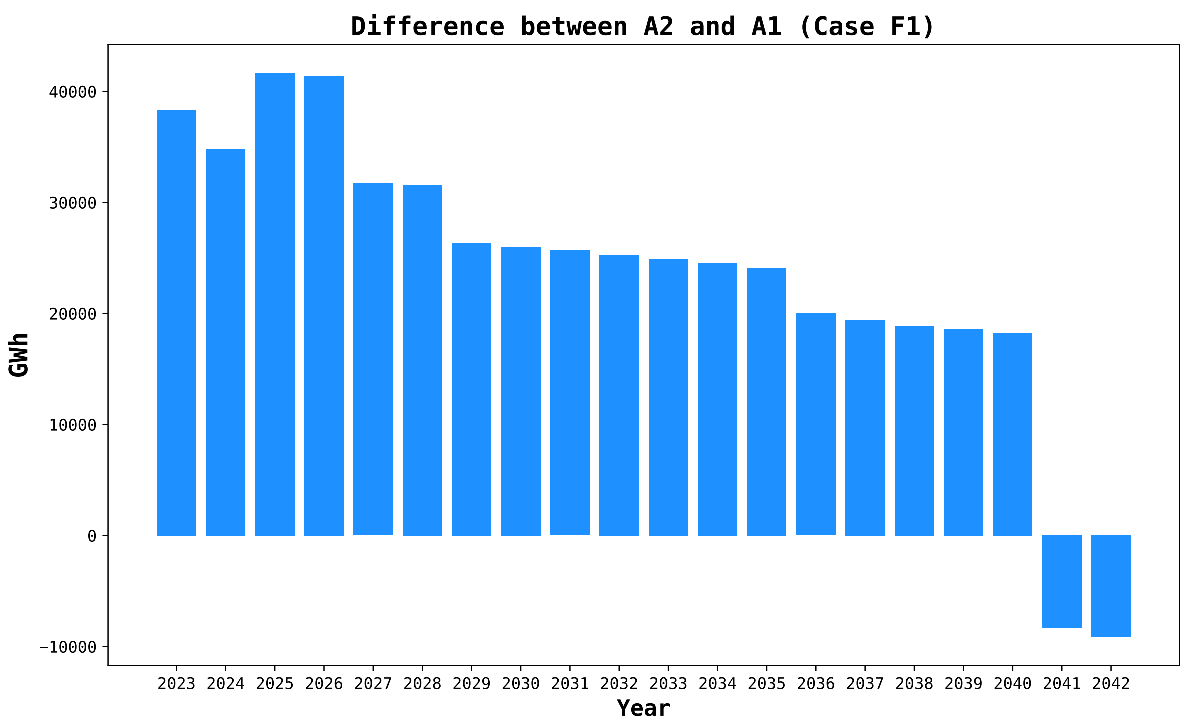

Figure 3-10. Charging Energy Requirement

3.3.4. Scenario Analysis

In this section, multiple scenarios have been generated and evaluated considering different potential retirement and addition schedules of the generation fleet in MISO Zone 4.

3.3.4.1. Early Retirement of Coal Plants

For this scenario, it is assumed that the coal plants in MISO Zone 4 are retired earlier than originally planned and all coal plants are shutdown by the year 2040. The sequence in which the retirements have been assumed is shown in Table 3-2.

Table 3-2. Retired coal plants by year

Year	Retired Plant	Capacity (MW)
2030	Dallman4	208
	Marion 1,2,3	120
2035	PS-AMIL	761.98
	PS-CWLD	50.02
2040	Prairie State Energy	817

The impacts of these retirements on the capacity and energy adequacy of the system are then studied. The results, compared to the original plan, are shown in Fig. 3-11. It can be observed from the results that the gap between the total installed capacity and the load increases significantly when compared with the original plan due to the early retirements of the coal plants. Similar results are obtained for energy adequacy as well.

The ESS power and energy capacity requirements are also calculated for the early retirement scenarios. As expected, the minimum amount of ESS required to achieve capacity and energy adequacy increases significantly due the early retirements of the coal plants. The results are shown in Fig. 3-12.

As a part of this scenario analysis, it is assumed that the retired coal plants are replaced with wind and solar plants and the impact of these additions on system capacity and energy adequacy are studied. The sequence in which these new capacities are added is shown in Table 3-3. It is assumed that half of the retired coal-fueled generation capacity is replaced by solar while the other half is replaced by wind. The capacities are then scaled by the CVs of the respective resources. For example, in the year 2030, 328 MW of coal-fueled generation is replaced by wind and solar. We have replaced half of this capacity (164 MW) with solar. However, since the CV of solar is assumed to be 0.5, we have scaled the capacity to be replaced by 0.5. Hence, the solar capacity required to replace coal-fueled generation is $164/0.5 = 328$ MW. Similary, the capacity of wind plants required to replace 164 MW of coal-fueled generation capacity is $164/0.155 \approx 1060$ MW, where the CV of wind plants is assumed to be 0.155.

