



Flexibility Measures and Energy Management Strategies for Large-scale PV Integration into Grid system – A Case Study for Saudi Arabia

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Abstract

It is widely believed that the incorporation of renewable energy to the current power grid is the way forward in achieving sustainable power generation. Currently, with the reduction of PV prices, many countries have started connecting PV systems into their grid network, hence leading to a sharp increase of the penetration levels of renewable electricity production. In particular, the Saudi government is moving towards exploiting renewable energy, and specifically solar PV to meet its future high energy demands and diversify its economy. This will bring significant change in the load pattern and the ramping requirements of the grid's conventional generation system due to the varying nature of the renewable energy generation. This significant change affects the stability of the grid frequency, and it becomes more challenging for the system operators to maintain the equilibrium between the generation and load. Additionally, this significant change affects the PV system potential hosting capacity of the traditional grid because of the PV system's curtailment to comply with the constraints of the grid's conventional generation system. This thesis aims to investigate and develop flexibility measures and energy management strategies to minimise the impact of integrating large-scale PV systems into the grid system, taking the Saudi Grid as a case study. In doing so, will improve the grid's flexibility that will result in the enhancement of the grid's potential hosting capacity with the projected large-scale PV integration into Saudi grid system.

This thesis introduces the developed PV curtailment algorithms using MATLAB program, that ensures having the PV system's participation in the grid's generation mix at its maximum without violating the grid's constraints. This enabled studying the change in load pattern effect and the ramping requirements needed by the grid's conventional generation system in the situation of increasing the penetration level of the large-scale PV power into the grid. In addition, this enabled the evaluation of the grid's current potential hosting capacity with large-scale PV systems at various penetration levels to the grid. Also, this aided in showing the substantial affects that each grid constraint has on the performance of the PV system in terms of PV curtailment, and provides the bases that can be used to establish the appropriate flexibility measures capable of ensuring both the reduction of the PV curtailment and minimising the impact of integrating large-scale PV into the grid. The results show that the grid operators will face increasingly variable net load patterns and steeper ramping events as the PV system's penetration level increases in which the PV curtailment percentage will increase from 0.08% to 21.99% as the PV penetration level to the grid increases from 10% to 50%. Additionally, the results show the requirement of having flexibility measures that target each grid constraint as the PV system penetration level increases. Therefore, a diurnal storage system in the form of lithium-ion batteries is proposed to be employed as the flexibility measure for the ramping constraint, while a seasonal storage system is proposed to be employed as the flexibility measure for the baseload constraint.

The thesis also examines the grid's frequency stability due to increasing penetration level of PV generation into the grid. This includes illustrating the effect of the size of the PV

disturbance on the grid's frequency. In doing so, provides insight on the impact of PV variability on the grid, since the frequency stability of the grid senses the variations between the generation and demand. Finally, this thesis introduces the developed optimal sizing and energy management strategies of the proposed flexibility measures to enhance the grid's PV hosting capacity and minimise the impact of integrating large-scale PV systems into the Saudi grid. In addition, the technical effectiveness of the developed optimal sizing and energy management strategies of the proposed flexibility measures, will be analysed in the form of case studies based on the Saudi's 2030 PV energy target. Results showing the performance of each proposed flexibility measures are presented in detail, and it demonstrates that each proposed flexibility measure can enhance the grid's PV hosting capacity and minimise the impact of integrating large-scale PV systems into the Saudi grid. Having no flexibility measures will result in curtailing 20.71% of the PV system's generation sum throughout the year. A diurnal storage system with a capacity of 2918 MWh/day, will eliminate the curtailment of the PV system's output due to the grid's ramping constraint, and it will allow the displacement of roughly 315 GWh of conventional generation with furthering the reduction of the peak load by 2.67%. Furthermore, a seasonal storage system with a capacity of 82 GWh, will further reduce the peak load by 4.67% via targeting the peak load of 220 hours.

List of Publications

A. Alshahrani, S. Omer, Y. Su, E. Mohamed, and S. Alotaibi, "The Technical Challenges Facing the Integration of Small-Scale and Large-scale PV Systems into the Grid: A Critical Review," *Electronics*, vol. 8, no. 12, 2019. doi: 10.3390/electronics8121443.

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List of Abbreviations

Abbreviation	Definition
AGC	Automatic Generation Control
BSS	Battery Storage System
CAES	Compressed Air Energy Storage
CAISO	California Independent System Operator
DG	Distributed Generation
DOD	Depth of Discharge
DSM	Demand Side Management
ECRA	Saudi's Electricity and Cogeneration Regulatory Authority
EDLC	Electrochemical Double-Layer Capacitors
EES	Electricity Energy Storage
EMS	Energy Management System
GHI	Global Horizontal Irradiance
GRC	Grid's Ramping Constraint
ILR	Inverter Loading Ratio
K.A.CARE	King Abdullah City for Atomic and Renewable Energy
LAES	Liquid Air Energy Storage
LFC	Load Frequency Control
LLE	Loss of Load Event
LOLP	Loss of Load Probability
MPPT	Maximum Power Point Tracking
NREL	National Renewable Energy Laboratory
PCC	Point of Common Coupling
PHS	Pumped Hydro Storage
PPA	Power Purchase Agreement
PTES	Pumped Thermal Energy Storage
PV	Photovoltaic
SEC	Saudi Electricity Company
SOH	State of Health
VRE	Variable Renewable Energy

Chapter 1 General Introduction

1.1 Introduction

Energy from renewable sources is becoming a growing component of the electricity grid around the world, due to its contribution to achieving decarbonisation, energy security and improving the energy access. The integration of renewable energy resources into existing electrical grids is the way forward to achieve clean and sustainable power generation due to the rapid depletion of the conventional power sources, better known as fossil fuels, which contribute to the increasing greenhouse gas emissions and create environmental concerns such as the depletion of the ozone layer, change in global climate and acid rain [1]. On the other hand, the usage of nuclear energy can raise hazardous concerns to the health of living creatures and the environment, and this gives renewable energy the advantage for future sustainable power generation [2].

The average energy supplied from the sun's radiation that the Earth's surface receives is approximately 1.2×10^{17} W of solar power, which is enormous and less than an hour of this can meet the demand of the whole population for a whole year [3]. However, most renewable energy resources are not available for use all the time due to factors that are outside our control, better known as intermittent nature. Intermittent renewable energy resources may be predictable, but they cannot be dispatched in a flexible way for meeting the fluctuating demand because their output cannot be altered quickly. Thus, there is a relationship between the intermittency and dispatchability of the electricity resources in which most non-dispatchable electricity sources are often highly intermittent. There are many different types of non-dispatchable renewable energy, including tidal and wave energy, but the two main types of non-dispatchable renewable energy that contribute noticeably to the electrical grid are wind and solar energy.

The intermittency experienced from both wind and solar energies brings the following distinct characteristics of power generation, including partial unpredictability, non-controllable variability, and location dependency. Those distinct characteristics of the intermittent renewable energy sources can impact both the operation and security of the grid when integration is considered. Partial unpredictability can be referred to as the uncertainty or the inability to predict the exact available energy production of the intermittent renewable energy power generation at a timescale of an hour or a day from the present time. Thus, it complicates the grid's management for the operators because of their usage of the process "unit commitment" that schedules the generation in advance [4]. At present, the "unit commitment" process is considered largely deterministic because once the generator is scheduled to operate, it is expected to be available and ready to operate at full capacity. This shows the relative predictability and controllability that traditional power plants such as coal brings.

However, the operation of the "unit commitment" becomes more complex when dealing with a stochastic generation that has an output at the active time displaying some degree of

uncertainty resulting in an increased cost of the function due to the need of balancing the actual production with the predicted one [5]. Forecasting technologies can be used here to predict the weather and hence the generation output of the intermittent renewable energy sources at various time scales to allow the grid operators to facilitate the scheduling and dispatching of the sources more effectively. In addition, the grid operators will need an advanced “unit commitment” process that is unlike the deterministic one and capable of predicting the uncertain outcomes that the forecasting technologies cannot predict [6]. Therefore, it is recommended that the resources scheduling of the system take into account the stochastic nature of intermittent renewable energy power generation and their level of concentration on the system, which results in a cost-effective way to maintain the system’s flexibility and avoids risking the system’s reliability [7].

Intermittent renewable energy sources are usually located in remote locations far away from the centre of the loads except for solar energy in which may be installed near the load vicinity. Thus, apart from day-to-day management of the grid system, the long-term planning of the siting of the renewable energy power generation and the utilisation of new transmission lines to carry out the renewable energy to the market are very crucial. Transmission planning for renewables is very complex because it is influenced by the regional politics affecting the capacity of generation, the location of transmission and the load sizes. In addition, technical needs will arise of the type of transmission technology used since it will carry a primarily partially unpredictable and variable electricity. On the other hand, using a distributed renewable energy generation topology rather than a central one will give the grid an alternative future vision which is the micro-grid. This is because it will eliminate the costs of the line losses and the expensive cost of the transmission lines making the electricity grid conceptualised as a dependent collection of micro-grids [8].

Variability in terms of the intermittent renewable energy sources such as wind and solar refers to the fact that their output is not constant, which is a quite distinct character of the term unpredictability. Thus, even if the operator is successful in predicting the output of the intermittent renewable energy power generation correctly, the output would still be variable, posing great challenges to the grid. It is worth noting that each type of renewable energy has its typical and unique generation pattern.

Grid operators must deal in the transmission system with fluctuations in terms of frequency and voltage on a timescale of seconds to minutes so that the system and its equipment are not affected. It is performed through ancillary systems which order generators to inject active or reactive power into the grid to balance the actual and predicted power, thus maintaining the frequency and voltage levels of the grid. The followings are the types of ancillary services:

- Voltage support which uses the reactive power of the generators to raise the voltage whenever it is necessary.
- Frequency regulation which is performed through signals to the generators from the automatic generation control (AGC) on the basis of seconds to minutes [9].

- Spinning and non-spinning reserves which uses the generator's available power to act as a generation reserve whenever the system goes down. If the generator provides the power within a couple of few minutes, it is classified as spinning and if it takes a longer time, it is classified as non-spinning.
- Black-start capacity which is the generator's ability to start the system in the case of a black-out.

In addition, the grid operators must track the demand of the loads for electricity from the consumption side to ensure that the generation and load are matching all the time. This function is called load-following, which becomes vital at peak demand times and is met through ancillary services. The aforementioned functions are not new to the grid because the load is variable itself. The consumers demand for electricity can be predictable but not controllable, thus adding a degree of variability. In addition, the conventional generator can experience problems of not performing as scheduled all the time. Therefore, the grid can deal with a low-level variability added to it in the form of intermittent renewable energy at a low level of penetration because the integration challenges are primarily specific on the device and local-grid such as harmonics and sub-synchronous resonance [10]. On the other hand, at high penetration levels of intermittent renewable energy, the grid will experience more variability than it has managed in the past leading to an increase in demand for those ancillary services and energy balancing overall, which is quite challenging to manage at device level. Thus, grid level actions, strategies and technologies are needed to overcome this.

1.2 Background

1.2.1 Electricity Market in Saudi Arabia

The Kingdom of Saudi Arabia lies between the latitude of 32°N and 17°N, and the longitude of 56°E and 28°E. It is considered the largest country in the region with an area of 2.15 million square kilometre and a land elevation that varies from 0 to 3,000 meter above the sea level in which the complex terrain is located in the southwest of the kingdom [11].

Furthermore, the west and the east coasts of the kingdom are located on the Red Sea and the Arabian Gulf respectively. The kingdom can be characterised by an arid environment with low annual rainfall and high temperature variability in which there are mainly two seasons during the year: winter and summer.

According to the Saudi's General Authority for Statistics [12], there has been a dramatic growth in the population of Saudi Arabia, from 20,846,884 in 2000 to 32,612,846 in 2017 with an average annual growth rate of 2.5%. This dramatic growth in population resulted in an increased demand in energy and other various utilities. In this sense, as the population grows, the number of electricity users will follow this growth. The number of electricity users in Saudi Arabia increased from 3.6 million in 2000 to roughly 8.09 million in 2015 [13]. The kingdom's peak load historical data, obtained from the Electricity and Cogeneration Regulatory Authority (ECRA) [14] shows a significant surge in the peak load during the last two decades in which the peak load increased from 15.5 GW in 1993 to 62.121 GW in 2017. In addition, Saudi Arabia has one of the highest energy consumption rate per capita in the

world, which is three times more than the world's average [15]. Furthermore, the energy consumption per capita in Saudi Arabia increased from 4,422 kWh/Capita in 1993 to 9,167 kWh/Capita in 2017 [16]. This dramatic increase in the energy consumption is due to a combination of the extreme weather conditions and the historically low energy prices. Figure 1.1 shows the 2017 electricity consumption by sector in the Saudi Arabia.

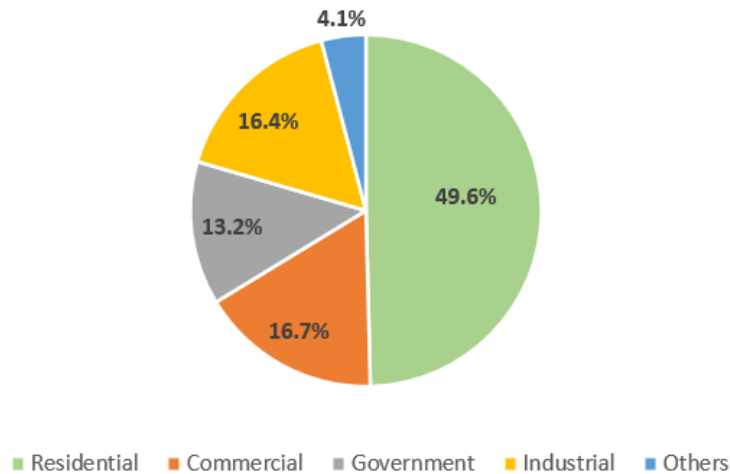


Figure 1.1. The 2017 electricity consumption by sector in Saudi Arabia [14].

The Saudi government has long set the domestic energy prices below international market levels via energy subsidisation to keep an affordable stable price to support low income households. However, this subsidisation has encouraged a wasteful consumption and a higher demand growth. The authors of [17] found that, the electricity consumption could drop with the rise of the energy price. Also, the authors of [18] indicated that increasing the energy price resulted in a smaller energy usage. Therefore, the energy subsidies represent a vital element for setting up the energy prices that plays an important role in setting the energy demand and consumption [19]. In late 2015, the Saudi government started its ambitious plan to reduce energy consumption through reforming the energy prices, though the prices are still below the global energy prices level [20]. Table 1.1 shows the electricity tariffs in Saudi Arabia. It is worth noting that the current electricity tariffs in Saudi Arabia haven't increased since the start of 2018.

Table 1.1. The electricity tariffs in Saudi Arabia [20].

Sector	End-2015	Start-2018	Change (%)
Residential: 1-6000 kWh/month	0.05 SR/kWh	0.18 SR/kWh	260
	0.014 \$/kWh	0.048 \$/kWh	
Residential: above 6000 kWh/month	0.30 SR/kWh	0.30 SR/kWh	0
	0.08 \$/kWh	0.08 \$/kWh	

Industry	0.18 SR/kWh	0.18 SR/kWh	0
	0.048 \$/kWh	0.048 \$/kWh	
Government	0.32 SR/kWh	0.32 SR/kWh	0
	0.085 \$/kWh	0.085 \$/kWh	

The development of the Saudi's electricity market is overseen by four major government entities which are the Ministry of Energy, the Electricity and Cogeneration Regulatory Authority (ECRA), the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) and the Saudi Electricity Company (SEC). The Ministry of energy plans and sets the long-term energy policies and oversees the investment of the private companies in the sector. ECRA is an independent government entity that standardises the electricity sector and is responsible for assessing the tariffs, license issuing, complaints investigation, monitoring the service providers and establishing the quality of service standards that endorses the fair competition among providers and suppliers. Meanwhile, the K.A.CARE is responsible for driving the integration of renewable energy initiative and the development of the energy efficiency programs. The Saudi Electricity Company (SEC) is the power supply utility responsible for the electricity generation, transmission, and distribution. It is divided into four main regions: Central, West, South and East in which the company interconnected those regions. The SEC deals with the continuous demand for electricity by the construction of additional power plants or improving on the existing ones. In addition, they request some of their large customers to switch off their supply from the grid and turn on their emergency generators in order to reduce the grid load during the summer peak period [21].

Saudi Arabia uses more than half a million barrels of oil per day directly for its power generation [22]. This burning of fossil fuel is largely responsible for the pollution in the form of CO₂ emissions that causes environmental deteriorations such as global warming. The research efforts in [23] indicated that energy consumption via fossil fuels will lead to long term economic growth in Saudi Arabia, but could also result in the deterioration of the environmental quality through increasing of the CO₂ emissions in the country. Therefore, the Saudi government has committed in maintaining its national contributions on taking climate change sustainable actions in line with the 2015 Paris climate change agreement [24].

1.2.2 Solar PV Energy Prospect in Saudi Arabia

The current dependence status for Saudi Arabia, relying on oil and its revenue is not sustainable, and if it is left unchecked can cause serious stress on the environment, climate, and economy stability of the country. Also, another important factor is the increase of domestic energy consumption in the kingdom which is due to the following:

- Low energy prices.
- Population growth.

- Consumer's wasteful habits.
- Economical & Industrialisation development.

Despite the kingdom being among the largest in the world in having abundant energy sources such as the unexploited renewable energy sources, oil reserves and gas reserves; it is also one of the largest energy consumers in the world in which their oil consumption has more than doubled in the past decade [25]. The research efforts in [26] assessed the potential of solar energy in various sites of Saudi Arabia in which all the sites recorded high Global Horizontal Irradiance (GHI) values with low variability. These high GHI values are well suited for large deployment of the solar PV technology across Saudi Arabia.

Thus, in April 2016, the Saudi government has launched a new economic blueprint called the Saudi Vision 2030, which aimed at reducing the kingdom's dependence on oil, to diversify their economy away from oil and to tackle the challenges posed from climate change. Specifically, one of its main targets is to localise a significant portion of the renewable energy value chain in the kingdom's economy which includes research, development, and manufacturing among other stages. The Saudi Vision 2030 states that at present Saudi Arabia lacks a competitive renewable energy sector. Therefore, they have set an initial target of generating 9.5 GW of renewable energy in order to build up the sector by 2030 [27]. However, this initial target was later increased to 58.7 GW in which they are committed to install 40 GW of solar PV technology [28].

Saudi Arabia auctioned the first utility-scale solar PV plant called the Sakaka 300 MW solar photovoltaic project, located north of the kingdom for bidding. It received offers to supply solar electricity for the cheapest prices ever recorded in which Abu Dhabi Future Energy Co (Masdar) and EDF Energies Nouvelles made a bid to supply power from a 300 MW photovoltaic plant for as little as 6.69736 halalas per kWh or 1.79 cents per kWh [29]. Up till recently, the kingdom supported only large-scale projects of renewable energy. However, this changed for the small-scale renewable energy projects since the kingdom adapted new rules or regulations such as the new net metering scheme that is approved by the kingdom's Electricity & Cogeneration Regulatory Authority (ECRA). This scheme allows the residents to install small PV systems of no more than 1 MW of capacity that can be connected to the distribution network of the grid [30].

1.3 Aim & Objectives

The main aim of this research is to investigate and develop flexibility measures and energy management strategies to minimise the impact of integrating large-scale PV systems into the Saudi grid. In doing so, this will improve the grid's flexibility that will result in the enhancement of the grid's potential hosting capacity with the large-scale integrated PV systems. Figure 1.2 shows a block diagram which illustrates an overview of the issues that prompted the motivation of this research. The issues are due to the variable nature of the PV generation which causes the mismatch between the supply and demand. In addition, the motivation of this research is prompted by the current approach of the grid operators in dealing with this issue in which is unreliable in the future, costly, wastes clean energy, increases the environmental deteriorations and increases the stress on the conventional generation system. The following are the objectives of this research:

- To identify the localised technical challenges and grid stability challenges facing the integration of large-scale PV systems into the transmission network of the grid. In addition, to analyse both the technical solutions and the current practices for managing the variability of large-scale PV systems by the grid operators.
- To review and compare the different Electricity Energy Storage (EES) technologies in order to determine the most suitable EES technologies to be used as the flexibility measure for enhancing the grid's potential hosting capacity with the large-scale integrated PV systems.
- To model both the grid's frequency and the PV curtailment algorithms in order to evaluate the grid's potential hosting capacity with large-scale integrated PV plants. This will provide insight on the impact of PV variability on the grid. Also, it enables studying the change in load pattern effect and the ramping requirements needed by the grid's conventional generation system.
- To evaluate the grid's current potential hosting capacity with large-scale PV systems at various penetration levels to the grid. This will enable showing the substantial affects that each grid constraint has on the performance of the PV system in terms of PV curtailment. Also, it will provide bases that can be used to establish the appropriate flexibility measures capable of ensuring both the reduction of the PV curtailment and minimising the impact of integrating large-scale PV into the grid.
- To develop the optimal sizing and energy management strategies of the flexibility measures that are applied in order to enhance the grid's potential hosting capacity with the large-scale integrated PV systems. A diurnal storage system in the form of lithium-ion batteries will be applied as the flexibility measure for the ramping constraint while a seasonal storage system will be applied as the flexibility measure for the baseload constraint.

- To examine the PV system's performance without applying the proposed flexibility measures at a more PV accommodating grid through lowering the baseload constraint and increasing the ramping constraint.
- To model and simulate the proposed flexibility measures under various capacities in order to investigate their effects on the PV system's performance, frequency stability and the net load in terms of peak load and ramping stress. This enables analysing the technical effectiveness of the proposed flexibility measures and their energy management strategies that could be implemented in such a way to enhance the grid's PV hosting capacity and minimise the impact of integrating large-scale PV systems into the Saudi grid.

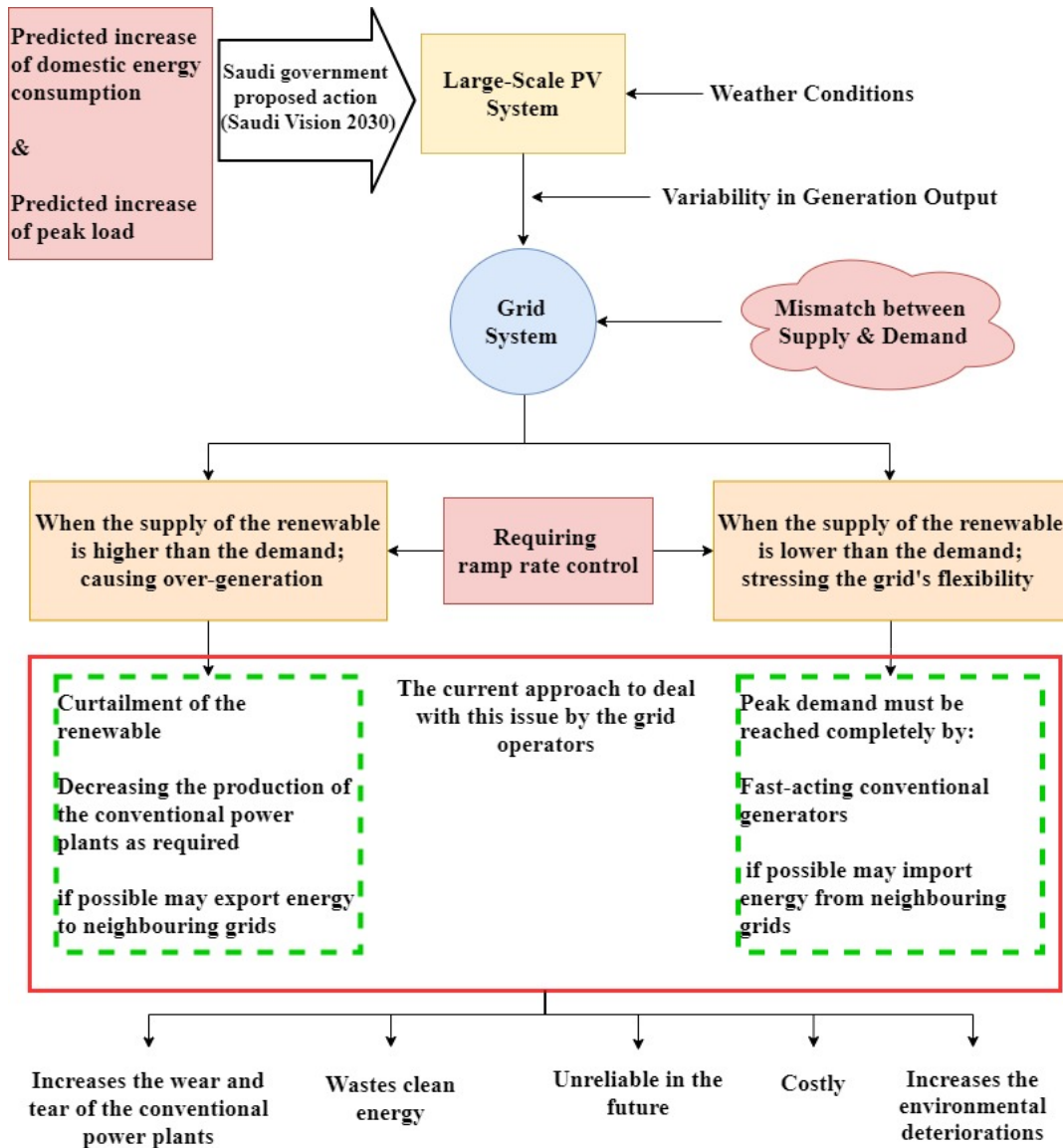


Figure 1.2. Block diagram illustrating an overview of the issues that prompted the motivation of this research.

It is worth mentioning that the results documented, and the conclusion drawn in this thesis are based on detailed and thorough simulations. The MATLAB software was used to generate all the results and a copy of the MATLAB code is included in the appendices of this thesis. Furthermore, an overall block diagram illustrating the methodology used in this research is shown in Figure 1.3 and this block diagram can be expressed into the following steps:

1. Establishing the scene for the issues and possible solutions by assessing the impact of PV integration into the grid. Then, reviewing the energy storage technologies in order to identify the most suitable technologies that can be used as the proposed flexibility measures. This step will be illustrated in both Chapter 2&3.
2. Collecting data for the chosen location of study in the form of the load profile and meteorological data. The Saudi Electricity Company (SEC) will be the source of the collected load profile data. Meanwhile, the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) will be the source of the collected meteorological data that will be used as the input for the PV system.
3. Presenting the collected meteorological data then modelling and validating the PV system's design and output. This step of the PV system modelling will be illustrated in Chapter 4.
4. Presenting the collected load profile data then analysing the net load in terms of both the net load pattern and ramping requirements. Also, modelling both the grid's frequency and the PV curtailment algorithms in order to evaluate the grid's potential hosting capacity with large-scale integrated PV plants. This step will be illustrated in Chapter 5.
5. Proposing the optimal sizing strategy and energy management strategy for both flexibility measures based on the results of the evaluation of the grid's potential hosting capacity with large-scale integrated PV plants that was already done in Chapter 5. This step will be illustrated in Chapter 6.
6. Applying the proposed optimal sizing and energy management strategies of the flexibility measures in the form of case studies based on the country's future PV energy target (Saudi vision 2030). In doing so, will validate the technical effectiveness of the proposed flexibility measures and their energy management strategies. This step will be illustrated in Chapter 7.

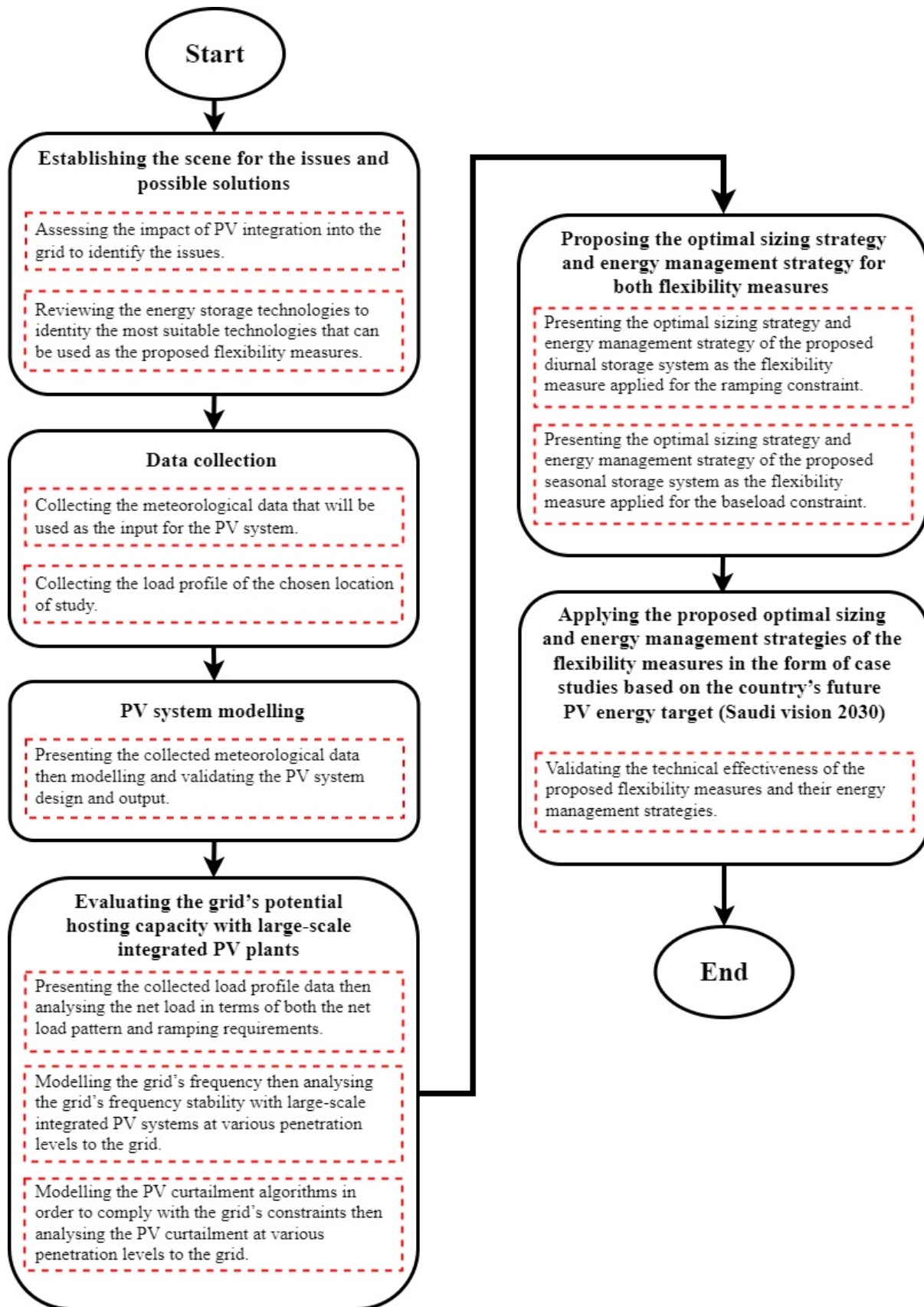


Figure 1.3. Block diagram illustrating the overall methodology used in this research.

1.4 Thesis Structure

In chapter 1, the distinct characteristics of renewable energy generation that impacts the grid system in the form of partial unpredictability, non-controllable variability and location dependency have been described. Then, the electricity market in Saudi Arabia was presented including their governing structure, growth factors and the government's ambitious plan to reduce energy consumption through reforming the energy prices. In addition, the solar PV energy prospect in Saudi Arabia was presented since the Saudi government is moving towards exploiting renewable energy and in particular solar PV in order to meet its future energy demands and diversify its economy. Furthermore, the chapter includes the overall aim and objectives of this thesis. The remainder structure of the thesis follows.

Chapter 2 presents the impact of PV integration into the grid which includes a review of the technical challenges, potential technical solutions and the research carried out in integrating high shares of small-scale PV systems into the distribution network of the grid in order to give a clearer picture of the impact since most of the PV systems installations were at small scales and connected into the distribution network. Also, it reviews the localised technical challenges, grid stability challenges and technical solutions on integrating large-scale PV systems into the transmission network of the grid. In addition, it illustrates the current practices for managing the variability of large-scale PV systems by the grid operators and discusses the way forwards.

Chapter 3 presents an overview of the Electricity Energy Storage (EES) technologies and illustrates their various applications. This overview will cover a review of each EES technology which includes their drawbacks, further work or development carried on improving the energy storage technology and examples of large-scale installations of the energy storage technology. In addition, it illustrates the conducted overall comparison of the EES technologies in terms of the technical characteristics and technical suitability to different applications.

Chapter 4 presents the modelling of the PV system which demonstrates a detailed description of the steps undertaken to design and model the PV system, which includes the sizing of the PV array, the performance of the inverter, other miscellaneous system losses and the PV array mathematical representations. Also, it studies the two simplified mathematical models for calculating the PV array in order to illustrate which simplified mathematical model gives the upmost accurate result in comparison to the PVSYST software results.

Chapter 5 demonstrates the methods used to calculate the grid's frequency and illustrates the PV curtailment method which is applied in order to comply with the grid's constraints. Also, it presents a load profile analysis and a net load analysis based on both the collected 2017 global horizontal irradiance (GHI) data used to produce the PV system's output and the collected 2017 hourly load profile data of the city of Riyadh in the central region of Saudi Arabia. In addition, it presents the grid's frequency stability analysis with large-scale PV systems at various penetration levels to the grid. Furthermore, it presents a brief evaluation of

the grid's current potential hosting capacity with large-scale PV systems at various penetration levels to the grid. This brief evaluation showcases the substantial affects that each grid constraint has on the performance of the PV system in which provides bases that can be used to establish the appropriate flexibility measures.

Chapter 6 demonstrates the methodology used to optimally size and manage the operation of the flexibility measures that are applied in order to enhance the grid's potential hosting capacity with the large-scale integrated PV systems. This includes the aging effect estimation, optimal sizing strategy and energy management strategy of the proposed diurnal storage system in the form of lithium-ion batteries as the flexibility measure applied for the ramping constraint. Also, this includes the optimal sizing strategy and energy management strategy of the proposed seasonal storage system as the flexibility measure applied for the baseload constraint.

Chapter 7 applies the proposed optimal sizing and energy management strategies of the flexibility measures illustrated from chapter 6 in the form of case studies based on the country's future PV energy target (Saudi vision 2030). Firstly, it presents the base case (case study A) which represents the traditional method of dealing with the PV system's variability in the form of PV curtailment. Then, it presents the case (case study B) with applying the flexibility measure in terms of diurnal storage system with its energy management strategy to target the PV curtailment due to grid's ramping constraint violations. After that, it presents the case (case study C) with applying the flexibility measure in terms of seasonal storage system with its energy management strategy to target the PV curtailment due to grid's baseload constraint violations. Finally, it illustrates a discussion which will consist of a comparison among the three cases and a reflection on the optimal measures.

Chapter 8 presents the thesis conclusions, contributions, limitations and suggests several directions for future work that could be investigated by other researchers.

The structure of the thesis as described in this section is represented in Figure 1.4.

Thesis Structure

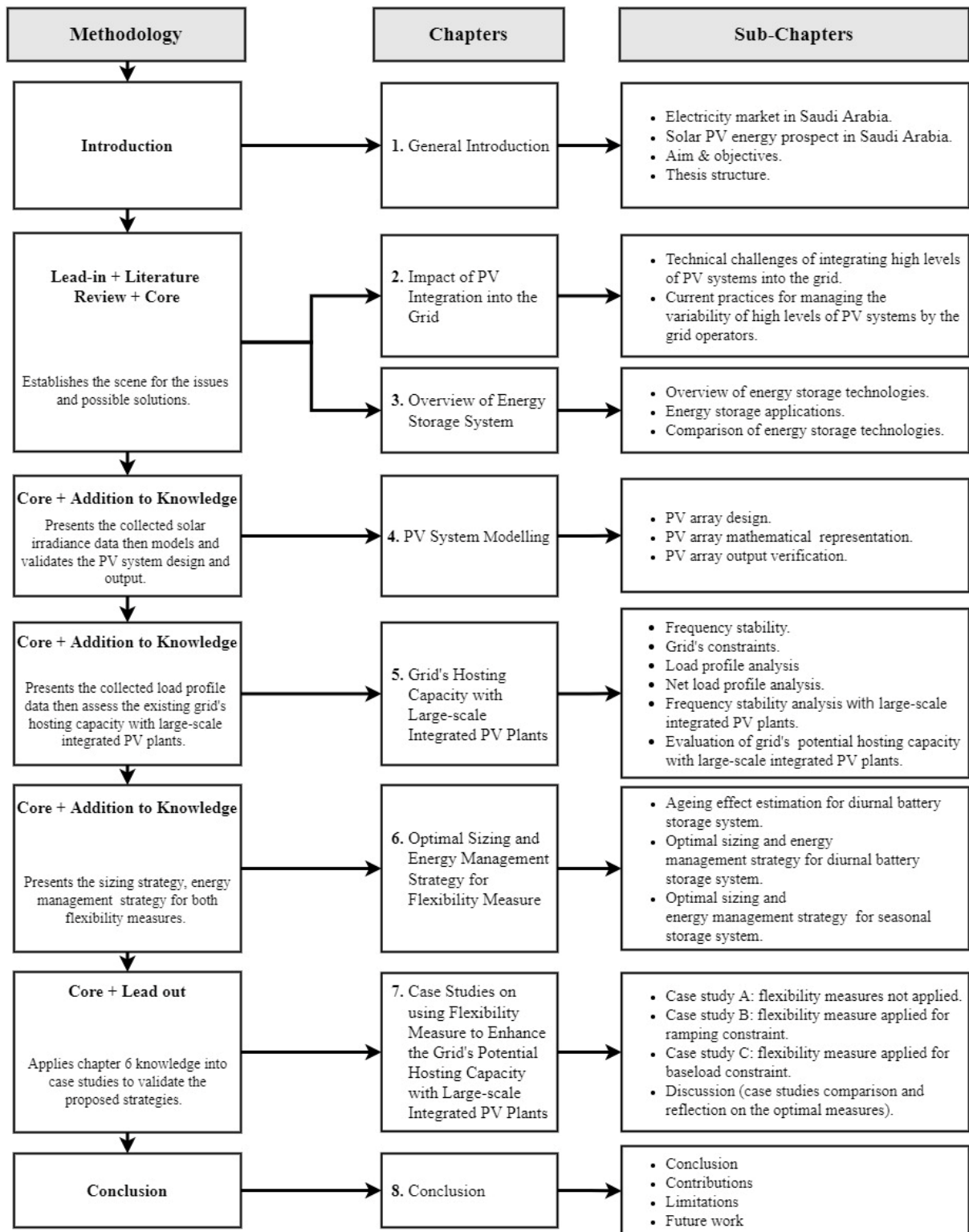


Figure 1.4. Structure of the thesis.

Chapter 2 Impact of PV Integration into the Grid

2.1 Introduction

Photovoltaic (PV) technology is considered as one of the major sources of distributed renewable energy that has no limitation in supply [31, 32]. It is predicted that by 2040, PV technology will become the most significant electricity generation contributor among all other candidates of renewable energy [33]. In the emerging countries, currently there is a great interest for small-scale PV systems' installations in the form of roof-top domestic systems from customers at their premises that are interconnected with the distribution network of the grid, thus leading to a sharp increase in penetration levels of that distributed renewable. The interest for small-scale PV system installations in the form of roof-top domestic systems from the customers at their premises is due to the sharp decrease in the PV technology prices, in addition to the continuous rise of electricity prices from the grid and various incentives that are provided from the governments to make the PV technology a viable and cost-effective option [34]. There is a large volume of material in the literature that assesses the impact of integrating high penetration levels of small-scale PV systems into the distribution network of the grid. However, the research that is recently published and showed a more explicit assessment of this impact is available in [35-37]. Figure 2.1 presents the world solar energy map, and it clearly shows the potential of solar energy as one of the major renewable energy sources.

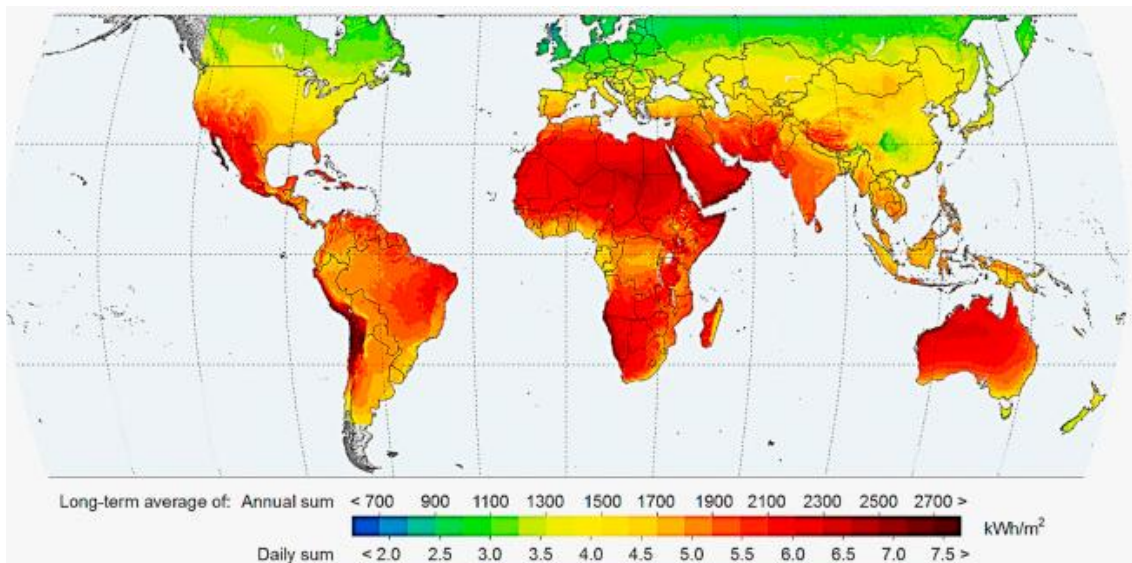


Figure 2.1. World solar energy map [38].

It is expected that large-scale renewable energy will be injected into existing grid in the near future in many countries. Wind and solar energy are the most promising renewable energy (RE) sources that have the capability of producing large quantities of electricity. Wind energy conversion is more efficient and the technical challenges of large-scale integration of wind energy to the grid are similar to those of solar [39]. In addition to the technical challenges, integration of large-scale wind energy also poses some environmental issues compared to

solar energy. The availability, unpredictability and variability of wind is harder to forecast, unlike solar energy which can easily be predicted since it is only available during the day except when there are clouds [40]. Therefore, the focus will be on the challenges of integrating solar energy and specifically solar photovoltaics (PV) into the grid because of the following:

- Solar energy is the most abundant energy available, and Figure 2.1 proves that most countries have the potential to harvest it.
- Currently it has the most attention in the energy sector due to the sharp decrease of the PV prices which was one of the main barriers of its mass deployment [34].
- The location of where the renewable will be deployed at large-scale is an important factor and since the Gulf area of the middle east is targeted which means solar energy has more potential and market than wind energy.

There are many publications in the literature that assess the impact of integrating large-scale PV systems into the electricity transmission network of the grid. However, the most recently published works that present a more explicit assessment of the impact of integrating large-scale PV systems into the grid system are shown in [41-44]. This section will review the technical challenges, potential technical solutions and the research carried out in integrating high shares of small-scale PV systems into the distribution network of the grid in order to give a clearer picture of the impact since most of the PV systems installations were at small scales and connected into the distribution network. Also, this section will review the localised technical challenges, grid stability challenges and technical solutions on integrating large-scale PV systems into the transmission network of the grid. In addition, the current practices for managing the variability of large-scale PV systems by the grid operators will be illustrated.

The challenges for the integration can be classified into technical, commercial, and regulatory challenges that are needed to be dealt with to fully utilise the available renewable energy. The commercial and regulatory challenges are not discussed further because the focus is on the technical challenges only.

2.2 Challenges of Integrating High Penetration Levels of Small-Scale PV Systems into the Grid

The technical challenges of integrating high penetration levels of small-scale PV systems into the distribution network of the grid come in the form of voltage regulation, power quality, harmonics, and protection challenges according to the majority of published papers [35-37, 45-51]. The reason for many of these technical challenges is that the distribution network when constructed did not take into account the possibility of large penetration levels of the PV technology connected to it, altering the operation of the network from passive (unidirectional) to active (bidirectional).

2.2.1 Technical Challenges

The technical challenges of integrating high penetration levels of small-scale PV systems into the distribution network of the grid in the form of voltage regulation, power quality, harmonics and protection challenges will be covered here.

2.2.1.1 Voltage Regulation

Due to the intermittent nature of the PV technology; implementing a large amount of it in the distribution network of the grid will cause fluctuations and unbalance in the voltage profile. The voltage change in the distribution network is sensitive to short term fluctuations which can cause the malfunction of the voltage regulation equipment due to the rapid alternations between sunshine and clouds [52]. In general, the PV system can create irradiance fluctuations either for a short or long period due to climate change, which affects the voltage output from the PV system in the point of common coupling (PCC). The voltage problem of the distribution network due to the connection of large amounts of PV systems can be characterised as voltage unbalance, voltage rise and voltage flickers in the network.

2.2.1.2 Power Quality

Power quality can be defined as the concept of powering and grounding sensitive equipment in a suitable way for the operation of that equipment [53]. Despite this definition, the term power quality is being used generically. Commonly, power quality considers two important aspects: the transient voltage variations and the harmonic distortion of the network voltage. It is known that power quality is improved when there is power supplied on-site such as PV. However, it comes with a cost when connected to the grid; such issues that might arise are voltage flickers, voltage sag, harmonics and stress on the distribution transformer [36]. The authors of [54] suggested that the change in the network voltage profile and the reversal of power flow caused by distributed generation (DG) are the main issues of power quality.

2.2.1.3 Harmonics Distortion

The harmonic distortion of the current and the voltage waveforms is becoming an important issue that needs addressing as the penetration levels of the PV systems increase in the distribution network. Harmonic distortion is a result of current conversion from dc to ac,

which is provided via an inverter with inherent non-linearity and results in an injection of current harmonics [55]. Therefore, the inverters of the PV systems are the main source of current harmonics injected into the distribution system, which can cause the voltage harmonic and total harmonic distortion (THD) in the network [56]. These harmonics contribute to the increase of the losses in the distribution network via heat generation.

2.2.1.4 Protection Challenges

The straight protection scheme of each feeder in the distribution network was designed with the assumption that the feeder is radial, meaning the power flow is unidirectional. However, the presence of PV systems on the feeder will cause bidirectional power flow resulting in the feeder no longer being radial, thus creating several problems to the current protection schemes used [57]. When connecting high penetration levels of PV systems to the distribution network, it is necessary to address some aspects such as the protection of the generation equipment from internal fault, anti-islanding protection and fault current protection of the distribution network [58]. An islanding scenario is often considered as the final undesirable initiative to save the system before it completely collapses [59]. Figure 2.2 shows a typical system configuration of detecting the islanding scenario in which the point of common coupling (PCC) will play the role of the point of interface between the local distribution system and the grid.

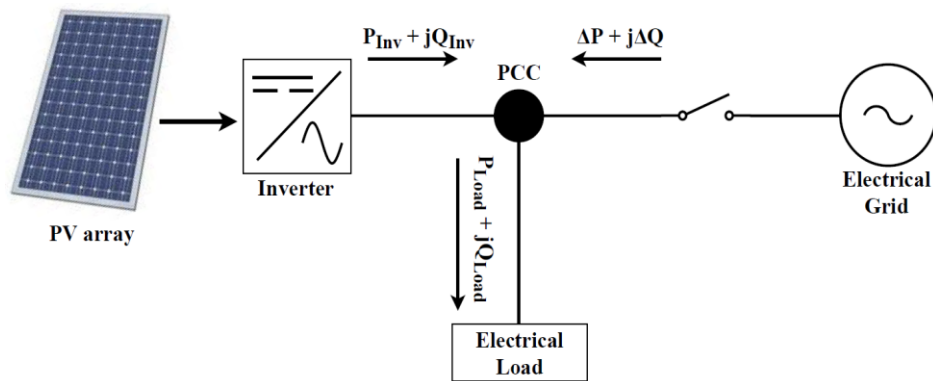


Figure 2.2. Typical system configuration of islanding detection.

2.2.2 Technical Solutions

The authors of [60] suggested that, of the above-mentioned technical challenges, voltage regulation is the most significant technical challenge that prevents or limits the penetration level of the distributed generation in the distribution network, in which the following are the advanced methods or solutions to help mitigate this issue:

- Area based on load tap changer (OLTC) coordinated voltage control.
- Generation curtailment during low demand.
- Consumption shifting and curtailment.

- Energy storage system with coordination.
- Reactive power control.

There has been much research on how these advanced methods can increase the penetration levels of the PV systems in the distribution network [61-73]. In [61], a new supervisory tool based on the voltage control scheme for control and data acquisition to coordinate among the DGs, OLTC and capacitor banks is presented, which sets a new principle for selecting the tap positions of an OLTC. The first stage of the new principle for selecting the tap positions of an OLTC is done through a micro-genetic algorithm and the second stage involves using a recursive genetic algorithm to reduce power losses to find the optimal reactive powers for the distribution network. The results suggest that the proposed method can reduce the complexity of the voltage regulation process. The authors of [62] introduced a three-stage fuzzy-based voltage regulator without needing to run an optimisation algorithm in order to manage the violations of the voltage ranges. The first stage involves utilising reactive power provision at the DG units and, if it is not enough, the second stage is used, which triggers the OLTC operation. The last stage is real power curtailment for when the OLTC is not enough to tackle the problem. This method showed proper voltage regulation with a lower cost of communication compared to centralised and distributed methods of controlling the voltage. The authors of [63] introduced a new voltage control system for selecting the tap position of the OLTC based on the Fuzzy Logic (FL) concept, which aids the integration of large shares of PV systems to the residential area networks in Saudi Arabia. The implementations of the proposed method showed its novelty, but the drawback of this method is the dependency on both the characteristics of the load and the network's parameters.

In [64], a centralised optimisation approach is proposed to reduce the MW curtailment of the distributed generation (DG), which eliminates the voltage constraints, and it is done through coordination between various interactions control means such as OLTC, shunt banks, active/reactive power management and remotely controlled switches (RCS). The outcomes showed that using RCS in the case of voltage constraints on transferring DG between the feeders will reduce the curtailment of DG. The authors of [65] proposed an adaptive method for capping real power to make sure that voltage is regulated within the permissible limit while keeping the power curtailment share of the customers PV systems fair. The work reported in [66] shows that overvoltage in low voltage (LV) feeders can be prevented using droop based active power curtailment techniques, which achieves an increase in both PV system installed capacity and energy yield.

The research presented in [67] addresses the scheduling of the distributed generation's available opportunities of consumption reduction and shifting aiming to optimally minimise the operation costs via using demand response programs and virtual power player that manages the distributed generation resources with consumption shifting constraints into account. In [68], a robust multi-objective optimisation based integrated scheduling approach is proposed and investigated to solve the micro-grid supply and demand scheduling problem

under uncertainty. The approach uses a minimax multi-objective optimisation formulation to minimise the operating costs and emissions under the worst-case realisation of that intermittent renewable and the uncertainty of the loads.

The research efforts in [69] show a coordinated control method that includes distributed and localised controls for the energy storage system to aid voltage regulation for the distribution network with high penetration levels of rooftop PV systems during the period of PV systems peak generation. The findings demonstrate that the proposed control method ensures that the voltages in the networks are maintained within the required limits during daily operation. The authors of [70] proposed a coordinated use of PV system, battery energy storage (BES) and the reactive capability of the PV system's inverter to address voltage regulation problem, which is evaluated for rural and urban scenarios. The results show that coordinated PV system and BES support is required for the rural scenario with the high resistance feeder to maintain acceptable voltage profile, whereas reactive compensation from the PV system's inverters alone is sufficient to maintain acceptable voltage profile in an urban scenario.

The authors of [72] presented a distributed control method for a residential battery energy storage (BES) units connected to PV system that aims to utilise the customer-owned BES units for solving the over-voltage issues caused by high PV system penetration levels without significantly affecting the owners BES unit local objectives. This method utilises the reactive power when the active power is not enough, and the results show that the aim has been met. The authors of [73] attempted to increase the penetration levels of PV systems in the distribution network using solar inverters that are capable of reactive power control. They introduced a reactive control method that is based on sensitivity analysis, which illustrates that, if the solar inverter is located at the end of a feeder, then the same amount of reactive power becomes more effective for the grid's voltage support.

This section showed an assessment of the technical challenges, technical solutions and the research done on integrating high shares of small-scale PV systems into the distribution network of the grid. This area of work is well addressed for the consumer purposes because it has had the most attention in the recent years, leaving the integration of large-scale PV systems connected to the grid's transmission network for utility purposes not being fully addressed well.

2.3 Challenges of Integrating Large-Scale PV Systems into the Grid

A power plant is a centralised system that independently supplies power to the grid system and not to a particular customer that complies with the grid system's regulations. To enhance the grid's stability, security and reliability, grid codes and standards are established to define the requirements for the power plants to be connected to the grid which were traditionally based for the conventional power plants. However, the usage of renewable energy to produce electricity at large-scale (for utility purposes) compared to the conventional power plants were initially very low. However, recently, this has changed drastically, making the development of grid codes for renewable energy power plants that avoids affecting the operation of the grid quite the necessity.

The grid codes development path for wind power plants attained more interest, i.e. stepped up, due to its early entry to the utility market. The purpose of the grid codes development for the wind power plants is to enable it to operate as closely as possible to the operation of the conventional power plant, by providing support to the grid in terms of voltage regulation, frequency regulation, reactive power regulation and active power regulation. In [74], the authors illustrated wind power plants integration with in-depth analysis of the grid codes. On the other hand, the PV's standards such as IEEE 1547 were designed for small-scale PV systems that are interconnected to the distribution network of the grid for residential, commercial and industrial purposes that resulted in the prevention of that small-scale PV systems from providing ancillary services [75].

However, owing to the advancements in power electronics, semiconductor technology and cost reduction of the technology, which makes the penetrations of PV systems not only limited to the distribution network but also in the transmission network at large-scale. The global cumulative power in GW of utility and non-utility PV systems up to 2019 can be shown in Figure 2.3. The most significant large-scale PV plants worldwide are listed in Table 2.1. Thus, due to the growth of PV systems at large-scale for utility purpose in the recent years, there has been a development of grid codes to allow the integration of large-scale PV systems in the transmission network of the grid. Germany, in 2008, developed the first grid code that is specifically for large-scale PV systems interconnected to the transmission network of the grid, which was four years after the first grid code was developed for wind power plants by Denmark [76]. It is worth mentioning that, after Germany developed the first grid code for the large-scale PV systems integration, other countries created their version. If a comparison is required of the different requirements requested by different countries grid codes to interconnect large-scale PV systems to the transmission network of the grid, then the following four specific categories should be considered [41]:

- Fault-ride through requirements.
- Active power and frequency control.
- Reactive power and voltage control.
- Voltage and frequency boundaries.

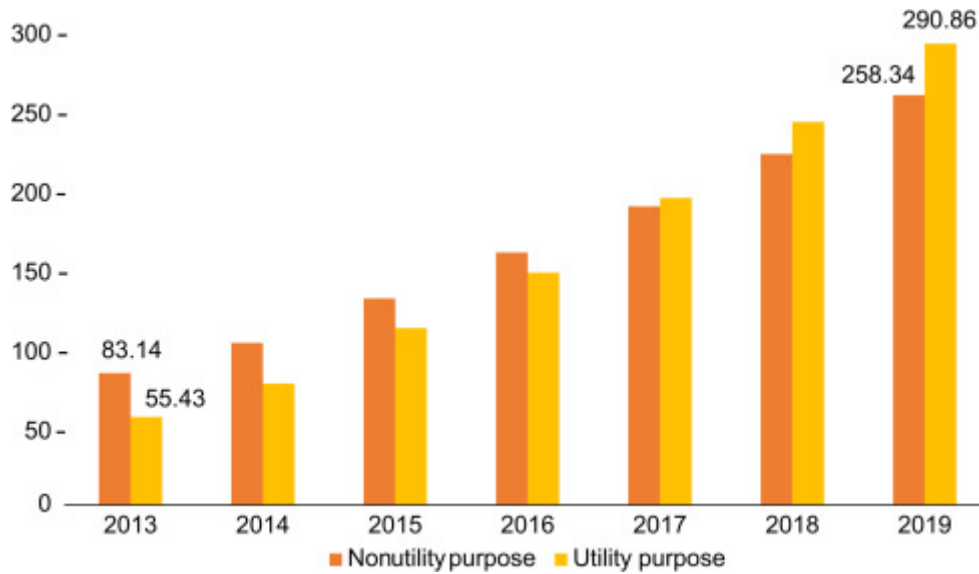


Figure 2.3. Global cumulative power (GW) of utility and non-utility PV systems up to 2019 [41].

Table 2.1. Significant large-scale PV plants worldwide [77].