The impacts of adding new solar and wind capacities on capacity and energy adequacy of system are shown in Fig. 3-13. The new minimum ESS requirements for achieving adequacy are shown in

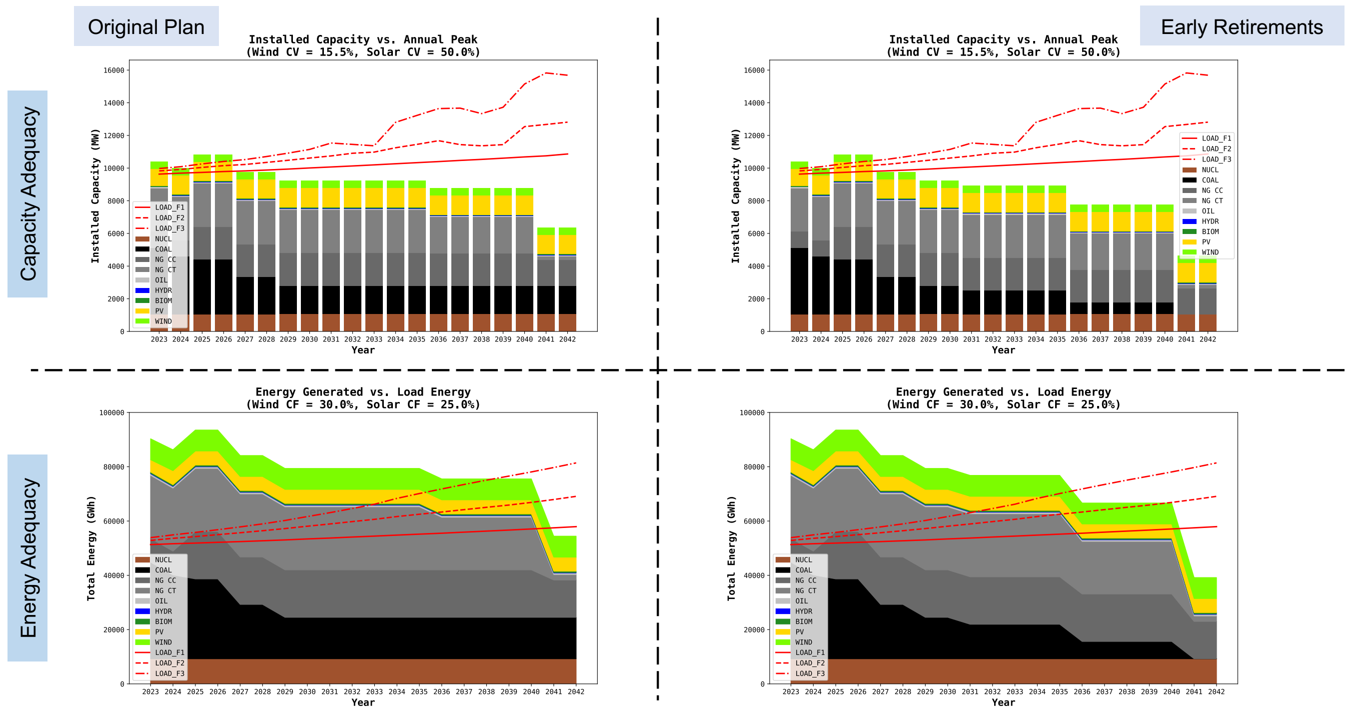

Figure 3-11. Capacity and energy adequacy of system due to early shutdown of coal plants.