PV Plant Name	Location	Size (MW)	Commissioned year
Yanchi Solar PV Station	China	1000	2016
Solar Star Projects	USA	575	2015
Desert Sunlight Solar Farm	USA	550	2015
Topaz Solar Farm	USA	550	2011–2014
Longyangxia Hydro-Solar PV Station	China	480	2013–2015
Copper Mountain III Solar Facility	USA	350	2015
Charanka Park PV power plant	India	345	2012–2015

Several thousand PV modules need to be connected to get the MW range of power to be considered a large-scale PV system, which requires a significant land area for the deployment of that large-scale system. In addition, with the requirement of significant land area for the deployment comes a higher set up cost with lower capacity factor compared to other renewable technologies. The authors of [78] presented an extensive review of the topologies for the large-scale PV plants taking into consideration the internal topology and the AC collection grid. The authors of [79] illustrated an thorough analysis of control strategies of grid-connected inverters with their applications in PV plants. Therefore, it is essential to

know the impact of integrating large-scale PV systems to the transmission network of a grid for utility purposes since it will outgrow the PV systems shortly for non-utility purposes. An interesting comparison between the characteristics of various PV inverter topologies for large-scale PV system are shown in Figure 2.4.

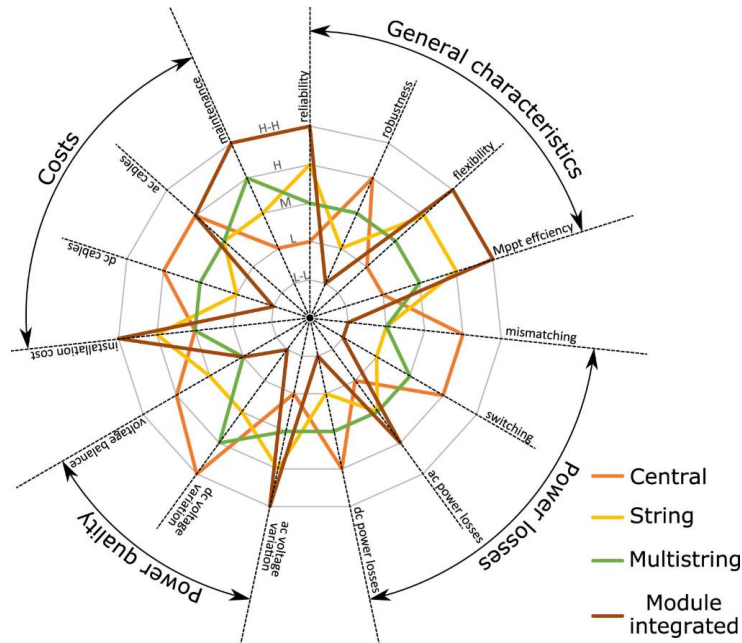


Figure 2.4. Comparison between the characteristics of various PV system inverter topologies for large-scale PV system [78].

2.3.1 Technical Challenges

The technical challenges of integrating large-scale PV systems into the transmission network of the grid in the form of the localised technical challenges of the PV plant and the grid system stability challenges will be covered here.

2.3.1.1 Localised Technical Challenges of the PV Plant

The localised technical challenges of integrating large-scale of PV systems into the transmission network of the grid comes in the form of active power regulation, reactive power regulation and power quality, according to the majority of published papers on this topic [41-44]. A PV solar power plant should meet the minimum requirements given by the grid codes of the different countries, and because of these grid codes there are many challenges of integration.

a) Active Power Regulation

The current PV system inverters' operating power point is set to give the maximum active power that varies according to the solar irradiance, which is thanks to the development of various algorithms such as particle swarm optimisation, ripple correlation and fuzzy logic control that are explained by the research efforts in [80, 81]. However, these algorithms bring

drawbacks such as the number of sensors used, time of response and the delay to notice the radiation changing. Using these algorithms means that the large-scale PV system will always be working at the maximum power in each solar radiation, which increases the system's risk of large and quick fluctuations of active power due to cloud transition affecting power balance in the grid. Thus, most grid codes require at least two types of active power control, which are ramp rate control and power curtailment, as well as power reserve in some countries. In this case, the maximum power point tracker will suffer modification as it does not need to operate at maximum power all day; instead, it needs to track the required power by the operator. It is worth mentioning that the maximum operating point of the large-scale PV system should be less than its power capacity; otherwise, energy storage should be deployed. In addition, due to the current control and technology of the large-scale PV system, it will not be easy to reduce the power at a constant ramp rate.

b) Reactive Power Regulation

The technology of the current PV system inverters that are used in the distribution network of the grid does not have a PQ control as the IEEE 1547 regulation does not require this, although the inverters can perform according to the regulation. The MPPT control used in the normal PV system's operation does not allow complete control of the PQ capability during the day, which limits the performance of the system. However, according to the grid code requirements of integrating large-scale PV systems to the grid, the PV system inverters are responsible for controlling reactive power and active power [82]. Therefore, it is important to understand the limitations of the PV system inverters because they were developed without reflecting the variations of the solar radiation, temperature, and the dc voltage on their capability curve. In the case of wind power plants, there are already deep studies on their reactive power capability [83]. For instance, the authors of [84] studied the reactive power capability curve of a doubly-fed induction generator in which when the wind power plant does not provide sufficient amounts of reactive power to meet the grid requirements, thus other pieces of equipment are installed such as STATCOMs, SVCs or capacitor banks to meet the required amount of reactive power. The quadrants of the inverter's operation are clearly shown in Figure 2.5.

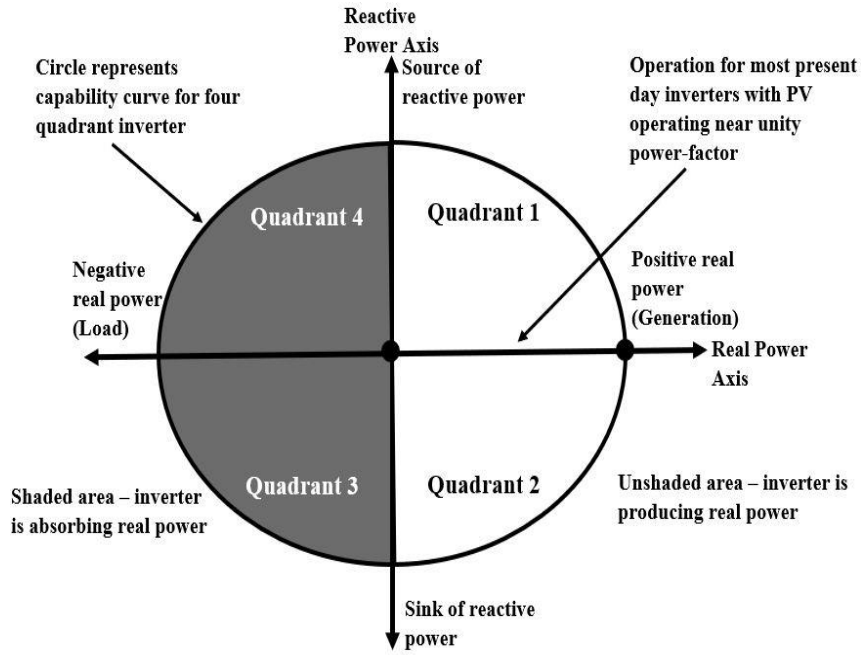


Figure 2.5. Quadrants of inverter operation [85].

c) Power Quality

The integration of large-scale PV systems into the grid involves many power electronics devices that will cause the injection of harmonics into the grid. Harmonic is usually the result of the switch delay of the inverter, which becomes quite significant when the output power of the PV fluctuates. The experience from the practical operation of a large-scale PV system shows that the output current harmonics is small for a single grid-tied inverter, but with the case of multiple shunt inverters their output current harmonics might greatly exceed the normal standard [86]. The research efforts in [87] analysed the resonance caused by a filter capacitor when large-scale PV systems are integrated to a weak network through a long distance cable in which some specific harmonics might be amplified due to the resonance.

2.3.1.2 Grid System Stability Challenges

The grid power system is the largest and most complex human-made dynamic system that has been ever created. Therefore, due to the size and complexity of the grid power system, it makes the stability factor extremely important. Power system stability according to Kundur et al. [88] is defined as “*The ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact*” by both the Institute of Electrical and Electronics Engineers (IEEE) and the International Council for Large Electric Systems (CIGRE). The following are the classification of grid stability:

- Voltage stability is the ability of the power system to sustain the acceptable voltage levels across all the buses of the system during normal operating conditions and after being subjected to a disturbance. Instability of the voltage levels may occur as a result of an uncontrollable and progressive rise or fall in voltage levels of some buses in the system.
- Rotor angle stability is the ability of the traditional synchronised generators in the grid power system to maintain that synchronism after being subjected to a disturbance. To have a better understanding of rotor angle stability, it is useful to separate it into small disturbance rotor angle stability better known as small signal stability and large disturbance rotor angle stability better known as transient stability.
- Frequency stability is the ability of the power system to maintain or restore the balance between the generation and load after being subjected to a disturbance, which is done by maintaining the frequency within its applicable limit. The disturbance causes a significant mismatch between generation and load.

Grid system instability can be shown in several ways depending on the configuration and operating conditions of the grid system. Since the grid system is a highly non-linear system, it tends to keep operating continuously under small disturbances such as the alteration in the loads or generators. Furthermore, due to the grid system covering a large geographical area, it is likely exposed to large disturbances such as the loss of their main components. However, the grid system must have the ability to respond to these disturbances and remain stable by returning to the original operating conditions or reaching new operating conditions [89].

Grid system stability classes can be categorised by their time frame and their disturbance size, which is clearly shown in Figure 2.6. Stability concerning time frame can be categorised into short- and long-term stability. The stability concerning the size of disturbance can be categorised into small and large disturbances stability, in which the first can be examined via the linearisation of the system's dynamic equation while the second can be examined via non-linear simulation [90].

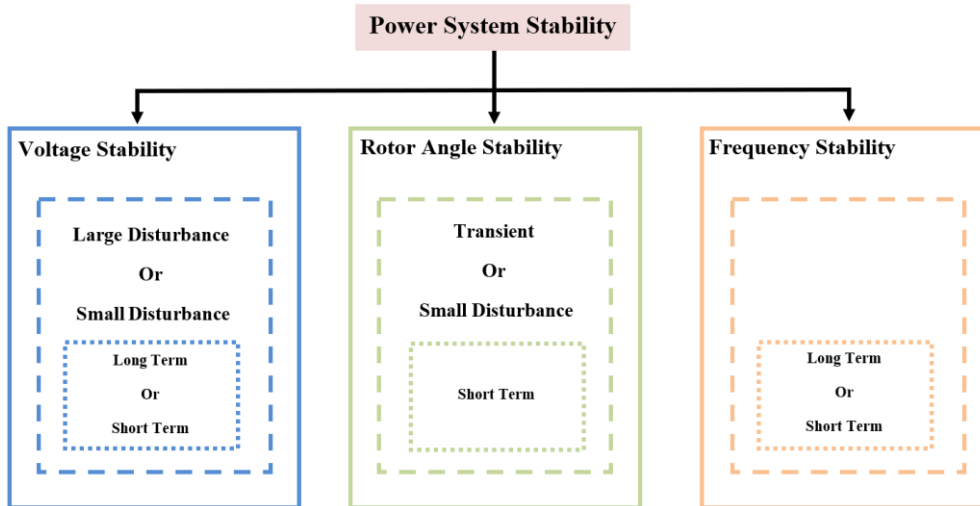


Figure 2.6. Stability classifications of the grid system.

Grid system stability is a core requirement to ensure the security and reliability of the grid system's operation while reducing the chances of a blackout occurring, which is done through the maintenance of that stability that becomes more challenging to the system operators due to the large-scale integration of variable renewable energy such as solar. Therefore, it is crucial to comprehensively understand the grid system stability with large-scale solar energy generation, which means it is essential to analyse the operational reliability of the grid system to aid the development of the methods to mitigate the adverse effects that large-scale solar energy integration has on the grid system stability.

a) Voltage Stability

Voltage stability relates to the ability of the power system to maintain at all the nodes its voltage levels at an acceptable level during normal operating conditions and after being encountered with a disturbance. Generally, voltage instability is a local phenomenon, but the widespread impact of such as the voltage collapse of the entire system can happen as a result of the voltage instability [91]. In addition, the severe voltage collapse of the entire power system can be linked with rotor angle instability due to a gradual loss of synchronism or in other words rotor angle separation of the traditional generators which will result in a rapid voltage drop in the power system [92]. Voltage stability can be divided into the following:

- Large disturbance voltage stability is when the power system must uphold constant voltages after being ejected with a severe disturbance such as a loss of large generator. The voltage stability phenomenon can be either long term or short term. Therefore, the time frame of this kind of study may vary from a few seconds to minutes to capture the performance of the power system equipment [91].
- Small disturbance voltage stability is when the power system must uphold constant voltages after being ejected with a small disturbance such as the changes in the load of

the system. Small disturbance voltage stability can be investigated via linearising the power system equations considering the appropriate computation assumptions. However, it is better to keep in mind that, with the linearised method, non-linear effects such as time delays and tap changer controls are not considered [93]. The time frame to conduct this study is similar to the large disturbance voltage stability time frame.

The distinct characteristics of the PV system and the current grid codes will significantly affect the voltage stability of the system when large-scale PV systems are introduced to the transmission network of the grid. The effects of large-scale PV systems integration on the voltage stability of the transmission network of the grid are studied in [94-97].

The authors of [94] studied the impact of increasing the penetration of the PV systems on the static performance and the transient stability in the transmission network and showed that the system from the steady state stability point of view could experience both beneficial and detrimental effects. The authors of [95] investigated the effects on the static voltage stability of the Ontario power system from integrating large-scale centralised PV system and distributed PV system. They considered various penetration levels and found that the distributed PV system might improve the static voltage stability of the system while the large-scale centralised PV system experienced less improvement in terms of voltage stability margin.

In [96], the authors studied the impact on the voltage profile from installing large-scale PV system at different sites of the grid and showed that the voltage at the feeder gives a parabolic trend when the output power of the large-scale PV system increases. They concluded that the maximum point of the voltage profile is dependent on the total impedance of the transmission line and the large-scale PV system. The authors of [97] presented a detailed theoretical analysis of the impact of integrating large-scale PV system on the static voltage stability of the grid and found that the integration of large-scale PV system brings a positive impact in terms of static voltage stability in the grid. The studies above considered that the large-scale PV system supplies the maximum possible power without considering the output power variations during the day such as cloud coverage. Therefore, it is essential to understand the effects on the voltage profile from integrating large-scale PV systems to the grid by accounting for its source variability, the cloud coverage and the temperature.

b) Rotor Angle Stability

Rotor angle stability relates to the ability of the traditional synchronised generators in the grid to remain synchronised after being encountered with a disturbance. Normally, all the connected traditional generators to the grid are rotating at the same speed level, meaning there is a balance between the mechanical input and the electromagnetic output of each traditional generator in the grid. However, a disturbance occurring would lead those traditional generators to accelerate or decelerate their rotating speed affecting the angular position between the rotors or in other words the balance between the mechanical input and

the electromagnetic output. The grid can maintain the rotor angle stability if the difference between the rotor's angular position is reduced until the synchronised speed level has been reached again. Otherwise, the rotor angle stability will be lost, resulting in the generator losing its synchronism with the rest of generators and leading to large fluctuations in its output in the form of power, voltage and current. Therefore, the grid system stability for any particular condition can be deduced by whether the deviations in the angular position of the rotors are capable of resulting in sufficient restoring torques [91]. Rotor angle stability is categorised as a short-term phenomenon and can be divided into the following:

- Large disturbance rotor angle stability, better known as transient stability, is when the power system must remain synchronised after being ejected with a severe disturbance such as transmission line short circuit. The transient stability depends on both the original operating state of the system and the severity of the disturbance.
- Small disturbance rotor angle stability, better known as small signal stability, is when the power system must remain synchronised after being ejected with small disturbance such as the changes in the load of the system. The small signal stability depends on the strength of the system, the original operating state of the system and the type of generator excitation controls used.

A static source element such as the PV system will not contribute in the power angle oscillation leading to a significant reduction of the grid system equivalent inertia due to the intermittent power output of the integrated large-scale PV system. In addition, the integration of large-scale PV system into the grid will cause an alteration in the original grid power flow and the power of transmission channel which means that during fault ride-through of the PV system, it will present a different dynamic support characteristic compared to the conventional generators [98]. The rotor angle stability is mainly affected by the topology of the power network, the mode that the grid operates at, the PV system's capacity, its location and its control strategy [43]. The PV system's inability to cope with the fault ride-through may lead to it being off-grid which would have a severe impact on the stability of the system, especially when there is a centralised large-scale PV system integrated to the grid. Therefore, the aforementioned shows the importance of rotor angle stability which should not be ignored when integrating the large-scale PV system to the grid.

c) Frequency Stability

Frequency stability relates to the ability of the grid system to keep the frequency levels within its acceptable limits after being subjected to a disturbance which results in the mismatch between the generation and the load [99]. Figure 2.7 illustrates the concept of the grid's frequency stability using the analogy of the water-level in a container. Frequency stability depends on the ability of the grid system to either maintain or restore equilibrium between the generation and load [88]. Generally, frequency stability issues are linked with the inadequate responses from components of the system, the insufficient generation reserve or the poor coordination of control and protection equipment. The time frame of this kind of study may

vary from a fraction of a second to several minutes. The longer time corresponds to the response for example load voltage regulators, whereas the shorter time corresponds to the response for example under frequency load shedding relays [92].

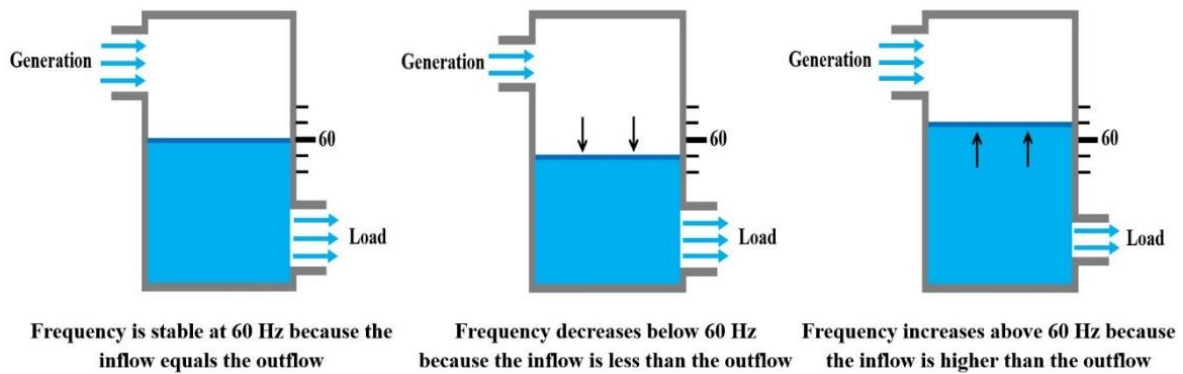


Figure 2.7. Concept of grid's frequency stability using the water-level in a container analogy.

Currently, the grid's frequency is related to the rotating speed of the conventional synchronous generators in which the control of these generators manages the frequency by accelerating or deaccelerating them depending on the balance between the load and the power generated in order to increase or decrease the frequency. Therefore, this kinetic energy limits the initial rate of frequency decline in the case of power imbalance occurring which means this inertial response of the conventional synchronous generators plays a crucial role in frequency control in the grid system [100]. The PV technology lacks rotating machinery or in other words inertial support which together with its power variability causes problems in the grid in terms of frequency stability [101]. The authors of [102] studied the effects of four 50 MW PV power plants as well as four 700 MW conventional power plants on the frequency stability of the grid and concluded that the frequency stability is not drastically affected by the PV power plants, but they did not consider any reduction of the conventional power plants. Therefore, the lack of inertia from the large-scale PV system needs more attention from in-depth studies to understand its impact on the current grid which might be beneficial. The study by Rahmann and Castillo [103] gives a good start to understanding this phenomenon.

2.3.2 Technical Solutions

Nowadays, the grid codes and the operators are demanding that the integrated large-scale PV system has as similar as possible operational behaviour to the conventional power plants. Therefore, the integrated large-scale PV system should be capable of controlling the active power to provide frequency support to the grid, control the reactive power to provide voltage support to the grid and possess the fault ride through capability during various disturbances. Without controlling the aforementioned, the grid will face new challenges in grid balancing which affects the flexibility of the grid through the frequent mismatches between the supply and the demand in which matching the response of the supply to the demand becomes less predictable due to the integration of the large-scale PV systems into the transmission network

of the grid [104]. Thus, maintaining the balance of the grid flexibility is essential on both the demand and supply sides, whereas the supply side flexibility can be achieved via energy storage, renewable energy curtailment and flexible generation while the demand side flexibility can be achieved via energy storage, demand response and smart loads [105]. The common denominator between achieving flexibility to the supply and demand side is energy storage, as shown in Figure 2.8.

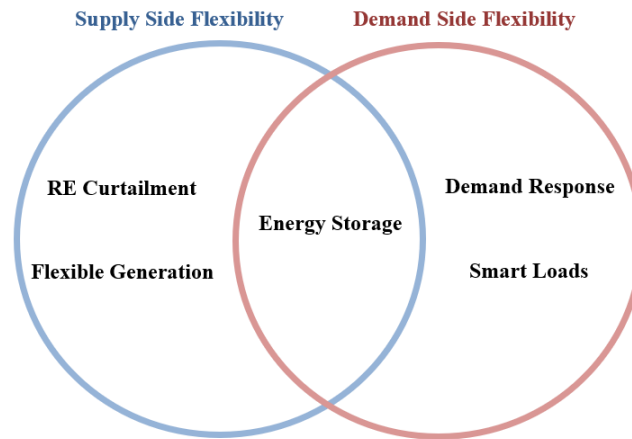


Figure 2.8. Overview of flexibility in supply-demand side.

In addition, the research efforts in [106] suggests that the flexibility of the grid system can increase by applying the following methods:

- Upgrading the grid which is done to strengthen and improve the grid via processes such as expansion and integration. However, grid upgrade can be considered a costly option among other aspects.
- Improving the forecasting of renewable energy which successfully eliminates the uncertainty aspect of the renewable energy but not its output variability.
- Increasing back-up power which is done through using the traditional dispatchable power. However, this method emits large quantities of greenhouse gas (GHS) because it is hydrocarbon-based.
- Demand side management (DSM) which reduces its potential for viability due to the consumer's behavioural aspects in decision making [107].
- Integration of energy storage technologies which is a very promising method because it can offer time-shifting ability, decouple the supply and demand, reduce curtailment, relieve the grid's congestion and regulate the grid by smoothing the fluctuations of the frequency and voltage to ensure both security and reliability of the grid [108].

The authors of [41] illustrated that during the last years two solutions had been developed to aid the integration of the large-scale PV systems into the transmission network of the grid which are the addition of various equipment such as energy storage and developing smart controls for the large-scale PV system.

2.4 The Current Practices for Managing the Variability of Large-Scale PV Systems by the Grid Operators

In the early 2000s, many utilities expressed concerns about the intermittent nature of solar generation [109]. Accurately, it is a fluctuating output that possibly could stress their systems, producing voltage issues on the grid and increasing the wear on the conventional power plants [110]. The increased growth in solar energy did not eliminate the integration issues facing both utilities and grid operators. However, both the utilities and grid operators are getting better at handling the issues using new software systems, updating the infrastructure of both grid and generation and the installation of new technologies such as smart inverter and electricity storage. This section discusses the current methods or precautions used by grid operators in some regions in dealing with the variability of the grid-connected PV plants. Among some of the many places where renewable energy installation is increasingly taking place, Germany and California (USA) are the two regions chosen due to their high shares of solar energy in their generation mix.

2.4.1 Germany

Germany is categorised as the largest European energy market with the most ambitious energy transition “Energiewende” to renewable energies, thus the share of renewable energy production has increased dramatically from 17% to 28% between June 2011 and 2015 [111]. Germany’s carbon emissions rose slightly in 2015 after years of decline because it is forcing conventional power plants to keep operating even if there is a sufficient amount of renewable energy capable of supplying nearly all of the demand to deal with its variability in generation output which leads the country to generate more electricity than it needs [112]. The German feed-in tariff system played an important role in increasing the penetration levels of renewable energy to the grid. Taking the solar PV technology as an example, from 2004 to 2011, the installed capacity of PV technology sharply increased from below 1 GW to 24 GW [113]. Figure 2.9 shows an interesting pie chart of the PV system share by cumulative capacity in Germany 2017 [114].

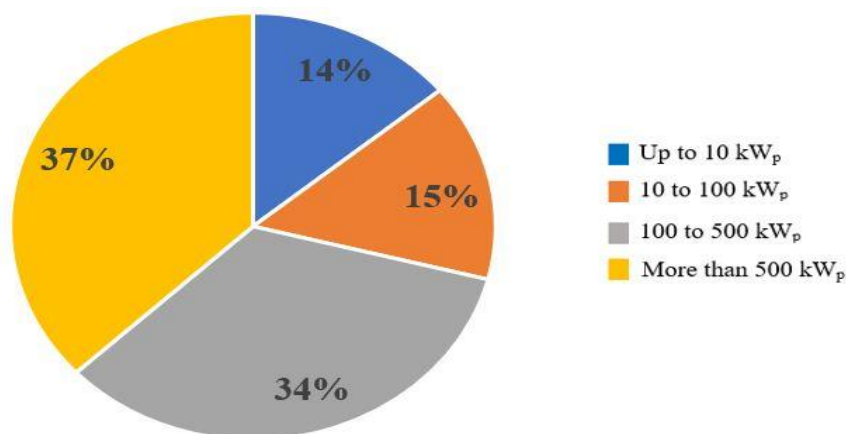


Figure 2.9. PV system share by cumulative capacity in Germany 2017 [114].

The authors of [115] stated the following seven reasons for enabling Germany to manage to balance the integration of close to a 30% of renewable energy share with the very modest alteration to its power system:

1. The existing strength of the grid implies that outages rarely occur, and it possesses more capacity than required for the given current demand. However, Germany has needed to increase the strength of its transmission lines with planning to increase its capacity further to accommodate more renewable energy [116].
2. The operational flexibility of the conventional power plants means there is a surplus of conventional power capacity that is being utilised effectively to provide the required balancing power to offset the variability that comes with renewable generation. Most of the conventional power plants were originally designed or later modified to provide a flexible output by being able to ramp on an hourly basis to a value much lower than the highest output and being able daily to cycle on and off [117]. In addition, these conventional power plants can sell their power into the ancillary electricity market to provide minute-by-minute and hour-by-hour balancing in order to eliminate any mismatch between the supply and demand [113]. However, these conventional power plants are not selling much of their power on the day-ahead wholesale market because of solar and wind energy receiving priority of dispatch in the mentioned market [118].
3. The improved design of the ancillary power markets implies that both the balancing and intraday electricity market have been modified to provide greater flexibility to accommodate renewables.
4. The improved system control software and day-ahead weather forecasting means that the grid operators have greatly improved their software to accommodate higher ramp rates, evolving the system's reliability calculations to consider renewables. In addition, improving the day ahead weather forecasting is a vital part of improving the balancing of renewable energy in the grid.
5. The technical adjustments to the local-level distribution system are executed to cope with the reverse power flow effect due to the presence of the renewable in the distribution level.
6. The ability to export power to the neighbouring countries; the high levels of renewable energy generation on peak days causes the prices of the electricity market to drop to zero or even be negative which leads to the effect of reducing the output of the conventional power plants and exporting power to neighbouring countries. However, the approach of importing and exporting power from the neighbouring countries has a very modest part in balancing renewables because of the regulation of the markets in the form of prohibiting importing power in Germany for example and the bidding time frame is too long for importing or exporting power for renewable energy balancing purposes [115]. The electricity exported from Germany throughout the recent years are shown in Figure 2.10 [114].

7. Solving the 50.2 Hz inverter issue implies that the inverters cut-off frequency has been modified to vary rather than having it all the same to avoid a massive threat on the grid's stability as it has much solar energy.

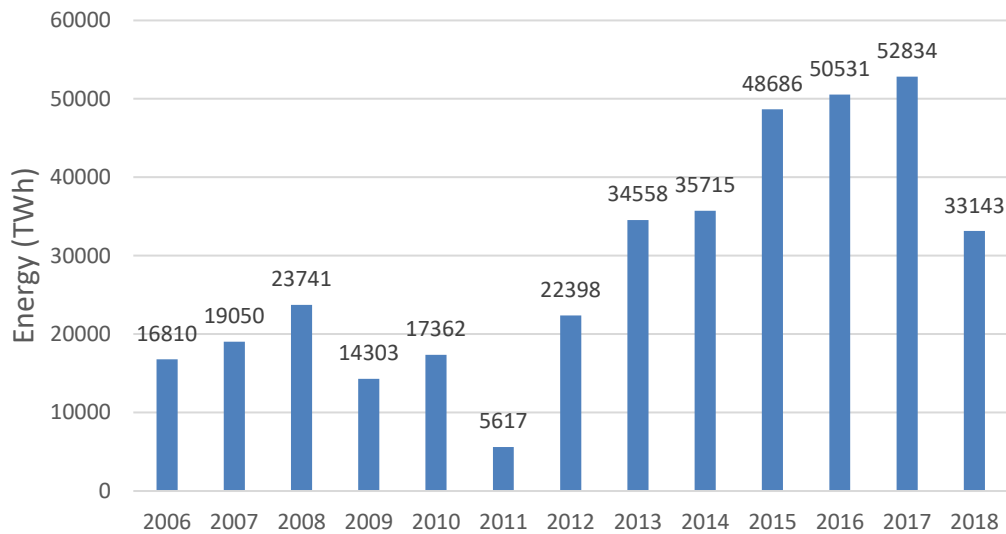


Figure 2.10. Electricity exported for Germany [114].

By 2020, the Germans aim to satisfy 35% of their demand from renewable energy but the article in [119] states that, in the first half of 2017, Germany has exceeded its 2020 target for renewable energy by having 37.6% of renewable energy resulting in Germany becoming Europe's leading exporter at that time. It is worth mentioning that large-scale energy storage had almost no part in integrating and balancing renewable energy because they do not expect it to play a role until the share of renewable exceeds 40% [115]. Therefore, in the future, bigger changes will be necessary to ensure that large-scale renewables are integrated with being able to balance their variability effect.

2.4.2 California (USA)

California is categorised as a well-known world leader in the renewable energy technology deployment, especially when it is reported that the state's utilities are well ahead of their Renewables Portfolio Standard (RPS) target of 33% by 2020 and 50% by 2030 [120]. Furthermore, California is likely to meet its 2030 RPS target by 2020. Figure 2.11 presents the existing and projected solar and wind installed generation in CAISO (the California Independent System Operator). CAISO handles the over generation phenomenon of renewable energy using curtailment of the renewable generation which is a quite wasteful approach in utilising clean energy, and it leads to relying more on the use of non-clean energy sources [121]. This section presents how the California ISO grid operator manages the integration of the large-scale PV systems.



Figure 2.11. Existing and projected solar and wind installed generation in CAISO [122].

2.4.2.1 California ISO Using Utility-Scale PV Systems to Provide Ancillary Services

The increase of renewable energy integration has sparked concerns over the resilience and reliability of the grid. However, some grid operators such as the California ISO have demonstrated how to successfully integrate large-scale of renewable energy sources such as solar PV systems with keeping the reliability of the grid intact as successfully as a natural gas plant [123]. Currently, the California state performs much of its essential and ancillary grid services with natural gas plants. However, the methane leak incident from the Aliso Canyon storage facility has led stakeholders to advocate for a more reliable and diverse resource in which renewable energy arguably fits the role [124].

The reason for this rise in need of reliability services to manage the increasing penetration levels of renewables is because the California ISO experienced in 2015 its first event of not having the required ancillary services [125]. Therefore, California ISO collaborated with the National Renewable Energy Laboratory (NREL) and First Solar on a 300 MW solar power plant project that illustrated the ability of renewable energy to sustain the reliability of the power system as effectively as the natural gas plant with more efficiency [123]. This result is due to the presence of the intelligent inverters combined with advanced plant controls that provide the ability to respond accurately, making the solar power plant have the three fundamental services of ramping capability, voltage and frequency control [123].

2.4.2.2 California ISO Dealing with a Solar Eclipse

Today's solar eclipse can be used to assess how grid operators that rely on the supply of large-scale solar energy manage this phenomenon without compromising the operation of its system. The United States of America experienced a solar eclipse on the morning of 21 August 2017 [126]. Since, California relies on solar energy to generate more than a quarter of its electricity, thus it would be hit harder than neighbouring states by an eclipse covering more of the sun's rays [127]. The article in [128] shows a clear illustration of how the grid operator has managed to deal with this phenomenon that has been projected to knock out an estimate of 5600 MW of solar energy at an expected up to 70 MW per minute drop and rebound. The grid operator has dealt with this in the past on certain days when moving clouds met with the sunset or sunrise. The biggest challenge for the grid operator is not replacing that lost energy with another source but managing that strong ramp down and sharp ramp up. The California ISO managed that strong ramp down and sharp ramp up of solar energy using its established sources of flexibility including the following [128]:

- The adjustable-rapid power plants such as gas-fired and hydroelectric ones.
- The regional power market that is built purposely to balance the quick shifting of renewable energy.
- The growing capability of storing electricity via energy storage.
- The capability of shaping the demand of power in real time via demand response.

The California ISO still did not take any chances with the solar eclipse even with its established sources of flexibility mentioned above and more than doubled the amount of reserve power beyond the 350 MW that they normally have secured during these hours [128]. This approach undertaken by the California ISO of bulking up reserve power is done by following the example of what European countries such as Germany did to counter the solar eclipse that occurred in 2015 in which nearly 17 GW of solar power generation across the continent was knocked out, yet their frequency of the grid remained stable [129, 130]. However, the California ISO is planning to exploit battery storage to the maximum extent and demand response in order to lower the strains on the grid.

It is worth mentioning how the grid operator known as Duke Energy of North Carolina managed the solar eclipse which estimated that its solar generation would be falling from about 2.5 GW to 0.2 GW at the peak of the eclipse [131]. Therefore, to manage that fall and subsequent rise, it followed Italy's lead of requesting their solar power suppliers to ramp down their output ahead of the eclipse which aided in reducing the rate of ramping up the gas-fired plants. This method can be compared to gently pressing the gas pedal rather than a costly stamping on it.

2.5 Discussion and Way Forwards

Large-scale PV systems bring up a new set of technical challenges if connected to grid because of their uncontrollable variability in generation and their location dependency, which is often far from the population demand centres due to the requirement of large area of land for the installation. The cause of variability in renewable energy is the weather fluctuations that brings up uncertainties to the generation output in the scale of seconds up to days in which those uncertainties can affect up to 70% of day time solar capacity due to the passing clouds [132]. Furthermore, the aggregation of the large-scale renewable energy over large areas reduces the variability of the individual components. However, this does not eliminate the uncertainty, which is sometimes greater than the relative predictable variation in demand that the grid can deal with regularly. It is worth mentioning that the impact of the variable renewable energy generation could be mitigated if the grid could match the supply of the renewables to the demand.

Germany and California were the two regions examined due to their high shares of solar energy in their generation mix. In the case of Germany, it managed balancing the integration of close to a 30% of renewable energy share with very modest alteration to its power system. It is worth mentioning that large-scale energy storage had almost no part in integrating and balancing renewable energy. This is because Germany does not expect it to play a role until the share of renewable exceeds 40% of its generation. This might be due to the neighbouring countries not requiring much excess power that can be exported to them. On the other hand, California's biggest challenge for their grid operator during the solar eclipse was not replacing that lost energy with another source but rather managing that strong ramp down and sharp ramp up, which they managed by their established sources of flexibility. Furthermore, the overgeneration phenomenon of renewable energy was handled by means of curtailment in the renewable generation. This is a quite wasteful approach in utilising clean energy, and it leads to more reliance on the use of non-clean energy sources.

Currently, the grid operators handle the variability of renewable energy almost exclusively by ramping up or down the conventional generators or reserves based on the weather forecast. This will increase the stress and wear on the conventional power plants. Furthermore, in the near future, the grid will experience large shares of renewables making the current approach costly and unreliable in some cases. This leads to the need of a cost effective and reliable approach from the generation side in dealing with this matter which can be in the form of the following:

- By installing large-scale energy storage to balance the surplus and shortage of renewable energy generation, and hence stabilises the grid.
- By increasing transmission flexibility to enable accessing large shares of resources in order to aid balancing both local and regional deficits or excesses.

Some of these ideas are discussed in [133], which gives a realistic assessment on future scenarios with suggestions of making the global agenda move towards grid connected large-scale PV at a multi-TW scale. This study also concludes that energy storage and increasing transmission flexibility among other factors makes it possible to reach that multi-TW scale.

2.6 Summary

This chapter illustrated first the challenges of integrating high penetration levels of small-scale PV systems into the distribution network of the grid, including their technical challenges and the advanced methods to tackle those technical challenges with mentioning related work that has been done in solving the voltage regulation issue. It is worth mentioning that voltage regulation is the most significant technical challenge that prevents or limits the penetration levels of the small-scale PV systems into the distribution network of the grid. It is believed that this area of work is well addressed for the consumer purposes because it had the most attention in the recent years, leaving the integration of large-scale PV systems into the transmission network for utility purposes not being fully addressed well. Then, this chapter focused on the challenges of integrating large-scale PV systems into the transmission network of the grid, including their localised technical challenges, grid stability challenges, technical solutions and the current practices used by the grid operators in dealing with the variability that accompanies that large-scale PV system generation. The challenges associated with integrating large-scale PV systems into the transmission network are different from the challenges associated with integrating high penetration levels of small-scale PV systems into the distribution network. For example, when there is a moving cloud, the output of the PV system will change sharply, which becomes one of the main problems in the distribution level. However, in the transmission level, it is minimised because of the natural averaging effect since the PV plant is installed over a large area of land. The grid needs to deal with the greater variability and uncertainty, which operators currently handle almost exclusively by the ramping up or down of the conventional generators or reserves by forecasting the weather on a minute by minute or an hourly basis. However, in the near future, the grid will experience large shares of renewables making this current approach costly and unreliable in some cases leading to the need of a cost-effective and reliable approach from the generation side and that approach is likely storage and flexible transmission. It is worth noting that there are various types of energy storage technologies that can be application specific. Therefore, the next chapter will review and compare the different energy storage technologies in order to determine the most suitable energy storage technologies to be used as the flexibility measure.

Chapter 3 Overview of Energy Storage System

3.1 Introduction

Large-scale variable renewable energy (VRE) such as solar and wind are the expected path to energy transition in the near future. Studies showed that the current power grid has the capability of dealing with variations or uncertainties that the VRE brings up to a level of a small percent of the system's installed capacity without additional substantial cost or major technical problems [134]. Thus, the grid will face new challenges in grid balancing which affects the flexibility of the grid through the frequent mismatches between supply and demand when integrating high penetration levels of VRE. Grid balancing can be expressed as the matching response of the supply to the demand which has become less predictable due to the renewable energy integration to the grid [104]. In this sense, maintaining the balance of the grid flexibility is essential both on the demand and supply side [105]. Supply side flexibility can be achieved via energy storage, renewable energy curtailment and flexible generation. On the other hand, demand side flexibility can be achieved via energy storage, demand response and smart loads. Clearly, the common denominator between achieving flexibility to the supply and demand side is energy storage.

The previous chapter already established the scene for the issues and possible solutions of this research in which it concluded in the need for a reliable flexibility measure from the generation side that is likely to be in the form of energy storage. Energy storage means the energy formation in different forms that can be used to perform a useful future operation [135]. The conversion process can be classified into Power-to-Power, Power-to-Thermal, Power-to-Gas, Power-to-Liquid and Solar-to-Fuels [136]. The classification of the energy storage system can be determined via the converted energy form. Thus, it is divided into 5 classes which are mechanical, thermal, chemical, electrochemical and electrical energy storage [137]. However, only the Power-to-Power conversion classification is considered in this chapter. In doing so, the focus will be on the process of converting electricity into another energy form and restoring that electricity when required better known as Electricity Energy Storage (EES). Furthermore, this section will present an overview of the EES technologies with illustrating their applications. Then, an overall comparison will be conducted on the EES technologies in terms of the technical characteristics and technical suitability to different applications.

3.2 Overview of Energy Storage Technologies

There are various electricity energy storage (EES) technologies that are classified here into mechanical, electrical and electrochemical energy storage technologies classes. This classification will aid in presenting the EES technologies more clearly. A review of each EES technology will be covered here which will include their drawbacks, further work or development carried on improving the energy storage technology and examples of large-scale installations of the energy storage technology.

3.2.1 Mechanical Energy Storage Technologies

The working principles of the mechanical energy storage system can be kinetic energy, pressurized gas, potential energy and forced springs which is advantageous because it can deliver the energy when required [138]. In this part, the mechanical energy storage technologies will be illustrated with showing their drawbacks, further work or development carried on improving the energy storage technology and examples of large-scale installations of the energy storage technology. The mechanical energy storage technologies discussed in this part are the following:

- Pumped hydro storage (PHS).
- Flywheel system.
- Compressed air energy storage (CAES).
- Liquid air energy storage (LAES).
- Pumped thermal energy storage (PTES).

3.2.1.1 Pumped Hydro Storage (PHS)

Pumped hydro storage (PHS) is considered as the most mature and broadly installed large-scale electricity energy storage (EES) across the world, with an estimated global installed capacity of ~165 GW [139]. According to [140], 95% of the global installed large-scale electricity storage capacity is provided via PHS facilities that are classified as either pure or off-stream. Moreover, there are 11 operational pumped hydro storage plants in India with installed capacity of 4804 MW and another 1 GW of capacity expected to be soon operational [141]. Currently, the Three Gorges Dams located in China are the largest pumped hydro plant across the world with an installed capacity of 22.5 GW [142]. The PHS system can be described as two water reservoir connected by pipes and turbo-machinery in which the different elevation of the water reservoirs can result in energy storage when the water is pumped upwards to the upper reservoir or energy restoration when the water returns to the lower reservoir [143]. A schematic of the pumped hydro storage plant is shown in Figure 3.1.

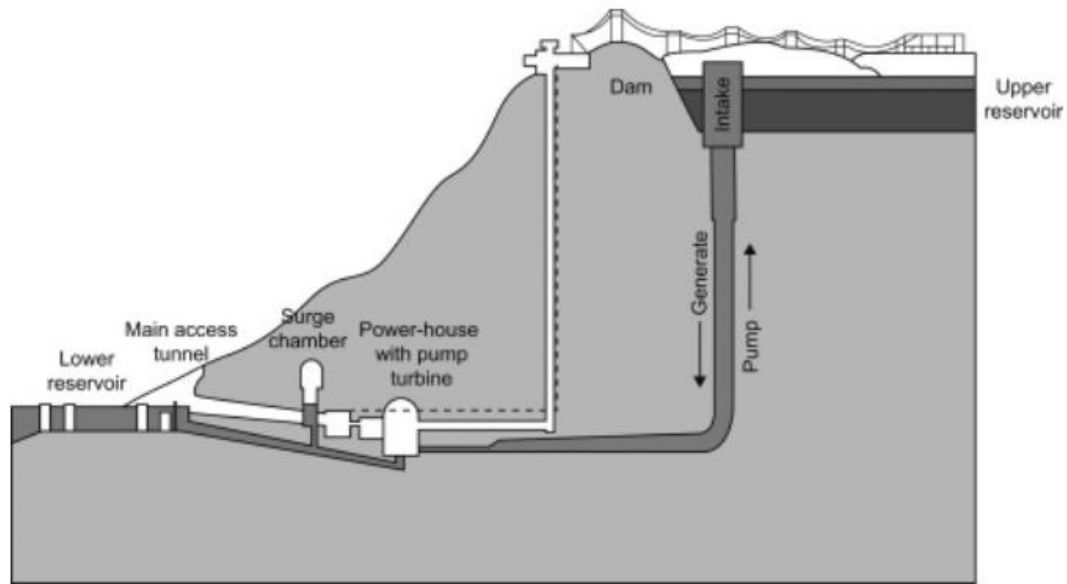


Figure 3.1. Schematic of the pumped hydro storage (PHS) plant [144].

The major drawbacks of the conventional PHS technology are geographical restrictions, long lead time, high cost of the implementation and environmental impact [136]. The conventional PHS needs an innovative solution to tackle some of its drawbacks which can be done under the ground by using vertical shaft with an internal piston. This results in eliminating the geographical restriction meaning there is no environmental impact with keeping the same characteristics as the conventional PHS except that its power rating is lower than the conventional PHS [145].

3.2.1.2 Flywheel System

In the early 20th century, the flywheel system was designed based on research done to overcome the stress on the rotational disk in which it paved the way to a new possibilities in the design and applications of flywheel [146]. Flywheel energy is stored as kinetic energy by using a motor that charges or spins up the flywheel rotor via electricity and then the motor acts like a generator by reducing the speed of the flywheel rotor when discharging [147]. Furthermore, the storage capacity of the flywheel system can be dependent on the rotor's function meanwhile the power rating of the flywheel system can be dependent on the characteristics of the motor and the power electronics involved [148]. There are two configuration of flywheel system based on their maximum rotor speed, which are low-speed and high-speed. Due to the difference in the rotor's materials; low-speed flywheels are five times cheaper than the high-speed flywheels [149]. A schematic of the flywheel technology is shown in Figure 3.2.

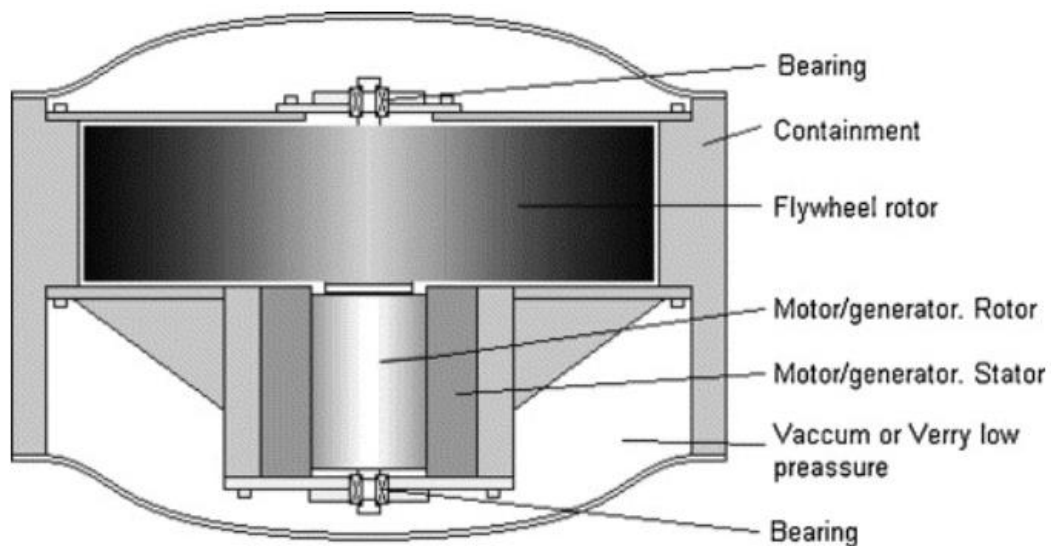


Figure 3.2. Schematic of the flywheel technology [147].

There are high noise that accompanies the flywheel operation which can be as one of its major drawbacks [149]. Also, a case can be made that the flywheel technology's drawback in grid energy storage is its high discharge rate [150]. The loud noise when operating the flywheel system especially the low-speed ones can be overcome via underground installation unlike the high-speed one which has considerably low noise due to the vacuum enclosure [151].

3.2.1.3 Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) is considered a commercial mature technology just like PHS technology for storing large amounts of energy with high delivery [152]. However, the compressed air energy storage technology is not deployed as much as the PHS technology in which only two full-scale CAES systems are in operation [152]. In 1978, the first 290 MW CAES plant was built at Huntorf, Germany and the other 110 MW CAES facility is located in McIntosh, Alabama, USA, 1991 [153]. The CAES technology functions based on using electricity on the compressor resulting in the stored compressed air (charging process) then this is discharged based on the gas turbine generation with using additional natural gas to pre-heat the gas in order to expand the turbine and generate electricity [154]. When the heat generated to compress the air is wasted in which requires an external heat source for air expansion; this reduces the overall efficiency of the system and that CAES arrangement is better known as Diabatic CAES (D-CAES) [155]. A schematic of the Diabatic CAES technology is shown in Figure 3.3.

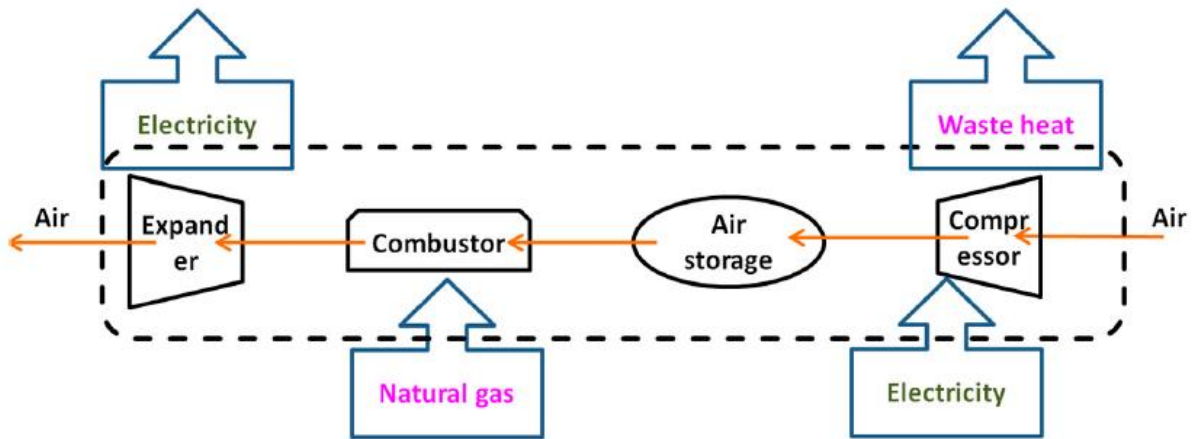


Figure 3.3. Schematic of the Diabatic CAES technology [156].

According to [154] the following are the drawbacks of the D-CAES technology:

- Geographical restrictions at large-scale since it uses underground sites such as rock caverns and salt mines to store the compressed air.
- Higher operational cost because of the usage of the fuel for the discharging process.
- Low efficiency since the heat generated to compress the air is wasted which requires an external heat source for air expansion.
- Environmental impact such as being carbon emitting system by using fuel in the process.

Innovation on the D-CAES technology resulted into the following arrangements of CAES which are Adiabatic CAES (A-CAES), Isothermal CAES (I-CAES) and Underwater CAES (UW-CAES) in which all have higher capital cost compared to the D-CAES [154]. In the A-CAES technology heat storage is added which resulted in an improved high efficiency ranging from 75% to 95% which is suitable for large-scale meanwhile I-CAES focuses on ways to reduce the amount of heat stored which is generated from the compression process [157]. In the UW-CAES technology the compressed air is stored underwater using bags under waterbodies which is an interesting solution since it improves thermal efficiency [158].

3.2.1.4 Liquid Air Energy Storage (LAES)

Liquid Air Energy Storage (LAES) is considered an emerging technology that liquefies the air to store it in a thermally insulated tanks as thermal energy for later use. In 1977, the university of Newcastle in the UK proposed the first concept of the LAES technology which was proposed for peak shaving [159]. The LAES's charging principle is to use electricity to drive the air liquification process for storage then it is discharged by increasing the pressure of the liquefied air through heat exchangers to generate high pressure air for the expansion process of the turbine to generate electricity as an output [160]. One of the major advantages

of the LAES technology is its significant higher energy density if compared to PHS or D-CAES technologies [161]. Also, LAES has no geographical restrictions in terms of installation as everything is constructed above ground with no environmental impact associated with it. Figure 3.4 shows a schematic of Highview LAES system which illustrates the concept of the LAES technology.

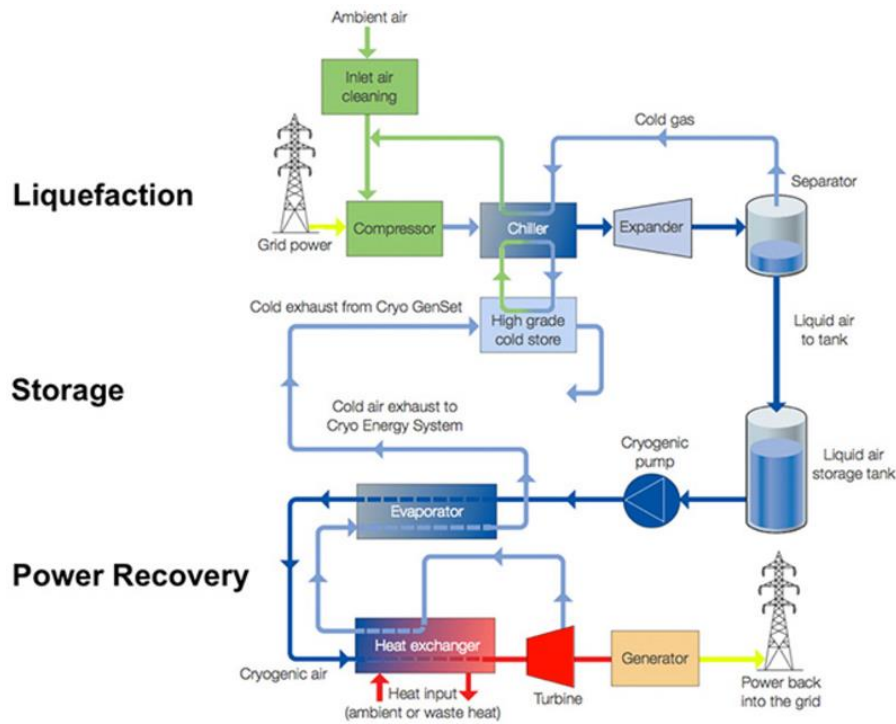


Figure 3.4. Schematic of the Highview LAES system [162].

The major drawbacks of the LAES technology are the low efficiency which can be addressed by utilising the wasted heat and the high cost of the liquification process [163]. Also, the size of the storage vessels in terms of the manufacturing and transportation process can be another drawback for the LAES technology. The LAES presents an interesting solution for grid scale energy storage as it has a high energy density with respect to its size with no geographical restrictions. Further work has been done to improve both the efficiency and energy density of the LAES respectively by using waste heat storage techniques and increasing the heating temperature via combustion of natural gas [164]. Also, using different cryogens such as nitrogen might be a potential solution because there is a surplus of nitrogen with less demand compared to the air and since the thermos-physical properties of both nitrogen and air are similar [165]. However, in [166] it was suggested that liquid air will be employed more over time as new production capacity is being built because of the advantages of liquid air over liquid nitrogen which will become more compelling since it requires less equipment thus low cost and that the air liquefiers are already commercially available at wide ranges.

3.2.1.5 Pumped Thermal Energy Storage (PTES)

Pumped Thermal Energy Storage (PTES) is categorized as an under-development technology that was first suggested in 1920 [167]. The PTES uses reversible heat pumps in which the electricity is stored as heat, the heat in general can be in the form of sensible or latent heat [168]. The PTES system consists of solid materials inside two storage tanks and a thermal machine that functions as both the heat pump and heat engine [169]. In the charging process the electricity causes the heat pump to produce high pressure hot gas which is injected into the first tank while the second tank has cold gas injected into in which that temperature difference between the two tanks will make when needed the heat engine generate shaft work to produce electricity from the generator [170]. The working fluid characteristics and solid materials can affect the temperature levels and the pressure ratio of the two tanks in the PTES system [171]. Figure 3.5 shows a schematic of the PTES technology.

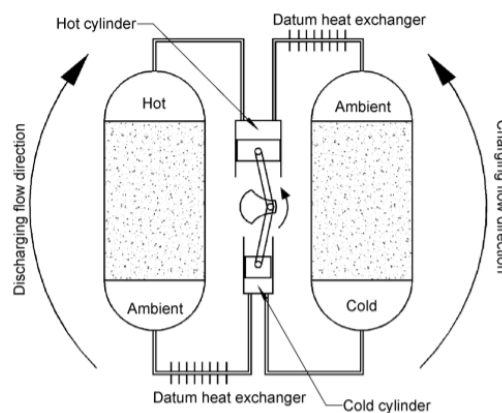


Figure 3.5. Schematic of the PTES technology [172].

There are no drawbacks in terms of location wise because of the flexibility of the implementation and in terms of the environment in which both the working fluids and solid materials are harmless [173]. The efficiency of the PTES system does not rely on the waste heat like the LAES system even though they have similar advantages compared to other energy storage technologies. Research are being conducted in the aspects of the thermal insulation efficiency, the performance of the reversible heat pump operation and the solid material performance to improve the PTES system [174, 175].

3.2.2 Electrical Energy Storage Technologies

Electrical energy storage can be classified as a direct storage technology because it can store the energy immediately in the form of a magnetic or electric field. In this part, the electrical energy storage technologies will be illustrated with showing their drawbacks and the further work or development carried on improving the storage technology. The electrical energy storage technologies discussed in this part are the following:

- Supercapacitors.
- Superconducting Magnetic Energy Storage (SMES).

3.2.2.1 Supercapacitors

The first attribution of the conventional capacitors was in 1745 by Ewald Georg Von Kleist in Germany in which found that connecting a high voltage electrostatic generator by a wire to a volume of water glass could result in the storage of electric charge [176]. Condensers is a term that was used for early capacitors by Alessandro Volta in 1782 in which relates the ability to store electric charge at higher density than a normal isolated conductor [177]. Conventional capacitors directly store electricity by inducing a static electric field from the accumulation of the positive and negative charges, but it comes with drawbacks of low energy density, moderate to high efficiency and high self-discharge rate [178]. Therefore, the conventional capacitors drawbacks are improved with the development of supercapacitors which has three types either electrochemical double-layer capacitors (EDLC) or pseudocapacitors or hybrid capacitors [179].