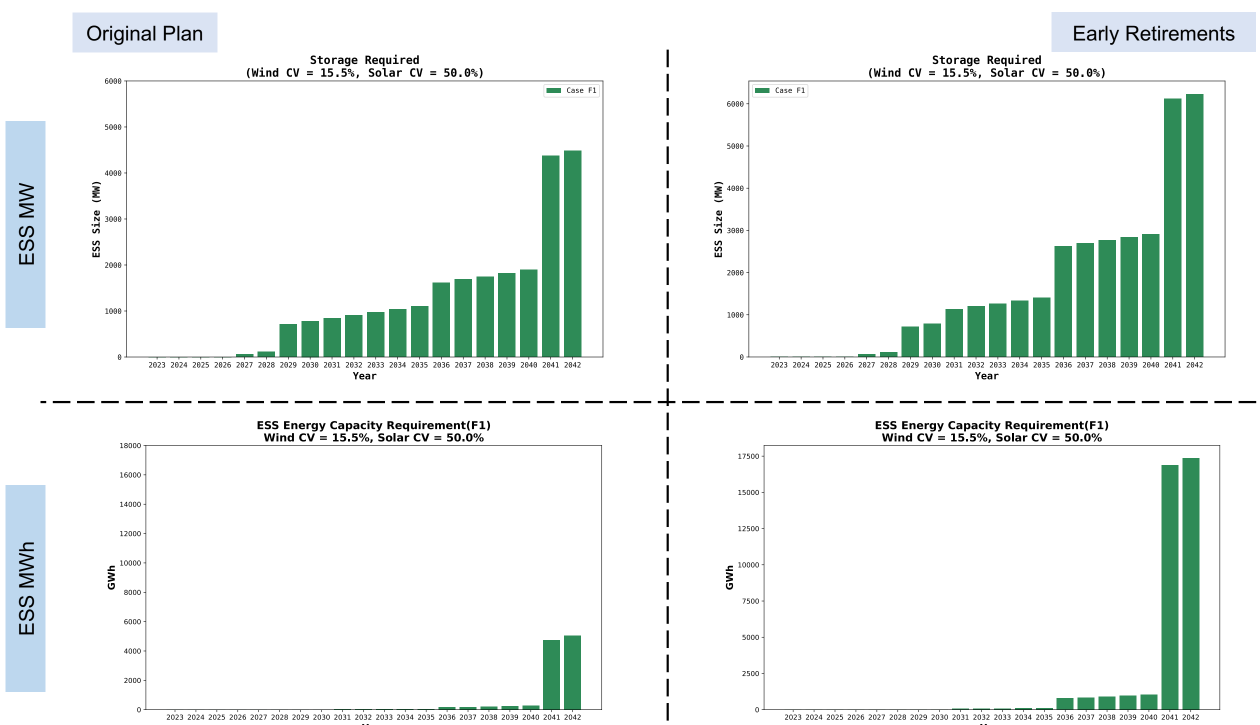

Figure 3-12. Minimum ESS required to achieve capacity and energy adequacy due to early shutdown of coal plants.

Table 3-3. Solar and wind additions by year

Year	New Solar (MW)	New Wind (MW)
2030	328	1060
2035	812	2620
2040	817	2635

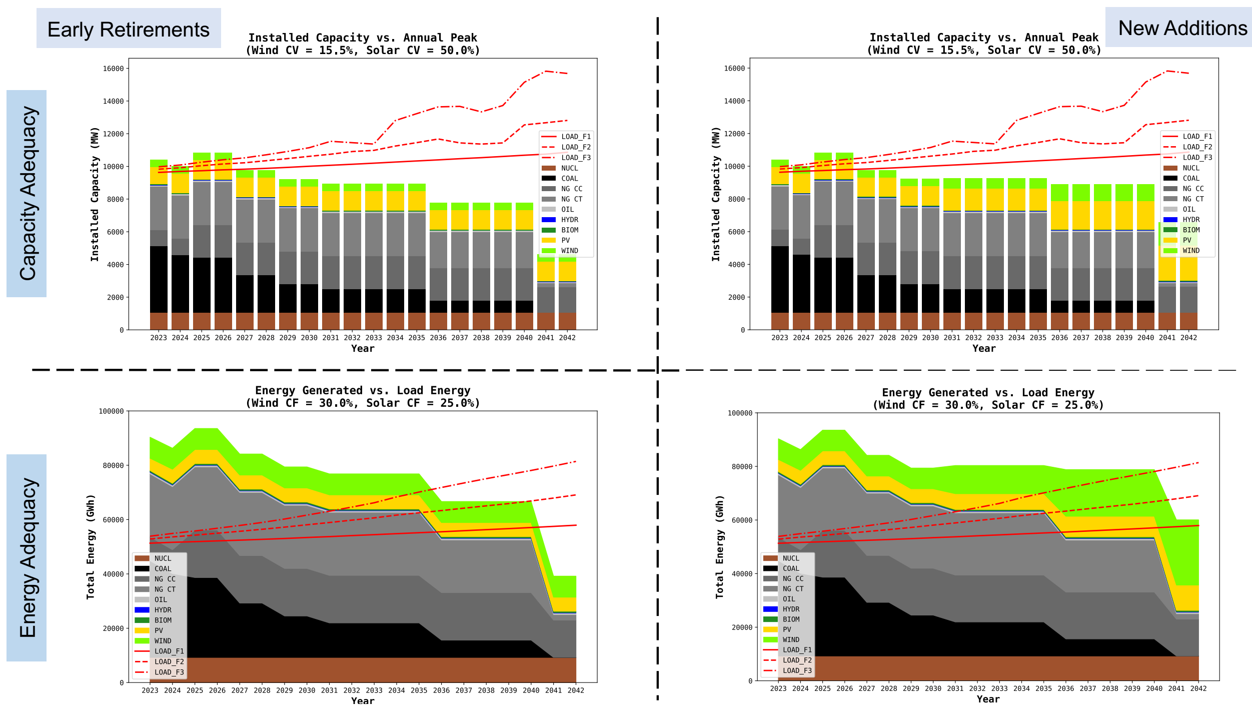

Figure 3-13. Capacity and energy adequacy of system due to new solar and additions.

Fig. 3-14. As expected, new solar and wind additions help in closing the gap between the installed capacity and the annual peak load and thus decrease the ESS sizes required to achieve resource adequacy. More detailed results are presented in the Appendix.

3.3.4.2. New solar additions with original retirement plan

For this scenario it is assumed that new solar PV capacity is added every year while adhering to the original retirement plan. Three cases are considered here: low (15%), average (24%), and high (30%) annual growth rate of PV additions. For the low case, PV capacity is assumed to be added every year from 2024 till 2041; for the average case, PV capacity is assumed to be added every year from 2024 till 2035; for the high case, PV capacity is assumed to be added every year from 2024 till 2033. The end year is selected by comparing the installed capacity with the load futures, that is, new addition has been stopped when the total installed capacity becomes sufficient to meet the annual peak load. The results are shown in Fig. 3-15.

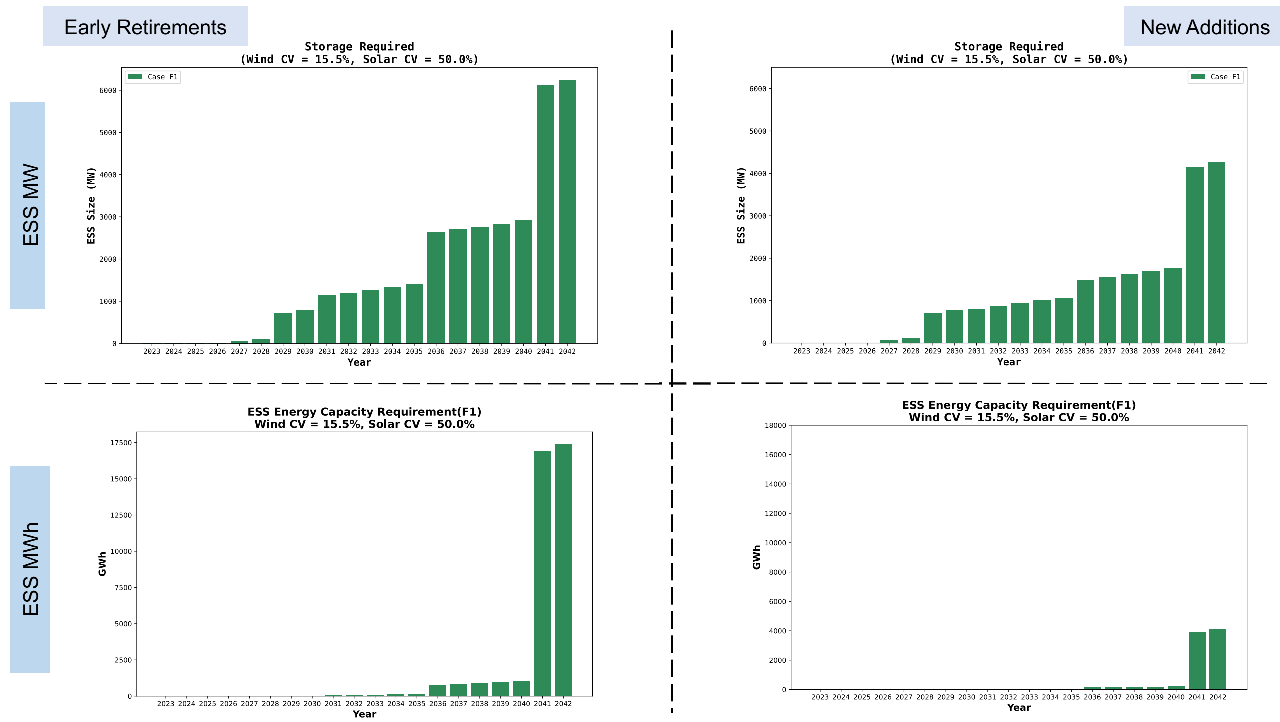

Figure 3-14. Minimum ESS required to achieve capacity and energy adequacy of system due to new solar and additions.

It can be observed from the results that even if solar is added at 15% growth rate, the system will have sufficient capacity to to serve the peak load and will be energy adequate as well. **However, it should be noted that the system will still need ESS to cater to nighttime load. Also, if the peak demand occurs after sunset, then the system will not be able to meet the demand without the aid of ESS.**

3.3.4.3. New wind additions with original retirement plan

For this scenario it is assumed that new wind power generation capacity is added every year while adhering to the original retirement plan. Two cases are considered here: average (9.4%) [2], and high (20%) annual growth rate of PV additions. New wind capacity is assumed to be added every year from 2024 till 2042. The impacts of the new additions are illustrated in Fig. 3-16.

It can be observed from the results that even with high annual growth rate, the system will not be able to achieve capacity adequacy with new additions of wind alone.