The first electrochemical double-layer capacitors (EDLC) was patented in 1957 by General Electric in which used activated charcoal as the plates [180]. The electrode of the electrochemical double-layer capacitors (EDLC) is made of nanoporous carbon materials which is due to their low cost, availability, existing production infrastructure and high specific-surface area that leads to a higher capacitance compared with electrostatic capacitors [181]. On the other hand, pseudocapacitors are based on metal oxide electrodes that arises from redox reactions in which increases both the energy density and specific capacitance in comparison with EDLC [182]. However, both lower cycle life and power density are the drawbacks of pseudocapacitors in comparison with EDLC [182]. Hybrid capacitors are comprised of an EDLC electrode and a pseudocapacitive electrode in which this combination enhances the properties [183]. Most of the focused development or research is conducted on the hybrid capacitors since it gives improved power and energy density but still presents the redox kinetic limitations which can be reduced through the design of the hybrid material [184].

3.2.2.1 Superconducting Magnetic Energy Storage (SMES)

Superconducting Magnetic Energy Storage (SMES) is categorised as another method to store electricity directly like supercapacitors, but here magnetic field is generated instead of the static electric field by passing the current through superconducting coil [185]. Also, SMES maintains the coil material superconducting state to achieve no resistance thus there is almost zero losses by operating in a vacuum enclosure with cooling system [185]. The superconducting magnetic energy storage technology was first introduced in 1969 as an energy source to deal with the variations in power demands [186]. In 1981, the first commercial application of the SMES technology was used along the 500 kV Pacific Intertie that interconnects the Northwest and California in which the SMES enhanced the transmission capacity via damping the inter-area modal oscillations [187]. Generally, the SMES consists of four parts which are the superconducting coil with the magnet (SCM), the cryogenic system (CS), the control unit (CU) and the power conditioning system (PCS) [188]. Figure 3.6 shows a schematic of the SMES technology.

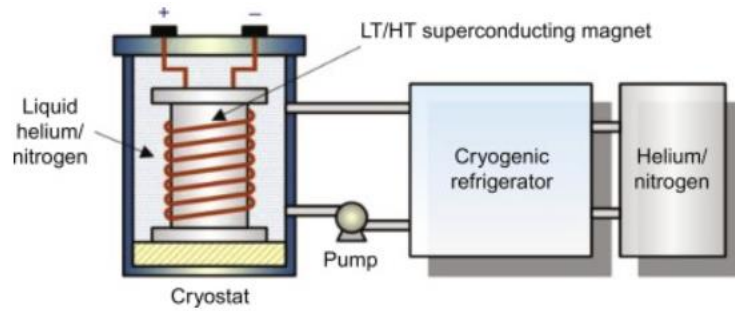


Figure 3.6. Schematic of the SMES technology [189].

The major drawbacks of the SMES technology are the technical difficulties and high cost due to the low temperature requirement of the superconducting phase transition [190].

Environmental effects such as the possible consequence of a strong magnetic field can be another drawback, even though some studies suggested that it does not pose a problem but an exclusion zone for the SMES plant is required [191, 192]. Currently, the SMES technology is only being utilised as a source of electric energy in high capacity and short term applications [193]. Furthermore, research is being focused on the technical and economic feasibility of the high-temperature superconductors rather than the low-temperature superconductors [194, 195].

3.2.3 Electrochemical Energy Storage Technologies

The concept of the electrochemical energy storage technologies is to use chemical reactions to store energy in the internal structure of a substance and recover this energy when required by forcing a reverse reaction. In this part, the electrochemical energy storage technologies will be illustrated with showing their drawbacks, further work or development carried on improving the energy storage technology and examples of large-scale installations of the energy storage technology. The electrochemical energy storage technologies discussed in this part are the following:

- Batteries which include Lead-acid, Nickel-cadmium & Nickel-metal Hydride, Lithium-ion, Sodium-sulfur, Metal-air and Flow batteries.
- Hydrogen and Fuel Cells.

3.2.3.1 Batteries

Chemical reactions are the reason for the electricity flow in the battery and each battery cell consists of these main elements which are electrolyte, positive electrode and negative electrode [196]. Also, in order to evaluate the cycle life of the batteries the following factors should be taken into consideration which are depth of discharge (DOD), ambient operating temperature and the rate of both charge and discharge. This part will feature the main groups of batteries that are industrially developed and commercialised.

a) Lead-acid Batteries

Lead-acid batteries can be categorised as the oldest rechargeable battery in which was invented by Gaston Plante in 1859, and has been widely used across the globe for more than 150 years [197]. Furthermore, the lead-acid batteries are widely adopted in the automotive industry and are implemented as uninterrupted power supply (UPS) for both telecommunication systems and medical emergency equipment [197]. The lead-acid battery is composed of lead metal electrode and lead oxide electrode in a sulfuric acid solution in which considered to be a mature technology that costs low, have a moderate efficiency of 70% and with design advancement the efficiency could reach 90% [196]. However, the lead-acid batteries have the following drawbacks according to [198]:

- Poor cycle life which is 400 to 1000 cycles at 80% of DOD.
- Regular maintenance requirement.
- Low specific energy which is 30 to 50 Wh/kg.
- The toxicity of the lead which is an environmental issue.
- Temperature control for storage requirement.

Valve regulated lead-acid (VRLA) batteries is a variation of the traditional flooded lead-acid batteries in which it was developed to reduce the maintenance requirement and improve the cycle life [199]. Valve regulated lead-acid (VRLA) batteries can be classified based on the method of retaining the electrolyte which can be via gel and absorbed glass mat (AGM) [199]. The following are examples of large-scale lead-acid batteries facilities according to [200]:

- 400 kW / 400 kWh facility in Hammermuehle, Germany in 1980 that was employed for peak shaving.
- 17 MW / 14 MWh facility in Berlin, Germany in 1986 that was employed for spinning reserve and frequency regulation.
- 20 MW / 14 MWh facility in San Juan, Puerto Rico in 1994 that was employed for spinning reserve, frequency and voltage regulation.
- 3.5 MW / 3.5 MWh VLRA facility in California, USA in 1996 that was employed for peak shaving.

b) Nickel-cadmium & Nickel-metal Hydride Batteries

The nickel-cadmium battery was first developed in 1899 by the Swedish inventor Ernst Waldemar Jungner [201]. The nickel-cadmium battery is composed of nickel hydroxide as positive electrode and cadmium hydroxide as negative electrode in an alkaline electrolyte

which is considered as another mature technology that has a longer cycle life and higher specific energy than lead-acid batteries [196]. Furthermore, the nature of the nickel-cadmium battery is highly conductive in which can be charged and discharged quickly [202]. In this sense, they deem suitable for generator starting and uninterrupted power supply (UPS) applications. However, the nickel-cadmium battery has the following drawbacks according to [203]:

- The toxicity of the cadmium which is an environmental issue.
- Memory effect when battery starts losing its capacity due to the cycle life.
- High initial cost.

A variation of the nickel-cadmium battery that improves its characteristics is nickel-metal hydride battery which is more environmentally friendly and have a higher specific energy [204]. However, nickel-metal hydride batteries exhibits reduction in cycle life and an increase in self-discharge rate due to the reaction between the dissolved hydrogen with the positive electrode [205]. An examples of a large-scale nickel-cadmium batteries facility is located in Alaska, USA in 2003 which is rated 27 MW for 15 minutes that was employed for spinning reserve and frequency regulation [206]. On the other hand, an examples of a large-scale nickel-metal hydride batteries facility is the 102 kWh facility located in Osaka, Japan in 2013 that was employed to balance the output of a 10 MW solar plant [207].

c) Lithium-ion Batteries

In the 1970s, fundamental works on the lithium-ion batteries started and it led to the success of developing the first commercial lithium-ion battery in 1991 [208]. Among the scientists who contributed to this success is the French scientist named Michel Armand who played an important role in the development of the cathodes, anodes, and electrolytes of the lithium-ion battery [208]. The lithium-ion battery operates on the intercalation principle that is based on the reversible insertion of a guest atom into a solid host structure without majorly disturbing its structure in which provided a huge step in improving the cycle life and the specific energy [209]. It is worth mentioning that the lithium-ion battery can be divided into groups based on their chemistry which are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP) and nickel cobalt manganese oxide (NMC) [209]. Furthermore, most of the research have focused on the lithium-ion batteries because they have higher specific energy, higher efficiency, very long cycle life, low self-discharge rate and quicker charging/discharging cycles [210]. In this sense, they deem suitable for portable electronics, electric vehicles and renewable energy integration applications. However, the lithium-ion battery has the following drawbacks:

- Higher costs which is considered as the main drawback of the lithium-ion batteries [210].

- Flammability, higher reactivity and toxicity of the lithium-ion batteries which can cause safety and environmental concerns [211].

The increase in demand for energy storage technologies, innovations in materials science, and the improvement in the manufacturing process are the attributes reducing the cost of the lithium-ion batteries, which are predicted to hit 100 USD/kWh in the next decade [212]. The following are examples of large-scale lithium-ion battery facilities according to [189]:

- 40 MW / 20 MWh facility in Miyagi Prefecture, Japan in 2013 that was employed for voltage support and frequency regulation.
- 40 MW / 40 MWh facility in Minamisoma City, Japan in 2016 that was employed for balancing the renewable energy output and demand.
- 14 MW / 63 MWh facility in Zhangbei, Hebei, China in 2012 that was employed for electrical energy time shifting, renewable capacity firming, ramping and frequency regulation in combination with a solar and wind plant.
- 100 MW / 129 MWh TESLA facility in Jamestown, Australia in 2017 which is considered the world largest facility that was employed for providing essential grid support services.

d) Sodium-sulfur Batteries

In the 1960s, the sodium-sulfur battery technology originated in the automotive applications by Ford Motor Company and by the late 1970s, variety of developers advanced this technology in applications that ranges from satellite communications to large stationary power [213]. The sodium-sulfur battery technology was selected by the Tokyo Electric Power Company during the early 1980s as the preferred method for dispersed utility energy storage in order to replace the growing dependence on the central pumped hydro energy storage [213]. The sodium-sulfur battery is composed of molten sulfur as the positive electrode and molten sodium as the negative electrode which is kept in a liquid state via high temperature [214]. The sodium-sulfur battery is an attractive technology because of its high specific energy, high efficiency, long life time, long storage capacity of up to several hours, good cycle life, high power rating up to several MW, features the pulse power delivery and the low cost of the composing materials of the battery [214, 215]. However, the sodium-sulfur battery has the following drawbacks according to [214, 215]:

- Safety concerns such as flammability because molten sodium is highly reactive.
- Increase in the self-discharge rate as the battery is at standby because it must maintain the high temperature through electric heaters located on the battery.

There is another high temperature battery called sodium-nickel-chloride battery that has a slightly similar characteristics as the sodium-sulfur battery with addition of being safer to

operate [216]. However, the sodium-nickel-chloride battery materials takes longer to heat up and it has a slightly lower specific energy than the sodium-sulfur battery [216]. The following are examples of large-scale sodium-sulfur batteries facilities according to [217]:

- 34 MW / 245 MWh facility in Aomari, Japan in 2008 that was employed for supporting the grid and wind energy stabilisation.
- 4 MW / 32 MWh facility in Presidio, Texas, USA in 2010 that was employed for supporting the grid and energy arbitrage.

e) Flow Batteries

Flow batteries varies from the conventional batteries in which they store their active materials in the form of two redox couple solutions in external tanks, and pumps it through electrochemical cells stack where both charge and discharge reactions take place at the inert electrode surfaces [218]. There are three types of flow batteries that shown commercial promise which are vanadium redox battery (VRB), zinc bromine battery (ZBB) and polysulfide bromide battery (PSB) [219]. The vanadium redox battery (VRB) is the most popular type of flow batteries because of its operational simplicity and lower costs if compared to the other types of flow batteries since it uses the same material across both electrolytes which removes the threat of cross contamination through the proton exchange membrane [219]. On the other hand, zinc bromine battery (ZBB) and polysulfide bromide battery (PSB) uses bromide which presents a fear of releasing the highly toxic bromine gas [219]. The first developed vanadium redox battery (VRB) was in the early 1980s and they are mostly used in small and medium scale applications with the addition of responding to the variable generation of the renewable energy sources [220]. Figure 3.7 shows a schematic of the flow battery technology.

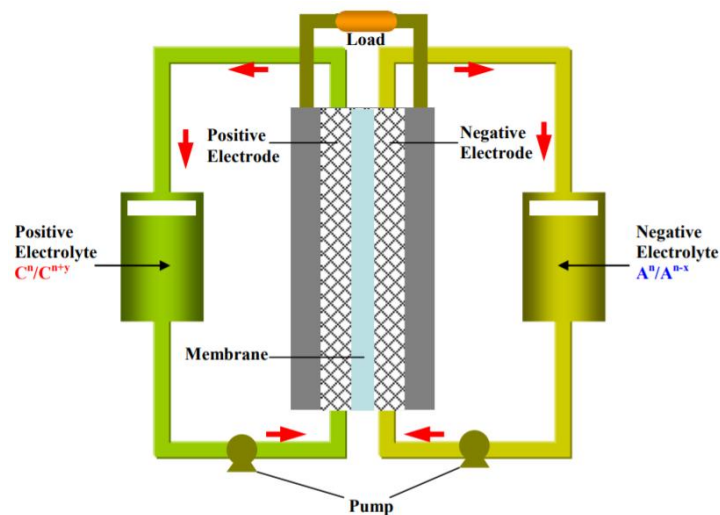


Figure 3.7. Schematic of the flow battery technology [221].

The flow batteries are scalable meaning they can be upgraded if needed with low incremental cost since the power rating and capacity of the flow batteries respectively depends on the active area of the cell stack and the volume of electrolytes solutions stored in the tanks [221]. Furthermore, the vanadium redox flow battery is an attractive technology because of its low maintenance requirement, safety, long lifetime, simplicity in designing and building larger systems and tolerating deep discharge without risking damages [221]. However, the vanadium redox flow battery has the following drawbacks according to [222]:

- Low specific energy and power which is related mainly to the low solubility and the low cell voltage of the vanadium species within a limiting temperature ranging from 5 °C to 40 °C.
- Low energy density in which can be 10 times lesser than lithium-ion batteries.
- The high cost of materials and installation.
- Parasitic losses of power and energy due to some flow field designs that inevitably introduces currents bypassing into the manifolds in the stack.

Research is being focused on flow batteries to improve both their power and energy densities through the usage of carbon-based conductive networks [223]. The following are examples of large-scale flow batteries facilities according to [224]:

- 15 MW / 60 MWh facility in Abira, Japan in 2015 that was employed for supporting the grid integration of renewable energy.
- 2 MW / 20 MWh facility in Pfinztal, Germany in 2019 that was employed for storing wind energy.
- 2 MW / 8 MWh facility in Washington, USA in 2016 that was employed for supporting the grid and renewable energy integration.
- 200 MW / 800 MWh facility in Dalian, China that is under construction and when completed will become the largest electrochemical energy storage facility in the world.

f) Metal-air Batteries

The metal-air battery is composed of oxygen from atmospheric air as the positive electrode and a metal as the negative electrode which is considered as an emerging technology with a promising future due to their potentially better technical performances specifically their high specific energy level that goes up to 11,100 Wh/kg [225]. Metal-air batteries are comprised of four parts which are electrolyte, metal anode, air cathode and separator [226]. The separator acts as an insulator that only allows the ions transformation and the reason for the metal-air batteries owning higher specific capacity is due to their open battery configuration that utilises air as the reactant [226]. The research on metal-air batteries began way earlier than

lithium-ion batteries in which the first zinc-air battery dates back to 1878 and following that the other types of metal-air batteries were developed in the 1960s [227].

Among the metal-air batteries family, lithium-air and zinc-air are the most promising commercial candidates because lithium is the lightest metal and most electronegative meanwhile zinc is cheaper, highly abundant and environmentally compatible [225]. On the other hand, there are other promising candidates that gained attention due to their high energy density, safety, abundance of materials such as aluminium-air and magnesium-air [228]. However, aluminium-air and magnesium-air batteries faces issues due to their chemistry such as the lack of rechargeability, short shelf life, high self-discharge rate and metal corrosion [228]. Currently, there is a lot of interest in the sodium-air batteries in comparison to the lithium-air one because they are a commoner metal on the earth and their cell reaction are easily reversed [229]. Furthermore, the current research on metal-air batteries are focused on the materials development in order to improve the performance, lifetime limitations and costs [229]. In doing so, will expand their large-scale applications in the foreseeing future which will help in aiding renewable energy integration.

3.2.3.2 Hydrogen and Fuel Cells

In 1671, Robert Boyle produced the first hydrogen by dissolving iron in a diluted hydrochloric acid in which was observed before discovering hydrogen as a distinct gas in 1766 by Henry Cavendish [230]. Hydrogen is the first element in the periodic table that constitutes at least 90% of the universe [230]. Hydrogen gas is considered as a clean non-toxic renewable fuel because when it is burnt it only releases water vapour and heat which doesn't rise the concern of spilling due to its quickness in dissipating to the atmosphere [231]. The interest in utilising hydrogen as a fuel source specifically for automotive industry has grown dramatically since 1990 due to the advancement in hydrogen production and utilisation technologies [232]. Furthermore, hydrogen can be employed as an energy storage medium even though they differ from the conventional energy storage technologies since they use different process for producing, storing and utilising hydrogen as an energy storage medium. Therefore, hydrogen in this sense is an energy carrier rather than a primary energy source.

A typical hydrogen storage system consists of hydrogen storage tank, gas-engine turbine or if applicable fuel cell and an electrochemical converter called electrolyzer that aids the production of hydrogen via electricity [233]. Hydrogen production can be achieved via steam reformation of natural gas, extraction from fossil fuels, water electrolysis and the fermentation of biomass [234]. It is worth mentioning that hydrogen can be produced from renewable energy sources such as solar in which has great potential in the future due to the abundance of this energy [234]. Steam reformation can result in producing pollutants while the extraction of hydrogen from fossil fuels can be much expensive than using the hydrogen as fuel on itself [235]. The complexity of storing the hydrogen in terms of being a very light (less-dense) gas is the main challenge in which increasing the density is the only way of making hydrogen storage economically viable [236]. Furthermore, the demand of a particular

application dictates the suitable method of hydrogen storage. For instance, the purity of the hydrogen delivered is less critical in applications where hydrogen is going to be combusted with air which is unlike the applications when hydrogen is delivered to a proton-exchange-membrane fuel cell where the purity of the hydrogen delivered is critical [237]. Due to the vast possible hydrogen storage options, it can be categorised into the following methods based on the nature of interaction between the stored hydrogen and the storage vessel or material according to [237]:

- Physical storage that includes both compressed hydrogen and liquid hydrogen.
- Hydrogen storage via adsorption which exploits the physical Van Der Waals bonding between a material with a large specific surface area and the molecular hydrogen.
- Chemical storage which chemically bonds the hydrogen with metal hydrides or chemical hydrides.

Hydrogen can be utilised in the production of mechanical work, electricity and synthetic fuels. Electrical generation through hydrogen can be achieved via engine generator sets, gas-fired steam turbines and fuel cells [238]. On the other hand, fuel cells generate electricity like batteries through electrochemical reactions with the exception of requiring constant source of fuel to keep running if compared to batteries [239]. Among the fuel cells, hydrogen fuel cells have the best performances and lowest impact on the environment [239]. The type of electrolyte and electrode catalysts of the deployed materials dictates the possible fuels and operating conditions in which fuel cells are categorised based on the electrolyte employed [239]. According to [239], fuel cells can be categorised into polymer electrolyte FCs (PEFCs), solid oxide FCs (SOFCs), alkaline FCs (AFCs), phosphoric acid FCs (PAFCs) and molten carbonate FCs (MCFCs). It is worth mentioning that fuel cells require warm-up time which are not very suitable for on-demand power applications [238]. In terms of hydrogen as bulk storage, there are operational projects that stores large amounts of hydrogen in an underground salt cavity in which a 24 GWh facility is located in Teeside, UK and a 83 GWh facility is located in Texas, USA [240]. Overall, hydrogen storage is currently the only low-carbon technology capable of storing above 100 GWh with the capability of operating over a timescale of months, even though this is countered by its higher equipment costs and low round-trip efficiency [240].

3.3 Energy Storage Applications

Energy storage has wide variety of applications that delivers the needed flexibility to the grid system. The term application is defined here as the electrical operation that is achieved via the usage of the energy storage system. Based on [241], the energy storage applications can be grouped into 4 groups depending on the location of the energy storage system and the following are the energy storage applications groups:

- Generation side applications of energy storage.
- Transmission and Distribution side applications of energy storage.
- End-consumer side applications of energy storage.
- Renewable energy side applications of energy storage.

This section illustrates the energy storage applications of each group with mentioning their technical requirements in terms of power rating, response time and storage capacity. The first group is the generation side which includes the following applications according to [241]:

- *Time Shifting*: better known as energy arbitrage which stores the electricity when its price is low and consumes or sells the stored electricity during peak periods. The technical requirements for time shifting application are moderate response time, a power rating in the range of a few MW to 100 MW and a considerable storage capacity [242].
- *Seasonal Energy Storage*: better known as long term time shifting which have a similar principle as time shifting except the energy is stored for a longer period that can extend to months. The technical requirements are like time shifting application except for the fact it must have a larger storage capacity and almost no losses in terms of self-discharge [242].
- *Large-scale Renewable Energy Integration*: which tries to smooth the generation of the variable renewable energy (VRE) generation. The technical requirements for large-scale renewable energy integration are fast response time to follow the variations of the VRE generation, a power rating compatible with the VRE generation in the range of a few tens or hundreds of MW and a considerable storage capacity that can fulfil the variations from minutes to several of hours [242].
- *Transmission & Distribution (T&D) Investment Deferral*: which reduces both the grid's stress and upgrading the infrastructure of the T&D. The technical requirements for T&D investment deferral are a response time of up to a few minutes, a power rating in the range of tens to hundreds of MW and a considerable storage capacity of several of hours [242].

- *Grid Regulation*: which involves balancing the supply-demand through frequency regulation and supporting the reactance control in a local level through voltage regulation. The technical requirements for grid regulation are fast response, a power rating up to a few MW and a storage capacity of some minutes [242].
- *Black-Start Ability*: which involves re-energising either the grid after a blackout or restarting other generation resources. The technical requirements here depend on the grid or the generation resources parameters.
- *Load Following*: which maintains the balance of the system by following the load pattern variations that are highly influenced by the consumer habits and weather. The technical requirements here are like the grid regulation application.

The second group is the transmission and distribution side which includes the following applications according to [114]:

- *Load Levelling*: which is done by smoothing the load curve through charging during low demand periods and discharging during high demand periods. The technical requirements here are like the time shifting application but in a relatively smaller scale in terms of power rating and storage capacity.
- *Transmission & Distribution (T&D) Investment Deferral*: which is previously explained with the addition of congestion relief in the T&D which results in extending the lifetime of the existing equipment.
- *Voltage Support*: which relates to the management of reactive power through the absorption or injection to the grid.
- *Power Quality*: which involves keeping the grid's supply stable via continuous countering disturbances such as harmonics. The technical requirements here are scalable except for the response time which needs to be very fast to overcome the grid fluctuations.

The third group is the end-consumer side which includes the following applications according to [114]:

- *Energy Management*: which has the same principle as time shifting except it is from the end-consumer side to reduce the demand for electricity.
- *Power Reliability*: it aims to ensure bridging power during power blackout which is very beneficial for uninterrupted power supply (UPS) applications. The technical requirements here are very rapid under a second response time, power rating and storage capacity depending respectively on the end user's load and time required for recovery of operations.

- *Integration of Distributed Renewable Energy Sources*: which aims to increase the self-consumption rate of the distributed renewable energy sources during peak hours. The technical requirements here are fast response time, a power rating compatible with the distributed renewable energy generation in the range of tens or hundreds of kW usually is enough and a storage capacity up to 6 hours [242].
- *Demand Side Management (DSM)*: which aids the deployment of various DSM programs such as time-of-use to attain the management of the load.

The final group is the renewable energy side which includes the following applications according to [114]:

- *Renewable Energy Capacity Firming*: which ensures the production of constant power output through absorption of peaks, suppressing valleys in generation and avoiding the need for renewable energy curtailment.
- *Renewable Energy Time Shifting*: which has the same principle as time shifting application with the addition of achieving an increase in the self-consumption of the renewable energy and reduction of renewable energy curtailment which will increase in profit.
- *Renewable Energy Ramp Rate Control*: which involves charging during fast ramp up and discharging during fast ramp down to limit the rate of change in the overall power output.

3.4 Comparison of Energy Storage Technologies

Each energy storage technology has its unique technical characteristics that determines both the energy storage scale and the appropriate application field. In this sense, a comparison of the technical characteristics of the energy storage technologies is required before deciding on the suitability of the energy storage technology. Furthermore, from a user point view there are typical characteristics of the energy storage technology that are used for the selection criteria depending on the application which can be represented into the following metrics according to [243]:

- *Power rating*: also called power output which is the amount of power that can be discharged within the normal discharging duration expressed in kW or MW.
- *Storage capacity*: which is the amount of energy available after the system is charged in terms of both the duration of storage and energy rating expressed in kWh or MWh.
- *Energy density*: which is described as the nominal storage of energy per unit of volume expressed in Wh/l.
- *Efficiency*: which is the ratio between the energy released and the energy required with including the losses.
- *Lifetime*: is the amount of time that the storage technology is capable of operating at.
- *Response time*: is the amount of time required for the storage system to start injecting power.
- *Capital costs*: which includes the power and energy costs of the energy storage technology to determine its economic feasibility.
- *Self-Discharge rate*: which is described as the portion of the initial energy stored that dissipated over a given amount of non-use time.

This section will illustrate a comparison of the energy storage technologies in terms of the technical characteristics and technical suitability to different applications. The research efforts in [242] gives an excellent review for the technical characteristics of the energy storage technologies which will be used in this part and is shown in Table 3.1.

Table 3.1. Technical characteristics of the EES technologies [242].

EES Technology		Power Rating (MW)	Storage Capacity (MWh)	Energy Density (W h/l)	Response Time	Efficiency (%)	Self-discharge Rate (%/day)	Capital Costs		Technology Maturity	Lifetime (years)
								Power (\$/kW)	Energy (\$/kWh)		
PHS	Conventional	100-5000+	1000+	0.5-1.5	~ 3 min	65-85	0.005-0.02	600-2000	5-100	Mature	30-60
	Underground	200-1000	8.5-200	0.5-1.5	< 1 min	75-80	Very small	1000	N/A	Demonstration	30
CAES	D-CAES	5-300+	1000+	3-12	~ 10 min	40-60	0.003-0.03	400-800	2-50	Commercial	20-40
	A-CAES	0.1-100+	100+	3-12	1 min	75-95	0.5-1	700-1000	40-80	R&D - Demonstration	20-30
	I-CAES	0.1-10	1-10	3-12	< 1 min	75-95	Very small	500-1000	10-100	Pre-commercial	20-30
	UW-CAES	1-1000+	1-1000+	3-12	< 1 min	75-95	Very small	750-2000	40-200	Pre-commercial	20-30
Flywheel		0.1-10	0.01-5	20-80	ms-s	75-95	55-100	250-350	1000-5000	Commercial	15-20
LAES		10-100+	10-1000+	50	5-10 min	40-85	Very small	900-2000	260-530	Demonstration – Pre-commercial	20-40
PTES		0.5-10+	0.5-60+	~ 110-170	< 1 min	70-80	1	~ 600	~ 60	R&D – Pre-commercial	25
Supercapacitors		0.001-10	10 ⁻⁶ -10 ⁻²	10-30	ms	85-95	20-40	100-360	300-2000	Demonstration – Pre-commercial	10-20
SMES		0.01-10	10 ⁻⁴ -0.1	0.2-2.5	ms	80-90	10-15	200-350	10 ³ -10 ⁴	Demonstration – Pre-commercial	15-20
Batteries	Lead-acid	0.001-50	0.1-100	50-90	ms	70-90	0.033-0.3	300-600	200-400	Mature	5-15
	Ni-Cd	0.01-40	10 ⁻³ -1.5	60-150	ms	60-73	0.067-0.6	500-1500	800-1500	Commercial-Mature	10-20
	Ni-MH	0.01-1	10 ⁻⁵ -0.5	140-300	ms	70-75	0.4-1.2	600-1800	960-1800	Commercial-Mature	5-10
	Li-ion	0.1-50	10 ⁻³ -100	200-500	ms	85-95	0.1-0.3	1200-4000	600-2500	Commercial-Mature	5-15
	NaS	0.05-50	6-600	150-250	ms	70-90	0.05-20	1000-3000	300-500	Commercial	10-15
	VRB	0.005-7	0.01-10	16-33	ms	60-85	0.2	600-1500	150-1000	Commercial	5-15
	ZBB	0.025-2	0.05-4	30-60	ms	60-75	0.24	700-2500	150-1000	Pre-commercial	5-10
	PSB	1-15	0.01-10+	16-60	ms	57-85	Very small	330-2500	120-1000	Demonstration	10-15
Hydrogen		0.1-1000+	100-1000+	500-3000	s-min	30-50	Very small	1900-6300	1-10	R&D – Pre-commercial	20-30

Mechanical Energy Storage Technologies Class

Electrical Energy Storage Technologies Class

Electrochemical Energy Storage Technologies Class

According to Table 3.1, the mechanical energy storage technologies class overall has the highest power rating and storage capacity if compared to the other energy storage technologies classes. Specifically, the PHS and CAES technologies have the highest power rating and storage capacity among the mechanical energy storage technologies class. The LAES technology has a high storage capacity, but it is lacking the maturity of the PHS and CAES technologies. It is worth mentioning that the electrochemical energy storage technologies class such as batteries has a higher power rating and storage capacity than the electrical energy storage technologies class such as supercapacitors. This can be due to the ease of scalability and the maturity of the electrochemical energy storage technologies class. The hydrogen storage technology presents the closest power rating and storage capacity capabilities to the mechanical energy storage technologies class. This can be due to the various methods of utilising the hydrogen in producing electricity which is different from the conventional methods of the batteries.

According to Table 3.1, the electrochemical energy storage technologies class overall has the highest energy density and fastest response time if compared to the other energy storage technologies classes. Specifically, the Li-ion, Ni-MH and NaS batteries have the highest energy density among the electrochemical energy storage technologies class. Among the other EES technologies classes, LAES, PTES and flywheel presents the closest energy density capabilities to the electrochemical energy storage technologies class. The very huge

size of the PHS and CAES is the reason of their low energy density in comparison to the other EES technologies. It is worth mentioning that the electrical energy storage technologies class such as supercapacitors has a similar fast response time as the electrochemical energy storage technologies class such as batteries. The flywheel technology presents a fast response time capability that can be near the capability of both the electrical and electrochemical energy storage technologies classes. Hydrogen storage lacks the fast response time as the electrochemical energy storage technologies class such as batteries. However, it has the highest energy density that requires advanced storage methods to attain this higher potential energy density.

According to Table 3.1, the technologies with the highest round-trip efficiency are Li-ion batteries, flywheel, electrical energy storage technologies class and all the CAES technologies except for the D-CAES type. The technologies which lack the round-trip efficiency are D-CAES, Hydrogen and the LAES technology that does not include wasted heat utilisation. On the other hand, the self-discharge rate per day is very low for most of the EES technologies except for the flywheel, NaS batteries and all the electrical energy storage technologies class such as supercapacitors. In terms of the EES technologies lifetime, the mechanical energy storage technologies class and hydrogen storage have a lifetime of 20 years and more, with the PHS technology having a lifetime of up to 60 years. Furthermore, the rest of the EES technologies have a lifetime of up to 20 years and lower. It is worth mentioning that the PHS and most of the batteries with the exception for the flow batteries and NaS batteries are considered mature technologies. Also, there are commercially available technologies such as D-CAES, flywheel, NaS and VRB batteries that are considered not mature enough to be used all over the world without improving the technology in the future. The remaining rest of the EES technologies have great potential and are either in the pre-commercial or demonstration or research and development (R&D) phase.

The most important factor in any project's commercialisation is its capital costs. An EES system with a very high capital cost is not considered a significant solution since the energy storage is there to overcome the high costs of the fuel-based generation in the peak hours. According to Table 3.1, all the mechanical energy storage technologies class with the exception of flywheel have higher power costs (\$/kW) in comparison to its lower energy costs (\$/kWh). The D-CAES, A-CAES, PTES and hydrogen technologies have the lowest energy costs (\$/kWh) among the EES technologies. On the other hand, all the electrical energy storage technologies class and the flywheel have higher energy costs (\$/kWh) in comparison to its lower power costs (\$/kW) in which are more suited for the short-term applications rather than long-term applications. Among the batteries, Li-ion has both the highest power costs (\$/kW) and energy costs (\$/kWh). Meanwhile, Lead-acid has both the lowest power costs (\$/kW) and energy costs (\$/kWh) among the batteries. The PHS technology has the edge over the batteries in terms of costs for large-scale applications, but this difference is declining in recent years. Also, it is worth mentioning that there are other factors such as the location and size of the system that can affect the costs in which can be different to the estimated ones in Table 3.1. Furthermore, the technical characteristics of the

EES technology dictates its suitable applications in which an overall comparison of the technical suitability of the EES technologies to different applications is presented in Table 3.2.

Table 3.2. Comparison of the technical suitability of EES technologies to different applications.

	EES Applications				
	Time shifting and Seasonal energy storage	T&D investment deferral	Large-scale RE integration and Power reliability	Grid regulation and Power quality	Distributed RE Integration
Specific Requirements	• 10-1000+ MW of power rating • 1-24+ h of discharge time • Very low self-discharge rate • Moderate response time in minutes	• 10-100+ MW of power rating • 1-6 h of discharge time • Moderate response time in minutes	• 0.1-10+ MW of power rating • m-h of discharge time • Rapid response time in under a second	• Up to a few MW of power rating • ms-m of discharge time • Very rapid response time in ms	• 10-100 kW of power rating • 1-6 h of discharge time • Rapid response time in under a second
Mechanical Energy Storage Technologies	All are suitable except for Flywheel	All are suitable except for Flywheel	If ignoring the response time requirement then all are suitable except for Flywheel and PHS	Only Flywheel is suitable	If ignoring the response time requirement then all are suitable at smaller scale except for Flywheel and PHS
Electrochemical Energy Storage Technologies	All are suitable except for NaS batteries	All are suitable	All are suitable	All are suitable except for Hydrogen storage	All are suitable
Electrical Energy Storage Technologies	Not suitable	Not suitable	Not suitable	All are suitable	Not suitable

According to Table 3.2, grid regulation and power quality applications are mainly suited for the electrical energy storage technologies class and flywheel since they have the highest discharge rate among the EES technologies. The mechanical energy storage technologies class with the exception of flywheel are suitable for both time shifting and transmission & distribution (T&D) investment deferral applications. In particular, the PHS technology is prominent in these types of applications if the location is suited for the implementation of the PHS technology since it has geographical constraints. On the other hand, the electrochemical energy storage technologies class specifically batteries are suitable for all types of applications in which is due to their scalability, high efficiency, high energy density, fast response time, low self-discharge rate and non-geographical constraint. Specifically, the Li-ion batteries presents the best technical characteristics among the rechargeable batteries but has the highest capital costs. This is its main drawback that is predicted to decrease in the future through the improvement of the cell technologies in terms of increasing the lifetime, increasing the production and reducing its physical size [244]. It is worth mentioning that except for the grid regulation and power quality applications; hydrogen storage presents a promising solution if the difficulty of storing it and its low efficiency is addressed. Furthermore, the ideal characteristics of the EES technology in terms of grid energy storage in order to ensure secure and stable supply of electricity are scalability, high storage capacity, high efficiency, high energy density, cost effective, fast response time, low self-discharge rate, high lifetime and non-geographical constraints. The ideal candidate for grid energy storage is the Li-ion batteries if its costs keep declining to reach the cost effectiveness level.

Also, it is a proven technology in grid energy storage in which a prime example of this is the 100 MW / 129 MWh TESLA facility in Jamestown, Australia. However, at the current time there is not a storage technology that can satisfy or meet all the mentioned characteristics. This means that different energy storage technologies target different aspects of the grid's needs. Thus, a hybrid system may be needed to satisfy the needs of the grid in which is done by the combination of two or more energy storage technologies chosen specifically to fill the gaps or drawbacks of the other energy storage technology. Also, it is worth taken into consideration that some EES technologies have some minor environmental effects in which toxic remains of the batteries is a prime example that requires proper recycling.

3.5 Summary

This chapter presented an overview of electricity energy storage that included a review of each of its technologies covering their drawbacks, the further work or development carried on improving the energy storage technology and examples of large-scale installations of the energy storage technology. Also, the applications of energy storage were presented and an overall comparison of the EES technologies in terms of the technical characteristics and technical suitability to different applications were conducted. The EES technologies were classified into mechanical, electrical and electrochemical energy storage technologies classes. It was evident that the electrochemical energy storage technologies class specifically batteries are the dominant EES technology to be used since they are suitable for all types of applications. This is due to their scalability, high efficiency, high energy density, fast response time, low self-discharge rate and non-geographical constraint. Among the rechargeable batteries, Li-ion batteries presented the best technical characteristics in terms of being lighter in weight, smaller in size, higher in energy density and higher in round-trip efficiency. However, for the Li-ion batteries to be fully adopted in large-scale applications such as grid energy storage, its cost must be reduced via the improvement of the cell technologies. Furthermore, hydrogen storage presents a promising solution except for the grid regulation and power quality applications if the difficulty of storing it and its low efficiency is addressed. It was evident that the electrical energy storage technologies class and flywheel are mainly suited for grid regulation and power quality applications since they have the highest discharge rate among the EES technologies. The PHS and CAES technologies have the highest power rating and storage capacity among EES technologies class in which can store more energy for longer duration. However, they are limited by geographical constraints. Therefore, it is apparent that at the current time there is not a single storage technology that is ideal to satisfy or meet all of the grid's needs. This may lead to the need of utilising a hybrid energy storage system to satisfy the needs of the grid in which can done by combining two or more energy storage technologies chosen specifically to fill the gaps or drawbacks of the other energy storage technology. After establishing the scene for the issues and identifying the most suitable energy storage technologies to be used as the flexibility measure; modelling the PV system will be required in order to assess its integration impact into the grid. Thus, the next chapter will demonstrate a detailed description of the aspects undertaken to model the PV system.

Chapter 4 PV System Modelling

4.1 Introduction

The previous chapter already identified the most suitable energy storage technologies to be used as the flexibility measure, and now modelling the PV system will be required in order to assess its integration impact into the grid. A photovoltaic (PV) cell is made of semiconductor materials that transforms solar energy absorbed from the sunlight by each individual PV cells in which the electrons of that semiconductor material are energized resulting in electricity in the form of direct-current. The connection of the PV cells into one another can be arranged as in series or in parallel to form a PV module. The typical capacities of these commercially available PV modules are typically between 60-200 W because only 6-20% of the incident solar radiation is transformed into electricity and the remaining of that incident solar radiation dissipates as heat [245]. Also, the PV modules can be joined with a bundle of application dependent components such as sun trackers, inverters, electrical components, mounting systems and batteries to form a highly modular PV system that has a capacity of a few watts up to tens of MW [246].

Generally, the detailed physical models such as the PVSYST software are advantageous in presenting the behaviour of PV arrays accurately. Such models are quite beneficial for examining the PV system's details as they offer PV cell-level parametric analysis. However, the PVSYST model may not be suitable for assessing the performance of the electrical grid system with the inclusion of the PV system because of their complexity [247]. Furthermore, such studies involve only calculating the PV power over extended time frames at different weather conditions. Therefore, more appropriate mathematical models are required for this kind of analysis, as the amount of calculations is minimised [248]. A perfect example is that the singular diode model can be simplified by the assumption of making the shunt resistance boundlessly massive or by eliminating both series and shunt resistance that will decouple the voltage and current from the model's main equation [249]. Additionally, there are some simplified models that directly relates at any instant of temperature and irradiance with the PV's maximum generated power such as [250-252]. These models are appropriate for use when the goal is to investigate the behaviour of the electrical grid with the inclusion of the PV system. However, before one of the aforementioned simplified PV models are used; they have to be evaluated against a detailed physical model such as the PVSYST software. In doing so, the simplified PV model with the upmost accurate result in comparison to the PVSYST software will be chosen in order to calculate the large-scale PV output at various penetration levels to the grid. Therefore, this chapter will demonstrate a detailed description of the aspects undertaken to design the PV array which includes the sizing of the PV array, the efficiency of the inverter and the other miscellaneous PV system losses. Also, the two simplified mathematical models for calculating the PV array will be studied; in order to illustrate which simplified mathematical model gives the upmost accurate result in comparison to the PVSYST software results.

4.2 PV Array Design

The solar cells are usually connected in series, forming a solar module, and the formed panels are further interconnected in series and parallel, forming PV strings and PV arrays. It is worth mentioning that PV arrays include design power diodes in their circuit, such as the bypass diode and blocking diodes. The bypass diode is connected in parallel to several modules in order to conduct the current in the event of some modules being damaged or shaded. The blocking diodes are interconnected in series with each string in order to protect the modules from reverse current flow [253].

4.2.1 PV Array Sizing

The quantity of modules in each string is limited to the mandatory voltage level of the array; meanwhile, the quantity of strings in the array is limited to the mandatory current rating of the array. Step by step procedures and algorithms used to accurately estimate the number of modules and strings for designing and configuring a PV system are detailed in [254]. The system's DC side operating voltage and the number of the panels are related as follows:

$$U_{imp} = \frac{U_{minmp} + U_{maxmp}}{2} \quad (4.1)$$

Where U_{minmp} is the minimum MPPT controller operating voltage, U_{maxmp} is the maximum MPPT controller operating voltage and U_{imp} is the optimum inverter MPPT controller operating voltage that represent the mean of the inverter's voltage ranges.

$$N_{modules} = \frac{U_{imp}}{V_{mp}} + 1 \quad (4.2)$$

Where $N_{modules}$ is the number of solar modules that are placed in series and V_{mp} is the PV module's maximum power voltage. The number of solar modules that are placed in series ($N_{modules}$) should be at least equal to the following:

$$(N_{modules} \times V_{mp}) \geq U_{imp} \quad (4.3)$$

The number of strings in parallel ($N_{strings}$) in the array is equal to the following:

$$N_{strings} = \frac{\text{Max DC input current of inverter}}{I_{sc} \text{ of PV module}} \quad (4.4)$$

The maximum number of strings that are necessary for preventing current limitation is estimated as:

$$(N_{strings} \times I_{sc}) < \text{Max DC input current of inverter} \quad (4.5)$$

The output of the PV system should be equal or closely related to the inverter's rated power. Moreover, in Europe the inverter's power must be in the range of the following in respect to the PV generation [254]:

$$0.8 \leq \frac{P_{inv}}{P_{PV}} \leq 1 \quad (4.6)$$

Where P_{inv} is the inverter's rated power and P_{PV} is the rated power of the PV array. It is important to ensure that the voltage does not go above the permissible value of the inverter's operating voltage during extreme conditions, both at low and high temperatures, which it may result in the destruction of the device. The following shows the method of relating the voltage at extreme low temperatures (V_{Tmin}):

$$V_{Tmin} = (V_{oc} \times N_{modules}) - \frac{(T_{low} - T_{stc}) \times TC_{Voc} \times V_{oc} \times N_{modules}}{100} \quad (4.7)$$

$$V_{Tmin} < \text{Inverter max DC voltage} \quad (4.8)$$

Where V_{oc} is open circuit voltage, T_{low} is the extreme low temperature, T_{stc} is the PV cell temperature used for standard test conditions and TC_{Voc} is the open circuit voltage temperature coefficient of the PV panel. Additionally, it is important to ensure that the voltage does not go below the minimum voltage of the inverter's MPPT controller in extremely high temperatures. The following shows the method of ensuring the voltage at an extremely high temperature (V_{Tmax}):

$$V_{Tmax} = (V_{mp} \times N_{modules}) + \frac{(T_{high} - T_{stc}) \times TC_{Vmp} \times V_{mp} \times N_{modules}}{100} \quad (4.9)$$

$$V_{Tmax} > \text{MPPT min DC voltage} \quad (4.10)$$

Where T_{high} is the extreme high temperature and TC_{Vmp} is the maximum power voltage temperature coefficient of the PV panel. The inverter configurations for the PV system should be known. The authors of [255] presented an excellent review that focuses on both the inverter's configurations and technologies used in the PV system. Figure 4.1 presents a clear representation of the possible inverter configurations for the PV system.

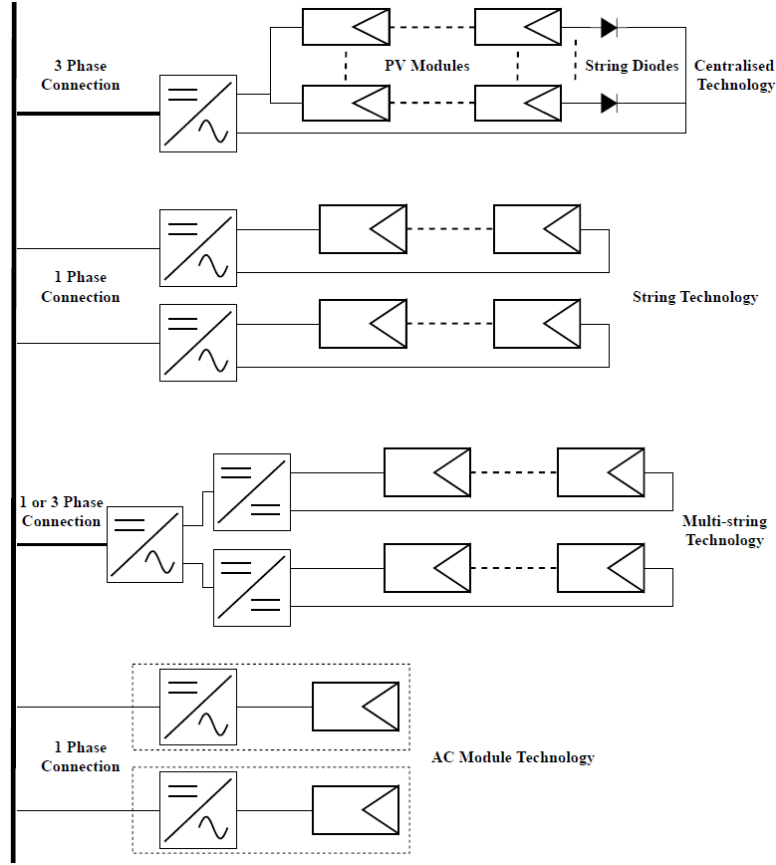


Figure 4.1. Possible inverter configurations for PV system.

4.2.2 Inverter Efficiency

The efficiency of the inverter is dependent on the DC input from the PV array, which means that the efficiency of the inverter will vary as the DC input from the PV array varies. Furthermore, the term inverter loading ratio (ILR) is used to describe the ratio of the PV array's DC power in relation to the inverter's peak AC power [256].

$$\eta_{ILR} = \frac{P_{array,dc}}{P_{inv,ac}} \times 100 \quad (4.11)$$

Where η_{ILR} is the inverter loading ratio (ILR) in percent, $P_{array,dc}$ is the PV array's DC power and $P_{inv,ac}$ is the inverter's peak AC power. To estimate the efficiency of the inverter, the η_{ILR} will be used where the $P_{array,dc}$ is increased, while keeping the $P_{inv,ac}$ constant. Additionally, the inverter's efficiency curve is essential in the estimation of the inverter's efficiency (η_{inv}). Since, the inverter's efficiency curve is rarely given by the manufacturers; the PVSYST database for inverters is used to obtain the ABB central 500 kW inverter's DC efficiency curve and the DC to AC conversion curve which can be shown in Figure 4.2. Thus, using Equation 4.11 and Figure 4.2 will enable the estimation of the efficiency of the inverter

which is shown below in Table 4.1. It is worth mentioning that the power factor of 1 is considered for the solar PV inverters.

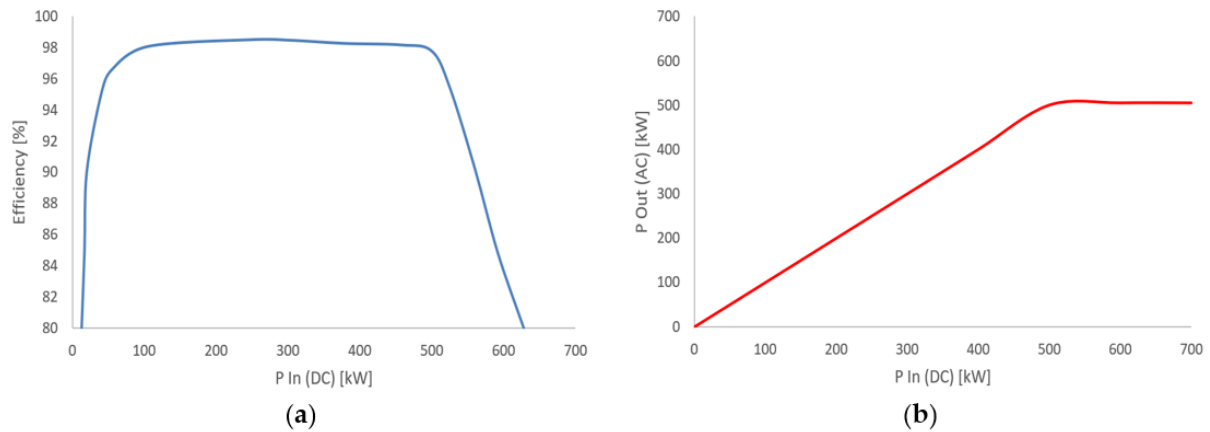


Figure 4.2. (a) ABB central 500 kW inverter DC efficiency curve; (b) ABB central 500 kW inverter DC to AC power curve.

Table 4.1. The estimated inverter efficiency.

Inverter's Loading Ratio (η_{ILR})	Inverter's Efficiency (η_{inv})
$10\% \leq \eta_{ILR} \leq 100\%$	98%
$1\% \leq \eta_{ILR} < 2\%$	85%
$2\% \leq \eta_{ILR} < 5\%$	92%
$5\% \leq \eta_{ILR} < 7\%$	95%
$7\% \leq \eta_{ILR} < 10\%$	97%
$100\% < \eta_{ILR} < 105\%$	96%
$105\% < \eta_{ILR} < 110\%$	94%
$110\% < \eta_{ILR} < 120\%$	85%
$\eta_{ILR} < 1\%$	0%
else	80%

4.2.3 Other Miscellaneous PV System Losses

The energy converted from the PV array undergoes several processes, in which the energy may be lost from the system. Figure 4.3 presents the factors that lead to the PV system's power losses [257]. The study reported in [258] showcased that the PV system performs at a 67% performance ratio due to the PV system losses and these losses account to 1% incident angle losses, 4% shading losses, 4% array temperature losses, 6% mismatch and MPPT losses, 9% inverter losses, and 9% other losses. Another study reported in [259] used the PVSYST software to simulate the performance ratio of a 20 MW grid-connected PV system, in which the performance ratio was 75% due to the PV system losses, excluding the inverter losses. Therefore, a performance ratio (P_{losses}) of 75% was set for the PV system due to PV system losses, excluding the inverter losses, since they were accounted for.

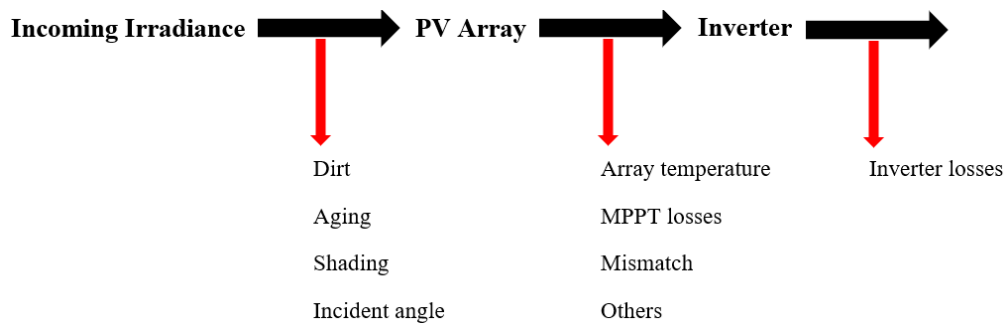


Figure 4.3. Factors in the power losses of the PV system.

4.3 PV Array Mathematical Representation

The PV system regularly over or under performs the yields that are forecasted by the performance modelling programs. This is because either barely all the loss factors are taken into account or the programs doesn't precisely model the real-world behaviour of the system or the actual irradiance varied from the predicted one [260]. Normally, the PV cell electrical characteristics can be demonstrated as the relation among cell current-voltage and the relation among cell power-voltage. Hence, there are several electric quantities that are vital to the functioning of the PV system, which are the current of the cell under short circuit conditions (I_{sc}), the voltage of the cell under open circuit conditions (V_{oc}), the maximum power voltage (V_{mp}), the maximum power current (I_{mp}) and the maximum power point (P_{mp}). The electrical characteristics of the PV cell relies mainly on the temperature of the cell and the irradiance received by the cell in which there is a substantial effect on both the cell's output power and the short circuit current. However, there is an insignificant effect on the open circuit voltage when the cell is at various levels of the irradiance with keeping the temperature constant. Meanwhile, changing the cell temperature with keeping the irradiance constant has a substantial effect on both the cell's output power and the open circuit voltage, but insignificant effect on the short-circuit current.

4.3.1 Simplified Method 1

This method is based on [250] in which it computes the PV generated power based on the solar irradiance and the efficiency of the inverters. However, the aforementioned method in [250] lacked taking into account the power loss of the PV module due to the temperature affect. Therefore, the power loss of the PV module due to the temperature affect will be added to this method in order to accurately generate the PV output power.

$$T_{cell}(t) = \text{Temperature}(t) + \frac{G(t)}{800} \times (T_{noct} - 20) \quad (4.12)$$

Where T_{cell} is the cell temperature, G is the global solar irradiance data on PV surface and T_{noct} is the nominal operating cell temperature of the PV cell.

$$P_{Tloss}(t) = (((T_{cell}(t) - T_{stc}) \times T_{coef}) \times \frac{I_{mp} \times V_{mp} \times (G(t) / G_{stc})}{100}) \quad (4.13)$$

Where P_{Tloss} is the PV module power loss due to temperature affect, T_{stc} is the cell temperature used for standard test conditions, T_{coef} is the temperature coefficient of PV module in percentage, I_{mp} is the maximum power current, V_{mp} is the maximum power voltage and G_{stc} is the global horizontal irradiance (GHI) for standard test conditions.

$$P_{module}(t) = ((I_{mp} \times V_{mp} \times \frac{G(t)}{G_{stc}}) + P_{Tloss}(t)) \quad (4.14)$$

$$P_{array}(t) = N_{modules} \times N_{strings} \times P_{module}(t) \times \eta_{inv}(t) \times P_{losses} \quad (4.15)$$

Where P_{module} is the first simplified method for calculating the power of the PV module, P_{array} is power of the PV array, $N_{modules}$ is the number of modules in series in a string, $N_{strings}$ is the number of strings in parallel in the array, η_{inv} is the inverter's efficiency and P_{losses} is the system's performance ratio due to the other miscellaneous power losses.

4.3.2 Simplified Method 2

This is another simplified method based on [251, 252] which computes the PV generated power based on the total area of the PV array (A_{array}) and the PV system conversion efficiency ($\eta_{conversion}$).

$$A_{array} = \frac{N_{modules} \times N_{strings} \times P_{nominal}}{G_{stc} \times (\eta_{module} / 100)} \quad (4.16)$$

where $N_{modules}$ is the number of modules in series in a string, $N_{strings}$ is the number of strings in parallel in the array, $P_{nominal}$ is the single PV module's nominal power in watts, G_{stc} is the global horizontal irradiance (GHI) for standard test conditions, and η_{module} is the single PV module's efficiency.

$$T_{cell}(t) = \text{Temperature (t)} + \frac{G(t)}{800} \times (T_{noct} - 20) \quad (4.17)$$

where T_{cell} is the cell temperature, G is the global solar irradiance data on PV surface, and T_{noct} is the nominal operating cell temperature of the PV cell. The PV system conversion efficiency ($\eta_{conversion}$) is estimated using the following equation:

$$\eta_{conversion}(t) = \frac{\eta_{module}}{100} \times (1 + (\frac{T_{coef}}{100} \times (T_{cell}(t) - T_{stc}))) \quad (4.18)$$

where T_{stc} is the cell temperature used for standard test conditions and T_{coef} is the temperature coefficient of the PV module in percentage. The array output power can be estimated as follows:

$$P_{array}(t) = A_{array} \times G(t) \times \eta_{conversion}(t) \times \eta_{inv}(t) \times P_{losses} \quad (4.19)$$

where P_{array} is power of the PV array, η_{inv} is the inverter's efficiency, and P_{losses} is the system's performance ratio due to the other miscellaneous power losses.

4.4 PV Array Output Verification

In this section the two simplified methods for calculating the PV array output (P_{array}) will be compared to the result of the PVSYST software at the same conditions in order to illustrate which method gives the most accurate result. The reasons for selecting the PVSYST software as the result we compare the calculations to, are being classified as a detailed physical model and the vast usage of the software among the researchers. The research conducted in [261] showed an interesting method of comparing the calculated irradiance to the measured irradiance using statistical measures of comparison in order to find the best model. Thus, a similar method is applied in this section of using those statistical measures of comparison in order to compare the two PV array (P_{array}) simplified methods with the PVSYST software output (P_{PVSYST}). The absolute percentage error (APE) and the mean absolute percentage error ($MAPE$) are the statistical measures of comparison that will be used in this section.

$$APE = \frac{|P_{PVSYST} - P_{array}|}{P_{PVSYST}} \times 100 \quad (4.20)$$

$$MAPE = \frac{1}{N} \sum_{i=1}^N APE(i) \quad (4.21)$$

Where P_{PVSYST} is the PVSYST software PV array output, P_{array} is the calculated PV array output and N is the number of cases or points examined.