3.3.4.4. New wind and solar additions with original retirement plan

For this scenario, it is assumed that both new wind and solar resources are added with their respective average annual growth rates (24% for wind and 9.4% for solar). Wind is added from 2024 till

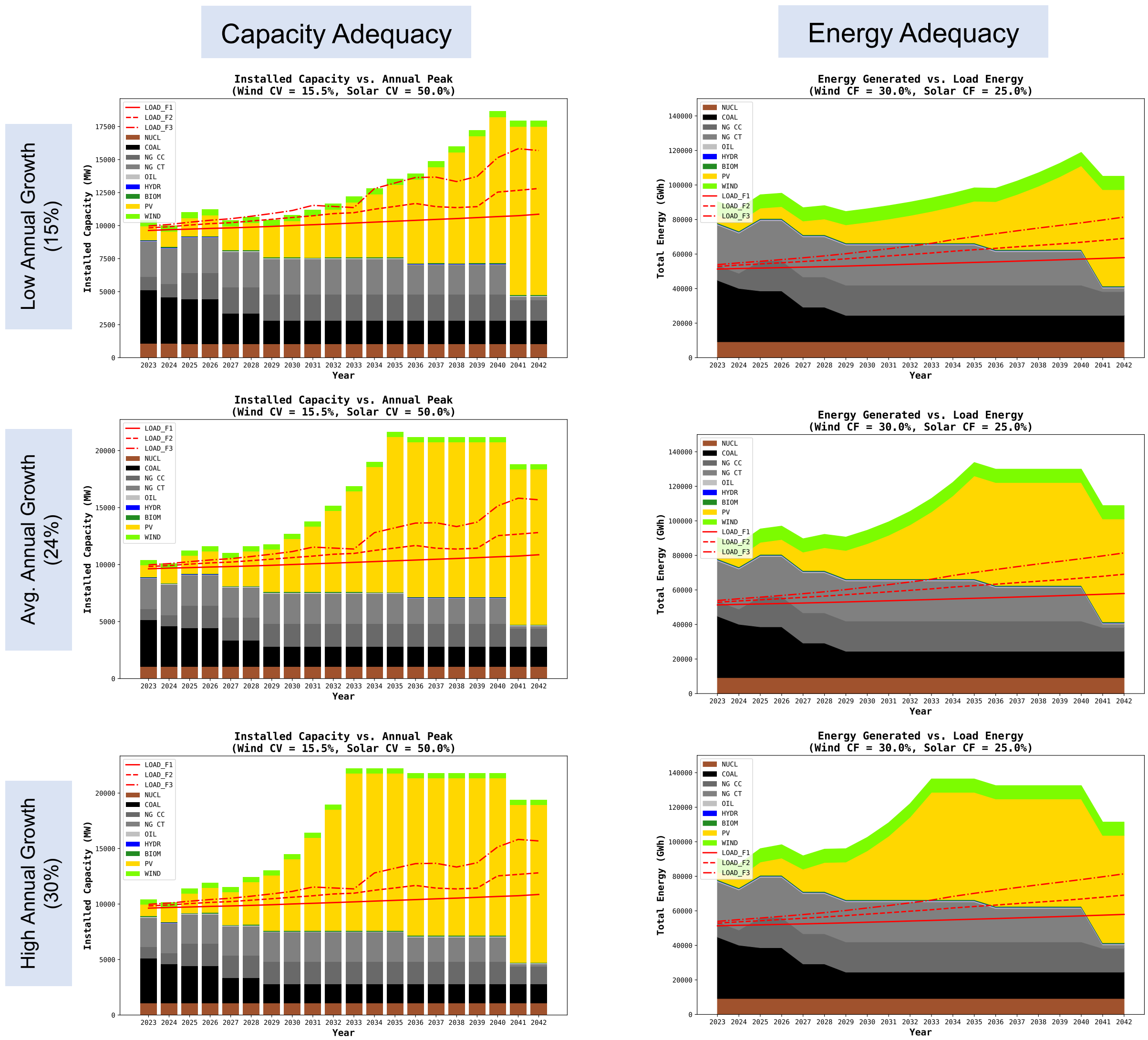

Figure 3-15. Capacity and energy adequacy with new solar PV additions.

2042 while solar is added from 2024 till 2033, when the system achieves capacity adequacy. The impacts on system capacity and energy adequacy are illustrated in Fig. 3-17.

It can be observed from the results that the system might be able to serve the peak load and also be energy adequate by using this combination of solar and wind. **However, similar to the scenario presented in Section 3.3.4.2, it should be noted that the system will still need ESS to meet the nighttime load. Also, if the peak demand occurs after sunset, then the system will not be able to meet the demand without the aid of ESS.**

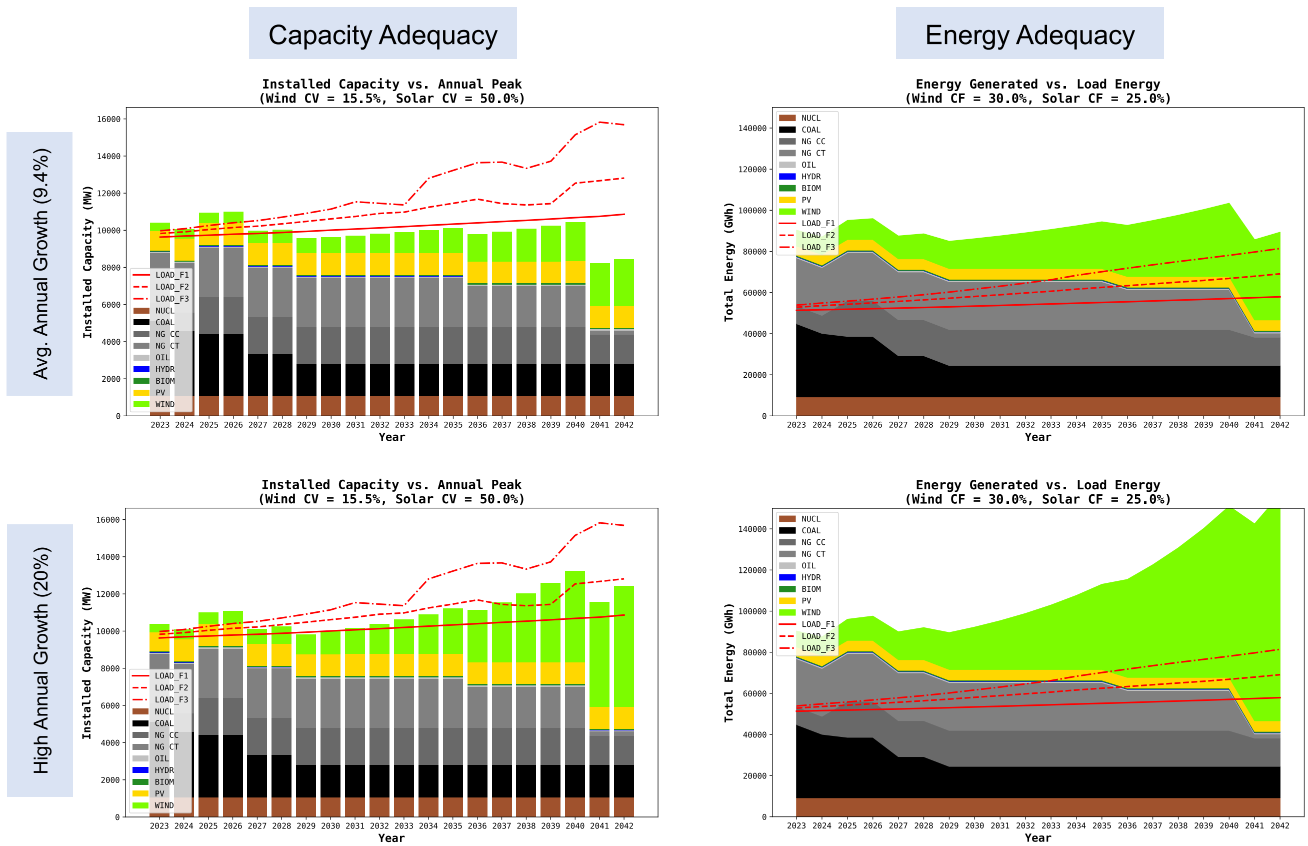

Figure 3-16. Capacity and energy adequacy with new wind additions.