The location that will be investigated is in the region of the city of Riyadh, Saudi Arabia with a latitude of 24.91° N and longitude of 46.41° E. The following are the components type used in this investigation:

- PV module: SolarWorld Pro SW 320 XL Mono.
- Inverter: ABB central inverters PVS800 500 kW.

The hourly Global Horizontal Irradiance (GHI) data and the ambient temperature data are obtained from King Abdullah City for Atomic and Renewable Energy (K.A.CARE). The collected daily average Global Horizontal Irradiance (GHI) data and the ambient temperature data are shown in Figure 4.4 and Figure 4.5, respectively. Furthermore, it will be better to showcase a clearer representation of the seasonal variation that the Global Horizontal Irradiance (GHI) data experiences throughout the year. Therefore, a specific month will be chosen to represent each season, since the Global Horizontal Irradiance (GHI) data does not change much across the months of a specific season. The chosen months for the winter, spring, summer, and autumn seasons corresponds respectively to the January, April, June and October months of the year. Figure 4.6 shows the average hourly solar irradiance of various seasons in Riyadh.

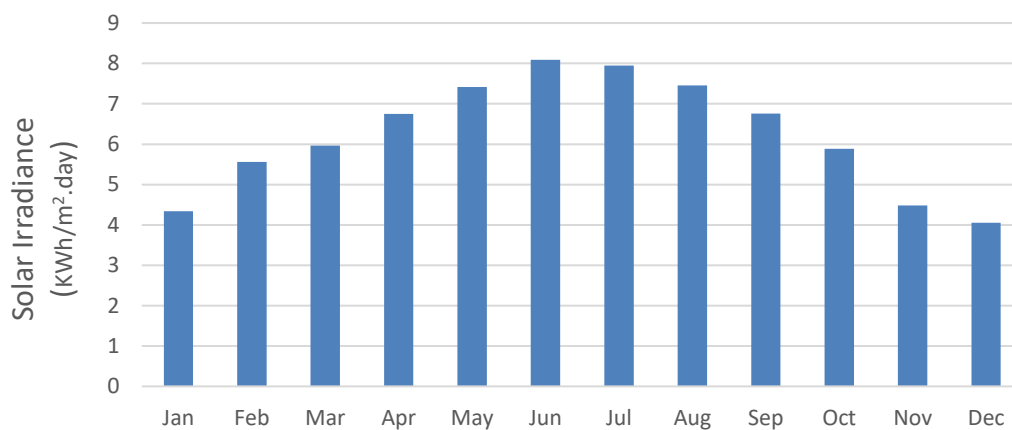


Figure 4.4. Average daily solar irradiance of each month in Riyadh 2017 [262].

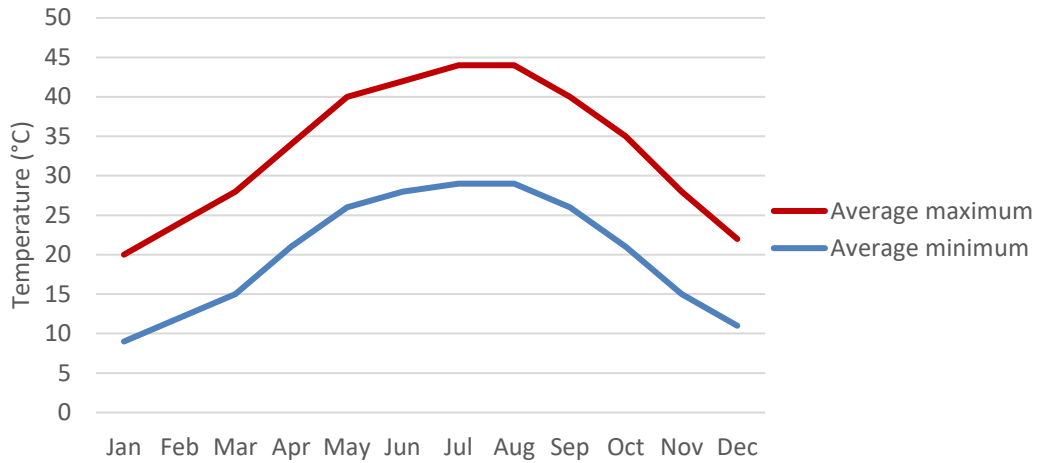


Figure 4.5. The average daily maximum and minimum temperature for each month in Riyadh 2017 [262].

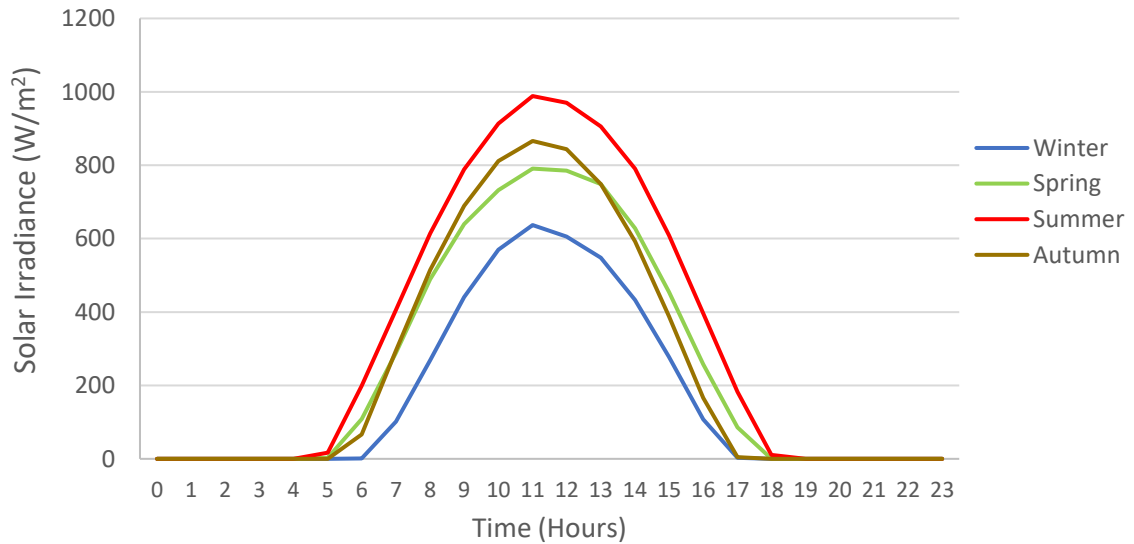


Figure 4.6. Average hourly solar irradiance of various seasons in Riyadh 2017 [262].

The minimum number of modules in series and the maximum number of strings in parallel are calculated in order to design the correct maximum PV array based on the technical specification data of the mentioned components. Therefore, from the calculations it shows that the number of modules in series in a string should equal 17, meanwhile the number of strings in parallel in an array should equal 101. Since the STC nominal power of the PV module is 320 W, the maximum array output will equal to 549 kW. Figure 4.7 shows the comparison of the PV array output (P_{array}) between the two simplified methods with the result of the PVSYST software. Table 4.2 shows the statistical measures of comparison for the PV array simplified methods.

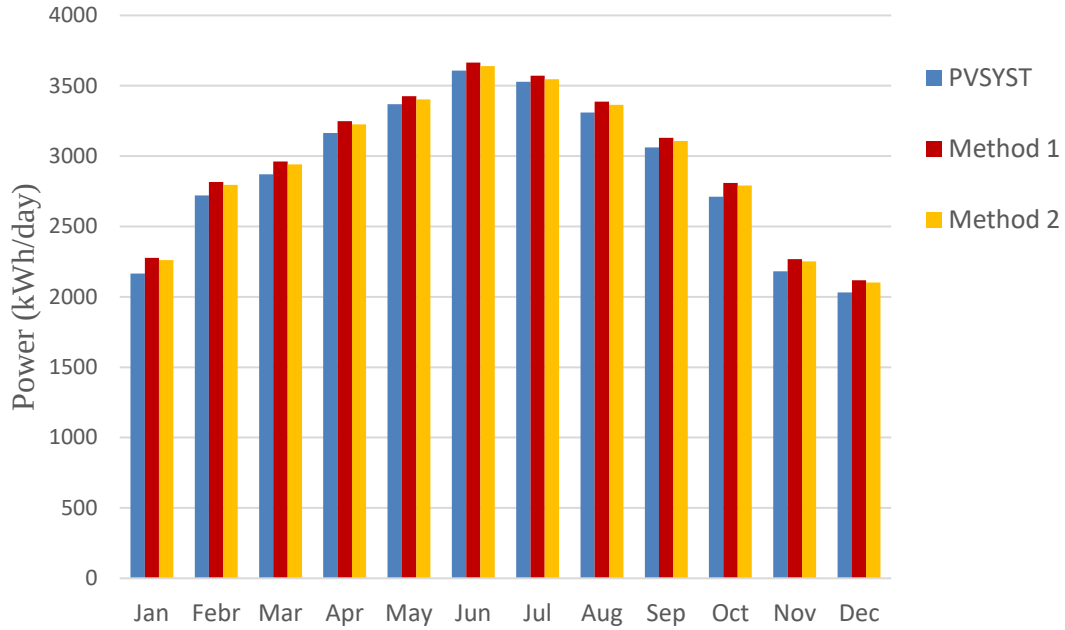


Figure 4.7. The comparison of PV array output (P_{array}) for the PV array simplified methods.

Table 4.2. The statistical measures of comparison for the PV array simplified methods.

Month	PVSYST (kWh/day)	Method 1 (kWh/day)	Method 2 (kWh/day)	APE Model 1 (%)	APE Model 2 (%)
Jan	2200	2278	2262	3.53	2.81
Feb	2768	2816	2797	1.74	1.04
Mar	2926	2962	2941	1.21	0.52
Apr	3225	3248	3226	0.73	0.03
May	3437	3426	3402	0.32	1.01
Jun	3685	3664	3639	0.57	1.26
Jul	3602	3571	3546	0.87	1.55
Aug	3375	3387	3364	0.37	0.32
Sep	3121	3130	3108	0.29	0.41
Oct	2762	2810	2791	1.74	1.03
Nov	2216	2268	2252	2.34	1.64
Dec	2061	2117	2103	2.74	2.03
				MAPE Model 1=1.37	MAPE Model 2= 1.13

According to Figure 4.7, the calculated PV array output using the two simplified mathematical models have a slightly similar result if they are compared to each other with singling out the PVSYST result. Furthermore, the calculated PV array output using the two simplified mathematical models have always shown a slightly higher value if the results are compared to the PVSYST result. The reason for those small variations might be because of the PVSYST's random generation of its own synthetic hourly data based on the GHI data we

inputted in the form of the average daily sum per month. Thus, in order to find the most accurate model the statistical measures are used for the comparison. Model 2 showed the most accurate result in comparison to the PVSYST result according to the *MAPE* on Table 4.2. The reason for choosing Model 2 as the PV array model because it showed the least amount of mean absolute error percentage. Hence, the PV array will use Model 2 in order to calculate the large-scale PV system's output at various penetration levels to the grid.

4.5 Summary

This chapter presented a detailed description of the aspects that were undertaken to design the PV array which included the sizing of the PV array, the efficiency of the inverter and the other system losses. The mandatory voltage level of the array dictates the quantity of PV modules in each string meanwhile the quantity of strings in the array is limited to the mandatory current rating of the array. The inverter loading ratio (ILR) alongside the inverter's efficiency curve were used in the estimation of the inverter's efficiency. The hourly Global Horizontal Irradiance (GHI) data and the ambient temperature data of the city of Riyadh, Saudi Arabia were obtained from King Abdullah City for Atomic and Renewable Energy (K.A.CARE). Furthermore, two simplified mathematical models for calculating the PV array were studied; in order to illustrate which simplified mathematical model gives the upmost accurate result in comparison to the PVSYST software results. The simplified mathematical model 1 computes the PV generated power based on the solar irradiance and the efficiency of the inverter with taken into account the power loss of the PV module due to the temperature affect. On the other hand, the simplified mathematical model 2 computes the PV generated power based on the total area of the PV array (A_{array}) and the PV system conversion efficiency ($\eta_{conversion}$). The simplified mathematical model 2 showed the upmost accurate result because it had the least amount of mean absolute error percentage. Therefore, the PV array will use the simplified mathematical model 2 in order to calculate the large-scale PV output at various penetration levels to the grid. After modelling and validating the PV system's design and output; analysing the net load, modelling the grid's frequency and modelling the PV curtailment algorithms will be required in order to evaluate the grid's potential hosting capacity with large-scale integrated PV plants. This will be demonstrated in detail in the next chapter.

Chapter 5 Grid's Hosting Capacity with Large-scale Integrated PV Plants

5.1 Introduction

The previous chapter already modelled and validated the PV system's design and output, and now evaluating the grid's potential hosting capacity with large-scale integrated PV plants will be required in order to assess the PV system's integration impact into the grid. Hosting capacity of a grid can be defined as the amount of new power generation that can be integrated into the grid without compromising its reliability [263]. As the electrical grid evolves to allow the integration of large volumes of renewable energy in respect to the generation mix portfolio, the system's operators must address the insurance of flexibility across all parts of the grid system. Flexibility of the grid's system can be known as the ability of the system to utilise its own resources to minimise the impact of change in the net load. Major sources of power system flexibility can be in the form of dispatchable power plants, energy storage systems, increasing forecasting accuracy, increasing the grid's strength and interconnection to neighbouring grids [264]. Therefore, the variability of the renewable energy should be assessed first in order to deduce the appropriate source of system flexibility that can be applied to minimise the impact of large-scale integration of renewable energy into the grid.

Currently, the generation mix portfolio of most traditional grids is capable of providing the source of flexibility to deal with the variability of the electricity demand. However, as the penetration level of the renewable energy to the grid increases; it changes the net load pattern in which it will become very crucial to plan for the impact of uncertainty and variability. Therefore, an assessment of the net load pattern after applying the grid's constraints in terms of the baseload constraint and ramping constraint of the conventional generation system of the grid; can provide insight on the impact of variability on the grid that accompanies the renewable energy generation of different capacities. Furthermore, the frequency stability of the grid senses the variation between the generation and demand in which can also provide insight on the impact of variability on the grid that accompanies the renewable energy generation of different capacities.

This chapter will demonstrate the methods used to calculate the grid's frequency and illustrate the PV curtailment method which is applied in order to comply with the grid's constraints. Also, a load profile analysis and a net load analysis will be presented based on both the collected 2017 global horizontal irradiance (GHI) data used to produce the PV system's output and the collected 2017 hourly load profile data of the city of Riyadh in the central region of Saudi Arabia. In addition, the grid's frequency will be analysed against the size of the PV system and the size of the PV disturbance, with or without applying the grid constraints to the PV system. Furthermore, a brief evaluation of the grid's current potential hosting capacity with large-scale PV plants at various penetration levels will be presented.

This brief evaluation will showcase the substantial affects that each grid constraint has on the performance of the PV system.

5.2 Grid Frequency Modelling

The demand for electricity continuously varies over time due to the consumer's habits and weather conditions; thus, the load of the power system is always fluctuating. It is fundamental that the generation matches these variations precisely through a function called load frequency control (LFC), in order to maintain the power system frequency [265]. At the same time, it is necessary that the generation units are economically dispatched in which these functions can be referred together as the automatic generation control (AGC) [265]. Accordingly, all modern grid systems run a software called energy management system (EMS) through its centralised control centres that with other functions monitors the generators output and frequency levels.

Frequency stability relates to the ability of the grid system to keep the frequency levels within its acceptable limits after being subjected to a disturbance which results in the mismatch between the generation and the load. Frequency stability depends on the capability of the grid system to either maintain or restore equilibrium between the generation and load [88]. Generally, frequency stability issues are linked with either the inadequate responses from components of the system or the insufficient generation reserve or the poor coordination of control and protection equipment. Furthermore, regulation is the practice used to ensure power balance and can be sensed by the variations in the system's frequency. If the load exceeds the generation input, it will result in the energy exiting the system's overtime leading to the extraction of energy from the kinetic energy of the generators rotating masses. Thus, the rotating masses of the generators will rotate slowly leading to the decrease of the system's frequency. On the other hand, if the generation exceeds the load, it will result in the increase of the system's frequency.

The governor of the generator is responsible of detecting the speed of deviations in which it adjusts the power input via the opening and closure of the valves as appropriately. The governor will alter the input power in proportion to the speed deviation. The drop or speed regulation (R) is measured in Hz/MW or as a percentage of the unit's rated capacity. In practice, typical drops are in the range of 5 to 10% in which if no further action is taken it will result in the system operating at this new frequency [266]. The research in [266], illustrates the method of calculating the grid's frequency in which the grid's frequency can be expressed using Equations 5.1-5.3.

$$R = \text{Typical drop} \times \left(\frac{\text{Nominal frequency}}{\text{Generator capacity in MW}} \right) \quad (5.1)$$

$$\Delta f = (-R) \times \Delta P \quad (5.2)$$

$$\text{Frequency} = \text{Nominal frequency} + \Delta f \quad (5.3)$$

Where R is the drop or speed regulation, Δf is the frequency deviation due to change in load and ΔP is the power change or ramp at a given period of time.

5.3 PV Curtailment Modelling

The grid's connection and dispatching regulations for integrated renewable energy in most countries, depending on their Power Purchase Agreement (PPA), is to oblige the grid operators to take in all the electricity produced by the renewables. However, the curtailment regulations or rules for the renewables needs a clearer addressing in the PPA. Furthermore, in countries with high penetration levels of renewable energy, such as Germany, curtailment might be due to the volume of that intermittent energy ;if not, it can be expected as a routine operation for the grid in order to balance the load [111]. Additionally, curtailment of renewable energy can be expected to be high in emerging economies because of the transmission network limitations. It is a common practice for the PPAs to allow up to a certain level or threshold of curtailment, for which the solar PV plant owner does not get compensated for reducing their output. However, above that threshold, the PPA might include the terms of payment in which the PV plant owner will be compensated for that curtailment; but in this case, clean energy is wasted and not being fully utilised. If the supply of the renewables and demand moved in the opposite directions it will result in the following:

- Over-generation phenomena: in which relates to the instance when the supply of the renewable exceeds the required demand with consideration of the grid's baseload constraint in terms of the minimum operational output that the conventional generation system is capable of.
- Loss of load phenomena: this relates to the instance when the demand is not met by the available supply due to exceeding the ramping capability of the grid's conventional generation system, as a result of the increase share of the renewable in the grid's generation mix, which affects the grid's frequency stability.

5.3.1 PV Curtailment for Baseload Constraint

The PV over-generation phenomena can be explained as the instant of time when the PV system's output exceeds the required demand in which can be represented as when the net load falls below the baseload point. A new variable defined as the difference between the load profile and the baseload point (DLB) will be introduced to aid the identification of a PV over-generation event caused by the grid's baseload constraint. Equation 5.4 shows the method of calculating the DLB variable.

$$DLB(t) = \text{Load profile}(t) - \text{Baseload point} \quad (5.4)$$

The baseload constraint implies that the grid's operational output of the conventional generation system cannot be furtherly lowered, and it will be difficult switching them completely off and on. Therefore, PV curtailment, in this case, is the only method viable to deal with these PV over-generation events if there are no other sources of grid flexibility such

as energy storage. An excellent illustration of the PV over-generation phenomena due to the grid's baseload constraint is shown in Figure 5.1.

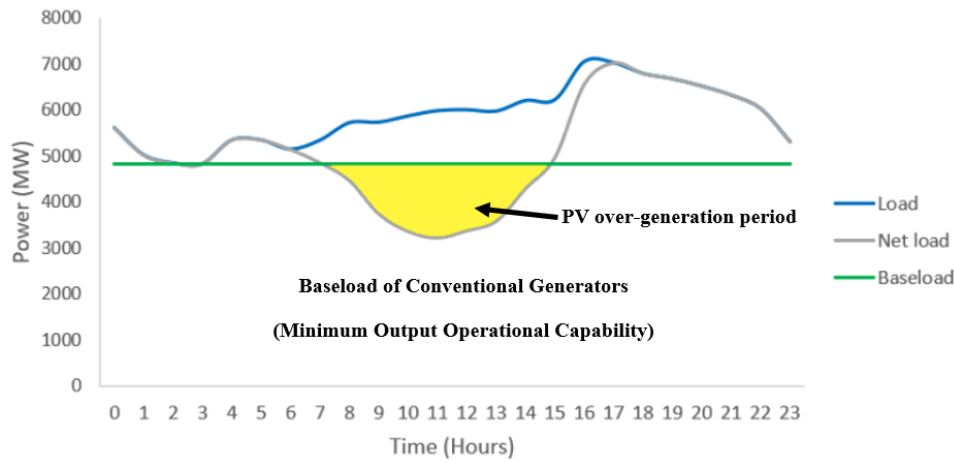


Figure 5.1. PV over-generation phenomena due to the grid's baseload constraint. Equation 5.5 illustrates the PV curtailment method applied for baseload constraint in which it will curtail the PV system's output to equate the value of the *DLB* when the PV system's output is higher than the *DLB* value.

$$PV_{out}(t) = DLB(t) \quad , \text{if } PV_{out}(t) > DLB(t) \quad (5.5)$$

The process of identifying and dealing with the PV over-generation phenomena through PV curtailment can be shown in Figure 5.2 and this can be expressed into the following steps:

1. Sizing and calculating the PV system's output based on the desired PV penetration level to the grid.
2. Applying the grid's baseload constraint and calculating the *DLB* value in order to identify the PV over-generation event.
3. Comparing the PV system's output to the calculated *DLB* value in which if there is a PV over-generation event identified; the PV system's output will be curtailed to a value equal to the *DLB* value.
4. Injecting the PV system's output to the grid if no PV over-generation event is identified.

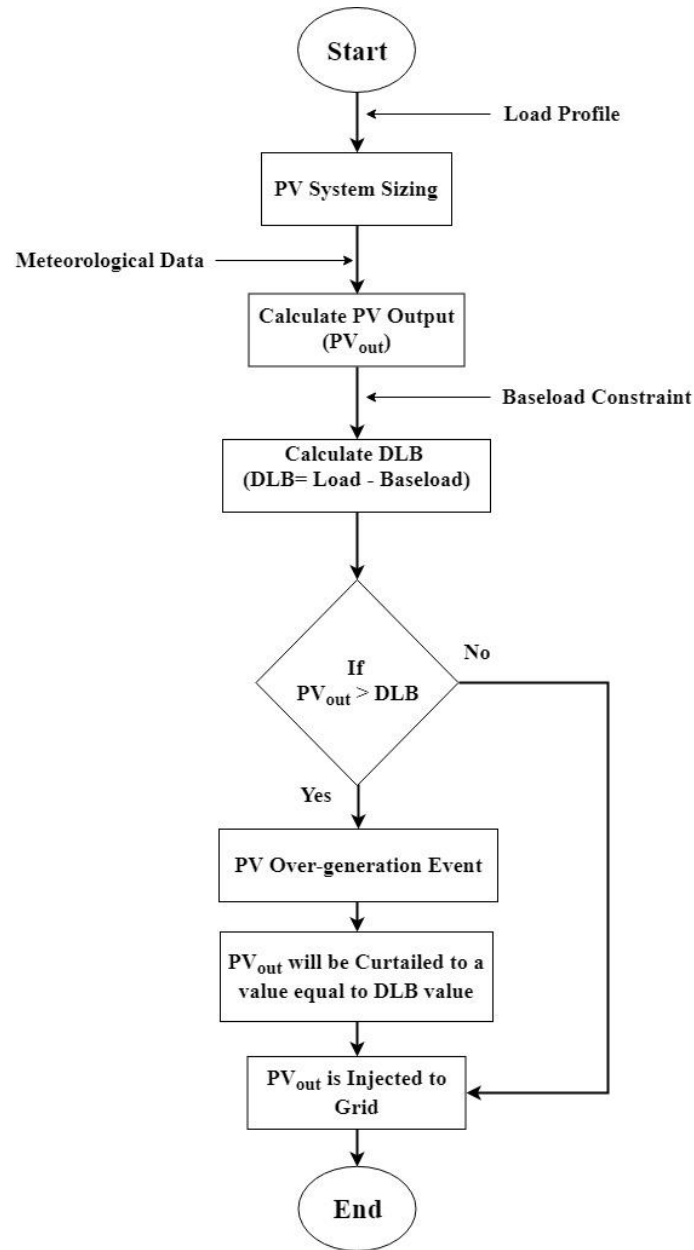


Figure 5.2. Process of identifying and dealing with the PV over-generation phenomena through PV curtailment.

5.3.2 PV Curtailment for Ramping Constraint

A ramp event can be described as the interval's deviation between the start and end point being larger than the set threshold value in which it is been suggested in [267]; to neglect ramping events occurring in the midpoint of an interval. Generally, for the power system operators, the down ramping events of the renewables are much more challenging than the up ramping events of the renewables. This is due to the requirement in the down ramping events of filling the shortage of supply by means of increasing other generation capacities rather than being managed by means of generation scheduling and renewable curtailment [268]. Therefore, at the current time, the main source of the grid's operational flexibility comes

from the cycling of the conventional generation system. Cycling is a term defined as the alteration of the conventional power plants output by means of starting up, turning off, or ramping [269]. The conventional generation operates between a minimum limit and a maximum limit, and this is restricted by the ramping limits as shown in Table 5.1. There is another dynamic constraint on the conventional generation operation that is known as the minimum up and down times, which will be ignored in this analysis.

Table 5.1. Flexibility characteristics of various power generation technologies [270].

Generation Technology	Minimum Output (%full load)	Ramping (%full load /min)
Nuclear	50	2
Coal	30	6
Lignite	50	4
Steam (Gas, Oil)	30	7
Simple Cycle Gas Turbine	15	20
Combined Cycle Gas Turbine	20	8

Gas turbines provides a better or faster flexibility option than the other generation types, but it comes with a costly cycling effect in which increasing the PV system share will increase the conventional generation cycling. However, since we are dealing with grid connected synchronous generation units; the ramping constraint can be deduced by the fast-acting speed governor system of the generation unit in which the normal set point of the governor drop setting is generally set at 5%. The ramping constraint that can be applied to the grid's conventional generation system can be deduced if we find the amount of power change or ramp that can cause a frequency deviation of ± 0.51 which is not within the permissible limit. Equation 5.6 shows the method of deducing the grid's ramping constraint (*GRC*) based on the frequency stability deviation method where *R* is the drop or speed regulation. However, since we are trying to minimise the impact of integrating large-scale PV into the grid; the *GRC* will be based on the maximum power ramp of the original load profile without the inclusion of the PV system. In doing so, will give a more realistic assessment of the current ramping requirement of the grid's conventional generation system.

$$\text{Grid's Ramping Constraint}(GRC) = \frac{\pm 0.51}{-R} = \pm \text{MW} \quad (5.6)$$

The increase share of the PV system will tend to increase towards these conventional generation technical cycling data. In particular, the ramping constraint that exceeds the ramping constraint threshold leads to the loss of the load phenomena [271]. The Loss of Load Probability (LOLP) is defined as the probability of the available generation capacity not being able to meet the load during a given period [272]. Furthermore, the loss of load event (LLE) in this research can be defined as when the absolute net load power ramp ($|NL_{PR}|$) exceeds the grid's ramping constraint (*GRC*) of its conventional generation system. In doing

so, a more realistic assessment of the current ramping requirement of the grid's conventional generation system is given.

The occurrence of the loss of load event (LLE) will result in the disconnection of the conventional generation system from the grid. Thus, these loss of load events must be dealt with in order to ensure the stability of the grid system. The ramping constraint implies that the grid's operational output of the conventional generation system cannot be furtherly ramped up or down in order to follow the change in the net load. Therefore, PV curtailment in this case is the only method viable to deal with these loss of load events if there are not any other sources of grid flexibility such as energy storage. *RC* and *DPRC* are the two new variables introduced to aid the PV curtailment method if there is an expected loss of load event due to the large share of PV power. The *RC* can be defined as the difference between the absolute net load's power ramp and the grid's ramping constraint. Meanwhile, the *DPRC* can be defined as the difference between the absolute PV system's power ramp and the absolute *RC*. Equations 5.7-5.8 shows the method of calculating the *RC* and *DPRC* variables where PV_{PR} is the PV system's power ramp and NL_{PR} is the net load power ramp.

$$RC(t) = |NL_{PR}(t)| - GRC \quad (5.7)$$

$$DPRC(t) = |PV_{PR}(t)| - |RC(t)| \quad (5.8)$$

The PV curtailment method applied will differ based on the period of the day since the PV system's output will increase sharply during the morning period and decrease sharply during the afternoon period of the day. Therefore, the PV curtailment method will be divided into the morning period method and the afternoon period method. In the morning period, the earliest loss of load event will be identified first, and the PV curtailment method will be applied on it before advancing forward in time if there are other loss of load events in the morning period until they are dealt with. In the afternoon period, the latest loss of load event will be identified first, and the PV curtailment method will be applied on it before advancing backward in time if there are other loss of load events in the afternoon period until they are dealt with. Equation 5.9 presents the PV curtailment method depending on the period of the day where the loss of load event is located.

$$\begin{cases} PV_{Out}(t) = PV_{Out}(t-1) + DPRC(t) & , \text{Morning Period} \\ PV_{Out}(t-1) = PV_{Out}(t) + DPRC(t) & , \text{Afternoon Period} \end{cases} \quad (5.9)$$

The process of identifying and managing the loss of load phenomena through PV curtailment can be shown in Figure 5.3 and this can be expressed into the following steps:

1. Sizing and calculating the PV system's output based on the desired PV penetration level to the grid.
2. Analysing the net load by calculating both the net load power ramp (NL_{PR}) and the power ramp of the PV system's output (PV_{PR}).
3. Applying the grid's ramping constraint (GRC) and comparing it to the net load power ramp (NL_{PR}) in order to identify the loss of load event.

4. Calculating both the RC and $DPRC$ values in order to apply the PV curtailment method.
5. Applying the PV curtailment method based on the period of the day where the loss of load event is located.
6. Injecting the PV system's output to the grid if no loss of load event is identified.

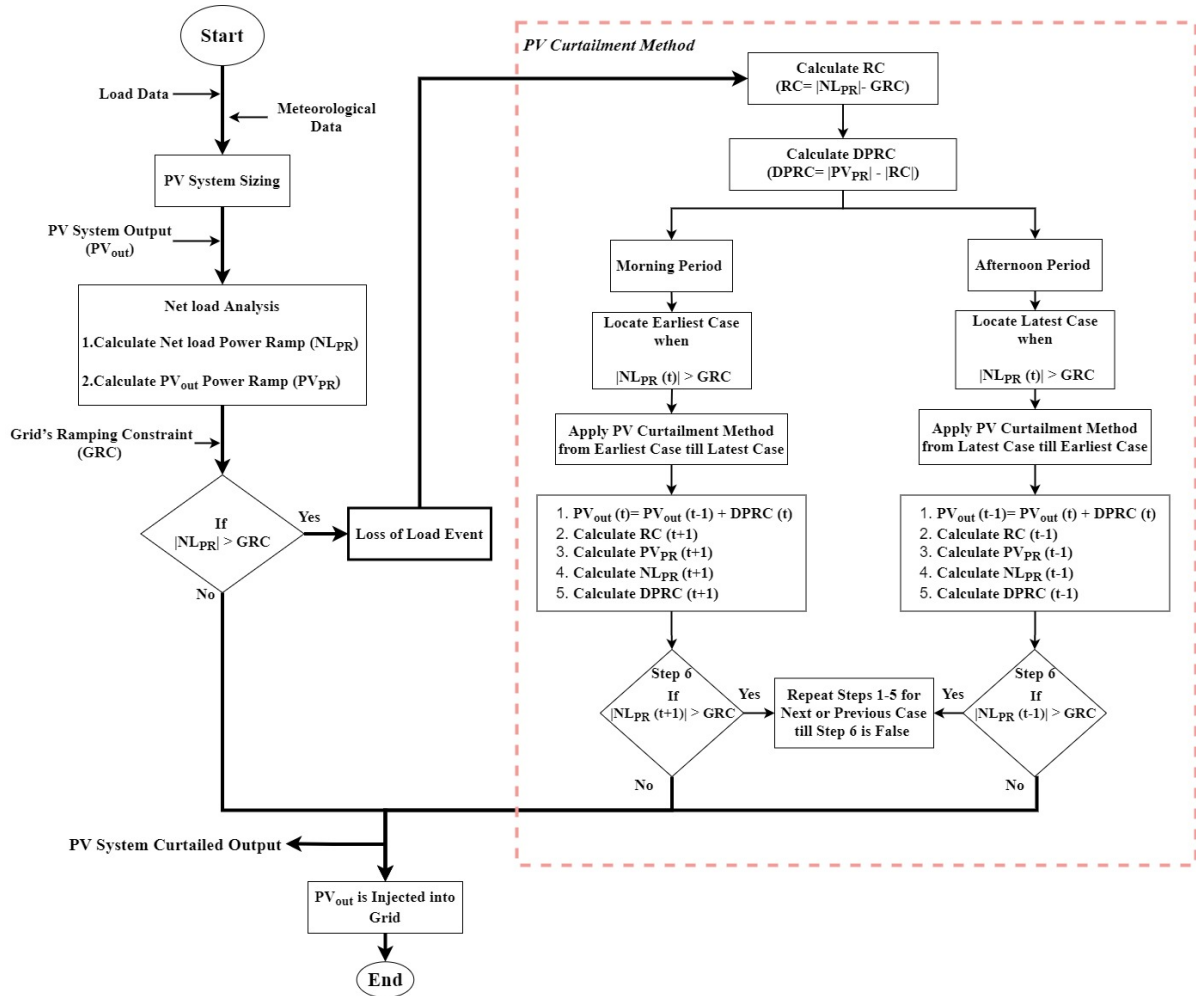


Figure 5.3. Process of identifying and managing the loss of load phenomena through PV curtailment.

5.4 Load Profile Analysis

The case study location that will be investigated is in the region of the city of Riyadh, Saudi Arabia, with a latitude of 24.91° N and longitude of 46.41° E. The chosen location is on the eastern part of the Najd plateau, which is characterized by an arid environment with low annual rainfall and high temperature variability. Firstly, in order to estimate the desired penetration level of the PV system; the load profile must be analysed. Therefore, an hourly load profile of the city of Riyadh have been collected for the whole 2017 year from the Saudi Electricity Company (SEC) and is presented in Figure 5.4. Furthermore, the collected load profile has been organised into the average hourly daily load profile for each month in the year and is presented in Figure 5.5. In doing so will show a clearer representation of the pattern for the load profile and show the seasonal variation that the load profile experiences throughout the year. The average representation might not give an accurate result, because the peak load will be slightly higher than the value used in the average data. However, since the aim here is to show a clearer representation of the pattern for the load profile and show the seasonal variation that the load profile experiences throughout the year; the average hourly daily load profile for each month is being used.

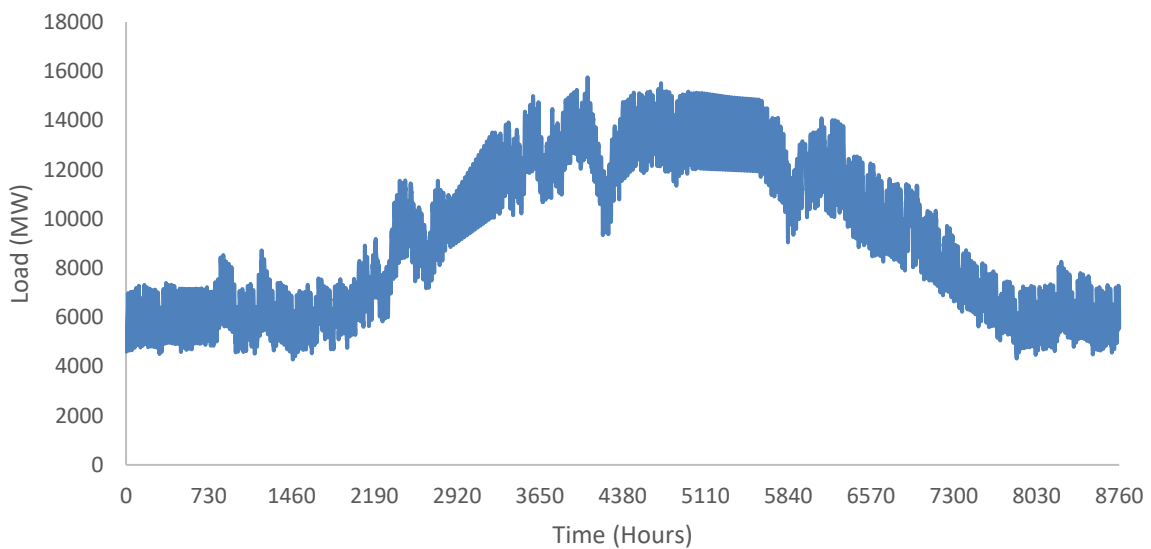


Figure 5.4. The collected 2017 hourly load profile of the city of Riyadh [273].

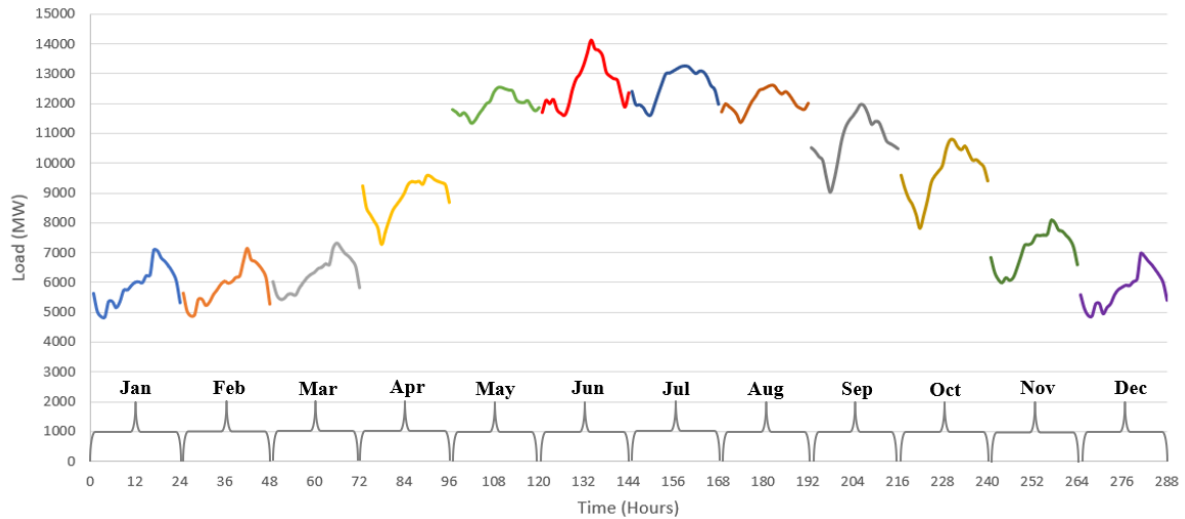


Figure 5.5. The 2017 average hourly daily load profile of each month for city of Riyadh [273].

The highest load profile point (peak load) corresponds to 15.753 GW, while the lowest load profile point (baseload) corresponds to 4.282 GW according to Figure 5.4. The identified peak load will aid in the estimation of the desired penetration level of the PV system, meanwhile the identified baseload will aid in setting the constraint that the conventional generation system of the grid cannot operate below that level. The pattern of the load profile for each month according to Figure 5.5; shows the seasonal variations that the load experiences throughout the year. The reason for the high load profile can be because of the geographical location of the Kingdom of Saudi Arabia which translates to the weather in which the temperature is mostly high throughout the year. This leads to the excess usage of air conditioning units, resulting in the sharp increase of the load during the summertime. There are other factors that contribute to the increase in the load profile that relates to the ongoing economic and population growth.

5.5 Net Load Profile Analysis

Net load can be defined as the load profile minus the renewable energy generated and, in this case, it accounts for the PV system's output. The net load is a useful metric in order to analyse the impact of integrating large-scale renewable energy into the grid, because it gives an insight to the ramping requirements to accommodate both the variability and the availability of the renewable. Also, it can aid the calculations of the measures used to minimise the impact on the grid such as the curtailment of the renewable. Therefore, this part will showcase the net load analysis to see the effect of increasing the PV system's penetration level up to 50% of the peak load of the year. The PV system model developed in chapter 4 will be used in this part. Furthermore, an assumption is made that the PV system's output has the priority over the output of the grid's conventional generation system in the participation of meeting the load. This means that the minimum operational output of the conventional generation system, ramping constraint and transmission constraints are ignored in this case.

The PV system's capacities used in this part based on the desired penetration levels to the peak load is shown in Table 5.2.

Table 5.2. PV system capacity based on the desired penetration level to the peak load.

Peak Load (GW)	PV Penetration Level	Number of Arrays (At Ideal Conditions 1 Array Equals 500 kW)	PV System Capacity (GW)
15.753	10%	3150	1.5753
15.753	20%	6301	3.1506
15.753	30%	9452	4.7259
15.753	40%	12,602	6.3012
15.753	50%	15,753	7.8765

5.5.1 Net Load Pattern

The grid operators are facing an increasingly various net load shape due to the increase share or capacity of intermittent renewable energy. Usually, in countries with a hot climate, the power generated from the PV units coincides with the electricity demand in the summer period. This is when there is an increase need for cooling that happens in the early afternoon period of the day in which corresponds to the peak generation period of the PV units, leading to the reduction of the peak load. On the other hand, in the winter months where there is a lower cooling demand leading to a different net load shape as the peak load tends to be much lower. The occurrence of the peak demand in the winter months will be in the early evening period when people tend to come home from work. This does not correspond to the peak generation time of the PV units, leading to the need for a steeper net load ramping to meet the peak load in the early evening period. Therefore, in this part, the shape of the hourly net load in Riyadh, 2017, during the winter (January), spring (April), summer (June), and autumn (October) months will be analysed to see the effect of increasing the PV system penetration level by up to 50% of the peak load, which is shown in Figures 5.6–5.9. The reason for choosing the aforementioned months in the analysis is because they represent different load pattern due to the seasonal load variations in the year.

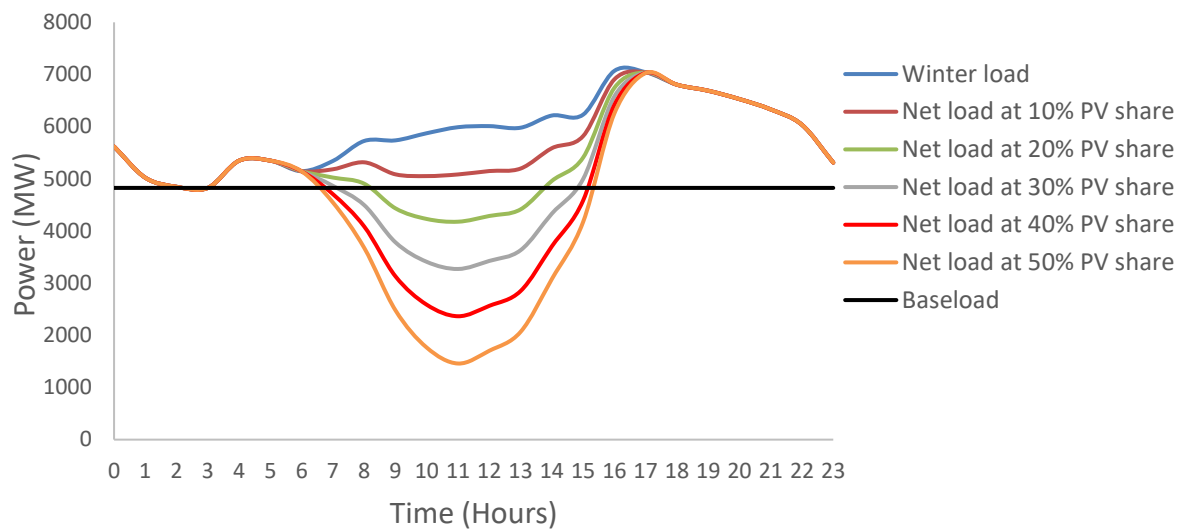


Figure 5.6. The impact of the PV penetration level on the grid in terms of net load during the winter season.

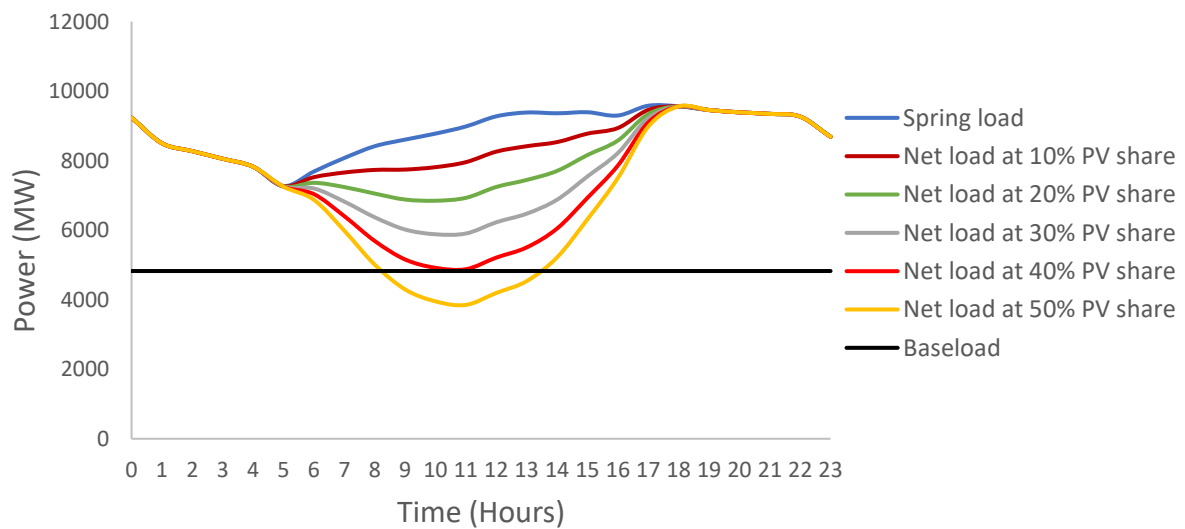


Figure 5.7. The impact of the PV penetration level on the grid in terms of net load during the spring season.

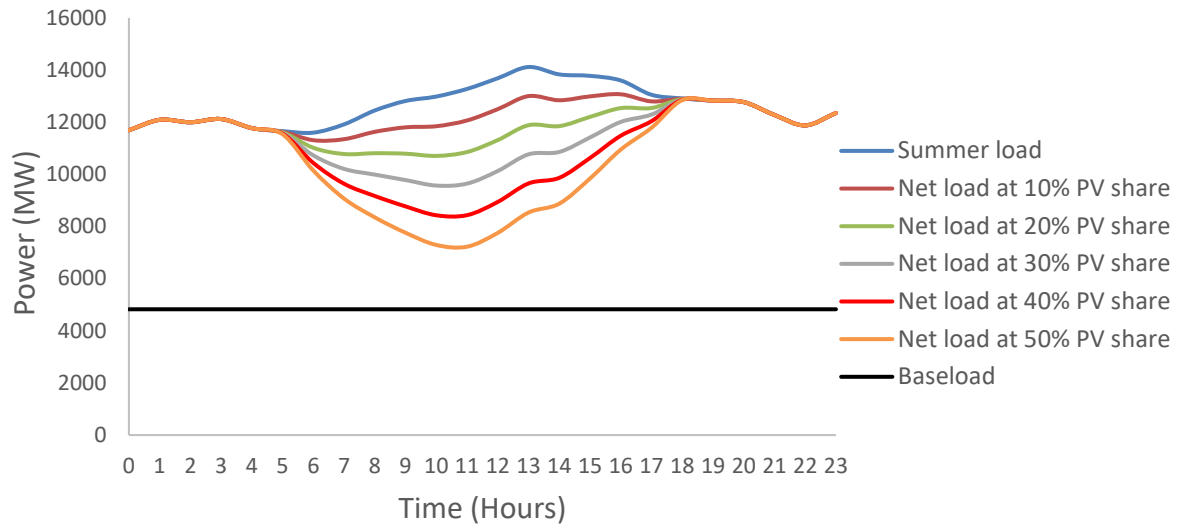


Figure 5.8. The impact of the PV penetration level on the grid in terms of net load during the summer season.

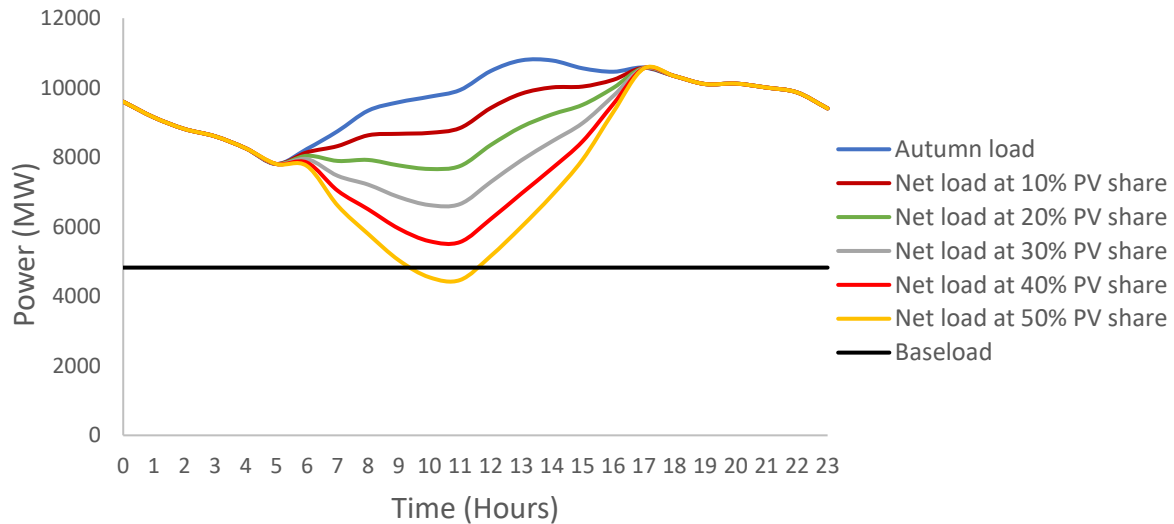


Figure 5.9. The impact of the PV penetration level on the grid in terms of net load during the autumn season.

According to Figure 5.6, the well-known California Independent System Operator (CAISO) duck curve [274] is visible in the winter load when the PV system's penetration level is 20% and above. The PV over-generation phenomena can be observed in the case when the net load falls below the baseload point set in which will enable us to determine the applicable penetration level of the PV system that can be integrated to the grid without causing stability issues. Therefore, based on Figure 5.6 the only case when the PV penetration level does not cause over-generation is at 10%. Meanwhile, the penetration levels from 20% to 50% needs a flexibility measure from the grid in order to avoid the PV over-generation phenomena.

Furthermore, it is worth mentioning that the net load pattern in the spring and autumn seasons is slightly similar, according to Figure 5.7 and Figure 5.9. This can be due to having a slightly similar temperature. The only case when the PV penetration level did lead to over-generation is at 50%. On the other hand, during the summer season, when the load is much higher than the winter season, the PV penetration levels did not cause any over-generation phenomena, which can be observed in Figure 5.8. It is worth mentioning that the reason for the different net load pattern in terms of the over-generation phenomena is that the size of the PV system compared to the load profile in winter is much smaller when compared to the summer load profile. This is because the PV system's penetration level is dependent on the peak load point which is located in the summer season.

5.5.2 Net Load Ramping

Ramping events is considered as a major concern to the grid's system operators due to the increase share of the variable renewable energy [275]. Beyond the diurnal variability of solar power, ramping events for solar power are mainly due to passing clouds in which the response of the inverter is to quickly ramp down the PV power. Meanwhile, load ramp events are mainly due to the weather conditions and the behavior of the consumers. Thus, with the increase share of the renewable energy and in this case PV; it becomes crucial to assess the net load ramping features even though the electrical load is relatively more stable than the renewable. Furthermore, under some circumstances of up ramping the grid's conventional generation system with down ramping the renewable and vice versa, can result in a severe net load ramp events that is beyond the grid's technical capability. Therefore, evaluating and comparing the ramping requirements in both the load and net load with various PV penetration levels can bring a better understanding to the quantified impacts of integrating large-scale PV to the grid's ramping requirements.

In this part, the most important factor assessed is the power ramps at different time horizons, rather than the power production profile. A power ramp (ΔP) can be defined as the change of power in a specific time interval [276]. Equation 5.10 shows the method of calculating the power ramp (ΔP) where $P(t)$ is the power produced at time (t).

$$\Delta P(t) = P(t) - P(t - 1) \quad (5.10)$$

The net load ramps are chosen as a metric to assess the ramping requirements of the grid system in which every alteration in the net load must be maintained by the grid's conventional generation system in order to ensure the stability of the grid's system. The ramping requirements of the net load can be clearly shown or represented by the ramp duration curve in which aids the assessment of the ramping flexibility needed [277]. Therefore, the power ramps of the net load at different PV penetrations levels to the grid will be compared to the power ramps of the original load. This will be represented in a duration curve in terms of the ramping requirements per hour which is shown in Figure 5.10. The duration curve in Figure 5.10, can be furtherly analysed to showcase the ramping requirements for the grid's conventional generation system at various PV penetration levels

to the grid. Table 5.3 showcases the ramping requirements for the grid's conventional generation system at various PV penetration levels to the grid in order to fully eliminate the curtailment of the PV energy due to the grid's ramping constraint.

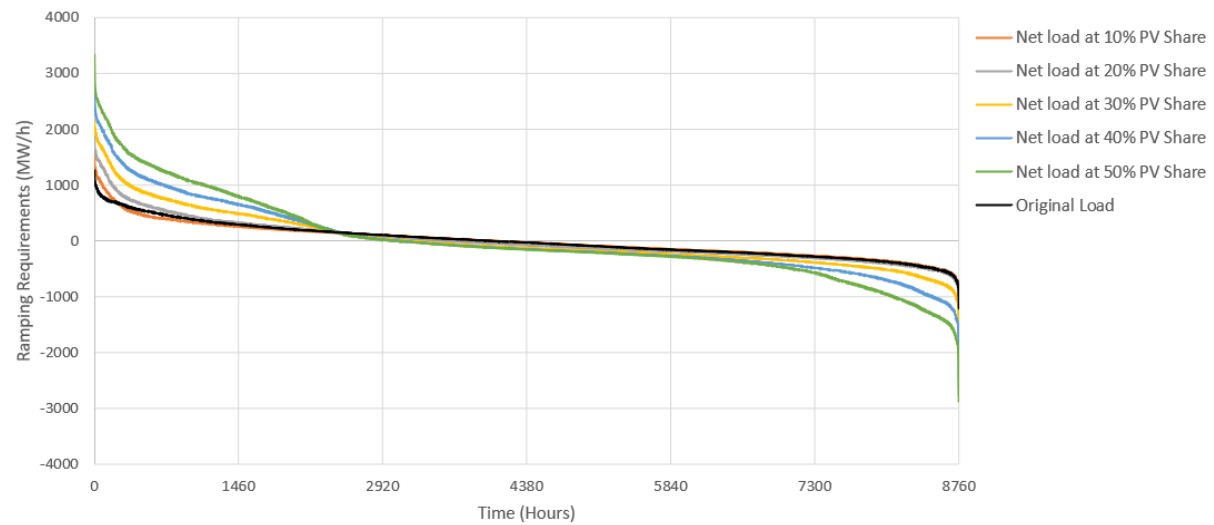


Figure 5.10. Duration curve of the net load ramping requirements at various PV penetration levels to the grid in Riyadh 2017.

Table 5.3. Ramping requirements for the grid's conventional generation system at various PV penetration levels to the grid in Riyadh 2017.

Ramping Requirements (MW/h)	PV System Penetration Level (%)					
	0%	10%	20%	30%	40%	50%
Up Ramping Requirements	1268	1561	1854	2148	2685	3338
Down Ramping Requirements	1214	1214	1365	2069	2773	2877

According to Figure 5.10, the period from 1 till 1460 (hours) coincides with the up ramping of the grid's conventional generation system due to the down ramping of the PV system. Generally, most of this period coincides with the afternoon period of the day. Meanwhile, the period from 7300 till 8760 (hours) coincides with the down ramping of the grid's conventional generation system due to the up ramping of the PV system. Generally, most of that period coincides with the morning period of the day. It can be deduced that, as the penetration level of the PV system increases; the ramping requirement of the grid's conventional generation system will increase significantly, which can be clearly shown in Table 5.3. For example, this can be demonstrated when comparing the original load with the net load at 50% PV share, in which the magnitude of the ramping requirement will increase

considerably from 1268 to 3338 MW/h. This means that the system operators of the grid will need more than double of their current ramping magnitude to deal with that PV system share. Furthermore, the up ramping of the grid's conventional generation system is generally higher in the winter months if compared to the summer months. The reason for this can be due to the peak load point of the winter months, occurring in the early evening period, which does not correspond to the peak generation of the PV system.