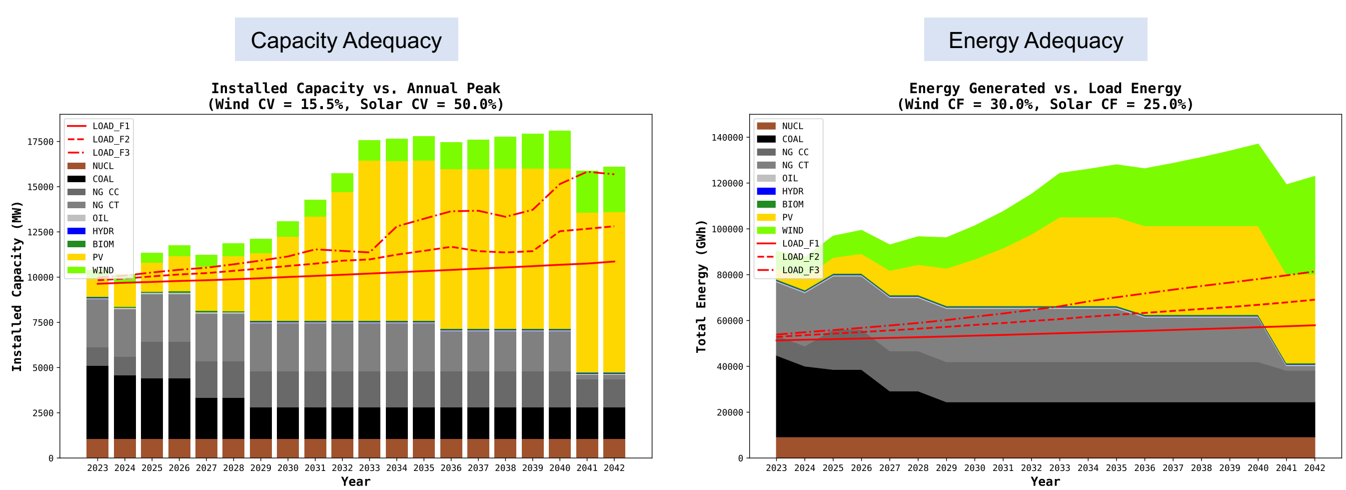

Figure 3-17. Capacity and energy adequacy with new solar and wind additions.

4. CONCLUSION & FUTURE WORK

In summary, this analysis shows that the current energy generation capacity in MISO Zone 4 of Illinois (omitting the impact of importing energy from resources outside of this zone) may not be sufficient to meet future energy demands. Under different future load scenarios, the analysis predicts that in the worst-case scenario the state could start experiencing capacity inadequacy as early as 2024. This shortfall is anticipated to widen progressively over the subsequent years, posing a significant challenge to the state's energy reliability.

The analysis also estimates the amount of energy storage needed to mitigate the generation gaps. The results indicate the ESS requirements align with the capacity adequacy findings. For example, the worst-case scenario for F1 showed an inability to serve the annual peak load starting in 2027, and consequently, the ESS was required for the first time in that year. The energy storage power rating and energy capacity increased steadily over time and exhibited exponential growth towards the end of the analyzed period.

It is important to highlight that these predictions have been modeled using a range of capacity values (CVs) for wind and solar power. By adjusting these CVs, the analysis predicts different scenarios of capacity inadequacy, which reiterates the crucial role of renewable energy and energy storage in the state's future energy mix. However, we must emphasize that the results derived from these scenarios should be used as an indicator of possible trends rather than concrete projections.

While this analysis provides valuable insights into Illinois's energy future, it only investigates the necessary conditions for potential generation gaps to happen. This work does not perform an hour-by-hour analysis based on optimized system operations, which could give a more precise understanding of the temporal variation in energy demand and supply.

Future work will focus on developing an optimization-based method to estimate the optimal generation mix and the amount of energy storage needed. This approach will allow for a more dynamic evaluation, taking into account various factors such as the variability of renewable energy generation, load shapes, and energy storage state of charge. It will also consider the delays in planned projects and the addition of new unplanned projects, to provide a more realistic evaluation of future energy scenarios. Moreover, the work could be expanded to include the calculation of CVs and capacity factors (CFs) of generating resources based on historical data, which could enhance the accuracy of the future energy scenario evaluations.

APPENDIX

Table 4-1. Installed capacity of MISO Zone 4

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
NUCL	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078	1078
COAL	4563	3960	3772	3772	2567	2567	1957	1957	1957	1957	1957	1957	1957	1957	1957	1957	1957	1957	1957	1957
NG CC	1282.98	1282.98	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2559.78	2011.78	2011.78
NG CT	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	3401.48	2837.48	2837.48	2837.48	2837.48	2837.48	297.2	297.2
OIL	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3	90.3
HYDR	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5
BIOM	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45	86.45
PV	2058.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4	2358.4
WIND	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7	2943.7