5.6 Frequency Stability Analysis with Large-scale Integrated PV Plants

This section will analyse the grid's frequency against the size of the PV system and the size of the PV disturbance, with or without applying the grid constraints to the PV system. According to [14], the available generation capacity in the central region of the Saudi grid is at a rated capacity of 16 GW, which will be used throughout this analysis. The city of Riyadh is part of the central region of the grid system, the generation type supplying the load is mainly thermal and, specifically, a gas turbine, with a smaller share of combined cycle [278]. According to the grid code of Saudi Arabia [279], the following points will be applied to the conventional generation system of the grid in order to determine the frequency change:

- The nominal frequency is at 60 Hz.
- All generating units must be capable of supplying their rated active output power within the system frequency range of 59.5 to 60.5 at the connection point.
- Each synchronous generation unit is fitted with a fast-acting speed governor system to aid with the control of the power and frequency.
- The governor drop setting shall have an adjustable value within 2% to 8% to regulate the frequency of the system. However, the normal set point of governor drop setting is generally set at 5% which will be used throughout.

From the earlier mentioned points of the grid code, it can be deduced that when the frequency change or deviation is higher than ± 0.5 Hz it causes the conventional generation system to be disconnected from the grid; thus, the loss of load phenomena occurs. For this scenario, the drop or speed regulation (R) at the normal set point of the governor droop setting (5%) is equalled to 1.875×10^{-4} Hz/MW. The overall assessment of the grid's frequency stability in terms of the highest and lowest frequency due to integrating the PV system without applying the grid constraints on the PV system, is shown in Table 5.4.

Table 5.4. Overall assessment of the grid's frequency stability due to integrating the PV system without applying the grid constraints on the PV system.

PV System Penetration		
Level (%)	Highest Frequency (Hz)	Lowest Frequency (Hz)
0	60.21	59.78
10	60.23	59.71
20	60.26	59.65
30	60.39	59.60
40	60.52	59.50
50	60.54	59.37

As the PV system's penetration level to the grid increases; the frequency stability deviates more, according to Table 5.4. This could be a result of the higher power ramps that accompanied the increase in the PV system's penetration level to the grid. It is worth mentioning that the grid's frequency experienced instability throughout the year when the PV system's penetration level is at 40% or higher. This is due to having a frequency deviation higher than the ± 0.5 Hz allowable range. Furthermore, a clearer representation of the grid's frequency deviation, due to being subjected to the inclusion of PV system with different penetration levels, could be showcased via a single day analysis, which is shown in Figure 5.11.

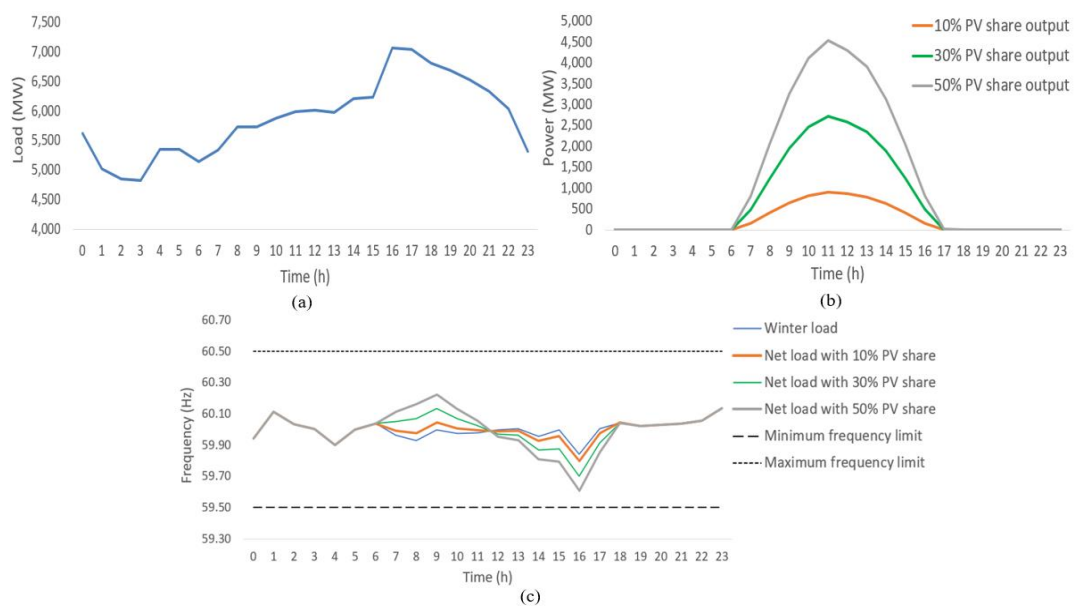


Figure 5.11. (a) January's average hourly daily load profile of Riyadh 2017; (b) January's PV output at various share capacities in Riyadh 2017; (c) grid frequency representation of the January load of Riyadh 2017 with the inclusion of the PV system at various capacities without grid constraints.

Figure 5.11 shows that the frequency stability is dependent on the net load's pattern in terms of the netload power ramp, the size of the PV system and the PV system's output in terms of the magnitude of the solar irradiance. The sharp decrease in the frequency is due to the sharp increase of the load in the afternoon period, which coincided with the depletion of the PV system's power. However, when the grid constraints were applied in this case, the frequency changed for the better, which is clearly shown in Figure 5.12. This positive affect on the frequency stability was due to the reduced participation of the reduced PV system.

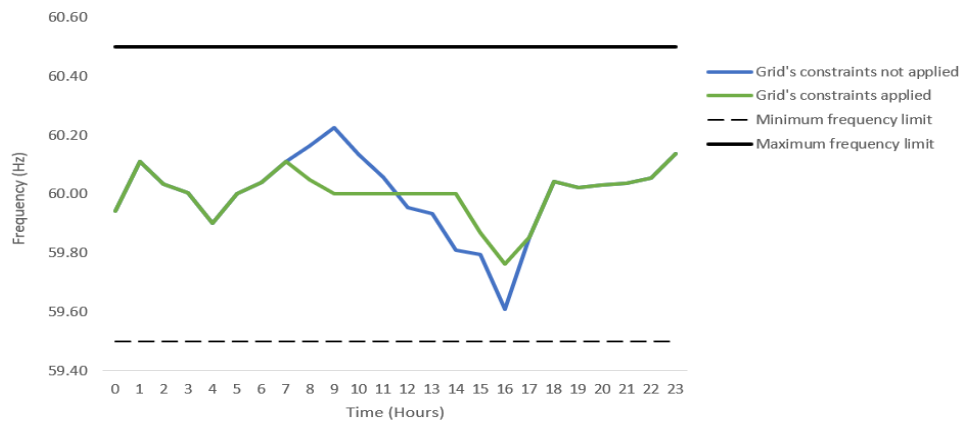


Figure 5.12. Grid constraints effect on the grid frequency representation of the January load of Riyadh 2017 with the inclusion of the PV system at 50% share.

The cause of the increase in the frequency is due to the increase in the negative net load power ramp, which could be a result of lowering the output of the conventional generation system. On the other hand, the cause of decrease in the frequency is due to the increase in the positive netload power ramp, which could be a result of increasing the output of the conventional generation system. The increase share of the PV output and the following load pattern are the reasons for alternating the output of the conventional generation system. So far, it is assumed that there is no disturbance occurring on the PV system. It is advised to investigate the effect of the size of the disturbance on the PV system with various PV capacities share, in which the frequency stability will be monitored at that disturbance instant. Thus, in this case, an assumption is made that a disturbance to the PV system with various sizes occurred at 12:00; therefore, the frequency stability was monitored at that instant of time, and this is presented in Figure 5.13.

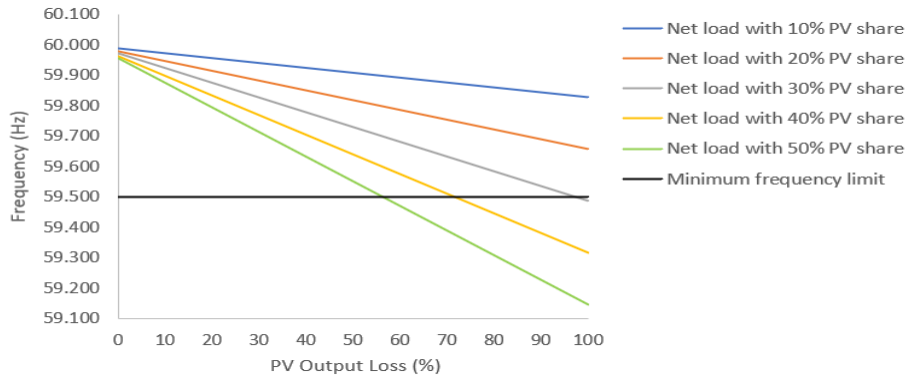


Figure 5.13. Grid frequency representation of the effect of the size of PV disturbance on the January load of Riyadh 2017 at 12:00, with the inclusion of the PV system at various capacities without grid constraint.

Figure 5.13 shows that the frequency is stable during the winter (January) load at all various PV disturbance sizes when the PV share capacity was lower than 30%. Meanwhile, the frequency withstood a PV disturbance of a size no more than 50% when the goal is to increase the share to 50% of the PV capacity to the winter load. However, if the grid constraints were applied in this case the frequency would change for the better because the participation of the PV system would be reduced.

5.7 Evaluation of Grid's Potential Hosting Capacity with Large-scale Integrated PV Plants

This part presents a brief evaluation of the grid's current potential hosting capacity with large-scale PV plants at various penetration levels to the grid. This brief evaluation will focus on showing the substantial affects that each grid constraint has on the performance of the PV system in terms of PV curtailment. The location of where this evaluation will be based at is in the capital city of Riyadh in the central region of Saudi Arabia in which both the collected 2017 global solar irradiance data and 2017 hourly load profile is used as the input of the model.

PV curtailment is the grid's traditional method of dealing with its constraints being violated by the large-scale PV system's variable generation. The PV system's performance in terms of the PV curtailment sum and the PV curtailment percentage will be assessed here with only applying the PV curtailment method to abide with the grid's constraints. In doing so, will provide bases that will be used to establish the appropriate flexibility measures that can ensure both the reduction of the PV curtailment and minimise the impact of integrating large-scale PV into the grid. Furthermore, it is worth mentioning that since we are trying to minimise the impact of integrating large-scale PV into the grid; the *GRC* will be based on the maximum power ramp of the original load profile without the inclusion of the PV system. Therefore, the applied grid constraints are 4282 MW for the baseload constraint and 1268 MW for the ramping constraint. Also, it is assumed that there are no transmission constraints

in terms of congestion or interconnected capability to import or export power from neighbouring grids. Table 5.5 shows PV system's performance in terms of the PV curtailment sum and PV curtailment percentage at various PV penetration levels to the grid.

Table 5.5. PV system's performance in terms of curtailing the PV system due to the grid's constraints at various PV penetration levels to the grid in Riyadh 2017.

PV System Penetration Level (%)	Due to Baseload Constraint		Due to Ramping Constraint	
	PV Curtailment Sum (GWh)	PV Curtailment Percentage (%)	PV Curtailment Sum (GWh)	PV Curtailment Percentage (%)
10	1.65	0.05	0.996	0.03
20	221	3.32	16.6	0.26
30	978	9.82	71.4	0.8
40	1979	14.9	157	1.39
50	3169	19.1	388	2.89

The PV system's performance throughout the year shown in Table 5.5; showcased the significant difference that each grid constraint has on performance of the PV system at various PV penetration levels to the grid. In particular, the baseload constraint resulted in the majority share of PV curtailment if compared to the results of the ramping constraint. Furthermore, it can be deduced that, as the PV penetration level to the grid increases; the PV curtailment will dramatically increase as well. An example of this can be illustrated in which the PV curtailment percentage will increase from 0.08% to 21.99% as the PV penetration level to the grid increases from 10% to 50%. Also, it is worth mentioning that, since the load profile and PV system output varies throughout the year; it is important to show the PV system performance of each month in order to illustrate the seasonal variations effects on the PV system's performance. Thus, a specific PV penetration level of 50% to the grid will be chosen in order to clearly illustrate the seasonal variations effects on the PV system's performance which is shown in Figure 5.14.

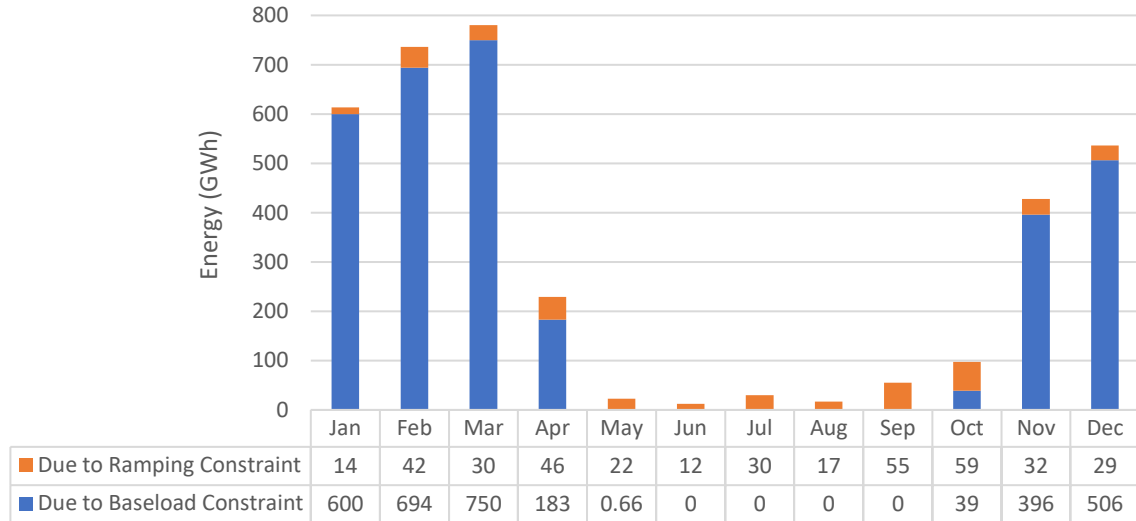


Figure 5.14. Sum of PV system's curtailed energy in GWh for each month due to the grid's constraints at 50% PV penetration level to the grid in Riyadh 2017.

According to the PV system performance of each month shown in Figure 5.14; the effects of the ramping constraint are present throughout the year, meanwhile the baseload constraint effects are only present in the winter season where the load profile is at its lowest. Hence, the potential flexibility measure applied might not be optimally or economically suitable to tackle at the same instance, leading to the point of having flexibility measures that target each grid constraint on itself. Therefore, a diurnal source of flexibility is required to manage the ramping constraint effects, while a seasonal source of flexibility is required to manage the baseload constraint effects.

5.8 Discussion

The variability of the renewables can be easily mitigated when the grid is capable of matching the supply of the renewables to the demand, meaning they both rise and fall together [280]. However, if the supply of the renewables and demand moved in the opposite directions, it will become very costly to accommodate it. For example, in the case of having a large supply of renewables when there is a low demand meaning that the excess of renewables can be only used if the conventional base-load generators are curtailed. This will be a costly and inefficient approach that might lead to significant reliability issues. On the other hand, in the case of having a low supply of renewables when there is a high demand meaning that the peak demand must be reached completely by the conventional generators. This means that there will be a requirement of having a conventional reserve that can successfully duplicates the capacity of the renewable energy. Therefore, it is a major challenge facing the integration of renewables to the grid, in reducing the cost of dealing with the two aforementioned cases.

A debate is there for whether curtailing the renewable energy is seen as a problem or a solution. On the one hand, curtailing the renewable energy can be problematic due to the fact

that it reduces the capacity factor of the renewable energy which can potentially decrease the revenue of that plant. This can lead to the weakening of the confidence of the renewable energy investors since the intermittent renewable energy such as solar has a low operating expenses but has a large capital costs that can be recovered by maximising the energy output. Likewise, there are negative wholesale prices sustained that can occur when the conventional generation system in the grid cannot be turned down to a lower output in order to accommodate more renewable energy that are available which leads to the reduction in the attractiveness of investing in renewable generation [281]. This debate can lead to a point in which will it be possible for a power system to technically at all hours of the year meet the demand at a given penetration level of renewable energy, assuming that the curtailing measure of the renewable energy's output is out of the picture. There is an interesting analysis illustrating that increasing the curtailment beyond a certain threshold in this case 5% will result in a significant risk of the owners facing not being able to pay off the loans taken for the existing project [282]. It is worth mentioning that a lot of utility scale PV power plants have already the capability of receiving curtailments signals from the operators of the grid which means that the transition to the automatic generation control operation is simply viable.

The grid operators currently handle the variability of renewable energy almost exclusively by the ramping up or down of the conventional generators or reserves based on the weather forecast. However, in the near future the grid will experience large shares of renewables making this current approach costly and unreliable in some cases. This leads to the need of a cost effective and reliable approach from the generation side in dealing with this matter which can be in the form of the following:

- By installing large-scale storage to the grid.
- By increasing transmission flexibility in order to enabling accessing large shares of resources in order to aid balancing both local and regional deficits or excesses.

There is an interesting paper in [133] that gives a realistic assessment on future scenarios with suggestions of making the global agenda move towards grid connected large-scale PV at a multi-TW scale. The study includes the technical, economical, policy, and infrastructure barriers that needs to be overcome in order for the grid connected PV technology to grow to the multi-TW scale. This study also concluded that storage and increasing transmission flexibility among other factors makes it possible to reach that multi-TW scale. It is worth mentioning that there are various types of energy storage technologies that can be application specific. This means that energy storage as a concept can be applied to be both the required diurnal source of flexibility to manage the ramping constraint effects and the required seasonal source of flexibility to manage the baseload constraint effects.

5.9 Summary

This chapter demonstrated the method used to calculate the grid's frequency and illustrated the PV curtailment method applied in order to comply with the grid's constraints. Also, it presented a load profile analysis and a net load analysis based on both the collected 2017 global horizontal irradiance (GHI) data used to produce the PV system's output and the collected 2017 hourly load profile data of the capital city of Riyadh in the central region of Saudi Arabia. Furthermore, it showcased the substantial affects that each grid constraint has on the performance of the PV system by executing a brief evaluation of the grid's current potential hosting capacity with large-scale PV plants at various PV penetration levels to the grid.

Frequency stability relates to the capability of the grid to maintain or restore the balance between the generation and load. Frequency regulation ensures maintaining the balance between the generation and load by sensing the variations in the system's frequency. The system's frequency will decrease if the load exceeds the generation input. On the other hand, the system's frequency will increase if the generation exceeds the load. This chapter introduced the grids constraints which are the baseload constraint and ramping constraint. These grid constraints limit the amount of PV energy that can be integrated to the grid.

The PV over-generation phenomena can be observed in the case when the net load falls below the baseload point set. The PV curtailment method applied for the baseload constraint will curtail the PV system's output to equal the value of the *DLB* when the PV system's output is higher than the *DLB* value. On the other hand, the loss of load phenomena can be observed in the case when net load power ramp (*NL_{PR}*) exceeds the grid's ramping constraint of its conventional generation system. The PV curtailment method applied for the ramping constraint will differ based on the period of the day. In the morning period, the earliest loss of load event will be identified first, and the PV curtailment method will be applied on it before advancing forward in time if there are other loss of load events in the morning period until they are dealt with. In the afternoon period, the latest loss of load event will be identified first, and the PV curtailment method will be applied on it before advancing backward in time if there are other loss of load events in the afternoon period until they are dealt with.

The net load was used in order to analyse the impact of integrating large-scale PV into the grid, because it gave an insight to the ramping requirements needed by the grid's conventional generation system to accommodate both the variability and the availability of the renewable. Furthermore, under some circumstances of up ramping the grid's conventional generation system with down ramping the renewable and vice versa, can result in a severe net load ramp events that is beyond the grid's technical capability. It can be deduced that as the penetration level of the PV system increases; the ramping requirement of the grid's conventional generation system will increase dramatically. Also, it is worth mentioning that the up ramping requirements of the grid's conventional generation system will be higher if the peak load point occurs in the period which does not coincide with the peak generation of the PV system.

Increasing the penetration level of the large-scale PV into the grid will cause the grid operators to face an increasingly variable net load patterns and steeper ramping events. This will be a major concern to the grid operators and will require grid flexibility measures to be applied that can be in the form of energy storage. The brief evaluation of the grid's current potential hosting capacity with large-scale PV plants at various PV penetration levels to the grid, showcased that the potential flexibility measure applied might not be optimally or economically suitable to tackle both constraints at the same instance. This leads to the point of having flexibility measures that target each grid constraint on itself. Therefore, a diurnal source of flexibility is required to manage the ramping constraint effects while a seasonal source of flexibility is required to manage the baseload constraint effects. In doing so, will ensure both the reduction of the PV curtailment and minimise the impact of integrating large-scale PV into the grid. The next chapter will demonstrate the methodology used for the proposed optimal sizing strategy and energy management strategy of both flexibility measures.

Chapter 6 Optimal Sizing and Energy Management Strategy for Flexibility Measures

6.1 Introduction

This chapter will demonstrate the methodology used to optimally size and manage the operation of the flexibility measure applied in order to enhance the grid's hosting capacity of the large-scale PV system. The brief evaluation of the grid's current potential hosting capacity with large-scale PV plants at various penetration levels presented in Chapter 5; showcased the substantial affects that each grid constraint has on the performance of the PV system. Therefore, the flexibility measure applied might not be optimally suited to tackle at the same instance leading to the point of having flexibility measures that target each grid constraint on itself. It is worth mentioning that a diurnal storage system in the form of lithium-ion batteries will be applied as the flexibility measure for the ramping constraint while a seasonal storage system will be applied as the flexibility measure for the baseload constraint. The optimal sizing and energy management strategy of the flexibility measure applied for ramping constraint will be presented firstly, followed by the optimal sizing and energy management strategy of the flexibility measure applied for baseload constraint.

6.2 Optimal Sizing and Energy Management Strategy of Flexibility Measure Applied for Ramping Constraint

This section will illustrate the methodology undertaken to optimally size the battery's capacity and optimally manage its operation in order to minimise the PV system's curtailment. In doing so, will increase the PV system penetration level into the grid's generation mix. An overview of the steps used in the battery's optimal sizing and energy management strategy is shown in Figure 6.1 and this can be expressed into the following steps:

1. Deducing the daily required storage capacity for each month based on the period of the day with the most PV curtailed energy in order to minimise the curtailment of the PV system's output.
2. Setting up the usable battery capacity by sizing it to the maximum daily required storage capacity with taken into account the depth of discharge (DOD) and the battery's capacity degradation.
3. Assigning the charging, discharging and light load periods in order to establish the energy management strategy of the battery storage system (BSS).
4. Accurately accounting all the PV curtailed energy that is situated in the assigned charging period with optimally discharging the already set usable battery capacity.
5. Optimally charging the battery.
6. Optimally discharging the battery.

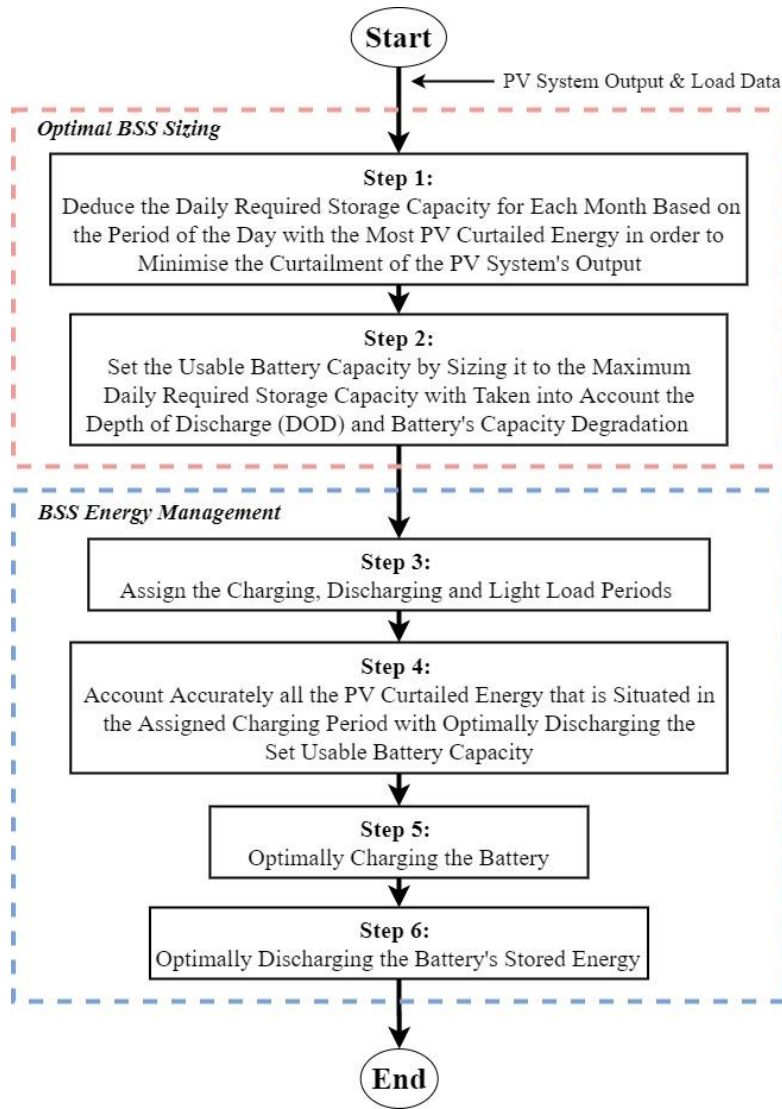


Figure 6.1. Overall methodology of the steps used in the battery storage system's (BSS) optimal sizing and energy management strategy.

6.2.1 Aging Effect Estimation for BSS

Degradation of lithium-ion batteries can be defined as the complex combination of the mechanical and electrochemical processes that leads to the battery's capacity loss [283]. In the electrodes or in the electrolyte while interacting with the electrodes is where the degradation process mainly happens [284]. When applying the lithium-ion batteries as the diurnal storage flexibility measure; it will be essential to analyse the degradation stress factors that impacts the batteries lifetime as it will limit the amount of electricity that can be stored and delivered. The degradation process from the application perspective, can be divided into two groups which are the degradation during passive charge better known as calendar aging and degradation during active use better known as cycle aging [285]. Calendar aging refers to the irreversible capacity loss and the increase in internal resistance that

happens during storage while cycle aging refers to all the degradation losses when the battery is charged or discharged [286].

The Arrhenius equation describes the relation between the rate of reaction and temperature for many physical and chemical reactions. A common form of the equation is shown in Equation 6.1 [287]. A more useful form of the relation is obtained by taking the logarithm of both sides of the equation which can be represented in Equations 6.2-6.5.

$$K = A \cdot e^{-E_a/RT} \quad (6.1)$$

$$\ln(K) = \frac{-E_a}{R} \cdot \left(\frac{1}{T}\right) + \ln(A) \quad (6.2)$$

$$y = m \cdot x + b \quad (6.3)$$

$$Slope = \frac{-E_a}{R} \quad (6.4)$$

$$Slope = \frac{Rise}{Run} , \left(\begin{array}{l} Rise = \Delta \ln(K) \\ Run = \Delta \frac{1}{T} \end{array} \right) \quad (6.5)$$

where K is the kinetic reaction rate, A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant and T is the absolute temperature. The state of health (SOH) represents the lithium-ion battery's new capacity with taken into account degradation losses. In order to estimate the state of health (SOH) of the lithium ion battery; a semi-empirical life model in [288] was used to account for both calendar aging loss and cycle aging loss. For the calendar aging equation, it adopts a square root of time relation to account for the diffusion limited capacity loss and an Arrhenius correlation is used to capture the influence of temperature. Equation 6.6 represents a simplified formula that accounts the battery's capacity loss due to calendar aging. Furthermore, after 400 days of testing by [288] and using a single step optimization process when mapping the logarithmic percentage of capacity loss as a function of inverse temperature; the simplified calendar aging loss equation can be expressed as Equation 6.7.

$$Calendar\ Aging\ Loss = A \cdot e^{-E_a/RT} \cdot t^\beta \quad (6.6)$$

$$Calendar\ Aging\ Loss = 14876 \cdot e^{-24.5kJ/RT} \cdot days^{0.5} \quad (6.7)$$

For the cycle aging, the dependence on rate is exponential while that for time or charge throughput is linear. Equation 6.8 represents a simplified formula that accounts the battery's capacity loss due to cycle aging in which C_{rate} is the discharge rate, B_1 is the pre-exponential factor and B_2 is the exponent factor. Both the pre-exponential and the exponent factors can be identified via Figure 6.2 as a function of temperature from the experimental results by [288]. The commercially available 1.5 Ah, 18650 cylindrical cells (UR18650W) from Sanyo are the one used in that study. Equation 6.10 represents the method used to calculate the state of health (SOH) of the lithium-ion battery. In the automotive industry, a battery pack has to be

replaced when the battery loses 20–30% of its original storage capacity which indicates that they reached their End of Life (EoL) [289]. It is worth mentioning that as soon as the batteries in the automotive industry reach their End of Life (EoL); they can be used in large-scale storage systems as they still have 70–80% of their original capacity [290].

$$\text{Cycling Aging Loss} = B_1 \cdot e^{B_2 \cdot C_{rate}} \cdot Ah_{throughput} \quad (6.8)$$

$$Ah_{throughput} = \text{Cycle number} \times \text{Depth of Discharge} \times \text{Full cell capacity} \quad (6.9)$$

$$SOH = 100 - (\text{Calender Aging Loss} + \text{Cycling Aging Loss}) \quad (6.10)$$

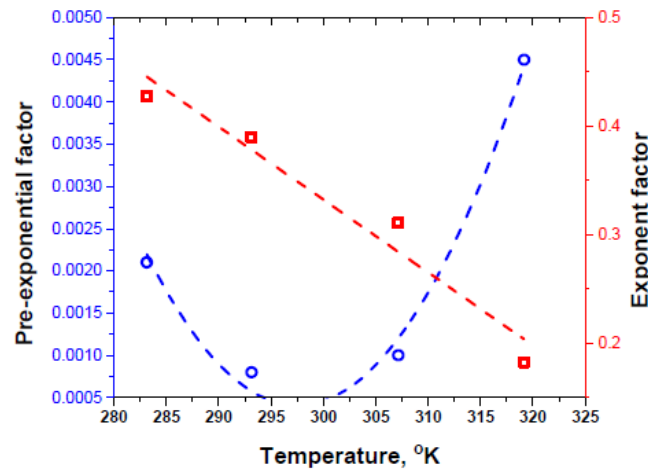


Figure 6.2. Experimental results of plotting both the pre-exponential and the exponent factors as a function of temperature [288].

6.2.2 Optimal Sizing Strategy

The ramping constraint of the grid's conventional generation, results in the curtailment of the PV system's output. This issue can be resolved by the incorporation of battery storage system which will minimise the curtailment of the PV system's output and increase the PV system's penetration level into the grid's generation mix. Therefore, it will be essential to optimally size the capacity of the battery system to meet the system requirement. An overview of the strategy used in optimally sizing the battery system's capacity is shown in Figure 6.3 and this can be expressed into the following steps:

1. Analysing the net load by calculating both the net load power ramp (NL_{PR}) and the power ramp of the PV system's output (PV_{PR}).
2. Applying the PV curtailment method in order to comply with the ramping constraint of the grid's conventional generation systems.
3. Identifying the period of the day with the most PV curtailed energy (morning or afternoon period).
4. Deducing the daily required storage capacity for each month based on the period of the day with the most PV curtailed energy in order to minimise the curtailment of the PV system's output.

5. Setting up the usable battery capacity by sizing it to the maximum daily required storage capacity with taken into account the depth of discharge (DOD) and the battery's capacity degradation.
6. Establishing the energy management strategy of the battery storage system (BSS) in terms of both the optimal charging and discharging processes.

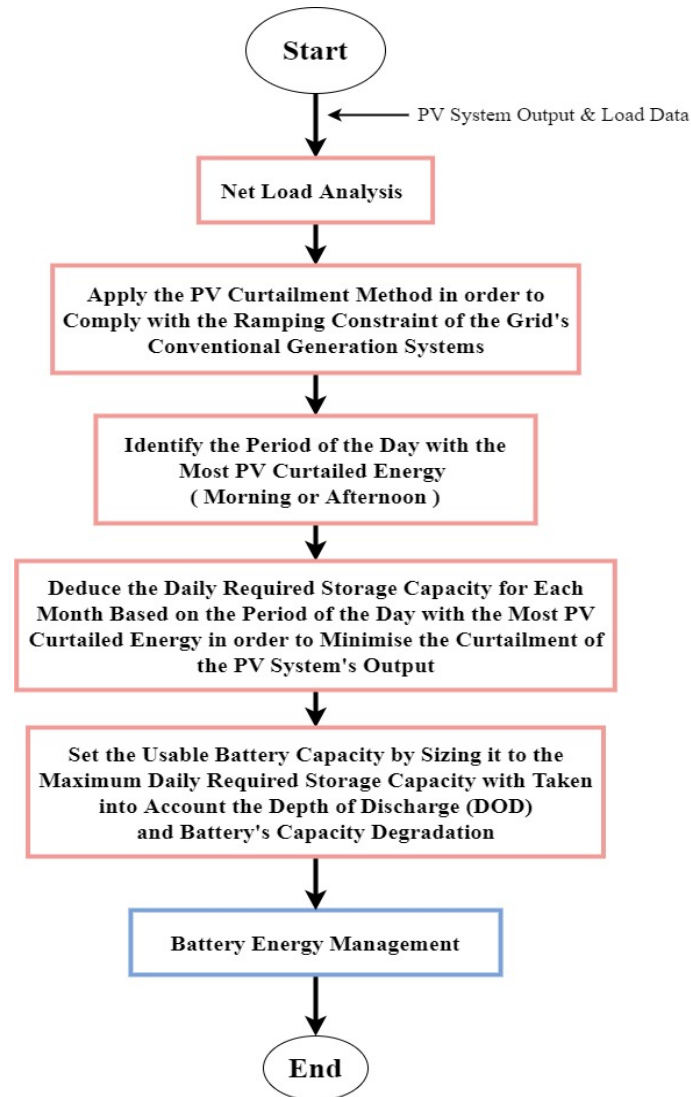


Figure 6.3. Overview of the strategy used in optimally sizing the battery system's capacity.

The previous chapter (chapter 5) already presented the net load analysis and applied the PV curtailment method in order to comply with the ramping constraint of the grid's conventional generation system. Furthermore, the previous chapter managed to produce the amount of PV energy curtailed which will be used as the basis for applying the strategy of the optimal sizing of the battery system's capacity. The PV curtailment method applied is dependent on the period of the day due to the dramatic increase in the PV system's output during the morning

period and dramatic decrease during the afternoon period of the day. Usually, most of the PV curtailment happens in the early stages of the morning period due to the ramping down constraint of the grid's conventional generation system. Meanwhile most of the PV curtailment happens in the late stages of the afternoon period due to the ramping up constraint of the grid's conventional generation system. Thus, the PV curtailment method will result in a period of the day with a higher curtailed energy compared to the other one.

The PV energy curtailment in the morning period can be mitigated via storing it by the battery storage system, then discharging it in the required period. On the other hand, the PV energy curtailment in the afternoon period can be mitigated via discharging the required energy from the battery storage system in order to meet the net load ramping requirement. Therefore, the battery storage system will operate in the charging mode at the morning period and in the discharging mode at the afternoon period. In doing so, will make the identification of the period of the day with the most PV energy curtailed crucial because it will be the basis for the deduction of the daily required storage capacity to meet the system requirement.

The morning period for charging the battery storage system will be assigned as the period from the PV system's availability till 12:00 PM. Meanwhile, the afternoon period for discharging the battery storage system will be assigned as the period from 2:00 PM till 8:00 PM. The period from 12:00 PM till 2:00 PM is kept unassigned due to it coinciding with the peak of the PV system generation, meaning its output doesn't drastically ramps up or ramps down making its operation as close to the operation of the conventional generation system.

Deducing the daily required battery storage capacity to meet the system requirement can be done via sizing it to the month with the highest daily PV curtailed energy sum situated in the assigned morning period. This deduction is valid only if the morning period is the identified period with the most PV energy curtailed. On the other hand, deducing the daily required battery storage capacity to meet the system requirement can be done via sizing it to the month with the highest daily sum of the required energy of discharging situated in the assigned afternoon period to meet the net load ramping requirement. The following are the steps taken to deduce the required energy to be discharged ($RQ_{Discharge}$) from the battery storage system in the afternoon period:

1. Locating the earliest case of the afternoon period when the net load power ramp (NL_{PR}) exceeds the grid's ramping constraint (GRC).
2. Calculating the value of the current hour of $RQ_{Discharge}(t)$ to meet the net load ramping requirement which is equal to the value of subtracting the GRC value from the value of the current hour of $NL_{PR}(t)$.
3. Calculating the next hour of $NL_{PR}(t+1)$ which is equal to the addition of the value of the current hour of $RQ_{Discharge}(t)$ with the value of the next hour of $NL_{PR}(t+1)$.
4. Repeating the aforementioned steps till the current hour of $NL_{PR}(t)$ and the next hour of $NL_{PR}(t+1)$ does not exceed the grid's ramping constraint (GRC).

Equation 6.11 illustrates the deduction of the daily required battery capacity based on the identified period with the most PV energy curtailed.

$$\left\{ \begin{array}{l} \text{Max}(\text{Sum}(\text{daily PV curtailed energy situated in the assigned morning period})) \\ \text{OR} \\ \text{Max}(\text{Sum}(\text{daily } RQ_{\text{Discharge}} \text{ situated in the assigned afternoon period})) \end{array} \right. \quad (6.11)$$

The daily required storage capacity (RQ_{Capacity}) varies throughout the year which explains the reason of choosing its maximum value. In doing so, will ensure the elimination of the PV curtailed energy throughout the year. However, the capacity degradation and the depth of discharge (DOD) which are closely related, plays a vital role in reducing the battery's usable capacity. This will impact the effectiveness of the sized storage capacity. Thus, will lead to furthering the increase in the size of the storage's capacity in order to accommodate the storage capacity losses. Equations 6.12-6.15 illustrates the process of calculating the battery capacity and the usable battery capacity, which considers the capacity degradation and the depth of discharge (DOD) aspects. without degradation and DOD consideration

$$A1 = \frac{\text{Max}(RQ_{\text{Capacity}})}{\frac{DOD(\%)}{100}} - \text{Max}(RQ_{\text{Capacity}}) \quad (6.12)$$

$$A2 = \frac{(\text{Max}(RQ_{\text{Capacity}}) + A1)}{\frac{SOH_E(\%)}{100}} - (\text{Max}(RQ_{\text{Capacity}}) + A1) \quad (6.13)$$

$$\left\{ \begin{array}{ll} \text{Battery Capacity} = \text{Max}(RQ_{\text{Capacity}}) & , \text{normal sizing} \\ \text{OR} & \\ \text{Battery Capacity} = \text{Max}(RQ_{\text{Capacity}}) + A1 + A2 & , \text{over sizing} \end{array} \right. \quad (6.14)$$

$$\text{Usable Battery Capacity} = \left(\left(\left(\text{Battery Capacity} \cdot \left(\frac{d(\%)}{100} \right) \right) \cdot \left(\frac{DOD(\%)}{100} \right) \right) \cdot \left(\frac{SOH(\%)}{100} \right) \right) \quad (6.15)$$

Where SOH is the battery's daily state of health, SOH_E is the battery's state of health at day number 365 (end of year) and d is the desired sizing percentage to the battery's maximum required capacity. The desired sizing percentage will be varied throughout the analysis in order to illustrate the reduction of curtailing the PV system's output.

6.2.3 Energy Management Strategy

Optimally managing the battery storage system's operation is a fundamental aspect in order to minimise the PV system's curtailment. The battery storage system's energy management includes setting the optimal strategy of the battery's charging and discharging process without causing the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC). The optimal charging process is applied once the usable battery capacity is identified from the optimal battery sizing strategy. An overview of the strategy used in managing the battery's optimal charging process is shown in Figure 6.4 and this can be expressed into the following steps:

1. Setting up the usable battery capacity ($X1$) after optimally sizing the battery's capacity.
2. Assigning the charging, discharging and light load periods.
3. Accurately accounting all the PV curtailed energy that is situated in the assigned charging period with optimally discharging the already set usable battery capacity ($X2$ is the daily sum of the PV curtailed energy in the charging period).
4. Comparing the $X1$ value with the $X2$ value and if the value of $X1$ is lower than the $X2$ value; then charge from the latest PV curtailed energy case till the earliest case if there is enough charging capacity. After that optimally discharge the battery's stored energy.
5. If the value of $X1$ is higher than the $X2$ value; then charge as much as possible without causing the current hour and next hour of the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC).
6. Checking if there is enough capacity to charge the reminder of the $X2$ and if there isn't enough capacity; then apply the $X2$ charging prioritisation step where it reduces the energy charged to a value that makes enough capacity to charge the reminder of $X2$. After that optimally discharge the battery's stored energy.
7. If there is enough capacity to charge the reminder of the $X2$ value; then continue the $X2$ charging prioritisation with charging as much as possible without causing the current hour and next hour of the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC).
8. Checking if the battery is charged fully and if it is not charged fully; then charge the reminder capacity of the battery equally from the light load period of the grid's conventional generation systems. Furthermore, an alert will be triggered if the optimal charging process does not fully charge the battery's usable capacity.
9. Optimally discharge the battery's stored energy.

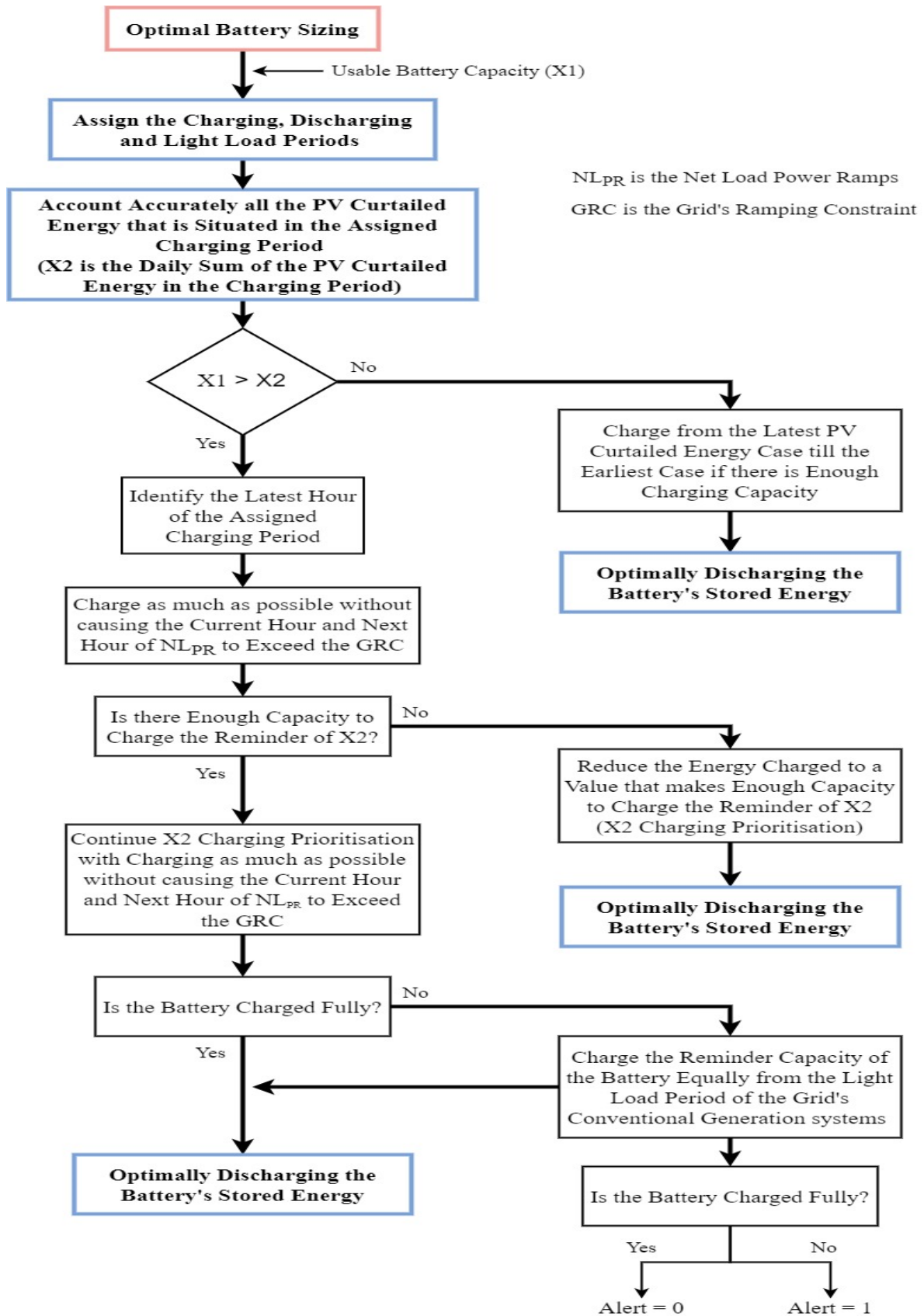


Figure 6.4. Overview of the strategy used in managing the battery's optimal charging process.

The core objective of the optimal charging process is to fully charge the usable battery capacity without causing the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC). The established optimal charging strategy will operate on filling the usable battery capacity with energy as much as possible from the PV system without causing the current hour of $NL_{PR}(t)$ and the next hour of $NL_{PR}(t+1)$ to exceed the GRC . This can be attained through identifying the latest hour of the assigned charging period, then applying Equation 6.16 which calculates the maximum viable energy to charge (Max_{VEC}) at that current hour.

$$Max_{VEC}(t) = NL_{PR}(t + 1) + GRC \quad (6.16)$$

The latest hour of the assigned charging period contains a much more significant PV energy if compared to the earliest hour of the assigned charging period. This is the reason for starting the charging process from the latest hour of the assigned charging period till the earliest hour if there is enough usable charging capacity. We only charge from the unassigned period first before the assigned charging period if the current hour of $NL_{PR}(t)$ in the unassigned period exceeds the GRC . The battery charge (B_{Charge}) and its effect on the NL_{PR} can be estimated according to Equations 6.17 and 6.18.

$$\begin{cases} B_{Charge}(t) = Max_{VEC}(t) & , \text{if } Max_{VEC}(t) < PV_{Output}(t) \text{ and } \text{if } Max_{VEC}(t) < X1 \\ B_{Charge}(t) = PV_{Output}(t) & , \text{if } Max_{VEC}(t) > PV_{Output}(t) \text{ and } \text{if } PV_{Output}(t) < X1 \\ B_{Charge}(t) = X1 & , \text{if } Max_{VEC}(t) > X1 \text{ and } \text{if } PV_{Output}(t) > X1 \end{cases} \quad (6.17)$$

$$NL_{PR}(t) = NL_{PR}(t) + B_{Charge}(t) \quad (6.18)$$

Where $X1$ is the battery's usable capacity. Since the charging process starts from the latest hour till the earliest hour of the assigned charging period; the $NL_{PR}(t)$ of the current hour will be affected by the battery charge ($B_{Charge}(t-1)$) of the prior hour. Thus, a constraint shown in Equation 6.19 will be applied in case the battery charge ($B_{Charge}(t)$) of the current hour causes the $NL_{PR}(t)$ of the current hour to exceed the GRC . However, this only applied if the battery charge ($B_{Charge}(t-1)$) of the prior hour is not high enough to allow the current hour of $NL_{PR}(t)$ to not exceed the GRC .

$$\begin{cases} S1(t) = NL_{PR}(t) - GRC \\ B_{Charge}(t) = B_{Charge}(t) - S1(t) & , \text{if } B_{Charge}(t - 1) < S1(t) \end{cases} \quad (6.19)$$

A light load period is assigned in case the energy stored from the PV system is not enough to fully charge the battery's usable capacity. The light load period for charging the battery storage system from the grid's conventional generation system, will be assigned as the period where the demand is at its minimum in which coincide to the period from 1:00 AM till 5:00 AM. Furthermore, the reminder of the battery's capacity will be charged equally from the light load period without causing the NL_{PR} to exceed the GRC .

The established optimal charging strategy will give a charging prioritisation to the PV curtailed energy situated in the assigned charging period in which the charging is executed

from the latest PV curtailed energy case till the earliest case if there is enough usable charging capacity. Furthermore, the charging prioritisation will fully utilise the PV curtailed energy due to the ramping constraint first before exploiting the PV curtailed energy due to the baseload constraint. It is worth mentioning that in some cases, the PV curtailment method applied in the afternoon period will result in a curtailed PV energy situated in the assigned charging period. Therefore, a higher usable battery capacity will result in a lower PV curtailed energy situated in the assigned charging period. An alert will be triggered if the optimal charging process does not fully charge the battery's usable capacity in which will be useful in the analysis part. The optimal discharging process is applied once the usable battery capacity is charged via the optimal charging strategy. An overview of the strategy used in managing the battery's optimal discharging process is shown in Figure 6.5 and this can be expressed into the following steps:

1. Comparing the battery's stored capacity ($X3$) value with the daily sum of $RQ_{Discharge}$ ($X4$) value and if the value of $X3$ is lower than the $X4$ value; then discharge the energy from the latest $RQ_{Discharge}$ case till the earliest case if there is enough $X3$ capacity.
2. If the value of $X3$ is higher than or equal to the $X4$ value; then calculate the excess energy ($J1$) that needs to be equally distributed into the discharging period. After that optimally discharge the battery's stored energy.
3. Checking if the next hour of $NL_{PR}(t+1)$ exceeds the grid's ramping constraint (GRC) for the latest hour of the discharging period and if it does; then add an extra hour to the discharging period and reduce the value of the added extra hour of discharging equally from the rest of the battery's optimal discharge ($B_{Discharge}$) cases. This step of adding an extra hour of discharge is repeated till the next hour of $NL_{PR}(t+1)$ does not exceed the grid's ramping constraint (GRC) for the latest hour of the discharging period.
4. Checking if the net load power ramp (NL_{PR}) exceeds the grid's ramping constraint (GRC) for the earliest hour of the discharging period and if it does; then calculate the value of ($J2$) with reducing it from the $B_{Discharge}(t)$ value. After that add the reduced value ($J2$) from the $B_{Discharge}$ of the earliest hour of the discharging period, equally from the rest of the $B_{Discharge}$ cases in the discharging period.

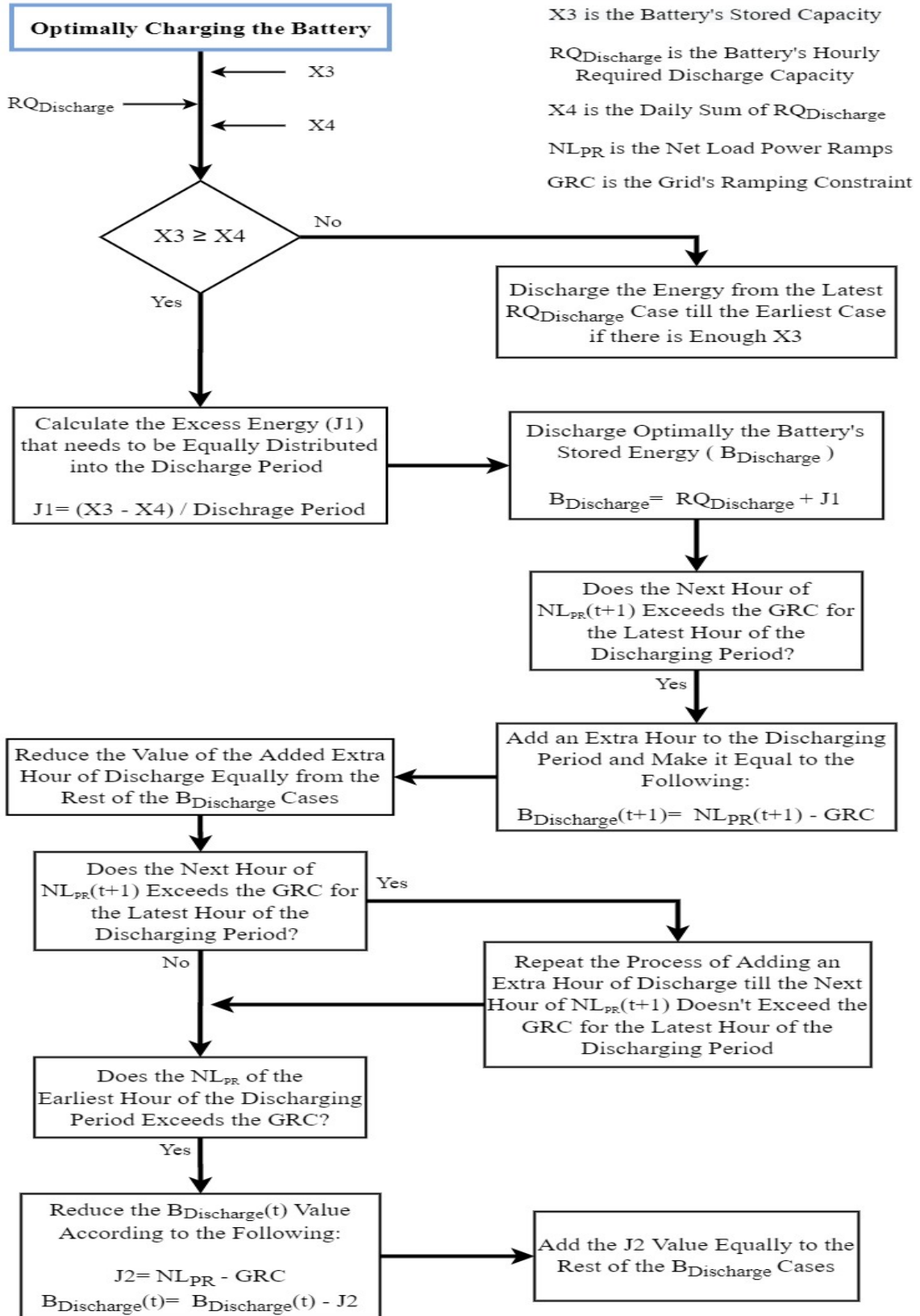


Figure 6.5. Overview of the strategy used in managing the battery's optimal discharging process.

The core objective of the optimal discharging process is to fully discharge the battery's available energy into the assigned discharging period, without causing the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC). The deduced required energy to be discharged ($RQ_{Discharge}$) from the battery, will be used as the basis for the operation of the established optimal discharging strategy. The required energy to be discharged ($RQ_{Discharge}$) from the battery is already deduced in the optimal sizing of the battery section. The following illustrates the applied process of optimally discharging the battery's available energy, which is executed after comparing the battery's available energy with the daily sum of the $RQ_{Discharge}$:

- The battery's available energy will be discharged in the assigned discharging period, from the latest $RQ_{Discharge}$ case till the earliest $RQ_{Discharge}$ case, if there is enough available energy from the battery. This is only applied if the battery's available energy is lower than the daily sum of $RQ_{Discharge}$.
- The battery's available energy will be discharged in the assigned discharging period, in the form of adding the $RQ_{Discharge}$ with the calculated excess energy ($J1$) that is equally distributed into the discharging period. This is only applied if the battery's available energy is higher than or equal to the daily sum of $RQ_{Discharge}$. Equation 6.20 illustrates the battery's optimal discharge ($B_{Discharge}$) process when the battery's available energy is higher than or equal to the daily sum of $RQ_{Discharge}$.

$$\begin{cases} J1 = \frac{X3 - X4}{Discharge\ Period} \\ B_{Discharge}(t) = RQ_{Discharge}(t) + J1 \end{cases}, \text{ if } X3 \geq X4 \quad (6.20)$$

Where $X3$ is the battery's available energy and $X4$ is the daily sum of $RQ_{Discharge}$. The battery's discharge ($B_{Discharge}$) effect on the NL_{PR} can be estimated according to Equation 6.21. The battery's discharge ($B_{Discharge}$) will take into account loss due to the battery's round-trip efficiency.

$$NL_{PR}(t) = NL_{PR}(t) - B_{Discharge}(t) \quad (6.21)$$

It is worth mentioning that applying the optimal discharging process when the battery's available energy is much higher than the daily sum of $RQ_{Discharge}$; will impact both the $NL_{PR}(t)$ for the earliest hour of the assigned discharging period and the $NL_{PR}(t+1)$ for the latest hour of the assigned discharging period. An extra hour will be added to the assigned discharging period if the $NL_{PR}(t+1)$ for the latest hour of the assigned discharging period exceeds the GRC . This added extra hour of $B_{Discharge}$ will be equal to the subtraction of the GRC from the NL_{PR} of the added extra hour. It is important to reduce the added extra hour of $B_{Discharge}$ equally from the rest of the $B_{Discharge}$ cases in the discharging period. In doing so will ensure that the sum of the $B_{Discharge}$ is equal to the battery's available energy. This process is repeated till the $NL_{PR}(t+1)$ for the latest hour of the discharging period doesn't exceed the GRC .

The $NL_{PR}(t+1)$ for the latest hour of the assigned discharging period will be dealt with first if both aforementioned cases of NL_{PR} exceeds the GRC . This is because dealing with it firstly will result in the reduction of the $B_{Discharge}$ for the earliest hour of the assigned discharging period, thus aids the $NL_{PR}(t)$ for the earliest hour of the assigned discharging period to meet the GRC . A constraint shown in Equation 6.22 will be applied to the earliest hour of the discharging period in case that reduction in the $B_{Discharge}$ for the earliest hour of the discharging period is not enough to keep its NL_{PR} from exceeding the GRC .

$$\begin{cases} J2 = NL_{PR}(t) - GRC \\ B_{Discharge}(t) = B_{Discharge}(t) - J2 \end{cases}, \text{ if } NL_{PR}(t) > GRC \quad (6.22)$$

It is important to add the reduced value ($J2$) from the $B_{Discharge}$ of the earliest hour of the discharging period equally from the rest of the $B_{Discharge}$ cases in the discharging period. In doing so will ensure that the sum of the $B_{Discharge}$ is equal to the battery's available energy.