Table 4-2. Data for MISO Load Futures

Key	Case	LRZ	Category	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
F1_LRZ 4_Energy (GWh)	F1	LRZ 4	Energy (GWh)	51,317	51,632	51,867	52,154	52,420	52,722	53,033	53,402	53,724	54,100	54,444	54,811	55,165	55,508	55,904	56,285	56,667	57,073	57,493	57,927
F1_LRZ 4_System Peak (MW)	F1	LRZ 4	System Peak (MW)	9,330	9,418	9,469	9,784	9,548	9,879	9,939	10,008	9,847	9,854	9,937	10,011	10,093	10,172	10,247	10,250	10,339	10,440	10,539	10,624
F1_LRZ 4_Zonal Peak (MW)	F1	LRZ 4	Zonal Peak (MW)	9,632	9,691	9,735	9,789	9,828	9,880	9,939	10,008	10,068	10,130	10,197	10,265	10,333	10,399	10,470	10,533	10,607	10,683	10,750	10,864
F2_LRZ 4_Energy (GWh)	F2	LRZ 4	Energy (GWh)	52,858	53,624	54,267	54,982	55,684	56,426	57,220	58,088	58,913	59,790	60,629	61,652	62,501	63,319	64,200	65,054	65,888	66,858	67,921	69,093
F2_LRZ 4_System Peak (MW)	F2	LRZ 4	System Peak (MW)	9,813	9,661	10,034	10,145	9,927	10,348	10,446	10,586	10,722	10,584	10,703	11,144	11,194	11,025	11,159	11,058	11,132	12,539	12,595	12,312
F2_LRZ 4_Zonal Peak (MW)	F2	LRZ 4	Zonal Peak (MW)	9,828	9,916	10,042	10,149	10,222	10,348	10,479	10,615	10,745	10,909	10,979	11,244	11,453	11,677	11,437	11,364	11,436	12,539	12,670	12,812
F3_LRZ 4_Energy (GWh)	F3	LRZ 4	Energy (GWh)	53,879	54,897	55,811	56,799	57,829	58,942	60,207	61,647	63,072	64,599	66,193	68,347	70,130	71,813	73,471	75,068	76,559	78,091	79,708	81,415
F3_LRZ 4_System Peak (MW)	F3	LRZ 4	System Peak (MW)	9,928	9,878	10,225	10,377	10,227	10,679	10,894	11,009	10,901	10,908	10,971	12,803	13,228	13,642	13,671	13,070	13,409	15,147	9,010	9,933
F3_LRZ 4_Zonal Peak (MW)	F3	LRZ 4	Zonal Peak (MW)	9,975	10,084	10,257	10,406	10,522	10,709	10,915	11,144	11,534	11,451	11,365	12,803	13,228	13,642	13,671	13,336	13,723	15,147	15,825	15,686

Table 4-3. Installed solar capacity data for new solar addition scenario (Section 3.3.4.2)

PV Annual Growth	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
Low (15%)	2058.4	2367	2722	3131	3600	4140	4761	5475	6297	7241	8327	9576	11012	12665	14565	16750	19262	22151	25474	25474
Medium (24%)	2058.4	2552	3165	3924	4866	6034	7483	9278	11505	14266	17691	21937	27201	27201	27201	27201	27201	27201	27201	27201
High(30%)	2058.4	2676	3479	4522	5879	7643	9935	12916	16791	21828	28376	28376	28376	28376	28376	28376	28376	28376	28376	28376

Table 4-4. Installed wind capacity data for new wind addition scenario (Section 3.3.4.3)

Wind Annual Growth	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
Avg. (9.4%)	2943.7	3220	3523	3854	4217	4613	5047	5521	6040	6608	7229	7908	8651	9465	10355	11328	12393	13558	14833	16226
High (20%)	2943.7	3385	3893	4477	5148	5921	6809	7830	9005	10356	11909	13695	15749	18112	20829	23953	27546	31678	36430	41894

BIBLIOGRAPHY

[1] Argonne National Laboratory. Survey of U.S. Ancillary Services Markets. https://publications.anl.gov/anlpubs/2016/01/124217.pdf. Accessed: 2023-09-14.

[2] CDI. Wind energy market size. https://www.contrivedatuminsights.com/product-report/wind-energy-market-65957. Accessed: 2023-07-27.

[3] Jim Eyer and Garth Corey. Energy storage for the electricity grid: Benefits and market potential assessment guide. *Sandia National Laboratories*, 20(10):5, 2010.

[4] Illinois Commerce Commission, The Brattle Group, Great Lakes Engineering. Illinois Renewable Energy Access Plan. Technical report, December 2022.

[5] Andrew Keane, Michael Milligan, Chris J. Dent, Bernhard Hasche, Claudine D'Annunzio, Ken Dragoon, Hannele Holttinen, Nader Samaan, Lennart Soder, and Mark O'Malley. Capacity value of wind power. *IEEE Transactions on Power Systems*, 26(2):564–572, 2011.

[6] Seyed Hossein Madaeni, Ramteen Sioshansi, and Paul Denholm. Comparison of capacity value methods for photovoltaics in the western united states. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2012.

[7] Seyed Hossein Madaeni, Ramteen Sioshansi, and Paul Denholm. Comparison of capacity value methods for photovoltaics in the western united states. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2012.

[8] MISO. MISO Futures Report. Technical report, December 2021.

[9] MISO. Planning Year 2022-2023 Wind and Solar Capacity Credit. Technical report, 2022.

[10] MISO Reliability Subcommittee. Overview of Winter Storm Elliott December 23, Maximum Generation Event. https://cdn.misoenergy.org/20230117%20RSC%20Item%2005%20Winter%20Storm%20Elliott%20Preliminary%20Report627535.pdf. Accessed: 2023-09-14.

[11] NC Clean Energy Technology Center. Renewable portfolio standards and clean energy standards, 2022.

[12] Nga Nguyen, Atri Bera, and Joydeep Mitra. Energy storage to improve reliability of wind integrated systems under frequency security constraint. *IEEE Transactions on Industry Applications*, 54(5):4039–4047, 2018.

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.