The battery's discharged ($B_{Discharge}$) energy might cause a violation in the baseload constraint of the net load. This is because the PV curtailment method for dealing with the baseload constraint; managed to keep the net load above the baseload point by limiting the PV contribution at that instant of time. The battery's discharged ($B_{Discharge}$) energy will reduce the net load and in some cases below the baseload point which will result in applying the curtailment method which will cancel the battery's discharged ($B_{Discharge}$) energy at that instant of time. Therefore, a constraint will be applied whenever the battery's discharged ($B_{Discharge}$) energy causes the net load to fall below the baseload point. This constraint will eliminate the $B_{Discharge}$ at that hour which will reduce the discharging period and thus the correct excess energy ($J1$) will be equally distributed into the remaining discharging period to ensure that the battery is fully discharged without causing the violation of the baseload constraint. An overview of the proposed model for the diurnal storage flexibility measure is shown in Figure 6.6. The varying inputs of the proposed model are the desired PV penetration percentage to the grid, the energy capacity of the battery storage system (BSS) and the grid's constraints. Furthermore, the energy management system of the proposed model will determine the charging and discharging of the BSS based on the input signals from the PV system, the BSS and the power grid. The goal of the energy management system is to reduce the PV system's curtailment, reduce the ramping stress on the grid's conventional generation system, further reduce the peak load and maintain both the SOC & SOH of the BSS. The proposed model assesses the PV system performance, the frequency stability, the net load and the BSS performance.

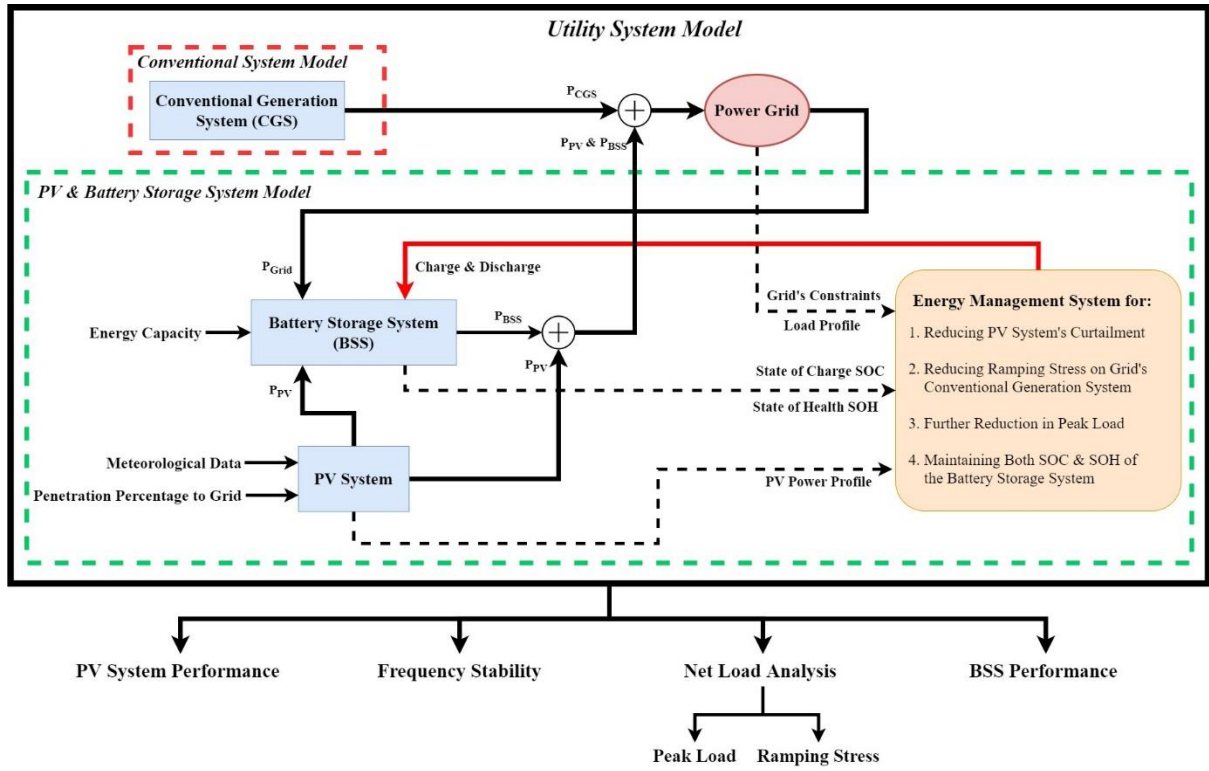


Figure 6.6. Overview of the proposed model for the diurnal storage flexibility measure.

6.3 Optimal Sizing and Energy Management Strategy of Flexibility Measure Applied for Baseload Constraint

This section will illustrate the methodology undertaken to optimally size the seasonal storage's capacity and optimally manage its operation in order to achieve the desired overall peak load reduction (%). An overview of the steps used in the seasonal storage's optimal sizing and energy management strategy is shown in Figure 6.7 and this can be expressed into the following steps:

1. Setting the overall desired peak load reduction percentage.
2. Deducing the seasonal storage's capacity by sizing it to the sum of the required discharge capacity to achieve the overall desired peak load reduction percentage.
3. Assigning the charging and discharging periods in order to establish the energy management strategy of the seasonal storage system.
4. Accurately accounting all the available PV curtailed energy that is situated in the assigned charging period with taken into account the hourly contracted regional export priority factor (*RegExp*)
5. Optimally charging the seasonal storage.
6. Optimally discharging the seasonal storage.

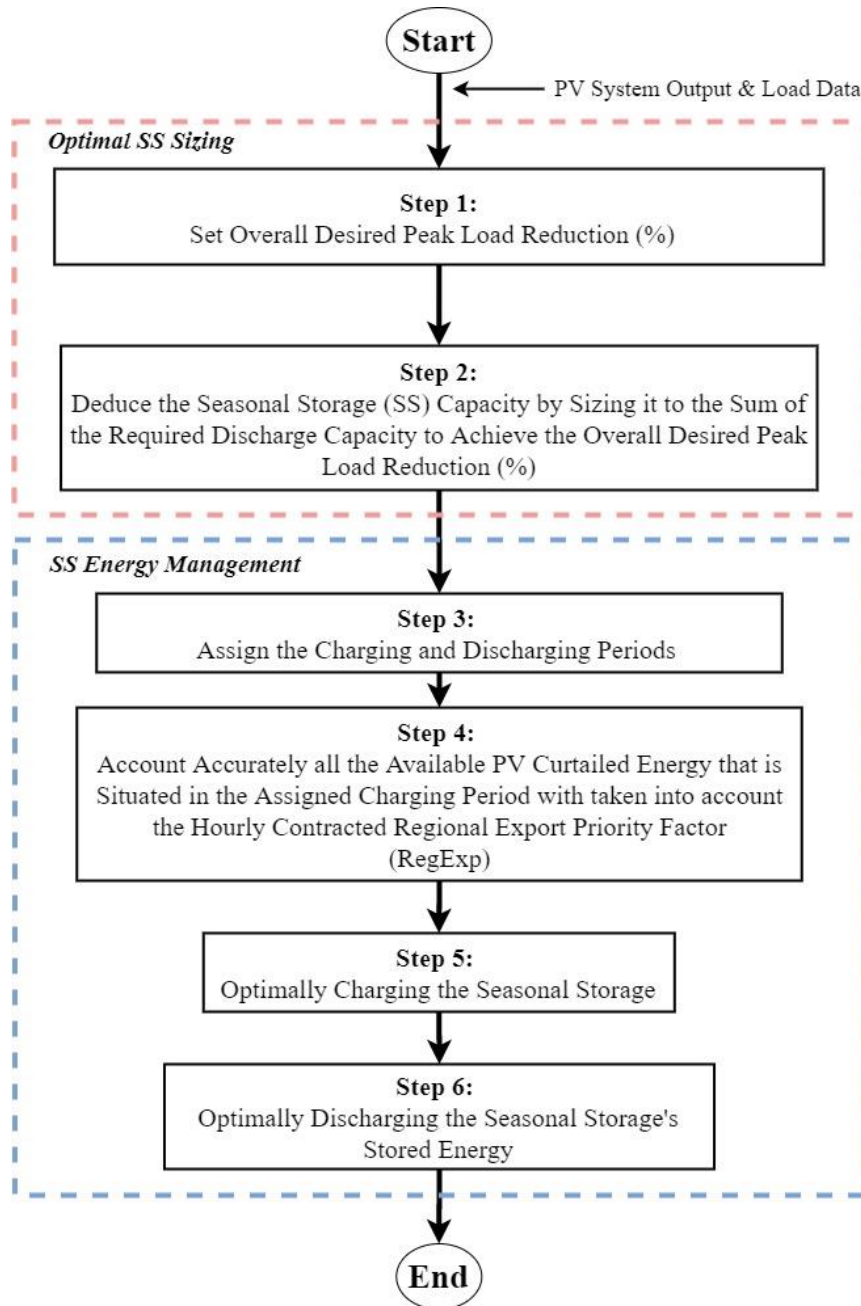


Figure 6.7. Overall methodology of the steps used in the seasonal storage (SS) system's optimal sizing and energy management strategy.

6.3.1 Optimal Sizing Strategy

The baseload constraint of the grid's conventional generation system, results in the curtailment of the PV system's output. This issue can be mitigated via exporting that PV curtailed energy to the neighbouring countries by investing in upgrading or establishing regional transmission capacities. Another possible solution is to incorporate a seasonal storage system which will utilise the PV system's curtailed energy in furthering the peak load reduction. It will be essential to optimally size the capacity of the seasonal storage system,

since there are only limited energy storage technologies that can achieve the requirements at the current time and most of them are costly. The required seasonal storage capacity is determined through the set overall desired peak load reduction ($DPKLR$) in percentage. Since the PV system and the diurnal storage system will contribute in reducing the peak load; the required seasonal storage capacity will be sized to the reminder of that desired peak load reduction percentage. Equation 6.23 represents the seasonal storage target of peak load reduction ($PKLR_{SS}$) percentage.

$$PKLR_{SS} = DPKLR - (PKLR_{PV} + PKLR_{DS}) \quad (6.23)$$

Where $PKLR_{PV}$ is peak load reduction percentage from the PV system and $PKLR_{DS}$ is peak load reduction percentage from the diurnal storage system. Equation 6.24 deduces the required peak load ($RPKL$) to achieve the seasonal storage target of peak load reduction ($PKLR_{SS}$) percentage.

$$RPKL = \left(\frac{\text{Original Peak Load}}{100} \right) \times (100 - DPKLR) \quad (6.24)$$

The required seasonal storage capacity will be sized to the sum of the required energy to be discharged ($RQ_{Discharge}$) from the seasonal storage system to achieve its peak load reduction ($PKLR_{SS}$) percentage target. The required energy to be discharged ($RQ_{Discharge}$) from the seasonal storage system is equal to the required energy to lower the current peak load point to the required peak load ($RPKL$) point. Equation 6.25 illustrates the method of calculating the seasonal storage required energy to be discharged ($RQ_{Discharge}$) and the required capacity ($RQ_{Capacity}$).

$$\begin{cases} RQ_{Discharge}(t) = Net\ Load(t) - RPKL & , if\ Net\ Load(t) > RPKL \\ RQ_{Capacity} = Sum(RQ_{Discharge}) \end{cases} \quad (6.25)$$

6.3.2 Energy Management Strategy

Optimally managing the seasonal storage system's operation is a fundamental aspect in order to utilise the PV system's curtailed energy in achieving the overall desired peak load reduction ($DPKLR$) in percentage. The seasonal storage system's energy management includes setting the optimal strategy of the seasonal storage's charging and discharging process. The optimal charging process is applied once the seasonal storage capacity is identified from the optimal seasonal storage sizing strategy. The seasonal storage flexibility measure is applied to further reduce the peak load at periods of less or no PV energy availability.

The PV curtailed energy due to the grid's baseload constraint is only present at the low load periods. Since the load varies throughout the year mostly due to the change in seasons; this means a seasonal storage approach is the only option other than exporting energy to neighbouring countries. In regions of hot climate such as the middle east, the peak load is located in the summer season mostly due to the air conditioning demand while the period of low demand is located in the winter season. The charging period of the seasonal storage will

be set at the regions period of low demand where the PV curtailed energy due to the grid's baseload constraint is located at. The seasonal storage will be charged fully only from the PV curtailed energy due to the grid's baseload constraint. An hourly contracted regional export priority factor ($RegExp$) is introduced which limits the amount of the PV energy curtailed due to the grid's baseload constraint that can be stored by the seasonal storage system. This hourly contracted regional export priority factor ($RegExp$) is a result of considering the regional energy export future projects, which is the future trend by most countries. Also, the hourly contracted regional export priority factor ($RegExp$) is only applied in the charging period of the seasonal storage. The seasonal storage's charging (SS_{Charge}) process is illustrated in Equation 6.26.

$$\begin{cases} SS_{Charge}(t) = PV_{Curtailed}(t) - RegExp & , if PV_{Curtailed}(t) > RegExp \\ SS_{Charge}(t) = X5 & , if (PV_{Curtailed}(t) - RegExp) \geq X5 \\ SS_{Charge}(t) = 0 & , if PV_{Curtailed}(t) \leq RegExp \end{cases} \quad (6.26)$$

Where $PV_{Curtailed}$ is the PV curtailed energy due to the grid's baseload constraint and $X5$ is the seasonal storage's capacity. The optimal discharging process commences once the seasonal storage is charged in the charging period. The discharging period is identified as the period of where the net load exceeds the required peak load ($RPKL$) to achieve the seasonal storage target of peak load reduction ($PKLR_{SS}$) percentage. The seasonal storage's discharging ($SS_{Discharge}$) process is illustrated in Equation 6.27.

$$\begin{cases} Discharge_{Ratio}(t) = \frac{RQ_{Discharge}(t)}{RQ_{Capacity}} \\ SS_{Discharge}(t) = Sum(SS_{Charge}) \times Discharge_{Ratio}(t) \end{cases} \quad (6.27)$$

Where $Discharge_{Ratio}$ is the seasonal storage discharge ratio which is a result of dividing the seasonal storage required energy to be discharged ($RQ_{Discharge}$) by its required capacity ($RQ_{Capacity}$). This discharge ratio methodology ensures maximising the reduction of the peak load as close as possible to the required peak load ($RPKL$) in case a lower seasonal storage capacity is applied. It is worth mentioning that the seasonal storage's discharging ($SS_{Discharge}$) process will take into account the loss due to the seasonal storage's round-trip efficiency. An overview of the proposed model for the seasonal storage flexibility measure is shown in Figure 6.8. The varying inputs of the proposed model are the desired PV penetration percentage to the grid, the energy capacity of the seasonal storage system (SSS), the grid's constraints and the hourly contracted regional export priority factor ($RegExp$). Furthermore, the energy management system of the proposed model will determine the charging and discharging of the SSS based on the input signals from the PV system, the SSS and the power grid. The goal of the energy management system is to reduce the PV system's curtailment and further reduce the peak load. The proposed model assesses the PV system performance, the frequency stability, the net load and the SSS performance.

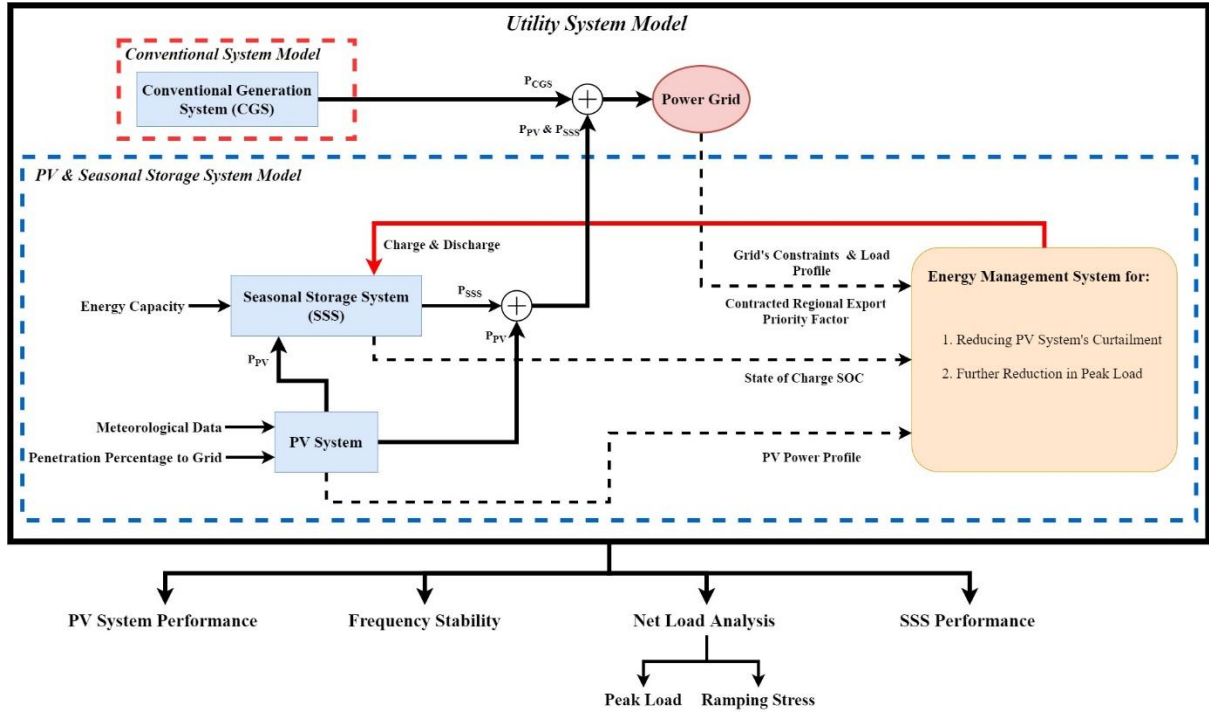


Figure 6.8. Overview of the proposed model for the seasonal storage flexibility measure.

6.4 Summary

This chapter demonstrated the methodology used to optimally size and manage the operation of the flexibility measures applied in order to enhance the grid's hosting capacity of the large-scale PV system. The flexibility measures applied targets each grid constraint on itself, since each grid constraint has different substantial effects on the performance of the PV system. Thus, the flexibility measure applied might not be optimally suited to tackle both grid constraints at the same instance. A diurnal storage system in the form of lithium-ion batteries is the flexibility measure applied for the grid's ramping constraint, while a seasonal storage system is the flexibility measure applied for the grid's baseload constraint.

The lithium-ion batteries capacity degradation in the form of calendar and cycle aging was analysed as it will limit the amount of electricity that can be stored and delivered throughout the battery's lifetime. The battery storage system will operate in the charging mode at the morning period and in the discharging mode at the afternoon period. The optimal battery capacity is sized to the highest daily PV curtailed energy sum situated in the assigned morning period, only if the morning period is the identified period with the most PV energy curtailed due to the grid's ramping constraint. On the other hand, the optimal battery capacity is sized to the highest daily sum of the required discharging energy ($RQ_{Discharge}$) situated in the assigned afternoon period to meet the net load ramping requirement, only if the afternoon period is the identified period with the most PV energy curtailed due to the grid's ramping constraint. The core objective of the optimal charging process is to fully charge the usable

battery capacity without causing the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC). The established optimal charging strategy will give a charging prioritisation to the PV curtailed energy situated in the assigned charging period in which will fully utilise the PV curtailed energy due to the ramping constraint first before exploiting the PV curtailed energy due to the baseload constraint. The optimal discharging process is then set to fully discharge the battery's available energy into the assigned discharging period, without causing the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC) and without violating the baseload constraint of the net load.

The seasonal storage system will utilise the PV system's curtailed energy due to the grid's baseload constraint in furthering the peak load reduction. The required seasonal storage capacity is determined through the set overall desired peak load reduction ($DPKLR$) in percentage. Since the PV system and the diurnal storage system will contribute in reducing the peak load; the required seasonal storage capacity ($RQ_{Capacity}$) is sized to the sum of the required energy to be discharged ($RQ_{Discharge}$) from the seasonal storage system to achieve its peak load reduction ($PKLR_{SS}$) percentage target. The seasonal storage will be charged fully only from the PV curtailed energy due to the grid's baseload constraint with taken into account the hourly contracted regional export priority factor ($RegExp$) which limits the amount of the PV energy curtailed that can be stored by the seasonal storage system. The optimal discharging process is then set to fully discharge the seasonal storage's available energy into the assigned discharging period in order to lower the current peak load point to the required peak load ($RPKL$) point. A discharge ratio methodology is used to ensure maximising the reduction of the peak load as close as possible to the required peak load ($RPKL$) in case a lower seasonal storage capacity is applied. The next chapter will apply the proposed optimal sizing and energy management strategies of the flexibility measures in the form of case studies in order to validate the technical effectiveness of the proposed flexibility measures and their energy management strategies.

Chapter 7 Case Studies on using Flexibility Measures to Enhance the Grid's Potential Hosting Capacity with Large-scale Integrated PV Plants

7.1 Introduction

This section will apply the flexibility measures illustrated from the previous chapter in the form of case studies in order to enhance the grid's hosting capacity of the large-scale PV system. This can be achieved through applying the flexibility measures targeting each grid constraint that is responsible for the PV system's curtailment. A brief evaluation of the grid's current potential hosting capacity with large-scale PV plants at various penetration levels was presented in Chapter 5. The aforementioned evaluation did not apply the flexibility measures nor was specific in terms of choosing one PV penetration level that will be a country's future renewable energy target. Therefore, the case studies will be based on the Saudi vision 2030 plans of diversifying the economy in which they are committed to install 40 GW of solar PV technology [28]. Furthermore, it will be essential to know the 2030 PV system's penetration level through predicting the 2030 peak load, which can be done via forecasting techniques. The Kingdom's peak load historical data which is obtained from the Electricity and Cogeneration Regulatory Authority (ECRA) [14] and presented in Figure 7.1, shows the significant surge in the peak load during more than the last two decades. That significant surge of the peak load is a result of the increase in energy demand due to the economic and population growth.

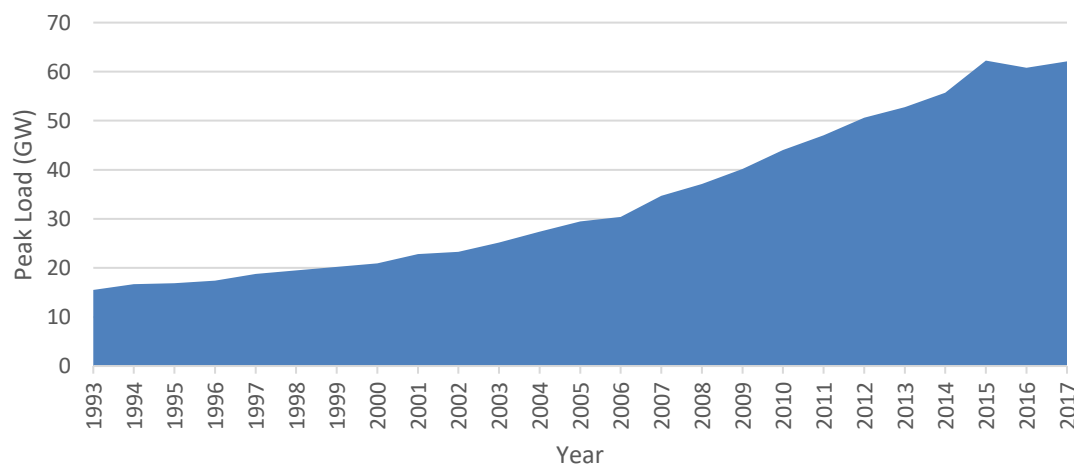


Figure 7.1. Peak Load of KSA (Historical Data).

The authors of [16], applied forecasting techniques to examine the future growth of the Kingdom's electricity sector in which they estimated by 2030, the peak load will be 83.85 GW. Thus, by knowing both the 2030's peak load and planned solar PV capacity; the penetration of that technology can be estimated, and, in this case, it is 48%. Figure 7.2 shows

the Saudi PV capacity target for its 2030 vision and the proposed PV penetration level for the case studies. Since, the hourly load profile of the whole year is required as an input of the model and is difficult to obtain it for the whole country due to the large geographical size and government regulations. Therefore, a specific city or region in the country will be chosen for these case studies. The location of the applied case studies will be in the capital city of Riyadh in the central region of Saudi Arabia in which both the collected 2017 global solar irradiance data and 2017 hourly load profile is used as the input of the model. An assumption will be made that the chosen location will follow the same future growth of the Kingdom's electricity sector, since it will be the location of most of the future mega projects, and in addition has the highest peak load compared to the other regions. Also, due to the kingdom's investment in strengthening the grid and its robust transmission network; it can be assumed that PV power generated will be aggregated across the country.

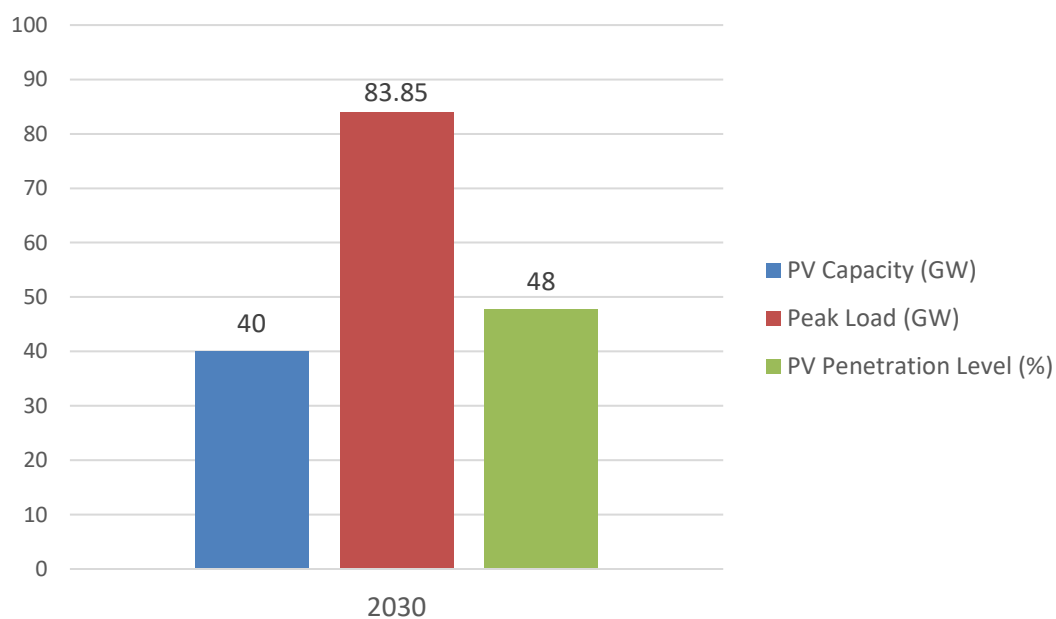


Figure 7.2. PV capacity targets for KSA's 2030 vision and proposed PV penetration level for case studies.

This chapter will present first the base case (case study A) which represents the traditional method of dealing with the PV system's variability in the form of PV curtailment. Then, it will present the case (case study B) with applying the flexibility measure in terms of diurnal storage system with its energy management to target the PV curtailment due to grid's ramping constraint violations. After that, will present the case (case study C) with applying the flexibility measure in terms of seasonal storage system with its energy management to target the PV curtailment due to grid's baseload constraint violations. It is worth mentioning that case study C will include the diurnal storage system applied in case study B. Finally, a discussion will be presented which will consists of a comparison among the three cases and will reflect on the optimal measures.

7.2 Case Study A: Flexibility Measure Not Applied

This part will showcase the grid's traditional method of dealing with its constraints being violated by the large-scale PV system's variable generation. The traditional method is to curtail the PV system's output to ensure the reliability of the grid's operation by abiding to its generation constraints that are in place to maintain the equilibrium between the demand and generation. The PV system performance, frequency stability and netload analysis of both the peak load and ramping stress will be assessed here with only applying the PV curtailment method. In doing so, will provide the base case that will be used to compare with when the flexibility measures are applied. The applied grid constraints are 4282 MW for the baseload constraint and 1268 MW for the ramping constraint. Also, it is assumed that there are no transmission constraints in terms of congestion or interconnected capability to import or export power from neighbouring grids.

7.2.1 PV System Performance

The PV system performance evaluation will be focused on the quantity and frequency of the energy curtailed from the PV system due to the grid's constraints. This can be accomplished through measuring the number of PV curtailment events, PV curtailment sum, PV curtailment percentage, PV capacity factor reduction and the highest PV energy curtailed per day and hour. The PV system model developed in chapter 4 will be used in this part. Table 7.1 shows the overall assessment of the PV system's performance in terms of curtailing the PV system due to the grid's constraints without applying the flexibility measure.

Table 7.1. Overall assessment of the PV system's performance in terms of curtailing the PV system due to the grid's constraints without applying the flexibility measures.

Parameters	Due to Baseload Constraint	Due to Ramping Constraint
Number of PV Curtailment Events	1371	521
PV Curtailment Sum (GWh)	2915	315
PV Curtailment Percentage (%)	18.29	2.42
Highest PV Curtailed Energy in a Day (GWh/day)	35.527	3.983
Highest PV Curtailed Energy in an Hour (GWh)	5.233	1.804
Overall PV Capacity Factor Reduction (%)	8.36	0.91

The overall assessment of the PV system's performance throughout the year without applying the flexibility measure shown in Table 7.2; showcased the significant difference that each grid constraint has on performance of the PV system. In particular, the baseload constraint results are at least more than double the results of the ramping constraint. Therefore, the flexibility measure applied might not be optimally or economically suitable to tackle at the same instance leading to the point of having flexibility measures that target each grid constraint on itself. Furthermore, having the PV capacity factor reduced by more than 9% and having the PV system's full year output curtailed by more than 20% are indications that grid

needs a flexibility measures in order to ensure the full economical utilisation of the PV system in the generation mix. It is worth mentioning that the highest PV curtailed energy in a day can satisfy at least 25% of the required load in a day of the winter season in which the load profile is at its lowest. Also, as the load profile and PV system output will vary throughout the year; it is important to show the PV system performance of each month, and this is shown in Figures 7.3-7.8.

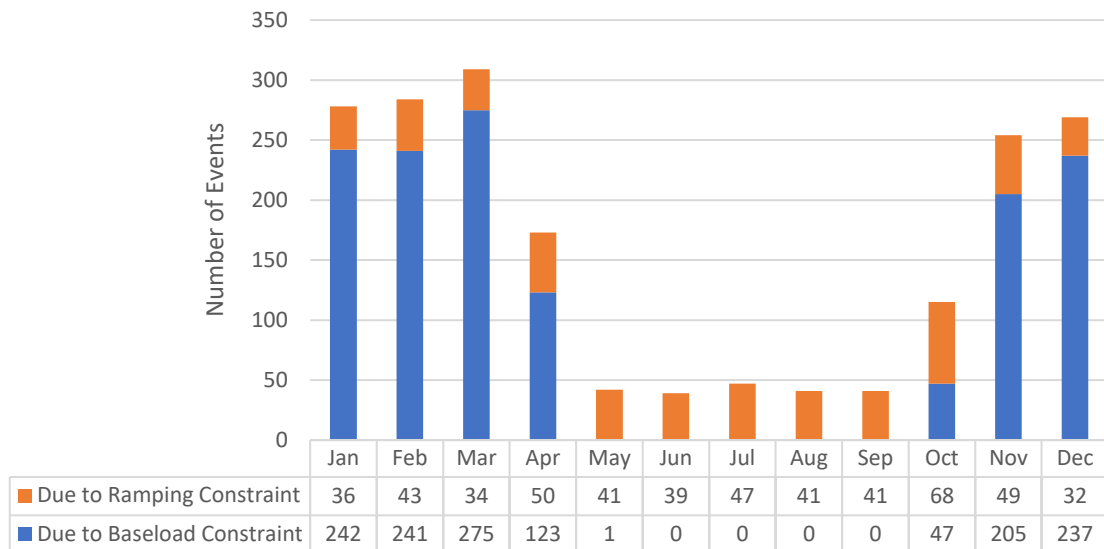


Figure 7.3. Number of PV curtailment events for each month due to the grid's constraints without applying the flexibility measures.

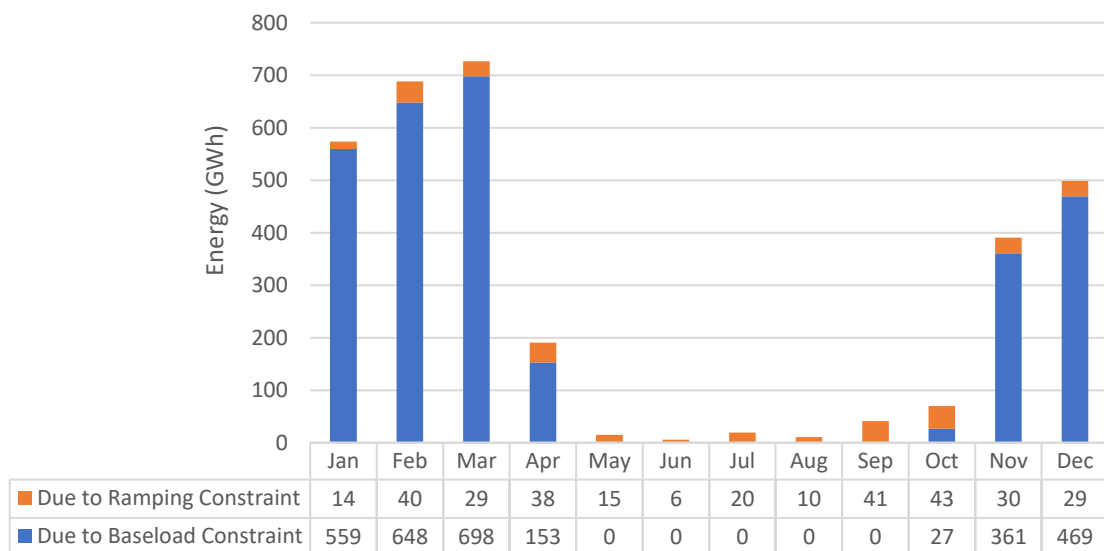


Figure 7.4. Sum of PV system's curtailed energy in GWh for each month due to the grid's constraints without applying the flexibility measures

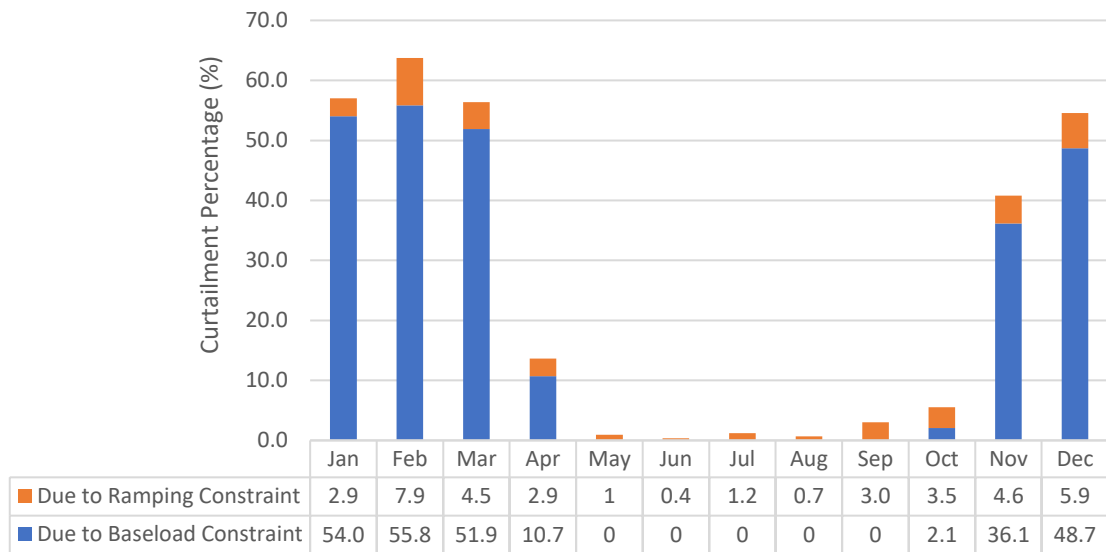


Figure 7.5. PV system's curtailment percentage for each month due to the grid's constraints without applying the flexibility measures.

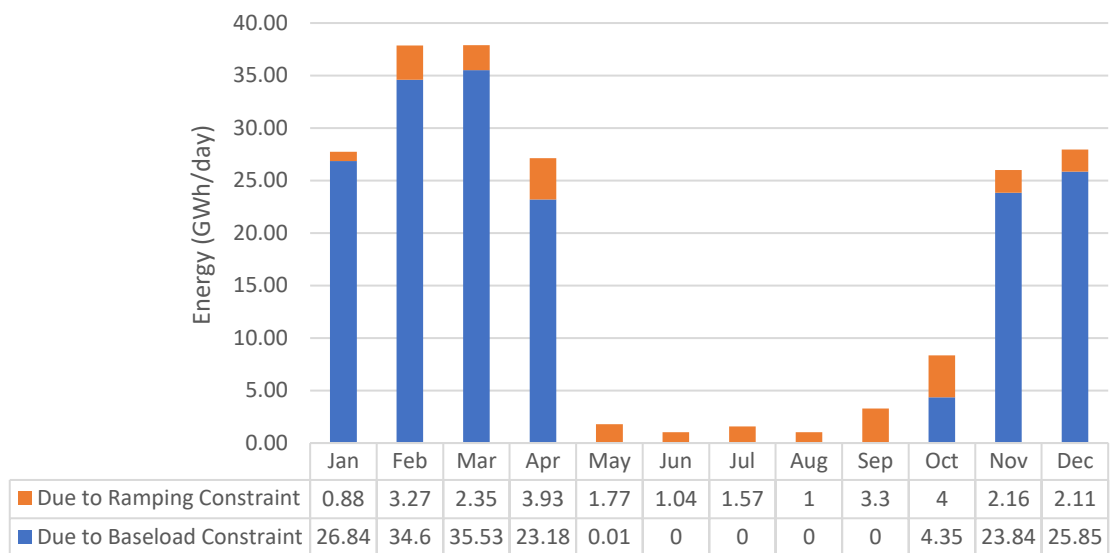


Figure 7.6. PV system's highest curtailed energy in a day (GWh/day) for each month due to the grid's constraints without applying the flexibility measures.

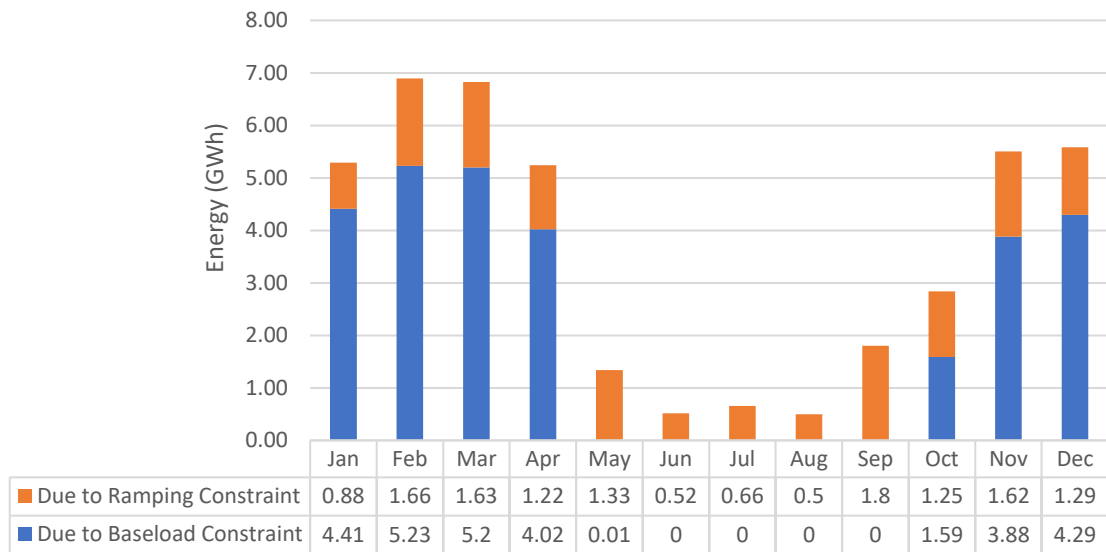


Figure 7.7. PV system's highest curtailed energy in an hour (GWh) for each month due to the grid's constraints without applying the flexibility measure.

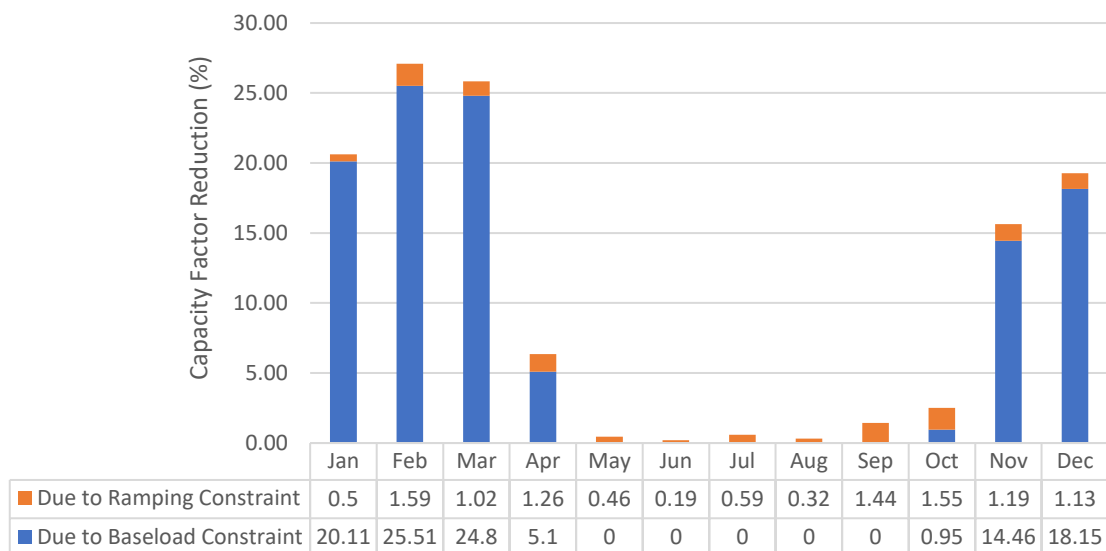


Figure 7.8. PV system's capacity factor reduction (%) for each month due to the grid's constraints without applying the flexibility measures.

According to the PV system performance of each month shown in Figures 7.3-7.8; the effects of the ramping constraint are present throughout the year meanwhile the baseload constraint effects are only present in the winter season where the load profile is at its lowest. Therefore, a diurnal source of flexibility is required to manage the ramping constraint effects while a seasonal source of flexibility is required to manage the baseload constraint effects. Also, it will be beneficial to examine the PV system performance at a more PV accommodating grid through lowering the baseload constraint and increasing the ramping constraint.

7.2.1.1 PV System Curtailment at Lower Baseload Constraints

This part will showcase the lowering of the baseload constraint (4282 MW) by 25% reduction steps in order to examine the curtailment of the PV system. The PV curtailment's number of events and full year sum; will decrease as we keep reducing the baseload constraint according to Figures 7.9-7.10 respectively. Also, the PV system's highest curtailed energy in a day and in an hour; will decrease as we keep reducing the baseload constraint according to Table 7.2. It is worth mentioned that for each 25% reduction step of the baseload constraint; the effectiveness or PV curtailed energy utilisation decreases. For example, the PV curtailed energy utilisation will be 44% if we decrease the baseload constraint by 25% based on Figure 7.10. Meanwhile, the PV curtailed energy utilisation will be 31% if we further decrease the baseload constraint from 25% to 50% based on Figure 7.10. It is worth mentioning that even if we completely shut down the grid's conventional generation system by not having a baseload constraint; there will be still roughly 12 GWh of PV over-generation throughout the year.

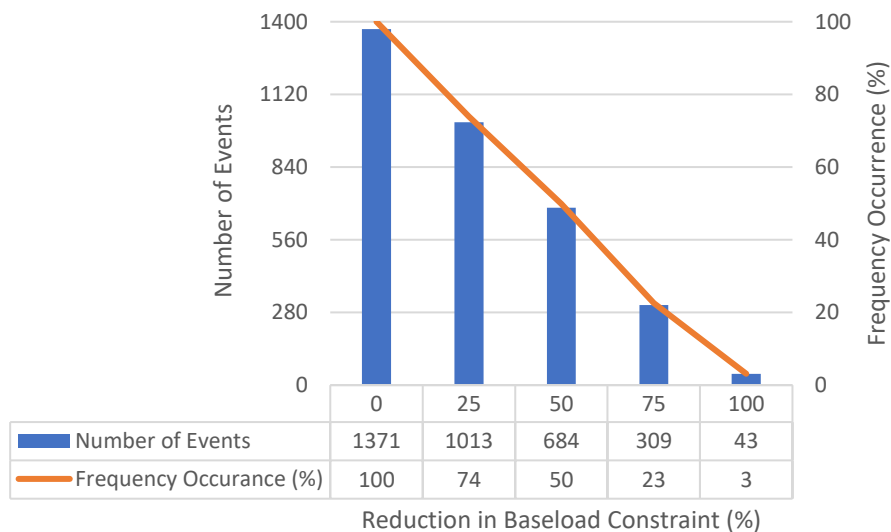


Figure 7.9. Number of PV curtailment events and its frequency occurrence at reduced baseload constraints without applying the flexibility measures.

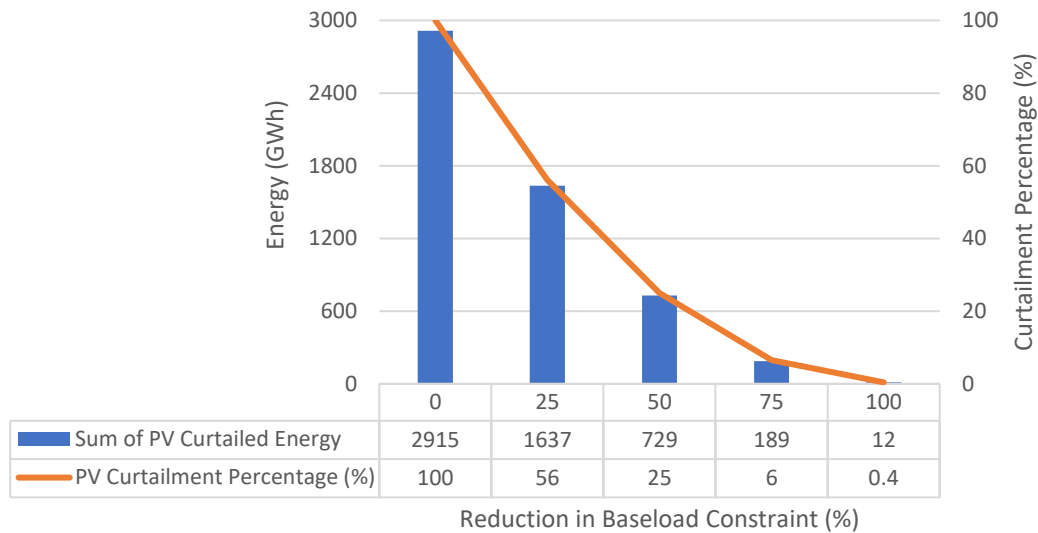


Figure 7.10. Sum of PV system's curtailed energy in GWh and its curtailment percentage at reduced baseload constraints without applying the flexibility measures.

Table 7.2. PV system's highest curtailed energy in a day (GWh/day) and in an hour (GWh) at reduced baseload constraints without applying the flexibility measures.

Reduction in Baseload Constraint (%)	Highest PV Curtailed Energy in a Day (GWh/day)	Highest PV Curtailed Energy in an Hour (GWh)
0	35.527	5.223
25	25.254	4.162
50	16.201	3.092
75	8.597	2.021
100	2.711	0.951

7.2.1.1 PV System Curtailment at Higher Ramping Constraints

This part will showcase the increasing of the ramping constraint (1268 MW) by 25% increase steps in order to examine the curtailment of the PV system. The PV curtailment's number of events and full year sum; will decrease as we keep increasing the ramping constraint according to Figures 7.11-7.12 respectively. Also, the PV system's highest curtailed energy in a day and in an hour; will decrease as we keep increasing the ramping constraint according to Table 7.3. It is worth mentioned that for each 25% step increase of the ramping constraint; the effectiveness or PV curtailed energy utilisation decreases. For example, the PV curtailed energy utilisation will be 69% if we increase the ramping constraint by 25% based on Figure 7.12. Meanwhile, the PV curtailed energy utilisation will be 20% if we further increase the ramping constraint from 25% to 50% based on Figure 7.12.

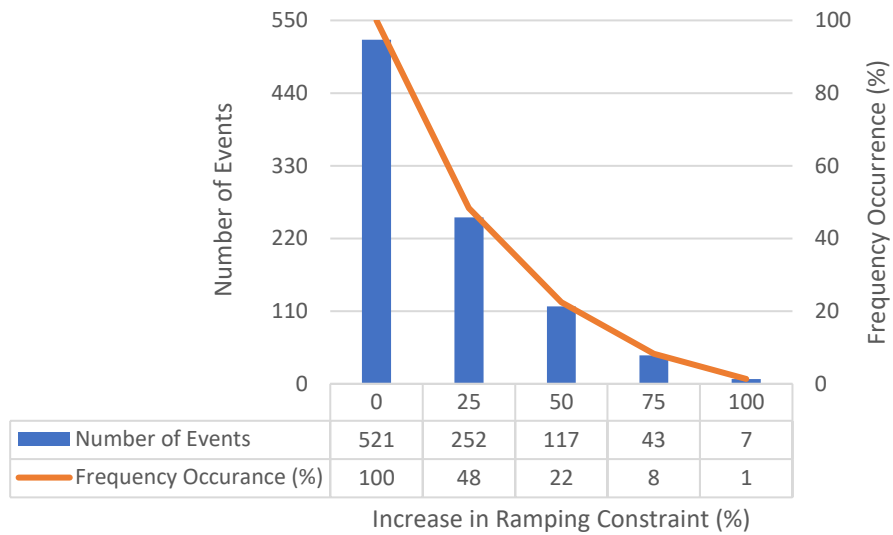


Figure 7.11. Number of PV curtailment events and its frequency occurrence at increased ramping constraints without applying the flexibility measures.

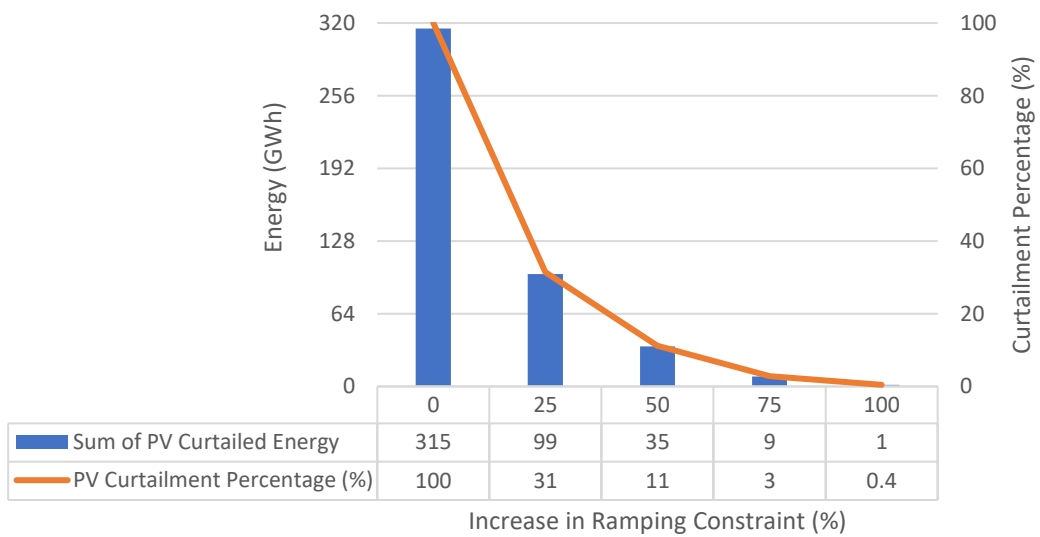


Figure 7.12. Sum of PV system's curtailed energy in GWh and its curtailment percentage at increased ramping constraints without applying the flexibility measures.

Table 7.3. PV system's highest curtailed energy in a day (GWh/day) and in an hour (GWh) at increased ramping constraints without applying the flexibility measures.

Increase in Ramping Constraint (%)	Highest PV Curtailed Energy in a Day (GWh/day)	Highest PV Curtailed Energy in an Hour (GWh)
0	3.983	1.804
25	1.882	1.487
50	1.170	1.170
75	0.853	0.853
100	0.536	0.536

7.2.2 Frequency Stability

According to the grid code of Saudi Arabia [279], the following points will be applied to the conventional generation system of the grid in order to determine the frequency change:

- The nominal frequency is at 60 Hz.
- All generating units must be capable of supplying their rated active output power within the system frequency range of 59.5 to 60.5 at the connection point.
- Each synchronous generation unit is fitted with a fast-acting speed governor system to aid with the control of the power and frequency.
- The governor drop setting shall have an adjustable value within 2% to 8% to regulate the frequency of the system. However, the normal set point of governor drop setting is generally set at 5% which will be used throughout.

From the earlier mentioned points of the grid code, it can be deduced that when the frequency change or deviation is higher than ± 0.5 Hz it causes the conventional generation system to be disconnected from the grid; thus, the loss of load phenomena occurs. For this scenario, the drop or speed regulation (R) at the normal set point of the governor droop setting (5%) is equalled to 1.875×10^{-4} Hz/MW. The grid's frequency (Hz) stability representation throughout the year without the inclusion of the PV system is shown in Figure 7.13. Figure 7.13 shows that the frequency of the grid throughout the year was well maintained. The Duration curve for the grid's frequency (Hz) throughout the year with and without applying curtailment on the PV system is shown in Figure 7.14. This duration curve shows that the grid's frequency is not stable when the PV curtailment is not applied due to having a frequency deviation higher than ± 0.5 Hz allowable range. Overall assessment of the grid's frequency stability in terms of the highest and lowest frequency due to integrating the PV system to it without applying the flexibility measure is shown in Table 7.4. The frequency changed for the better when the grid constraints were applied in which this positive affect on the frequency stability was due to the reduced participation of the PV system.

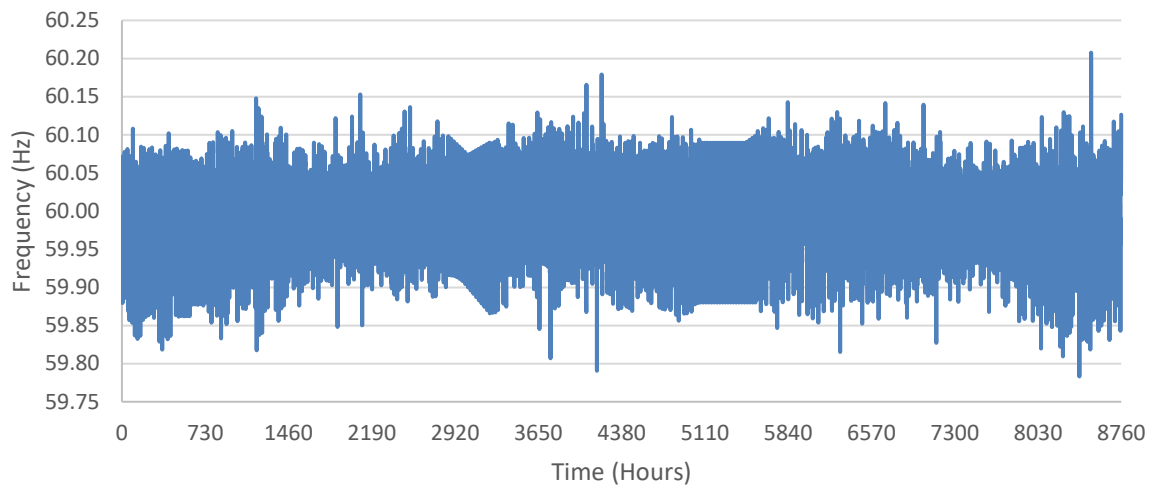


Figure 7.13. Grid's frequency (Hz) stability representation throughout the year without the inclusion of the PV system.

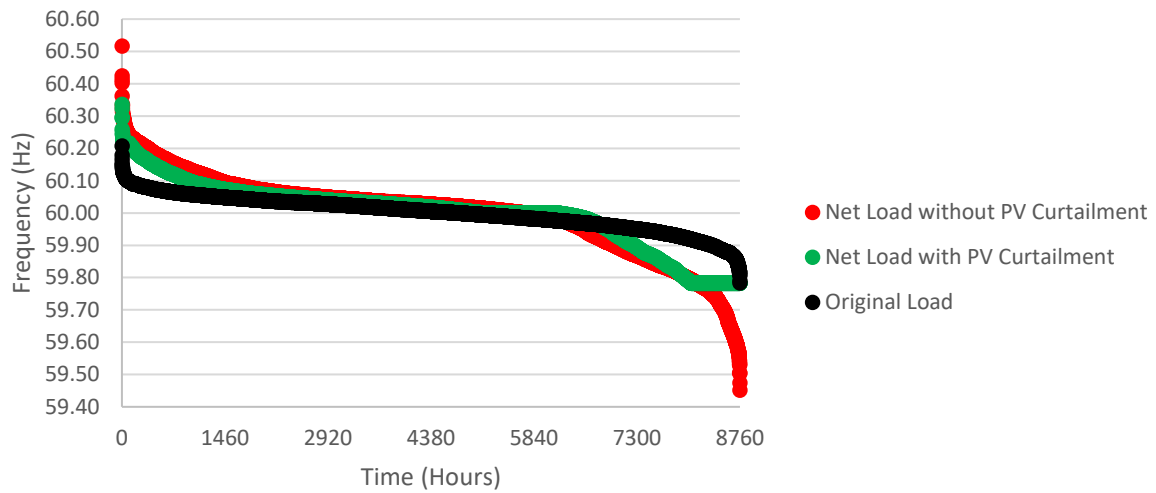


Figure 7.14. Duration curve for the grid's frequency (Hz) throughout the year with and without applying curtailment on the PV system.

Table 7.4. Overall assessment of the grid's frequency stability due to integrating the PV system to it without applying the flexibility measures.

Parameters	Highest Frequency (Hz)	Lowest Frequency (Hz)
Original Load	60.21	59.78
Net Load without PV Curtailment	60.52	59.45
Net Load with PV Curtailment	60.34	59.78

7.2.3 Net Load Analysis

The net load analysis in this part will showcase the performance of the grid's conventional generation system without applying the flexibility measure. The peak load will represent the needed capacity to meet the load while the ramping stress will represent the cycling needed by the conventional generation system to accommodate the PV system generation.

7.2.3.1 Peak Load

The load duration curve throughout the year with and without applying the curtailment on the PV system is shown in Figure 7.15. The peak load is not affected by the PV curtailment process since the peak load reduction was 5.66 % for both with and without applying the PV curtailment according to the overall assessment of the peak load reduction (%) shown in Table 7.5. This is because the peak load occurs in the middle of the day where there is abundant PV energy. Thus, the new peak load will shift to the afternoon period of the same day where there is less or no PV energy available. Furthermore, the peak load for each month with and without applying the curtailment on the PV system is shown in Table 7.6.

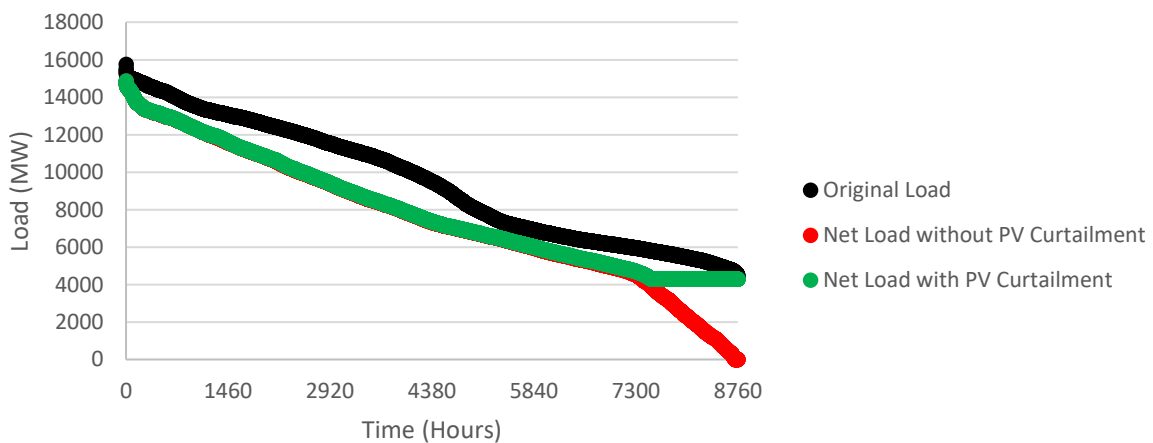


Figure 7.15. Load duration curve throughout the year with and without applying curtailment on the PV system.

Table 7.5. Overall assessment of the peak load reduction (%) due to integrating the PV system to the grid without applying the flexibility measures.

Parameters	Peak Load (MW)	Peak Load Reduction (%)
Original Load	15753	0
Net Load without PV Curtailment	14860	5.66
Net Load with PV Curtailment	14860	5.66

Table 7.6. Peak load (MW) for each month with and without applying curtailment on the PV system.

Parameters	Peak Load (MW)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Original Load	7395	8719	8915	11565	14993	15753	15517	15099	14088	12253	8947	8259
Net Load without PV Curtailment	7369	8719	8915	11310	13817	14284	14860	14545	13489	11810	8942	8185
Net Load with PV Curtailment	7369	8719	8915	11310	13817	14284	14860	14545	13489	11810	8942	8185

7.2.3.2 Ramping Stress

The duration curve of the ramping requirements throughout the year with and without applying the curtailment on the PV system is shown in Figure 7.16. The ramping requirements without applying the PV curtailment will be at least more than 148% of the ramping requirements for the original load according to the overall assessment of the ramping requirements shown in Table 7.7. Furthermore, the ramping requirements for each month with and without applying the curtailment on the PV system is shown in Table 7.8. It is worth mentioning that the ramping requirements of the winter months are generally higher than the summer months. This can be due to the peak load occurring in the afternoon period which means there will be a steeper ramping requirement as the PV system's generation ceases.

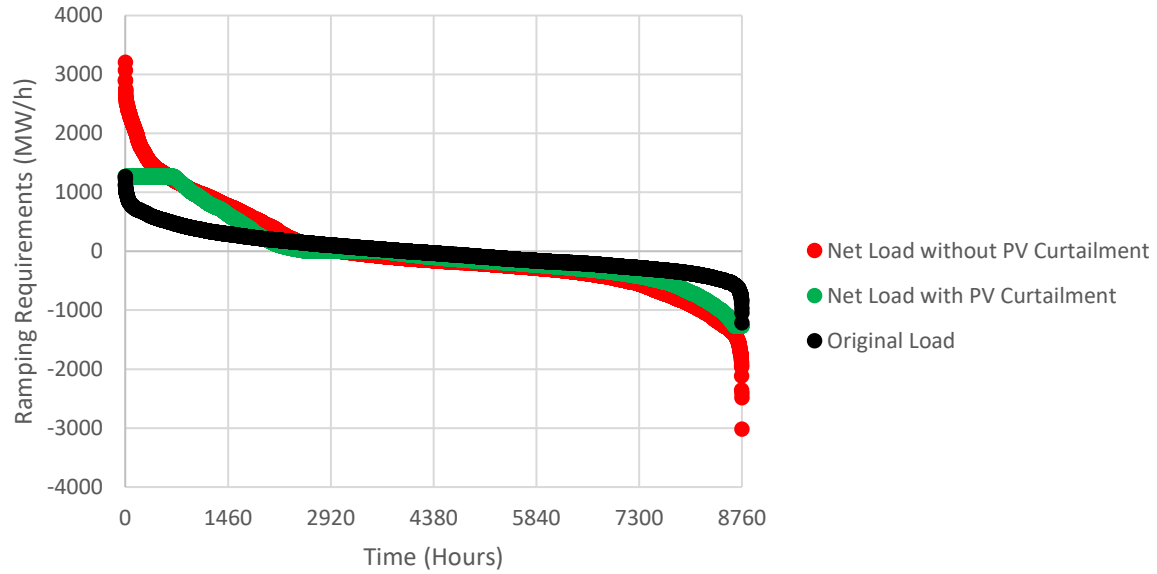


Figure 7.16. Duration curve of the ramping requirements (MW/h) throughout the year with and without applying curtailment on the PV system.

Table 7.7. Overall assessment of the ramping requirements (MW/h) due to integrating the PV system to the grid without applying the flexibility measures.

Parameters	Ramping Requirements (MW/h)	
	Up Ramping	Down Ramping
Original Load	1268	1214
Net Load without PV Curtailment	3207	3018
Net Load with PV Curtailment	1268	1268

Table 7.8. Ramping requirements (MW/h) for each month with and without applying curtailment on the PV system.

Parameters		Ramping Requirements (MW/h)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Original Load	Up Ramping	1062	1067	888	693	784	1224	841	896	1080	1010	845	1268
	Down Ramping	632	864	894	797	672	1047	721	712	835	828	541	1214
Net Load without PV Curtailment	Up Ramping	2735	2571	2899	2456	2596	1503	1889	1763	3072	2116	3207	2676
	Down Ramping	2117	1743	3018	2484	1427	1787	1650	1150	1964	1674	2412	1772
Net Load with PV Curtailment	Up Ramping	1268	1268	1268	1268	1268	1268	1268	1268	1268	1268	1268	1268
	Down Ramping	1025	1268	1268	1268	1268	1268	1268	1150	1268	1268	1268	1268

7.3 Case Study B: Flexibility Measure Applied for Ramping Constraint

This part will apply a flexibility measure that will overcome the grid's ramping constraint affects that are shown in case study A. The flexibility measure applied here will be a diurnal storage system that comprises of lithium-ion batteries and will be optimally managed to reduce the PV energy curtailed due to the grid's ramping constraint. The daily required storage capacity (MWh) to eliminate the curtailment of the PV system's output due to the grid's ramping constraint at various PV penetration levels is shown in Figure 7.17. The daily required storage capacity increases as the PV system's penetration level increase. The deduced daily required capacity ($RQ_{Capacity}$) of the battery storage system (BSS) for each month to eliminate the curtailment of the PV system's output due to the grid's ramping constraint varies for each month according to Table 7.9. To fully eliminate the PV curtailed energy; the maximum deduced daily required capacity ($RQ_{Capacity}$) of the BSS must be chosen and, in this case, it is the February one with a value of 2918 MWh.

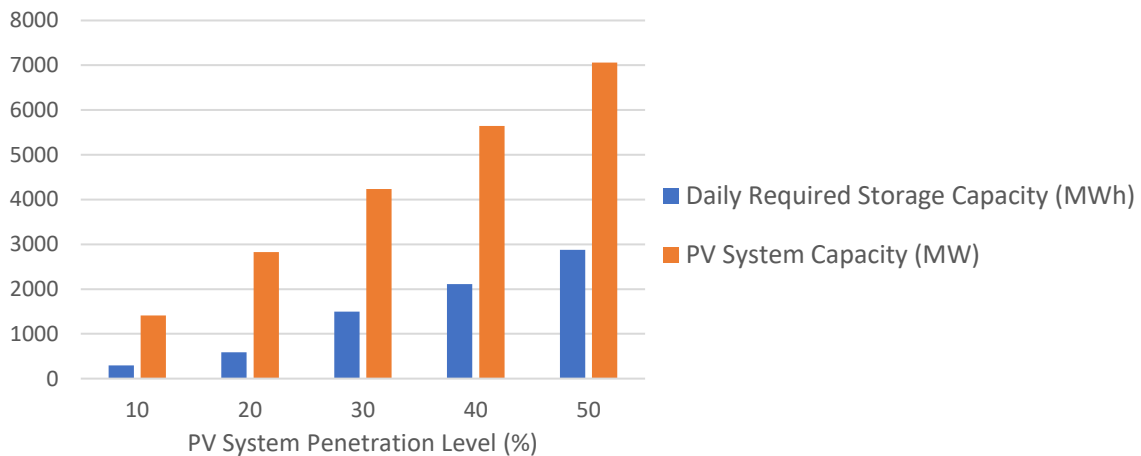


Figure 7.17. Daily required storage capacity (MWh) to eliminate the curtailment of the PV system's output due to grid's ramping constraint at various PV penetration levels.

Table 7.9. Deduced daily required capacity ($RQ_{Capacity}$) of BSS in MWh for each month to eliminate the curtailment of the PV system's output due to grid's ramping constraint.

Deduced Daily Required Capacity ($RQ_{Capacity}$) of BSS (MWh)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1266	2918	2151	2110	1317	243	779	685	1117	2376	2175	1974

The daily required capacity ($RQ_{Capacity}$) of the battery storage system (BSS) will decrease as we increase the grid's ramping constraint which is clearly illustrated in Figure 7.18. A comparison presented in Figure 7.19; illustrates that the majority of the PV curtailed energy happens in the afternoon period in which 91% of the PV curtailed energy due to the grid's ramping constraint is located at. The PV system performance, frequency stability and netload analysis of both the peak load and ramping stress will be assessed here at various (d) battery

system's desired sizing percentage to the battery's maximum daily required capacity ($RQ_{Capacity}$). In addition, the BSS performance in terms of capacity loss due to degradation will be assessed here as well. The applied grid constraints are 4282 MW for the baseload constraint and 1268 MW for the ramping constraint. Also, it is assumed that there are no transmission constraints in terms of congestion or interconnected capability to import or export power from neighbouring grids. In addition, the BSS's round-trip efficiency is set at 95% with operating at 100% depth of discharge (DOD) and in an ambient temperature of 10° Celsius throughout this case study.

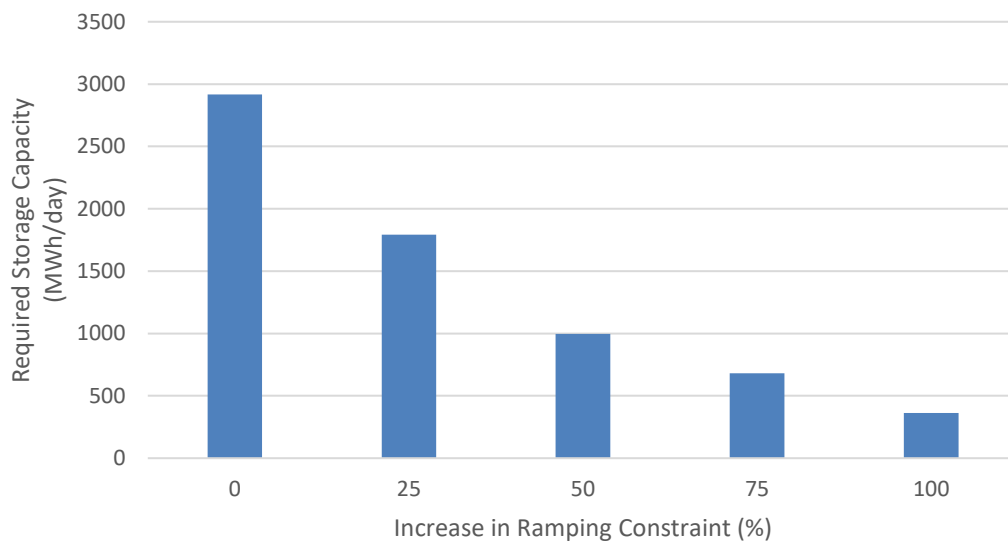


Figure 7.18. Daily required storage capacity (MWh) to eliminate the curtailment of the PV system's output due to grid's ramping constraint at increased ramping constraints.

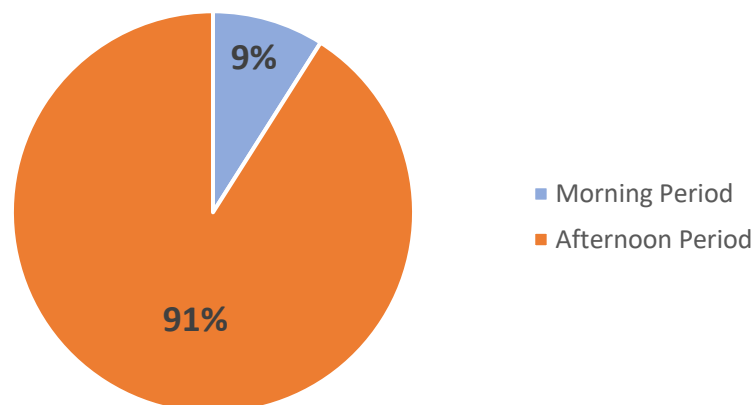


Figure 7.19. Comparison between the morning and afternoon period in terms of the PV system's curtailment percentage due to grid's ramping constraint without applying the flexibility measure.

7.3.1 PV System Performance

The PV curtailment's number of events will sharply decrease as we keep increasing the sizing percentage (d) of the BSS according to Figure 7.20. The PV curtailment's full year sum, curtailment percentage, highest curtailed energy in a day and in an hour; will sharply decrease as we keep increasing the sizing percentage (d) of the BSS according to Tables 7.10-7.11. It is worth mentioned that for each 25% increase step of the sizing percentage (d) of the BSS; the effectiveness or PV curtailed energy utilisation decreases. For example, the PV curtailed energy utilisation will be 72% if we increase the sizing percentage (d) of the BSS by 25% based on Table 7.10. Meanwhile, the PV curtailed energy utilisation will drop to 22.92% if we further increase the sizing percentage (d) of the BSS from 25% to 50% based on Table 7.10. Furthermore, the BSS's energy management have managed to decrease the PV curtailed energy due to the baseload constraint as well. This is the result of utilising the PV curtailed energy due the grid's baseload constraint in charging the BSS. There is still PV curtailed energy at 100% sizing percentage (d) of the BSS which is due to the round-trip efficiency and the capacity loss of the BSS caused by degradation over time and frequent usage. Therefore, we can over size the BSS capacity if the goal is to achieve absolute utilisation of the PV curtailed energy due to the grid's ramping constraint. The BSS at 100% sizing percentage (d) will need to be oversized by 9% if we take into account the BSS capacity degradation and round-trip efficiency which in return will utilise the remaining 224 MWh of the PV curtailed energy due to the grid's ramping constraint.

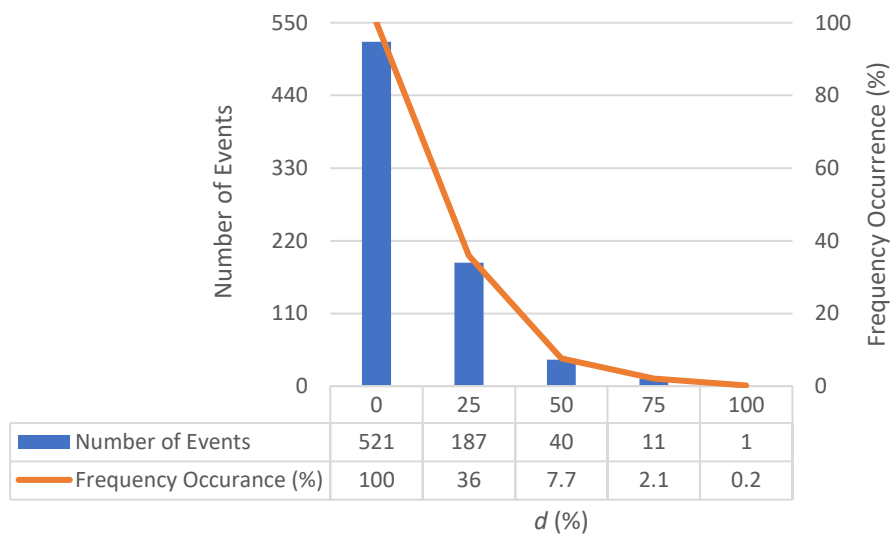


Figure 7.20. Number of PV curtailment events and its frequency occurrence at various (d) battery system's desired sizing percentage to the battery's maximum required capacity to fully utilise the PV system's curtailed energy.

Table 7.10. Sum of PV system's curtailed energy in GWh and its curtailment percentage at various (d) battery system's desired sizing percentage to the battery's maximum required capacity to fully utilise the PV system's curtailed energy.

d (%)	Due to Ramping Constraint		Due to Baseload Constraint	
	PV Curtailment Sum (GWh)	PV Curtailment Percentage (%)	PV Curtailment Sum (GWh)	PV Curtailment Percentage (%)
0	315	100	2915	100
25	89	28	2798	96
50	16	5.08	2678	92
75	2.96	0.94	2564	88
100	0.224	0.07	2459	84

Table 7.11. PV system's highest curtailed energy in a day (GWh/day) and in an hour (GWh) at various (d) battery system's desired sizing percentage to the battery's maximum required capacity to fully utilise the PV system's curtailed energy due to grid's ramping constraint.

d (%)	Highest PV Curtailed Energy in a Day (GWh/day)	Highest PV Curtailed Energy in an Hour (GWh)
0	3.983	1.804
25	3.178	1.545
50	1.082	1.082
75	0.898	0.898
100	0.224	0.224

7.3.2 Frequency Stability

Overall assessment of the grid's frequency stability at various sizing percentage (d) of the BSS to fully utilise the PV system's curtailed energy due to the grid's ramping constraint is shown in Table 7.12. The frequency stability improves as we keep increasing the sizing percentage (d) of the BSS. This is because the highest and lowest frequency keeps getting closer to the nominal frequency (60 Hz). The highest frequency with curtailment applied in case study A was 60.34 Hz which means having the sizing percentage (d) of the BSS at least at 25%; will show better frequency stability performance. On the other hand, the lowest frequency with curtailment applied in case study A was 59.78 Hz which means having the sizing percentage (d) of the BSS at 100%; will show a closer frequency stability performance. This is due to the frequency stability reducing as the up ramping requirement increases and in case there is not enough BSS capacity the grid will apply the PV curtailment method which means the lowest frequency will be 59.78 Hz again.

Table 7.12. Overall assessment of the grid's frequency stability at various (d) battery system's desired sizing percentage to the battery's maximum required capacity to fully utilise the PV system's curtailed energy due to grid's ramping constraint.

<i>d</i> (%)	Highest Frequency (Hz)	Lowest Frequency (Hz)
0	60.42	59.47
25	60.31	59.52
50	60.30	59.60
75	60.22	59.63
100	60.22	59.74

7.3.3 Net Load Analysis

The net load analysis in this part will showcase the performance of the grid's conventional generation system with applying the diurnal storage flexibility measure to overcome the grid's ramping constraint affects.

7.3.3.1 Peak Load

The peak load is not affected by the PV curtailment process since the new peak load will shift from the middle of the day to the afternoon period of the same day where there is less or no PV energy available. There will be further peak load reduction as we keep increasing the sizing percentage (*d*) of the BSS according to the overall assessment of the further peak load reduction (%) with applying the diurnal storage flexibility measure at various sizing percentage (*d*) shown in Table 7.13. This is because the energy management of the BSS that is designed to overcome the grid's ramping constraint will discharge its energy in the afternoon period where there is less, or no PV energy generated. Furthermore, the peak load for each month with applying the diurnal storage flexibility measure at various sizing percentage (*d*) is shown in Table 7.14.

Table 7.13. Overall assessment of the further peak load reduction (%) with applying the flexibility measure for the grid's ramping constraint at various (d) battery system's desired sizing percentage to the battery's maximum required capacity.

<i>d</i> (%)	Peak Load (MW)	Further Peak Load Reduction (%)
0	14860	0
25	14785	0.50
50	14678	1.22
75	14570	1.95
100	14463	2.67

Table 7.14. Peak load (MW) for each month with applying the flexibility measure for the grid's ramping constraint at various (d) battery system's desired sizing percentage to the battery's maximum required capacity.

d (%)	Peak Load (MW)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	7369	8719	8915	11310	13817	14284	14860	14545	13489	11810	8942	8185
25	7232	8719	8804	11279	13817	14186	14785	14334	13489	11708	8860	8077
50	7119	8719	8694	11189	13817	14078	14678	14228	13460	11602	8755	8077
75	6949	8596	8584	11105	13817	14060	14570	14121	13354	11496	8696	8073
100	6867	8429	8533	11105	13817	14060	14463	14014	13248	11473	8696	7947

7.3.3.2 Ramping Stress

The ramping requirements will keep getting closer to the ramping requirements of the original load as we keep increasing the sizing percentage (d) of the BSS according to the overall assessment of the ramping requirements with applying the diurnal storage flexibility measure at various sizing percentage (d) shown in Table 7.15. Furthermore, the ramping requirements for each month with applying the diurnal storage flexibility measure at various sizing percentage (d) is shown in Table 7.16. It is worth mentioning that even if we set the sizing percentage (d) of the BSS at 100%; the up ramping requirements will still exceed the original load's one (1268 MW). This can be due to the round-trip efficiency and capacity loss of the BSS since its capacity will experience degradation over time and frequent usage.

Table 7.15. Overall assessment of the ramping requirements (MW/h) with applying the flexibility measure for the grid's ramping constraint at various (d) battery system's desired sizing percentage to the battery's maximum required capacity.

d (%)	Ramping Requirements (MW/h)	
	Up Ramping	Down Ramping
0	3072	2484
25	2813	1798
50	2350	1742
75	2166	1295
100	1492	1268

Table 7.16. Ramping requirements (MW/h) for each month with applying the flexibility measure for the grid's ramping constraint at various (d) battery system's desired sizing percentage to the battery's maximum required capacity.

		Ramping Requirements (MW/h)											
d (%)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	Up Ramping	2151	2571	2899	2456	2596	1503	1889	1763	3072	2076	2890	2557
	Down Ramping	1025	1701	1479	2484	1427	1787	1650	1150	1964	1674	1590	1326
25	Up Ramping	1848	2350	2754	2409	1909	1268	1403	1313	2402	2063	2813	2524
	Down Ramping	1025	1268	1242	1481	1268	1557	1268	1150	1798	1632	1268	1243
50	Up Ramping	1268	2350	2089	1749	1274	1268	1268	1268	1732	1738	2182	1988
	Down Ramping	1025	1268	1242	1268	1268	1268	1268	1268	1742	1268	1268	1243
75	Up Ramping	1268	2166	1424	1268	1268	1268	1268	1268	1268	1662	1551	1360
	Down Ramping	1025	1268	1242	1268	1268	1268	1268	1268	1295	1268	1268	1243
100	Up Ramping	1268	1492	1268	1268	1268	1268	1268	1268	1268	1268	1268	1268
	Down Ramping	1025	1268	1242	1268	1268	1268	1268	1268	1268	1268	1268	1243

7.3.4 BSS Performance

The performance of the lithium-ion BSS in terms of capacity loss due to degradation will be assessed here. The assessment will focus on varying the factors that impacts the BSS's capacity loss such as the BSS ambient temperature and depth of discharge (DOD). The BSS's capacity degradation throughout the year at 100 % DOD and an operating temperature of 10° Celsius is shown in Figure 7.21. The BSS will lose 9.82% of its capacity in those conditions at the end of the year. The BSS's capacity loss at a lower operating temperature will be at a minimum according to the analysis of BSS capacity loss (%) throughout the years at various operating temperatures shown in Figure 7.22. On the other hand, the BSS's capacity loss at a lower DOD will be at a minimum according to the analysis of BSS capacity loss (%) throughout the years at various DOD shown in Figure 7.23. Therefore, the optimal method of reducing the BSS's capacity loss and maintaining the BSS's state of health is to operate at a low ambient temperature and low depth of discharge.

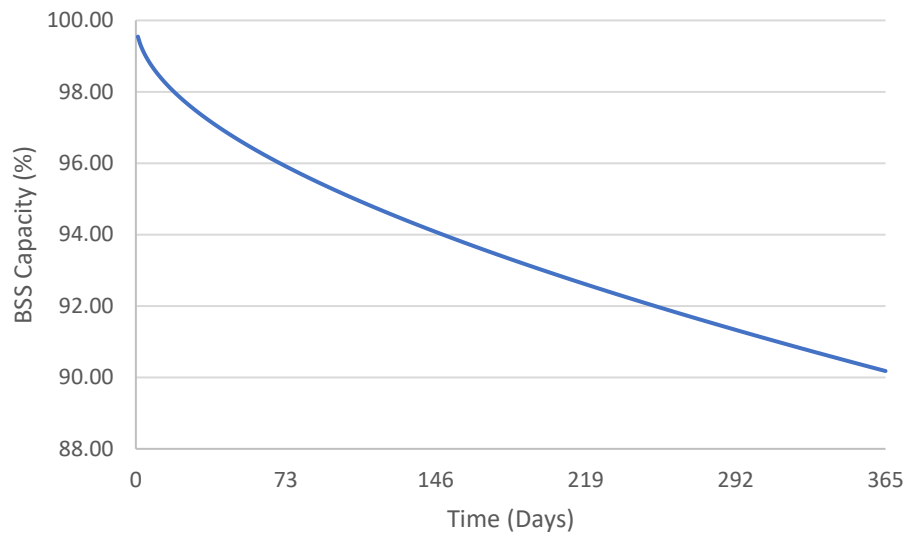


Figure 7.21. BSS capacity degradation throughout the year at 100 % DOD and operating temperature of 10° Celsius.

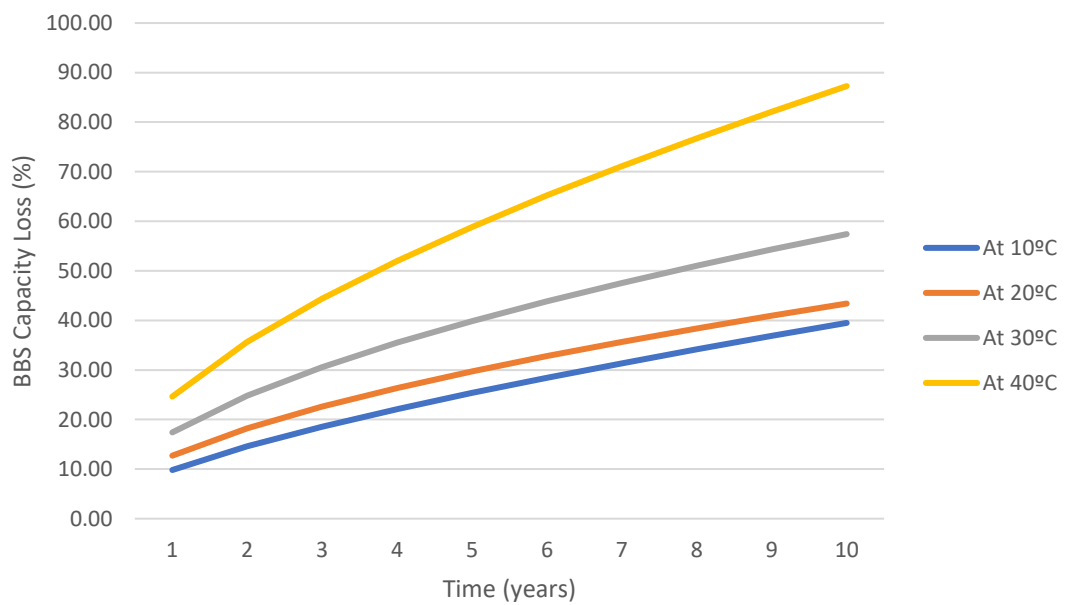


Figure 7.22. BSS capacity loss (%) throughout the years at various operating temperatures (Celsius) and 100 % DOD.

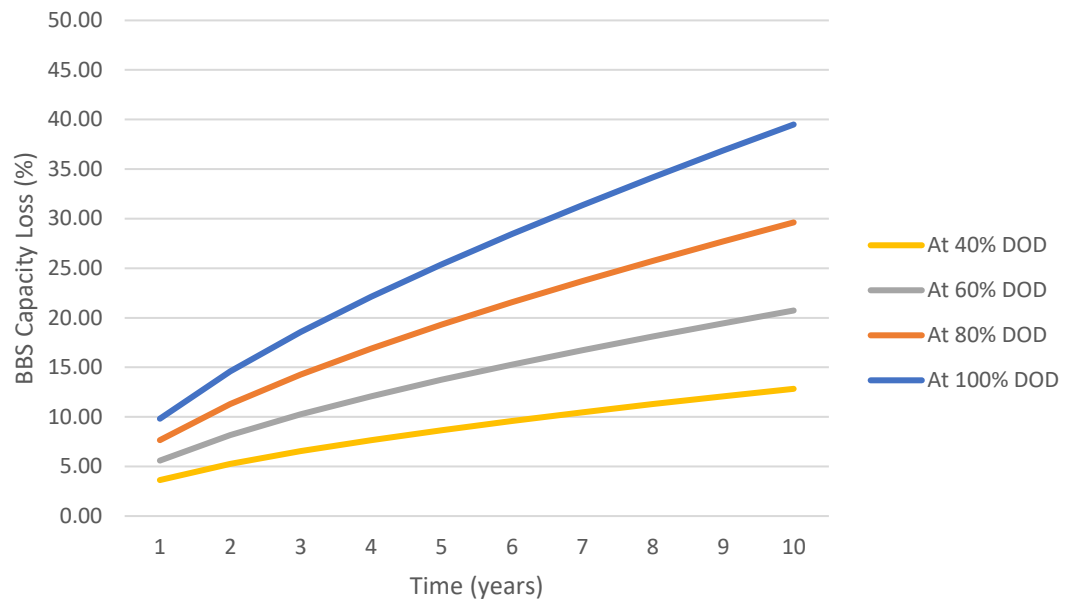


Figure 7.23. BSS capacity loss (%) throughout the years at various DOD (%) and an operating temperature of 10° Celsius.

7.4 Case Study C: Flexibility Measure Applied for Baseload Constraint

This part will apply a flexibility measure that will overcome the grid's baseload constraint affects that are shown in case study A. The flexibility measure applied here will be a seasonal storage system with a round-trip efficiency set at 70%. The reason for chosen that slightly higher round-trip efficiency of the seasonal storage is due to taken into account the constant and future development of improving the round-trip efficiency. The seasonal storage system will be optimally managed to reduce the PV energy curtailed due to the grid's baseload constraint via utilising its energy in furthering the reduction of the peak load. The applied grid constraints are 4282 MW for the baseload constraint and 1268 MW for the ramping constraint. Also, it is assumed that there are no transmission constraints in terms of congestion and there is regional export capability to neighbouring countries.

The required seasonal storage capacity (GWh) to achieve the overall desired peak load reduction (DPKLR) in percentage at various contracted regional export priority factors (RegExp) is shown in Figure 7.24. The hourly contracted regional export priority factor (RegExp) limits the amount of the PV energy curtailed due to the grid's baseload constraint that can be stored by the seasonal storage system. Also, the hourly contracted regional export priority factor (RegExp) is only applied in the charging period of the seasonal storage which is from January till the end of April. The maximum achievable overall desired peak load reduction (DPKLR) at ideal conditions is 27.4% when there is no hourly contracted regional export priority factor (RegExp) set in place. Meanwhile, the maximum achievable overall desired peak load reduction (DPKLR) at ideal conditions is 24.3% when there is a 1 GW of hourly contracted regional export priority factor (RegExp) set in place. The peak load representation for each month throughout the year of the original load and when the overall desired peak load reduction (DPKLR) is at 15% is shown in Figure 7.25. It is clearly shown that the seasonal storage system has managed to improve the peak load representation by flattening it in which reduces the grid's stress in providing peaking power throughout the year.

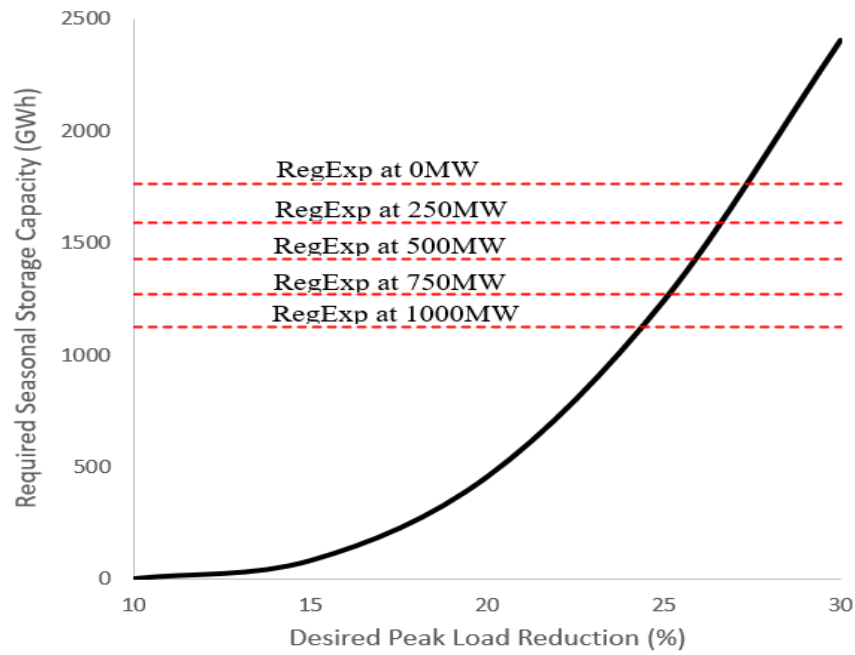


Figure 7.24. Required seasonal storage capacity (GWh) to achieve the overall desired peak load reduction (DPKLR) in percentage at various contracted regional export priority factor (RegExp).

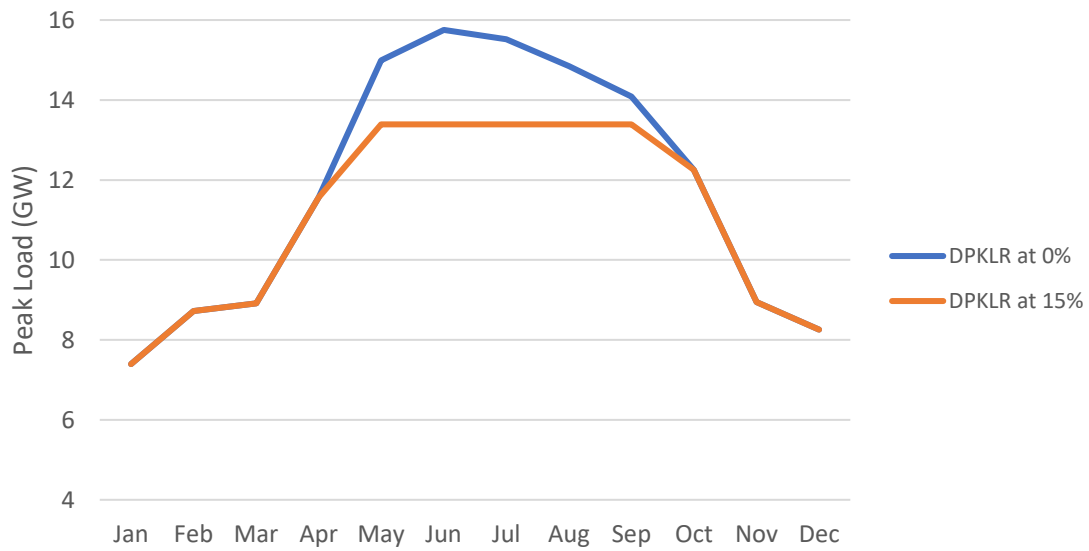


Figure 7.25. Peak load representation for each month throughout the year when the overall desired peak load reduction (DPKLR) is at 0% and 15%.

7.4.1 PV System Performance

The overall assessment of the PV system's performance in terms of curtailing the PV system due to the grid's baseload constraint with and without applying the seasonal storage is shown in Table 7.17. There will be more reduction of the PV curtailed energy due to the grid's baseload constraint as the overall desired peak load reduction (DPKLR) increases. This can be deduced from the overall assessment of the PV system's performance in terms of curtailing the PV system due to the grid's baseload constraint with applying the seasonal storage at various overall DPKLR percentages shown in Table 7.18.

Table 7.17. Overall assessment of the PV system's performance in terms of curtailing the PV system due to the grid's baseload constraint with and without applying the seasonal storage.

Parameters	Due to Baseload Constraint		
	Without Storage	With Diurnal Storage ($d = 100\%$)	With Diurnal & Seasonal Storage (DPKLR= 15%)
Number of PV Curtailment Events	1371	1112	1112
PV Curtailment Sum (GWh)	2915	2459	2377
PV Curtailment Percentage (%)	18.29	15.428	14.91
Highest PV Curtailed Energy in a Day (GWh/day)	35.527	32.724	32.724
Highest PV Curtailed Energy in an Hour (GWh)	5.233	5.233	5.233

Table 7.18. Overall assessment of the PV system's performance in terms of curtailing the PV system due to the grid's baseload constraint with applying the seasonal storage at various overall DPKLR percentages.

DPKLR (%)	Due to Baseload Constraint			
	PV Curtailment Sum (GWh)	PV Curtailment Percentage (%)	Highest PV Curtailed Energy in a Day (GWh/day)	Highest PV Curtailed Energy in an Hour (GWh)
10	2459	15.424	32.724	5.233
15	2377	14.914	32.724	5.233
20	2001	12.556	32.724	5.233
25	1332	8.357	23.201	4.294

7.4.2 Frequency Stability

The overall assessment of the grid's frequency stability in terms of the highest and lowest frequency due to integrating the PV system to it with and without applying the seasonal storage is shown in Table 7.19. The seasonal storage will have a small positive impact in which it matches the lowest frequency to the original load's one. Increasing the overall desired peak load reduction (DPKLR) which translates into increasing the seasonal storage capacity; will not affect or improve the frequency stability. This can be deduced from the overall assessment of the grid's frequency stability due to integrating the PV system to it with applying the seasonal storage at various overall DPKLR percentages shown in Table 7.20.

Table 7.19. Overall assessment of the grid's frequency stability due to integrating the PV system to it with and without applying the seasonal storage.

Parameters	Highest Frequency (Hz)	Lowest Frequency (Hz)
Original Load	60.21	59.78
Net Load without PV Curtailment	60.52	59.45
Net Load with PV Curtailment	60.34	59.78
Net Load with Diurnal Storage ($d = 100\%$)	60.22	59.77
Net Load with Diurnal & Seasonal Storage (DPKLR= 15%)	60.22	59.78

Table 7.20. Overall assessment of the grid's frequency stability due to integrating the PV system to it with applying the seasonal storage at various overall DPKLR percentages.

DPKLR (%)	Highest Frequency (Hz)	Lowest Frequency (Hz)
10	60.22	59.78
15	60.22	59.78
20	60.22	59.78
25	60.22	59.78

7.4.3 Net Load Analysis

The net load analysis in this part will showcase the performance of the grid's conventional generation system with applying the seasonal storage flexibility measure to utilise the grid's baseload constraint affects in furthering the reduction of the peak load.

7.4.3.1 Peak Load

The overall assessment of the peak load reduction due to integrating the PV system to it with and without applying the seasonal storage is shown in Table 7.21. The seasonal storage with a capacity of 82 GWh which translates into 15% of DPKLR; has managed to further reduce the peak load by 4.67%. The seasonal storage's round-trip efficiency plays an important factor in limiting the achievable overall desired peak load reduction (DPKLR). This can be deduced from the overall assessment of the peak load reduction due to integrating the PV system to it with applying the seasonal storage at various overall DPKLR percentages shown in Table 7.22. The seasonal storage with a capacity of 82 GWh has managed to further reduce the peak load of roughly 220 hours according to the load duration curve of the top 250 hours with and without applying the seasonal storage shown in Figure 7.26.

Table 7.21. Overall assessment of the peak load reduction (%) due to integrating the PV system to the grid with and without applying the seasonal storage.

Parameters	Peak Load (MW)	Peak Load Reduction (%)
Original Load	15753	0
Net Load without PV Curtailment	14860	5.66
Net Load with PV Curtailment	14860	5.66
Net Load with Diurnal Storage ($d = 100\%$)	14440	8.33
Net Load with Diurnal & Seasonal Storage (DPKLR= 15%)	13705	13

Table 7.22. Overall assessment of the peak load reduction (%) due to integrating the PV system to the grid with applying the seasonal storage at various overall DPKLR percentages.

DPKLR (%)	Peak Load (MW)	Peak Load Reduction (%)
10	14256	9.5
15	13705	13
20	13154	17
25	12602	20

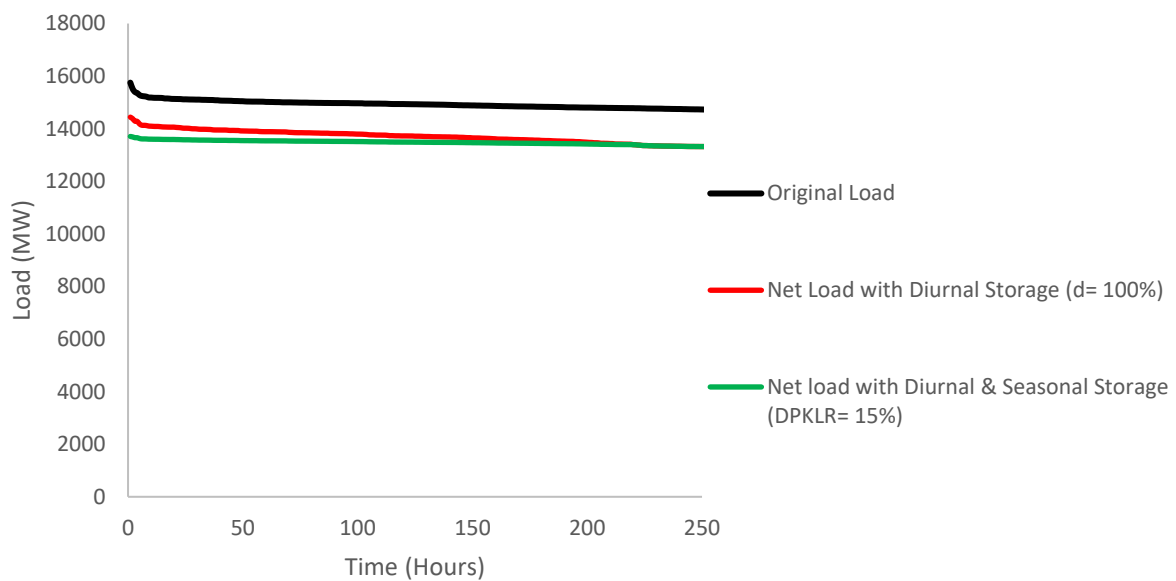


Figure 7.26. Load duration curve of the top 250 hours with and without applying the seasonal storage.

7.4.3.2 Ramping Stress

The overall assessment of the grid's ramping requirements due to integrating the PV system to it with and without applying the seasonal storage is shown in Table 7.23. The seasonal storage will have a small positive impact in which it matches the up ramping requirements to the original load's one. Increasing the overall desired peak load reduction (DPKLR) which translates into increasing the seasonal storage capacity; will not affect or improve the ramping requirements. This can be deduced from the overall assessment of the grid's ramping requirements due to integrating the PV system to it with applying the seasonal storage at various overall DPKLR percentages shown in Table 7.24.

Table 7.23. Overall assessment of the ramping requirements (MW/h) due to integrating the PV system to the grid with and without applying the seasonal storage.

Parameters	Ramping Requirements (MW/h)	
	Up Ramping	Down Ramping
Original Load	1268	1214
Net Load without PV Curtailment	3207	3018
Net Load with PV Curtailment	1268	1268
Net Load with Diurnal Storage ($d = 100\%$)	1305	1268
Net Load with Diurnal & Seasonal Storage (DPKLR= 15%)	1268	1268

Table 7.24. Overall assessment of the ramping requirements (MW/h) due to integrating the PV system to the grid with applying the seasonal storage at various overall DPKLR percentages.

DPKLR (%)	Ramping Requirements (MW/h)	
	Up Ramping	Down Ramping
10	1268	1268
15	1268	1268
20	1268	1268
25	1268	1268

7.4.4 Seasonal Storage Performance

The performance of the seasonal storage system at various round-trip efficiencies will be assessed here. There are limited suitable seasonal storage technologies that are bounded by their relatively low round-trip efficiencies. Therefore, it will be essential to examine the peak load reduction with applying a specific seasonal storage capacity at various round-trip efficiencies which will translate into the performance of different seasonal storage technologies. In this case, the peak load reduction evaluation for a 100 GWh of seasonal storage at various round-trip efficiencies (%) of the applied seasonal storage is shown in Figure 7.27.

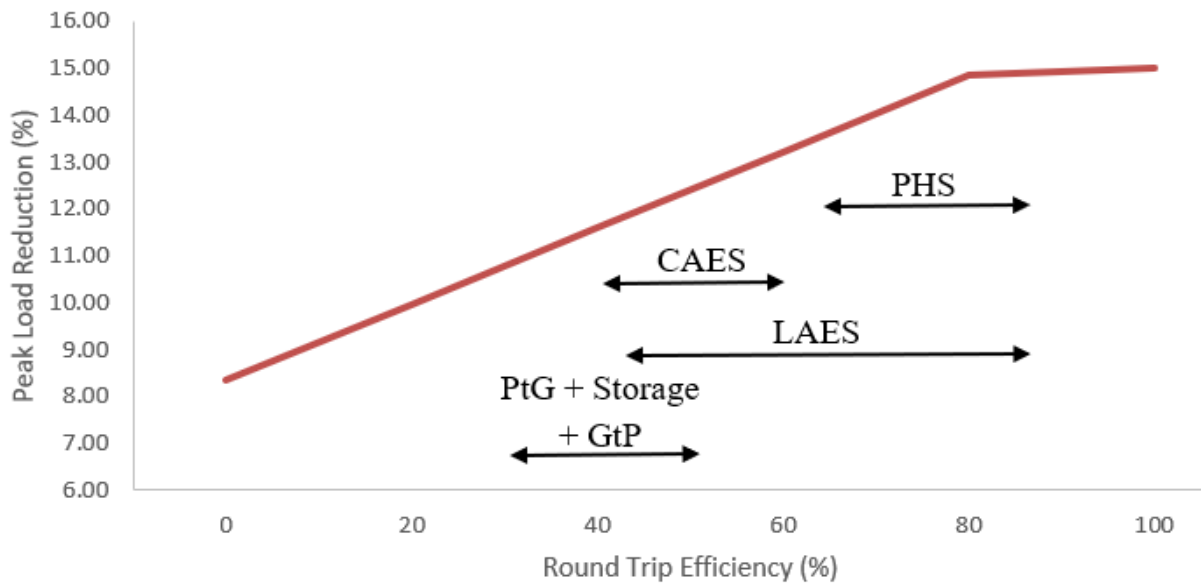


Figure 7.27. Peak load reduction (%) evaluation for a 100 GWh of seasonal storage at various round-trip efficiencies (%) of the applied seasonal storage.

7.5 Discussions

The large-scale PV system integration brings up a new set of technical challenges for the grid's operation due to their uncontrollable variable generation. The aggregation of the large-scale PV system over large areas will reduce the variability of the individual components. However, this does not eliminate the PV system's uncertainty in generation which is greater than the relative predictable uncertainties in terms of a few percent in demand that the grid deals with regularly. The variability of the PV system's generation can be easily mitigated if the grid can match the supply of the PV system to the required demand. On the other hand, it will become very costly to accommodate the PV system if its generation and required demand moved in the opposite directions.

We already established that the current grid operators, handle the variability of the PV system's generation almost exclusively by the ramping up or down of their conventional generators or reserves. Furthermore, those conventional generators or reserves have their own technical capability or constraints that must be abided to in order to maintain the grid's operation. If those constraints are violated, the grid operators will handle the situation by means of curtailing the PV system's output. This is a quite wasteful approach in utilising clean energy and will limit the grid's hosting capacity for the PV system. Case study A illustrated that having no flexibility measures will result in curtailing 3230 GWh of the PV system's generation throughout the year. This amount of PV system curtailment represents 20.71% of the PV system's generation sum throughout the year. Thus, there is a need for a more reliable and cleaner solution from the generation side in dealing with this matter in which can be implemented by applying flexibility measures such as energy storage.

The overall assessment in case study A of the PV system's performance throughout the year without applying the flexibility measure; showcased the substantial affects that each grid constraint has on performance of the PV system. In particular, the baseload constraint contributes in 90.24% of the overall PV curtailed energy throughout the year. Also, the effects of the baseload constraint are only present during the winter period where the demand is at its lowest. Meanwhile, the effects of the ramping constraint are present throughout the year. Therefore, the flexibility measure applied might not be optimally or economically suitable to tackle at the same instance leading to the point of having flexibility measures that target each grid constraint on itself.

The applied grid constraints in the case studies were based on what the grid currently deals with since the goal is to minimise the large-scale PV system's impact on the grid. The grid may be able to be a more PV accommodating without applying the energy storage flexibility measure through reducing the baseload constraint and increasing the ramping constraint. However, this will increase the stress and wear of the grid's conventional generation system. The overall evaluation of the sum of PV system's curtailed energy in GWh throughout the year and its curtailment reduction percentage at reduced baseload constraints and increased ramping constraints without applying the flexibility measures is shown respectively in Figure 7.28 and Table 7.25. Increasing the ramping constraint by up to 50% of the original load's one; results in no more than 17% curtailment reduction of the PV system's curtailed energy sum throughout the year. Meanwhile, reducing the baseload constraint by up to 50% of the original load's one; results in at least 58% curtailment reduction of the PV system's curtailed energy sum throughout the year.

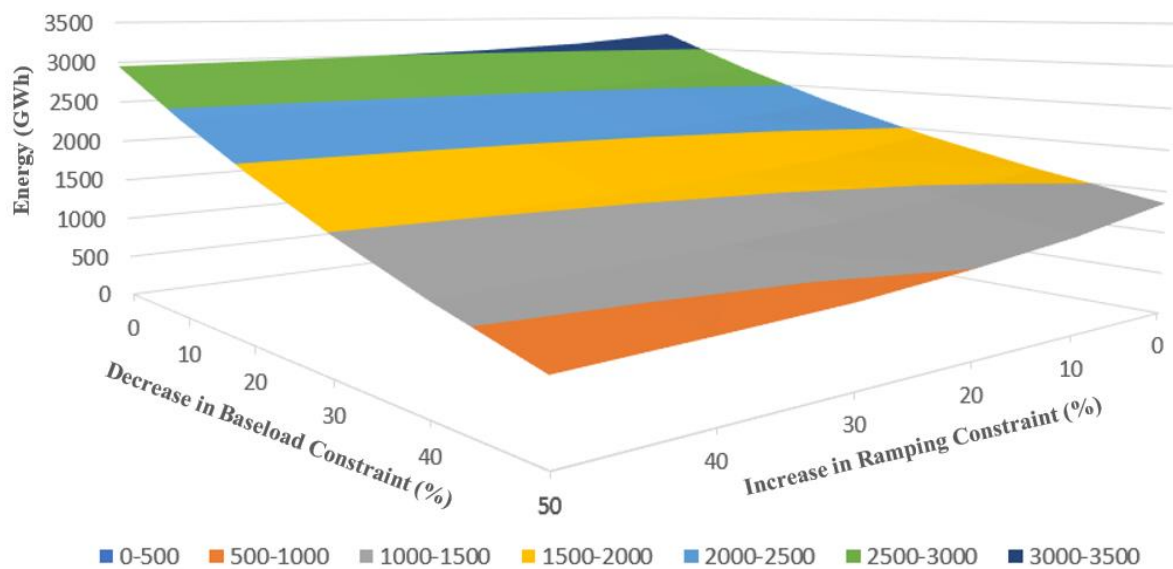


Figure 7.28. Overall evaluation of the reduction in the sum of PV system's curtailed energy in GWh at reduced baseload constraints and increased ramping constraints without applying the flexibility measures.

Table 7.25. Overall evaluation of the reduction in the sum of PV system's curtailed energy in percentage at reduced baseload constraints and increased ramping constraints without applying the flexibility measures.

		Decrease in Baseload Constraint (%)					
		0% (4282 MW)	10%	20%	30%	40%	50%
Increase in Ramping Constraint (%)	0% (1268 MW)	0%	15%	29%	40%	50%	58%
	10%	4%	20%	34%	46%	56%	65%
	20%	6%	22%	37%	49%	60%	69%
	30%	7%	24%	38%	51%	62%	72%
	40%	8%	25%	40%	53%	64%	74%
	50%	9%	26%	41%	54%	65%	75%

The Kingdom of Saudi Arabia generates all of its electricity from fossil fuel energy sources such as crude oil, diesel oil, heavy fuel oil and natural gas [291]. This type of generation mix provides the grid with more flexibility in accommodating more PV generation shares if compared to other less flexible generation sources such as coal and nuclear plants. The first 10% incremental step of either reducing the baseload constraint or increasing the ramping constraint; showed the highest effectiveness or PV curtailed energy utilisation. Therefore, it is recommended that we do not increase the ramping constraint by more than 20% of the original load's one. Meanwhile, it is recommended that we do not reduce the baseload constraint by more than 10% of the original load's one if we are taking into account the country's future plans of incorporating nuclear baseload plants to its generation mix.

Applying the diurnal flexibility measure in case study B, managed to overcome the effects that the grid's ramping constraint has on the PV system. The diurnal flexibility measure applied comprised of lithium-ion batteries that were optimally managed to reduce the PV energy curtailed due to the grid's ramping constraint. The reason for choosing lithium-ion batteries was due to them having the best technical characteristics in terms of being lighter in weight, smaller in size, higher in energy density and higher in round-trip efficiency compared to other types of batteries [210]. Furthermore, the increase demand of energy storage technologies, innovations in the material's science and the improvement in the manufacturing process are the attributes in reducing the cost of the lithium-ion batteries in which is predicted to hit 100 USD/kWh in the next decade [212]. There might be other energy storage technologies that may fall below the 100 USD/kWh cost, but they will lack the lithium-ion batteries applicability which is the main reason of their market demand gain in spite of their higher costs.

A BSS with a capacity of 2918 MWh/day is required to fully eliminate the curtailment of the PV system's output due to the grid's ramping constraint, which is 315 GWh throughout the year. The aforementioned daily required BSS's capacity is based on the original grid

constraints in which that required capacity can change as we reduce the baseload constraint or increase the ramping constraint. The overall evaluation of the diurnal storage required capacity (MWh/day) and its percentage change in capacity at reduced baseload constraints and increased ramping constraints is shown respectively in Figure 7.29 and Table 7.26. The diurnal storage's required capacity will increase as we reduce the baseload constraint. The reason for this is that there will be more PV energy integrated to the grid in which will lead to a slightly higher curtailment of the PV system's output due to the grid's ramping constraint. On the other hand, increasing the ramping constraint will reduce the diurnal storage's required capacity. The first 10% incremental step of increasing the ramping constraint; showed the highest effectiveness of reducing the BSS's required capacity in which that effectiveness will reduce as we further increase the ramping constraint.

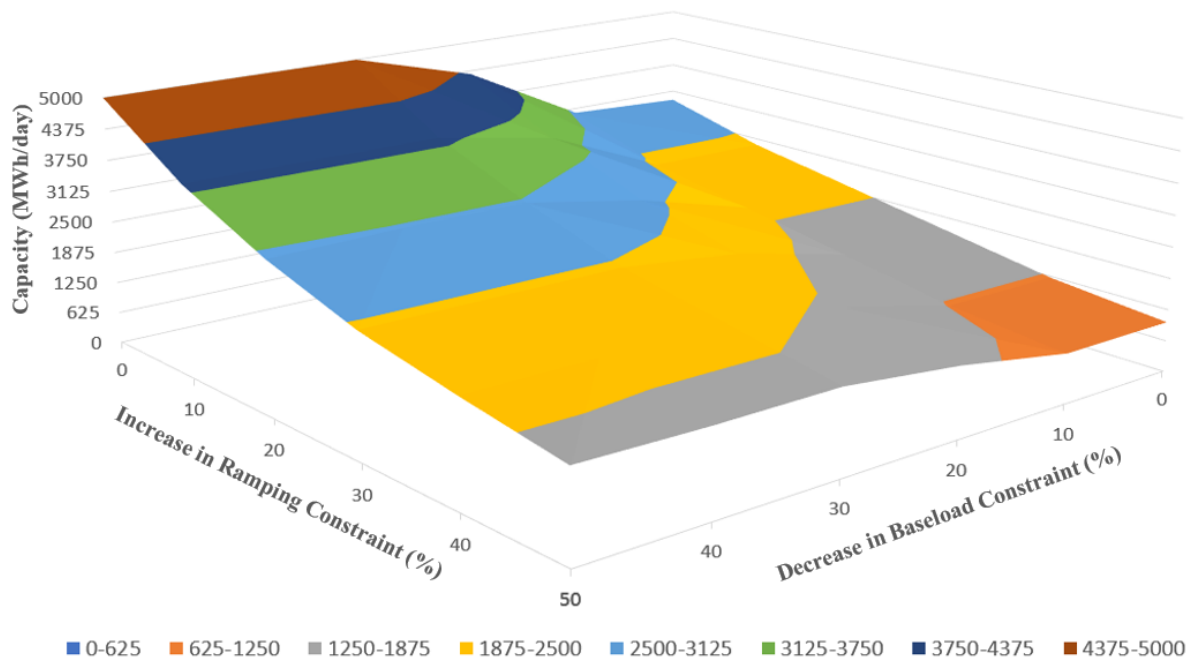


Figure 7.29. Overall evaluation of the diurnal storage required capacity (MWh/day) at reduced baseload constraints and increased ramping constraints.

Table 7.26. Overall evaluation of the percentage change in the diurnal storage required capacity at reduced baseload constraints and increased ramping constraints.

		Decrease in Baseload Constraint (%)					
		0% (4282 MW)	10%	20%	30%	40%	50%
Increase in Ramping Constraint (%)	0% (1268 MW)	0%	+4%	+48%	+71%	+71%	+71%
	10%	-19%	-19%	+16%	+32%	+32%	+32%
	20%	-32%	-32%	-10%	+6%	+6%	+6%
	30%	-45%	-45%	-26%	-17%	-17%	-17%
	40%	-58%	-58%	-39%	-30%	-30%	-30%
	50%	-66%	-66%	-52%	-43%	-43%	-41%

The overall evaluation of the variation in the battery system's desired sizing percentage (d) to the battery's maximum required capacity to fully utilise the PV system's curtailed energy throughout the year due to the grid's ramping constraint is shown in Figure 7.30. The PV curtailed energy utilisation or effectiveness decreases as the sizing percentage (d) of the BSS increases. The PV curtailed energy utilisation will be at its highest with roughly 72% if we set the sizing percentage (d) of the BSS to 25%. On the other hand, the PV curtailed energy utilisation will drop to 22.92% if we further increase the sizing percentage (d) of the BSS from 25% to 50%. Furthermore, the BSS's energy management have managed to decrease the PV curtailed energy due to the baseload constraint as well because of utilising part of that curtailed energy in charging the BSS. It is worth mentioning that the BSS at 100 % DOD and an operating temperature of 10°; will lose 9.82% of its capacity in those conditions at the end of the year due to degradation over time and frequent usage. The optimal method of reducing the BSS's capacity loss and maintaining the BSS's state of health is to operate at a low ambient temperature and low depth of discharge (DOD).

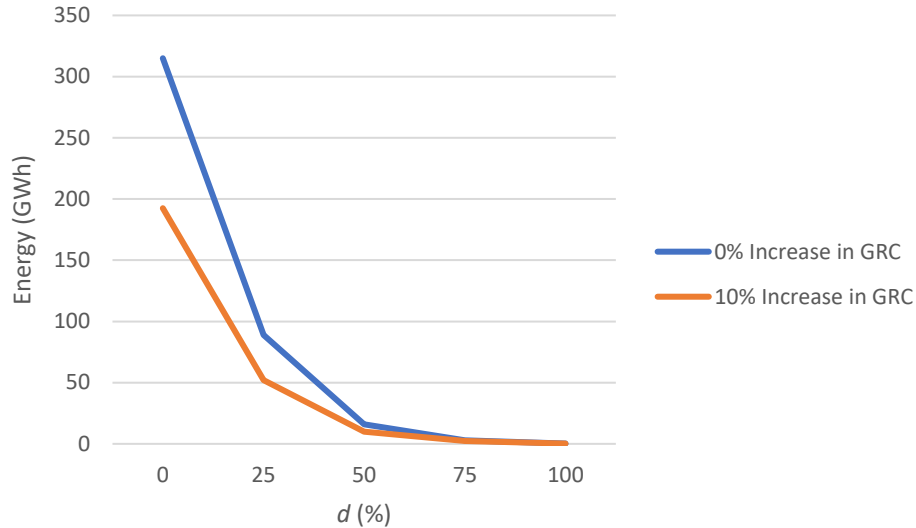


Figure 7.30. Overall evaluation of the variation in the battery system's desired sizing percentage (d) to the battery's maximum required capacity to fully utilise the PV system's curtailed energy (GWh) due to grid's ramping constraint (GRC).

Applying the seasonal storage flexibility measure in case study C, managed to utilise the effects that the grid's baseload constraint has on the PV system in furthering the peak load reduction. The seasonal storage flexibility measure targets the new peak load which is shifted from the middle of the day to the afternoon period of the same day where there is less or no PV energy available. It will be difficult to reduce the grid's baseload constraint to allow more PV energy, since the baseload power plants are only cost-effective if they run at constant output which is due to their high capital costs and low variable costs [292]. Therefore, it will be better to find another measure in utilising this wasted seasonal PV curtailed energy in which a seasonal storage can be applied to further reduce the peak load at periods of less or no PV energy availability. Seasonal storage has limited energy storage technologies that can achieve its requirements at the current time. Pumped Hydroelectric Storage (PHS) and Compressed Air Energy Storage (CAES) are the two nowadays close to ideal technology candidates for seasonal storage. However, they are limited by geographical constraints. On the other hand, Liquid Air Energy Storage (LAES) represent an intriguing solution that replaces the two nowadays close to ideal candidates by outweighing their disadvantages since LAES have no geographical constraints, but it is lacking the maturity of the PHS and CAES technologies. Furthermore, green ammonia might be a future perfect candidate of seasonal storage due to its high energy density, simple storage requirements, likelihood of a large future global supply chain and the potential of being the zero carbon option with the lowest costs [293]. It is worth mentioning that there is a great interest in exporting energy via green ammonia at Saudi Arabia in which they are planning to have a 4 GW green ammonia plant operational by 2025 [294].

Another possible measure is to export that PV curtailed energy to neighbouring countries by investing in upgrading or establishing regional transmission capacities. The overall

evaluation of the sum of the PV system's curtailed energy in GWh at various regional transmission capacities (GW) is shown in Table 7.27. A regional transmission capacity of 3 GW is needed in future if the goal is to export at least 90% of the PV curtailed energy due to the grid's constraints. It is worth mentioning that there is a future project to link the Saudi grid with the Egyptian grid, which will enable the transmission of 3 GW between the two countries. Furthermore, exporting the PV curtailed energy might be the simpler measure of utilising the PV curtailed energy. However, unlike the energy storage measure, it won't provide the grid with the needed PV hosting enhancement.

Table 7.27. Overall evaluation of the sum of PV system's curtailed energy in GWh at various regional transmission capacities (GW).

Regional Transmission Capacity (GW)	Without Storage		With Diurnal Storage ($d = 100\%$)		With Diurnal & Seasonal Storage (DPKLR= 15%)	
	PV Curtailment Sum (GWh)	Change (%)	PV Curtailment Sum (GWh)	Change (%)	PV Curtailment Sum (GWh)	Change (%)
No Regional Transmission Capacity	3230 GWh	0%	2459 GWh	24%	2377 GWh	26%
1 GW	1741 GWh	46%	1504 GWh	53%	1456 GWh	55%
2 GW	830 GWh	74%	776 GWh	76%	754 GWh	77%
3 GW	264 GWh	91.82%	262 GWh	91.88%	258 GWh	92%
4 GW	30 GWh	99%	30 GWh	99%	30 GWh	99%
5 GW	0.854 GWh	99.97%	0.584 GWh	99.98%	0.584 GWh	99.98%

We illustrated that having a large share of PV energy will result in a potentially higher ramping magnitudes that will stress the conventional generation system of the grid. So far, our analysis focused on the technical aspects of enhancing the grid's potential hosting capacity of the large-scale PV system without mentioning the economic aspects. The cost of PV integration can be defined as the cost of upgrading the grid in terms of building transmission capacity, plus the intermittency costs that comprises of the cost of ramping the existing conventional generation system and the cost of operating the up-spinning reserves [295]. Using the levelized cost of electricity (LCOE) on itself will not be sufficient in illustrating the economic benefits for comparing intermittent technologies with the dispatchable ones [296]. This is because the LCOE does not capture the incurred additional cost better known as the intermittency cost, which is added when the renewable technologies contributes in the generation mix [296].

The cost of ramping the grids conventional generation system with integrating the large-scale PV systems will be evaluated briefly. The ramping costs for the existing power plants in Saudi Arabia will be derived from [271], as shown in Table 7.28. An assumption will be made that the grid's conventional generation system will comprise of only combined-cycle gas turbines, which can be categorised as the best-case scenario of ramping cost. The grid's ramping cost at various PV system penetration levels without applying the flexibility measures is shown in Figure 7.31. The ramping cost will slightly reduce as the PV system's penetration level reaches 10%. Meanwhile the ramping cost will rise as the PV system's penetration level exceeds 10%. The grid's ramping cost to accommodate 48% of PV system

penetration level with and without applying the flexibility measure is shown in Table 7.29. The ramping cost will increase by 75% without applying any flexibility measures. On the other hand, applying the diurnal flexibility measure at 100% sizing percentage (d) will only further increase the ramping cost by 5%. It is worth mentioning that the 5% increase in ramping cost will allow the displacement of roughly 315 GWh of conventional generation and will utilise roughly 23.86% of the PV curtailed energy due to the grid's constraints. Future work may focus on performing an economic analysis that illustrate the overall cost of PV integration with applying the aforementioned flexibility measures. Specifically, the cost of operating the up-spinning reserves should be focused on, since it represents majority of the intermittency costs whereas the ramping cost only represents a small fraction of it. This project focuses on the technical aspects, and the evaluation of the economics are beyond the scope of this project. However, collecting detailed information about the scheduling of the conventional generation system and the costs associated in operating the up-spinning reserves are required in order to perform the economic analysis.

Table 7.28. The ramping costs for existing power plants in Saudi Arabia [271].

Generation Technology	Ramping Cost (\$/ΔMW)
Steam Turbines (Gas, Oil)	1.61
Open Cycle Gas Turbine	0.92
Combined Cycle Gas Turbine	0.58

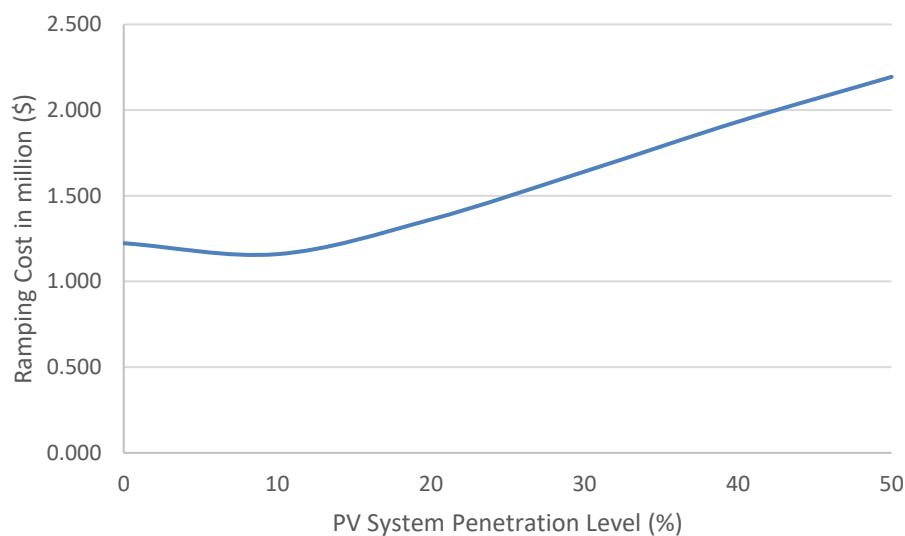


Figure 7.31. Grid's ramping cost at various PV system penetration levels without applying the flexibility measures.

Table 7.29. Grid's ramping cost to accommodate 48% of PV system penetration level with and without applying the flexibility measures.

Parameters	Ramping Cost (\$)	Increase in Ramping Cost (%)
Original Load	\$1.223 million	0
Net Load with PV Curtailment	\$2.145 million	75
Net Load with Diurnal Storage ($d = 100\%$)	\$2.204 million	80
Net Load with Diurnal & Seasonal Storage (DPKLR= 15%)	\$2.178 million	78

7.6 Summary

This chapter demonstrated applying the proposed optimal sizing and energy management strategies of the flexibility measures illustrated from chapter 6 in the form of case studies based on the country's future PV energy target (Saudi vision 2030). Firstly, it presented the base case (case study A) which represented the traditional method of dealing with the PV system's variability in the form of PV curtailment. Then, it presented the case (case study B) with the applied flexibility measure in terms of diurnal storage system with its energy management strategy that targeted the PV curtailment due to grid's ramping constraint violations. After that, it presented the case (case study C) with the applied flexibility measure in terms of seasonal storage system with its energy management strategy that targeted the PV curtailment due to grid's baseload constraint violations. Finally, it illustrated a discussion which consisted of a comparison among the three cases and reflected on the optimal measures.

The overall assessment of the PV system's performance throughout the year without applying the flexibility measures; showcased the significant difference that each grid constraint has on performance of the PV system. In particular, the baseload constraint contributed in 90.24% of the overall PV curtailed energy throughout the year, and its effects were only present during the winter period where the demand is at its lowest. Meanwhile, the effects of the ramping constraint were present throughout the year. Furthermore, the grid's constraints resulted in the reduction of more than 9% of the PV capacity factor and the PV curtailment of 3230 GWh, which represents 20.71% of the PV system's generation sum throughout the year. Thus, these are the indications that the grid needs the flexibility measures in order to ensure the full economical utilisation of the PV system in the generation mix.

The overall assessment of the grid's frequency stability without applying both the PV curtailment and the flexibility measures; showcased that the highest frequency reached was 60.52 Hz and the lowest frequency reached was 59.45 Hz. However, when the grid constraints were applied, the frequency changed for the better in which this positive affect on the frequency stability was due to the reduced participation of the PV system. On the other hand, the peak load was not affected by the PV curtailment process since the peak load reduction was 5.66 % for both with and without applying the PV curtailment. Furthermore,

the ramping requirements without applying the PV curtailment will be at least more than 148% of the ramping requirements for the original load.

The grid may be able to be a more PV accommodating without applying the energy storage flexibility measure through reducing the baseload constraint and increasing the ramping constraint. However, this increases the stress and wear of the grid's conventional generation system. Furthermore, Increasing the ramping constraint by up to 50% of the original load's one, resulted in no more than 17% curtailment reduction of the PV system's curtailed energy sum throughout the year. Meanwhile, reducing the baseload constraint by up to 50% of the original load's one, resulted in at least 58% curtailment reduction of the PV system's curtailed energy sum throughout the year. It is worth noting that the effectiveness of the PV curtailed energy utilisation decreases as we keep reducing the baseload constraint or keep increasing the ramping constraint.

Applying the diurnal flexibility measure in case study B, managed to overcome the effects that the grid's ramping constraint has on the PV system. The diurnal flexibility measure applied comprised of lithium-ion batteries that were optimally managed to reduce the PV energy curtailed due to the grid's ramping constraint. A battery storage system (BSS) with a capacity of 2918 MWh/day was required to fully eliminate the curtailment of the PV system's output due to the grid's ramping constraint, which was 315 GWh throughout the year. The diurnal storage's required capacity will increase as we reduce the baseload constraint. On the other hand, increasing the ramping constraint will reduce the diurnal storage's required capacity. Furthermore, the first 10% incremental step of increasing the ramping constraint; showed the highest effectiveness of reducing the BSS's required capacity in which that effectiveness will reduce as we further increase the ramping constraint.

The PV system's curtailment will sharply decrease as we keep increasing the sizing percentage (d) of the BSS. However, the PV curtailed energy utilisation or effectiveness decreases as the sizing percentage (d) of the BSS increases. Furthermore, there was still PV curtailed energy at 100% sizing percentage (d) of the BSS. This was due to the BSS's round-trip efficiency and the capacity loss of the BSS caused by the degradation over time and the frequent usage. It is worth noting that the BSS at 100 % DOD and an operating temperature of 10°; lost 9.82% of its capacity in those conditions at the end of the year in which was due to the degradation over time and frequent usage. Thus, the optimal method of reducing the BSS's capacity loss and maintaining the BSS's state of health is to operate at a low ambient temperature and low depth of discharge (DOD).

The frequency stability improved as we kept increasing the sizing percentage (d) of the BSS in which the highest and lowest frequency kept getting closer to the nominal frequency (60 Hz). In addition, there was further peak load reduction as we kept increasing the sizing percentage (d) of the BSS in which 2.67% of further peak load reduction was attained at 100% sizing percentage (d) of the BSS. This was due to the energy management strategy of the BSS, which discharged some of its energy in the afternoon period where the new peak load resides that was shifted from the middle of the day due to the integration of the PV

generation. Furthermore, the BSS's energy management strategy managed to decrease the PV curtailed energy due to the baseload constraint as well, because of utilising part of that curtailed energy in charging the BSS.

Applying the seasonal storage flexibility measure in case study C, managed to utilise the effects that the grid's baseload constraint has on the PV system in furthering the peak load reduction with taken into account the hourly contracted regional export priority factor (RegExp). The seasonal storage flexibility measure targets the new peak load which is shifted from the middle of the day to the afternoon period of the same day where there is less or no PV energy available. It will be difficult to reduce the grid's baseload constraint to allow more PV energy, since the baseload power plants are only cost-effective if they run at constant output. Furthermore, the maximum achievable overall desired peak load reduction (DPKLR) by the seasonal storage system at ideal conditions was 27.4%, when there was no hourly contracted regional export priority factor (RegExp) set in place.

There will be more reduction of the PV curtailed energy due to the grid's baseload constraint as the overall desired peak load reduction (DPKLR) increases. However, increasing the overall desired peak load reduction (DPKLR), which translates into increasing the seasonal storage capacity; will not affect or improve the frequency stability or the grid's ramping stress. Furthermore, the seasonal storage with a capacity of 82 GWh, which translates into 15% of DPKLR; has managed to further reduce the peak load by 4.67% via targeting the peak load of 220 hours. In addition, the seasonal storage's round-trip efficiency plays an important factor in limiting the achievable overall desired peak load reduction (DPKLR).

Chapter 8 Conclusions, Contributions, Limitations and Future Work

8.1 Conclusions

This thesis presented an investigation in the development of flexibility measures which included their optimal sizing and energy management strategies in order to enhance the grid's PV hosting capacity and minimise the impact of integrating large-scale PV systems into the Saudi grid. It is worth noting that the different chapters of this thesis divides and summarises the work performed, providing different individual conclusions which are compiled in the following.

The intermittency experienced from solar energy brings the following distinct characteristics of power generation, including partial unpredictability, non-controllable variability and location dependency. Those distinct characteristics of the intermittent renewable energy source can impact both the operation and security of the grid when integration is considered. In chapter 1, the electricity market in Saudi Arabia was analysed, including their governing structure, growth factors and the government's ambitious plan to reduce energy consumption through reforming the energy prices. The analysis of these topics showcased the future issues facing the Saudi energy sector in which a higher increase in both the domestic energy consumption and peak load were predicted. Furthermore, the solar PV energy prospect in Saudi Arabia was also evaluated in chapter 1. In doing so, showcased that the Saudi government is moving towards exploiting renewable energy and in particular solar PV in order to meet its future energy demands and diversify its economy.

In chapter 2, the technical impact of PV integration into the grid was analysed, including the current practices used by the grid operators in dealing with the variability that accompanies that large-scale PV system generation. It is worth noting that the overgeneration phenomenon of renewable energy was handled by means of curtailment in the renewable generation. This is a quite wasteful approach in utilising clean energy, and it leads to more reliance on the use of non-clean energy sources. Moreover, the grid needs to deal with the greater variability and uncertainty, which operators currently handle almost exclusively by the ramping up or down of the conventional generators or reserves by forecasting the weather on a minute by minute or an hourly basis. However, in the near future, the grid will experience large shares of renewables making this current approach costly and unreliable in some cases, leading to the need of a cost-effective and reliable approach from the generation side, and that approach is likely storage and flexible transmission.

As the electrical grid evolves to allow the integration of large volumes of renewable energy in respect to the generation mix portfolio, the system's operators must address the insurance of flexibility across all parts of the grid system. Currently, the generation mix portfolio of most traditional grids is capable of providing the source of flexibility to deal with the variability of the electricity demand. However, as the penetration level of the renewable

energy to the grid increases, it changes the net load pattern, which it will become very crucial to plan for the impact of uncertainty and variability. Therefore, an assessment of the net load after applying the grid's constraints in terms of the baseload constraint and ramping constraint of the conventional generation system of the grid can provide insight on the impact of variability on the grid that accompanies the renewable energy generation of different capacities. Furthermore, the frequency stability of the grid senses the variation between the generation and demand, which can also provide insight on the impact of variability on the grid that accompanies the renewable energy generation of different capacities.

Increasing the penetration level of the large-scale PV into the grid will cause the grid operators to face an increasingly variable net load patterns and steeper ramping events. This will be a major concern to the grid operators and will require grid flexibility measures to be applied that can be in the form of energy storage. In chapter 5, the brief evaluation of the grid's current potential hosting capacity with large-scale PV plants at various PV penetration levels to the grid, showcased the need for flexibility measure and that the potential flexibility measure applied might not be optimally or economically suitable to tackle both constraints at the same instance. Therefore, a diurnal source of flexibility is required to manage the ramping constraint effects, meanwhile a seasonal source of flexibility is required to manage the baseload constraint effects. In doing so, will ensure both the reduction of the PV curtailment and minimise the impact of integrating large-scale PV into the grid.

Furthermore, chapter 7 applied the proposed optimal sizing and energy management strategies of the flexibility measures illustrated from chapter 6 in the form of case studies based on the Saudi's 2030 PV energy target. Applying the diurnal flexibility measure in case study B, managed to overcome the effects that the grid's ramping constraint has on the PV system. A battery storage system (BSS) with a capacity of 2918 MWh/day was required to fully eliminate the curtailment of the PV system's output due to the grid's ramping constraint, which was 315 GWh throughout the year. It is worth noting that the diurnal storage's required capacity will increase as we reduce the baseload constraint. On the other hand, increasing the ramping constraint will reduce the diurnal storage's required capacity. Furthermore, the frequency stability improved as we kept increasing the sizing percentage (d) of the BSS in which the highest and lowest frequency kept getting closer to the nominal frequency (60 Hz). In addition, there was further peak load reduction as we kept increasing the sizing percentage (d) of the BSS in which 2.67% of further peak load reduction was attained at 100% sizing percentage (d) of the BSS. This was due to the energy management strategy of the BSS. Also, the BSS's energy management strategy managed to decrease the PV curtailed energy due to the baseload constraint as well, because of utilising part of that curtailed energy in charging the BSS.

Applying the seasonal storage flexibility measure in case study C, managed to utilise the effects that the grid's baseload constraint has on the PV system in furthering the peak load reduction with taken into account the hourly contracted regional export priority factor (RegExp). It will be difficult to reduce the grid's baseload constraint to allow more PV

energy, since the baseload power plants are only cost-effective if they run at constant output. It is worth noting that increasing the overall desired peak load reduction (DPKLR), which translates into increasing the seasonal storage capacity; will not affect or improve the frequency stability or the grid's ramping stress. Furthermore, the seasonal storage with a capacity of 82 GWh, which translates into 15% of DPKLR; has managed to further reduce the peak load by 4.67%. In addition, the seasonal storage's round-trip efficiency plays an important factor in limiting the achievable overall desired peak load reduction (DPKLR).

Another possible measure in utilising the PV curtailed energy due to the grid's baseload constraint, is to export that PV curtailed energy to neighbouring countries by investing in upgrading or establishing regional transmission capacities. In doing so, 90% of the PV curtailed energy due to the grid's constraints can be exported with a 3 GW of regional transmission capacity in which there is a future project to link the Saudi grid with the Egyptian grid, which will enable the transmission of 3 GW between the two countries. Furthermore, exporting the PV curtailed energy might be the simpler measure of utilising the PV curtailed energy. However, unlike the energy storage measure, it won't provide the grid with the needed PV hosting enhancement. It is worth noting that green ammonia might be a future perfect candidate of seasonal storage due to its high energy density, simple storage requirements, likelihood of a large future global supply chain and the potential of being the zero carbon option with the lowest costs. Also, there is a great interest in exporting energy via green ammonia at Saudi Arabia in which they are planning to have a 4 GW green ammonia plant operational by 2025.

The applied grid constraints were based on what the grid currently deals with, since the goal was to minimise the large-scale PV system's impact on the grid. The grid may be able to be a more PV accommodating without applying the energy storage flexibility measure through reducing the baseload constraint and increasing the ramping constraint. However, this increases the stress and wear of the grid's conventional generation system. The Saudi's electricity generation mix of traditional energy sources provides the grid with more flexibility in accommodating more PV generation shares if compared to other less flexible generation sources such as coal and nuclear plants. Therefore, based on the analysis of the results and with taken into consideration the Saudi's electricity generation mix; it was recommended that we do not increase the ramping constraint by more than 20% of the original load's one. Also, it was recommended that we do not reduce the baseload constraint by more than 10% of the original load's one if we are taking into account the country's future plans of incorporating nuclear baseload plants to its generation mix.

Furthermore, the cost of ramping the grids conventional generation system with integrating the large-scale PV systems was briefly evaluated in which the ramping cost increased by 75% without applying any flexibility measure. On the other hand, applying the diurnal flexibility measure at 100% sizing percentage (d) has only further increased the ramping cost by 5%. It is worth noting that this 5% increase in ramping cost allowed the displacement of roughly 315 GWh of conventional generation and utilised roughly 23.86% of the PV curtailed energy

due to the grid's constraints. Future work may focus on performing an economic analysis that illustrates the overall cost of PV integration with applying the aforementioned flexibility measures in which the cost of operating the up-spinning reserves should be focused on, since it represents majority of the intermittency costs.

8.2 Contributions

As can be extracted from this thesis and summarised with the previous conclusions in which this research introduced a series of contributions that can be mainly listed as:

- The assessment of the technical impact of integrating large-scale PV systems into the transmission network of the grid, with including the current practices used by the grid operators in dealing with the variability that accompanies that large-scale PV system generation.
- The development of the PV curtailment algorithms in order to comply with the grid's constraints. This enabled studying the change in load pattern effect and the ramping requirements needed by the grid's conventional generation system in the situation of increasing the penetration level of the large-scale PV power into the grid. It is worth noting that the developed PV curtailment algorithms, ensures having the PV system's participation in the grid's generation mix at its maximum without violating the grid's constraints.
- The examination of the the grid's frequency stability due to increasing the penetration level of large-scale PV generation into the grid. This included illustrating the effect of the size of the PV disturbance on the grid's frequency. In doing so, provided insight on the impact of PV variability on the grid, since the frequency stability of the grid senses the variations between the generation and demand.
- The evaluation of the grid's current potential hosting capacity with large-scale PV systems at various penetration levels to the grid. This enabled showing the substantial affects that each grid constraint has on the performance of the PV system in terms of PV curtailment. Also, provided bases that can be used to establish the appropriate flexibility measures capable of ensuring both the reduction of the PV curtailment and minimising the impact of integrating large-scale PV into the grid. Specifically, a diurnal storage system in the form of lithium-ion batteries was proposed as the flexibility measure for the ramping constraint, while a seasonal storage system was proposed as the flexibility measure for the baseload constraint.
- The development of the optimal sizing and energy management strategies of the proposed diurnal storage system with taking into account the battery's aging effect in terms of capacity degradation. It is worth noting that the developed optimal sizing strategy, ensures deducing the optimum required capacity of the battery storage system in order to meet the system requirement. In addition, the developed energy management strategies, ensures the optimal charging and discharging processes of the battery storage system. The established optimal charging strategy will give a charging prioritisation to the PV curtailed energy situated in the assigned charging period in

which will fully utilise the PV curtailed energy due to the ramping constraint first before exploiting the PV curtailed energy due to the baseload constraint. The optimal discharging process was then set to fully discharge the battery's available energy into the assigned discharging period, without causing the net load power ramp (NL_{PR}) to exceed the grid's ramping constraint (GRC) and without violating the baseload constraint of the net load.

- The development of the optimal sizing and energy management strategies of the proposed seasonal storage system in order to further the peak load reduction. It is worth noting that the developed optimal sizing strategy, ensures deducing the required capacity of seasonal storage based on the overall desired peak load reduction ($DPKLR$) in percentage. In addition, the developed energy management strategies, ensures the optimal charging and discharging processes of the seasonal storage system. The seasonal storage will be charged fully only from the PV curtailed energy due to the grid's baseload constraint with taken into account the hourly contracted regional export priority factor ($RegExp$). The optimal discharging process was then set to fully discharge the seasonal storage's available energy into the assigned discharging period in order to lower the current peak load point to the required peak load ($RPKL$) point. A discharge ratio methodology was used to ensure maximising the reduction of the peak load as close as possible to the required peak load ($RPKL$) in case a lower seasonal storage capacity is applied.
- The evaluation of the proposed flexibility measures under various capacities in order to investigate their effects on the PV system's performance, frequency stability and the net load in terms of peak load and ramping stress.
- The examination of the PV system's performance without applying the proposed flexibility measures at a more PV accommodating grid through lowering the baseload constraint and increasing the ramping constraint.
- Analysing the technical effectiveness of the proposed flexibility measures and their energy management strategies that could be implemented in such a way to enhance the grid's PV hosting capacity and minimise the impact of integrating large-scale PV systems into the Saudi grid.

8.3 Limitations

This conducted research is governed by some limitations that can contribute towards uncertainties in the results or analysis. The following are statements that can summarise the limitations within this research:

- The case studies are governed by a limitation in terms of being based on the prediction of the Kingdom's 2030 peak load using forecasting techniques. In addition, to the assumption made that the chosen location would follow the same future growth of the Kingdom's electricity sector since it will be the location of most of the future mega projects. This can introduce uncertainties to the results or analysis since it does not take into account events such as a world pandemic that can affect a country's

economy and the progress of the future mega projects in which are both associated in predicting the peak load.

- The hourly load profile of the whole year is required as an input of the model and is difficult to obtain it for the whole country due to the large geographical size and the government regulations. Thus, a specific city or region in the country was chosen for the case studies in which can introduce uncertainties to the results or analysis.
- There are no available raw data to be collected from a utility-scale solar PV project in Saudi Arabia because it is in the early stages of implementation. Therefore, the PV system modelled in this research was validated against the PVSYST software at the same conditions in which can introduce uncertainties to the results or analysis.
- Assigning the grid constraints of the conventional generation system; requires collecting detailed information about the scheduling of the conventional generation system in which is difficult to obtain due to it being considered as sensitive data. Therefore, the applied grid constraints of the conventional generation system in this research were based on the analysis of the collected load profile in which can introduce uncertainties to the results or analysis.

8.4 Future Work

There are variety of interesting directions for future work that can be identified as result of the work in this thesis in which are the following:

- To establish an economic evaluation based on applying the proposed flexibility measures in order to illustrate the cost of PV integration. The cost of PV integration can be defined as the cost of upgrading the grid in terms of building transmission capacity, plus the intermittency costs that comprises of the cost of ramping the existing conventional generation system and the cost of operating the up-spinning reserves.
- To develop a method of reducing the capacity requirements of the battery storage system with prolonging its operational life in which a hybrid design that includes an ultra-capacitor system can potentially be a promising solution. This is due to the high power density and fast response time of the ultra-capacitor. In addition, the relationship between added cost of the ultra-capacitor and its benefit to the battery storage system should be evaluated.
- Evaluating the applicability of green ammonia as a future candidate of seasonal storage due to its high energy density, simple storage requirements, likelihood of a large future global supply chain and the potential of being the zero carbon option with the lowest costs. In addition, there is a great interest in exporting energy via green ammonia at Saudi Arabia.

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Appendix

MATLAB Code

1. Defining the inputs and collected data part

```
%% Define input variables %%

Pt= 48;                %% penetration levels of PV in percent

Nm= 17;                %% maximum number of PV modules in a string
Ns= 101;               %% maximum number of PV strings in an array
PVmax= 320;            %% single PV module maximum power in watts
Tstc= 25;              %% Temperature of standard test condition
Tnoct= 46;             %% Nominal operating cell temperature
Tcoef= -0.43;          %% Temperature coefficient of PV module
Nf= 0.16;              %% solar module efficiency
Ne= 500000;            %% inverter size
Plosses= 0.75;         %% system's performance ratio due to the other miscellaneous
power losses

Peakload= 15753e06;    %% peak load of Riyadh
Baseload= 4282e06;     %% minimum load of Riyadh baseload constraint
GRC= 1268e06;          %% Grid's conventional generation system ramping constraint

x11= 100;              %% percentage of the sizing of battery capacity to the x111 (✓
highest required daily MWh energy capacity of storage of all months thus capacity✓
of storage )
DOD= 100;              %% Depth of discharge for storage
BSSEff= 95;            %% Battery storage roundtrip efficiency

Tper= 15;              %% Percentage target of peak load reduction using seasonal✓
storage
SSEff= 70;             %% seasonal storage roundtrip efficiency
x6= 100;               %% percentage of the sizing of seasonal storage capacity to the✓
SRqEC3 ( required energy capacity of seasonal storage to achieve the desired peak✓
load )
RegExp= 1000e06;        %% regional export restriction or limit factor
TransCap= 0e06;         %% regional transmission capacity

%% Define & read excel variables for collected data %%
Sdata= 'Yearly.xlsx';   %% excel solar data

Range1= 'A1:NA24';

Sheet1= 1;              %% excel sheet number for solar data
SAll= xlsread(Sdata, Sheet1, Range1);    %% data for All months

Sheet2= 2;              %% excel sheet number for temperature
TAll= xlsread(Sdata, Sheet2, Range1);    %% data for All months

Sheet3= 3;              %% excel sheet number for load
LAll= xlsread(Sdata, Sheet3, Range1);    %% data for All months
```

2. *PV system modelling part*

```

%% Calculate the PV system output %%
for t= 1:1:8760
    Nal= fix(((Peakload)/(100)) * (Pt/Ne)); %% number of fix arrays that are not
rounded up in MW represent penetration level of load
    Tc1(t)= TAll(t) + ((SAll(t)/800) * (Tnoct - 20));
    Ac= (Nm * Ns * PVmax)/(1000 * 0.16);
end
for t= 1:1:8760
    n(t)= Nf * (1 + ((Tcoef/100) * (Tc1(t) - Tstc)));
    PVarray(t)= Ac * SAll(t) * n(t) * Plosses;
end
for t= 1:1:8760
    Invrl(t)= ((PVarray(t)/ Ne) * 100);
    if Invrl(t) >= 10 && Invrl(t) <= 100
        Nel(t)= 0.98;
    elseif Invrl(t) >= 0.05 && Invrl(t) < 2
        Nel(t)= 0.85;
    elseif Invrl(t) >= 2 && Invrl(t) < 5
        Nel(t)= 0.92;
    elseif Invrl(t) >= 5 && Invrl(t) < 7
        Nel(t)= 0.95;
    elseif Invrl(t) >= 7 && Invrl(t) < 10
        Nel(t)= 0.97;
    elseif Invrl(t) >= 100 && Invrl(t) < 105
        Nel(t)= 0.96;
    elseif Invrl(t) >= 105 && Invrl(t) < 110
        Nel(t)= 0.94;
    elseif Invrl(t) >= 110 && Invrl(t) < 120
        Nel(t)= 0.85;
    elseif Invrl(t) < 0.05
        Nel(t)= 0;
    else
        Nel(t)= 0.8;
    end
end
%% PV over-generation study %%
for t= 1:1:8760
    PVarray1(t)= (PVarray(t) * Nel(t));
    if PVarray1(t) > Ne
        PVarray1(t)= Ne; %% DC to AC conversion
    end
    PVout1(t)= (PVarray1(t) * Nal); %% PV Plant output without constraiant
    maxPVAC= Ne * Nal; %% maximum AC output of PV system
    PVratio1(t)= (PVout1(t)/maxPVAC)*100; %% hourly Capacity factor of PV system
without baseload constraiant
end

```

3. *PV curtailment modelling part*

```

%% PV Curtailment Method %%
%% PV Curtailment Method for Baseload Constraint%%
for t= 1:1:8760

    DLB(t)= (LAll(t)*1000000) - Baseload;          %% maximum AC pv output

    if DLB(t) < PVout1(t)    %% to determine the PV overgeneration event and deal
with it through PV curtailment
        PVout2(t)= DLB(t);  %% to reduce the PV output by the value of DLB in order
to overcome the PV overgeneration event
        b(t)= 1;
        c111(t)= 1;
    else
        PVout2(t)= PVout1(t);
        b(t)= 0;
    end
end
    PVout12= PVout2;          % to show PV output with baseload constraint
for t= 1:1:8760
    PVout12(t);

    PVratio2(t)= (PVout12(t)/maxPVAC)*100;          %% hourly Capacity factor of PV
system with baseload constraint
    PVoper1(t)= (PVout12(t)/PVout1(t))*100;          %% The percentage of working
operation of a PV power plant due to baseload constraint
    PVoper1(isnan(PVoper1)) = 0;                      %% change NaN values to zeros in
table
    PVcurt(t)= 100 - PVoper1(t);                      %% The percentage of PV curtailment
due to baseload constraint
    PVcurt1(t)= PVratio1(t) - PVratio2(t);          %% The amount of capacity factor of
PV that is curtailed due to baseload constraint
    PVcurt11(t)= PVout1(t) - PVout12(t);          %% The amount of PV power that is
curtailed due to baseload constraint

    if DLB(t) < PVout12(t)    %% To check that the curtailment method applied is
working in the number of PV overgeneration events
        b1(t)= 1;
    else
        b1(t)= 0;
    end
end
%% Netload calculations %%
for t= 1:1:8760
    PVout1(t);
    PVout12(t);
    netload(t)= (LAll(t)*1000000) - PVout1(t);          %% netload without
baseload constraint
    netload1(t)= (LAll(t)*1000000) - PVout12(t);          %% netload with baseload
constraint
end
%% Define & read excel variables for Power ramps %%
Sheet4= 4;
Sheet5= 5;          %% excel sheet number

```

```

Sheet6= 6;
netload1;
PVout12(t);
Range2= 'A30:NA53';

PrAll= xlswrite(Sdata,netload1, Sheet5, Range1); %% write netload data with
baseload constraint to get power ramp
PrAll1= xlsread(Sdata, Sheet5, Range2); %% read the power ramp of netload with
baseload constraint
Prld= xlsread(Sdata, Sheet4, Range2); %% read the power ramp of load with no PV
PrPV= xlswrite(Sdata,PVout12, Sheet6, Range1);
PrPV1= xlsread(Sdata, Sheet6, Range2); %% read the power ramp of PV output with
baseload constraint
%% Loss of load Identification %%
PrNl=PrAll1; %% power ramp of netload with baseload constraint
NLpr=PrAll1; %% power ramp of netload without grid constraints

for t= 1:1:8760
    PrNl;
    if abs(PrNl(t)) > GRC %% To identify the number of loss of load events with
baseload constraint before the PV curtailment method is applied
        c11(t)= 1;
        c111(t)= 1;
    end
    if PrNl(t) > GRC %% To identify the number of loss of load events with
baseload constraint before the PV curtailment method is applied
        c(t)= 2; %% Loss of load event in evening period
    end
    if PrNl(t) < (-1*GRC)
        c(t)= 1; %% Loss of load event in morning period
    end
end
%% PV Curtailment Method for Ramping Constraint%%
RC= abs(PrAll1) - GRC;
DPRC= abs(PrPV1) - abs(RC);
c6= SAll * 0;
c7= SAll * 0;

for t= 1:1:8760
    PVout2(t);
    PrPV1(t);
    RC(t);
    PrAll1(t);
    DPRC(t);
    % PV down ramping and netload up ramping evening period
    if PrAll1(t) > GRC && PrAll1(t+1) < GRC && DPRC(t) > 0
        c1(t)= 1;
        c7(t)= 1;
        PVout2(t-1)= PVout2(t) + DPRC(t);
        PrAll1(t)= PrAll1(t) - RC(t);
        PrAll1(t-1)= PrAll1(t-1) + RC(t);
        RC(t-1)= abs(PrAll1(t-1)) - GRC;
        PrPV1(t-1)= PVout2(t-1) - PVout2(t-2);
    end
end

```

```

DPRC(t-1)= abs(PrPV1(t-1)) - abs(RC(t-1));

if PrA111(t-1) > GRC
c7(t-1)= 1;
PVout2(t-2)= PVout2(t-1) + DPRC(t-1);
PrA111(t-1)= PrA111(t-1) - RC(t-1);
PrA111(t-2)= PrA111(t-2) + RC(t-1);
RC(t-2)= abs(PrA111(t-2)) - GRC;
PrPV1(t-2)= PVout2(t-2) - PVout2(t-3);
DPRC(t-2)= abs(PrPV1(t-2)) - abs(RC(t-2));

if PrA111(t-2) > GRC
c7(t-2)= 1;
PVout2(t-3)= PVout2(t-2) + DPRC(t-2);
PrA111(t-2)= PrA111(t-2) - RC(t-2);
PrA111(t-3)= PrA111(t-3) + RC(t-2);
RC(t-3)= abs(PrA111(t-3)) - GRC;
PrPV1(t-3)= PVout2(t-3) - PVout2(t-4);
DPRC(t-3)= abs(PrPV1(t-3)) - abs(RC(t-3));

if PrA111(t-3) > GRC
c7(t-3)= 1;
PVout2(t-4)= PVout2(t-3) + DPRC(t-3);
PrA111(t-3)= PrA111(t-3) - RC(t-3);
PrA111(t-4)= PrA111(t-4) + RC(t-3);
RC(t-4)= abs(PrA111(t-4)) - GRC;
PrPV1(t-4)= PVout2(t-4) - PVout2(t-5);
DPRC(t-4)= abs(PrPV1(t-4)) - abs(RC(t-4));

if PrA111(t-4) > GRC
c7(t-4)= 1;
PVout2(t-5)= PVout2(t-4) + DPRC(t-4);
PrA111(t-4)= PrA111(t-4) - RC(t-4);
PrA111(t-5)= PrA111(t-5) + RC(t-4);
RC(t-5)= abs(PrA111(t-5)) - GRC;
PrPV1(t-5)= PVout2(t-5) - PVout2(t-6);
DPRC(t-5)= abs(PrPV1(t-5)) - abs(RC(t-5));

if PrA111(t-5) > GRC
c7(t-5)= 1;
PVout2(t-6)= PVout2(t-5) + DPRC(t-5);
PrA111(t-5)= PrA111(t-5) - RC(t-5);
PrA111(t-6)= PrA111(t-6) + RC(t-5);
RC(t-6)= abs(PrA111(t-6)) - GRC;
PrPV1(t-6)= PVout2(t-6) - PVout2(t-7);
DPRC(t-6)= abs(PrPV1(t-6)) - abs(RC(t-6));

if PrA111(t-6) > GRC
c7(t-6)= 1;
PVout2(t-7)= PVout2(t-6) + DPRC(t-6);
PrA111(t-6)= PrA111(t-6) - RC(t-6);
PrA111(t-7)= PrA111(t-7) + RC(t-6);
RC(t-7)= abs(PrA111(t-7)) - GRC;

```

```

PrPV1(t-7)= PVout2(t-7) - PVout2(t-8);
DPRC(t-7)= abs(PrPV1(t-7)) - abs(RC(t-7));

if PrA111(t-7) > GRC
    c7(t-7)= 1;
    PVout2(t-8)= PVout2(t-7) + DPRC(t-7);
    PrA111(t-7)= PrA111(t-7) - RC(t-7);
    PrA111(t-8)= PrA111(t-8) + RC(t-7);
    RC(t-8)= abs(PrA111(t-8)) - GRC;
    PrPV1(t-8)= PVout2(t-8) - PVout2(t-9);
    DPRC(t-8)= abs(PrPV1(t-8)) - abs(RC(t-8));

end
end
end
end
end
end
end
end
end
for t= 1:1:8760
% PV up ramping and netload down ramping morning period
if PrA111(t) < (-1*GRC) && DPRC(t) > 0 && PrA111(t-1) > (-1*GRC)
    c1(t)= 2;
    PVout2(t)= PVout2(t-1) + DPRC(t);
    PrA111(t)= PrA111(t) + RC(t);
    PrA111(t+1)= abs(PrA111(t+1)) + RC(t);
    RC(t+1)= abs(PrA111(t+1)) - GRC;
    PrPV1(t+1)= PVout2(t+1) - PVout2(t);
    DPRC(t+1)= abs(PrPV1(t+1)) - abs(RC(t+1));

if PrA111(t+1) > (GRC)
    PVout2(t+1)= PVout2(t) + DPRC(t+1);
    PrA111(t+1)= PrA111(t+1) - RC(t+1);
    PrA111(t+2)= abs(PrA111(t+2)) + RC(t+1);
    RC(t+2)= abs(PrA111(t+2)) - GRC;
    PrPV1(t+2)= PVout2(t+2) - PVout2(t+1);
    DPRC(t+2)= abs(PrPV1(t+2)) - abs(RC(t+2));

if PrA111(t+2) > (GRC)
    PVout2(t+2)= PVout2(t+1) + DPRC(t+2);
    PrA111(t+2)= PrA111(t+2) - RC(t+2);
    PrA111(t+3)= abs(PrA111(t+3)) + RC(t+2);
    RC(t+3)= abs(PrA111(t+3)) - GRC;
    PrPV1(t+3)= PVout2(t+3) - PVout2(t+2);
    DPRC(t+3)= abs(PrPV1(t+3)) - abs(RC(t+3));

if PrA111(t+3) > (GRC)
    PVout2(t+3)= PVout2(t+2) + DPRC(t+3);
    PrA111(t+3)= PrA111(t+3) - RC(t+3);
    PrA111(t+4)= abs(PrA111(t+4)) + RC(t+3);
    RC(t+4)= abs(PrA111(t+4)) - GRC;

```

```

PrPV1(t+4)= PVout2(t+4) - PVout2(t+3);
DPRC(t+4)= abs(PrPV1(t+4)) - abs(RC(t+4));

if PrA111(t+4) > (GRC)
    PVout2(t+4)= PVout2(t+3) + DPRC(t+4);
    PrA111(t+4)= PrA111(t+4) - RC(t+4);
    PrA111(t+5)= abs(PrA111(t+5)) + RC(t+4);
    RC(t+5)= abs(PrA111(t+5)) - GRC;
    PrPV1(t+5)= PVout2(t+5) - PVout2(t+4);
    DPRC(t+5)= abs(PrPV1(t+5)) - abs(RC(t+5));

    if PrA111(t+5) > (GRC)
        PVout2(t+5)= PVout2(t+4) + DPRC(t+5);
        PrA111(t+5)= PrA111(t+5) - RC(t+5);
        PrA111(t+6)= abs(PrA111(t+6)) + RC(t+5);
        RC(t+6)= abs(PrA111(t+6)) - GRC;
        PrPV1(t+6)= PVout2(t+6) - PVout2(t+5);
        DPRC(t+6)= abs(PrPV1(t+6)) - abs(RC(t+6));

    end
end
end
end
end
end
end
PVout3= PVout2;          %% PV system output with both baseload and Ramping✓
constraints
for t= 1:1:8760
    PVout1(t);
    PVout2(t);
    PVout12(t);
    PVout3(t);
    maxPVAC;
    PVratio1(t);

    PVratio3(t)= (PVout3(t)/maxPVAC)*100;          %% hourly Capacity factor of PV✓
system with both baseload and ramping constraint
    PVoper2(t)= (PVout3(t)/PVout1(t))*100;          %% The percentage of working✓
operation of a PV power plant due to both baseload and ramping constraint
    PVoper2(isnan(PVoper2)) = 0;                    %% change NaN values to zeros in✓
table
    PVcurt2(t)= 100 - PVoper2(t);                    %% The percentage of PV curtailment✓
due to both baseload and ramping constraint
    PVcurt3(t)= PVratio1(t) - PVratio3(t);          %% The amount of capacity factor of✓
PV that is curtailed due to both baseload and ramping constraint
    PVcurt33(t)= PVout1(t) - PVout3(t);              %% The amount of PV power that is✓
curtailed due to both baseload and ramping constraint
    PVcurt333(t)= PVout12(t) - PVout3(t);           %% The amount of PV power that is✓
curtailed due to ramping constraint only

    if PVcurt33(t) < 0
        c6(t)= 1;

```

```

end
end
%% Define & read excel variables for Power ramps after the PV curtailment method is
applied %%
PVout2(t);
PVout3(t);
for t= 1:1:8760
    netload2(t)= (LA11(t)*1000000) - PVout3(t);          %% netload with both
baseload & ramping constraint
end

Sheet7= 7;
PrAll4= xlswrite(Sdata,netload2, Sheet7, Range1); %% write netload data with both
baseload and ramping constraint to get power ramp after the PV curtailment method
is applied
PrAll5= xlsread(Sdata, Sheet7, Range2); %% read the power ramp of netload with
both baseload and ramping constraint after the PV curtailment method is applied
%% Validation of PV curtailment method for ramping constraint%%
for t= 1:1:8760
    PrAll5;
    if PrAll5(t) > GRC          %% To identify the number of loss of load events
after the PV curtailment method is applied
        c2(t)= 1;          %% Loss of load event in evening period
    end
    if PrAll5(t) < (-1*GRC)
        c2(t)= 1;          %% Loss of load event in morning period
    end
end
end

```

4. Optimal sizing and energy management strategy for BSS

```

%% Optimal Sizing and Energy Management Strategy for BSS %%

PVout21= PVout12;          % PV system output with only baseload constraint
% Battery capacity fading part
Sheet8= 8;
Range3= 'A1:NA1';          %% for aging of storage
Range4= 'NA1';              %% for aging of storage

AMAl1= xlsread(Sdata, Sheet8, Range3);    %% SOH in prcentage /100 for All months
(Sheet4 = 2)
AMAl2= xlsread(Sdata, Sheet8, Range4);    %% SOH in prcentage /100 at day 365 (1
year)

%Step 1: assigning the charging and discharging and light load periods in a matrix
Sheet9= 9;                    %% excel sheet number for timing
TMA11= xlsread(Sdata, Sheet9, Range1);    %% data for All months

%Step 2: the required discharge storage capacity to deal with ramping
z3= NLpr;
RC11= SA11 * 0;
for t= 1:1:8760
    NLpr;
    RqEC;

    if NLpr(t) > GRC && TMA11(t) == 10 && TMA11(t+1) == 10 && NLpr(t+1) < (-1*GRC)
%% incase ramping of unassinged hours is exceeded
        RqEC(t)= z3(t) - GRC;
        z3(t+1)= NLpr(t+1) + RqEC(t);
    end
    if z3(t) < (-1*GRC) && TMA11(t) == 10          %% To account z3 ramping change
that would happen in TMA11(t) == 9
        RC11(t)= abs(z3(t)) - GRC;
        z3(t)= z3(t) + RC11(t);
        z3(t+1)= abs(z3(t+1)) - RC11(t);
        RC11(t+1)= abs(z3(t+1)) - GRC;
    if z3(t+1) < (-1*GRC) && TMA11(t+1) == 10
        z3(t+1)= z3(t+1) + RC11(t+1);
        z3(t+2)= abs(z3(t+2)) - RC11(t+1);
    end
end
    if z3(t) > GRC && TMA11(t) == 9          %% To identify the earliest (first) case
in the afternoon of the day ramping is exceeded
        RqEC(t)= z3(t) - GRC;
        z3(t+1)= NLpr(t+1) + RqEC(t);
    if z3(t+1) > GRC
        RqEC(t+1)= z3(t+1) - GRC;
        z3(t+2)= NLpr(t+2) + RqEC(t+1);
    if z3(t+2) > GRC
        RqEC(t+2)= z3(t+2) - GRC;
        z3(t+3)= NLpr(t+3) + RqEC(t+2);
    if z3(t+3) > GRC
        RqEC(t+3)= z3(t+3) - GRC;
        z3(t+4)= NLpr(t+4) + RqEC(t+3);
    end
end
end

```

```

        if z3(t+4) > GRC
            RqEC(t+4)= z3(t+4) - GRC;
            z3(t+5)= NLpr(t+5) + RqEC(t+4);
            if z3(t+5) > GRC
                RqEC(t+5)= z3(t+5) - GRC;
                z3(t+6)= NLpr(t+6) + RqEC(t+5);
            end
        end
    end
end
end
end
end
end
end
%Step 3: set the usable battery capacity (MWh) with taken into account the
%DOD and Battery capacity fading
SRqEC= sum(RqEC); % To get the required daily MWh energy capacity of storage ✓
for each month
    x11= max(SRqEC(:)); % To get the highest required daily MWh energy capacity of ✓
    storage of all months thus capacity of storage is set here
    USC= ((DOD/100) * ((x11/100) * x11)); % Useable battery capacity in MWh
    USC1= USC * AMAll; % Useable battery capacity with Capacity fade in MWh
    x1= repmat(USC1,24,1); % forming the matrix
    %Step 4: To account an accurate method of the required PV curtailed energy
    %in the morning that needs to be stored
    x1= (x1 * (BSSeff/100));
    %Step 4.1: the optimal discharging methodology of the set usable storage capacity ✓
    to deal with ramping
        % in afternoon and evening period
    x2= repmat(SRqEC,24,1); % forming the matrix
    z31= z3;
    j1= SAll * 0;
    j11= SAll * 0;
    j2= SAll * 0;
    j3= SAll * 0;
    j4= SAll * 0;
    s87= SAll * 0;
    m1= SAll * 0;
    ssl= SAll * 0;
    xx1= SAll * 0;
    xxx1= SAll * 0;
    for t= 1:1:8760
        Pdischargel;
        if x2(t) <= x1(t)
            if TMAll(t) == 10 && RqEC(t) > 0 % to account of the pdischargel in the ✓
            unassigned period
                Pdischargel(t)= RqEC(t);
                ssl(t)= ((LAll(t)*1000000) - (PVout12(t) + Pdischargel(t))); % incase ✓
                discharging will cause baseload to be exceeded
                if ssl(t) <= Baseload
                    Pdischargel(t)= 0;
                end
            end
            z31(t)= z31(t) - Pdischargel(t);
            x1(t+1)= x1(t+1) - Pdischargel(t);

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x1(t+2)= x1(t+2) - Pdischargel(t);
x1(t+3)= x1(t+3) - Pdischargel(t);
x1(t+4)= x1(t+4) - Pdischargel(t);
x1(t+5)= x1(t+5) - Pdischargel(t);
x1(t+6)= x1(t+6) - Pdischargel(t);
x1(t+7)= x1(t+7) - Pdischargel(t);
m1(t)= x1(t+2);
x2(t+1)= x2(t+1) - Pdischargel(t);
x2(t+2)= x2(t+2) - Pdischargel(t);
x2(t+3)= x2(t+3) - Pdischargel(t);
x2(t+4)= x2(t+4) - Pdischargel(t);
x2(t+5)= x2(t+5) - Pdischargel(t);
x2(t+6)= x2(t+6) - Pdischargel(t);
x2(t+7)= x2(t+7) - Pdischargel(t);
end
end
if TMA11(t) == 9 && TMA11(t-1) == 10      %% To identify the first sequence of
desired set discharge hours in the afternoon of the day
    if x2(t) <= x1(t)                    % Scenario 1 of discharge
        j11(t)= 6;                      % desired discharge time in hours
        xxx1(t)= j11(t);
        xx1(t)= x1(t) - x2(t);
        j1(t)= xx1(t)/j11(t);           %% the excess energy disterbuted to 6 hours of
of desired set discharge hourse from 14:00 till 20:00
        Pdischargel(t)= RqEC(t) + j1(t);
        ssl(t)= ((LA11(t)*1000000) - (PVout12(t) + Pdischargel(t)));    %% incase
discharging will cause baseload to be exceeded
        if ssl(t) <= Baseload
            Pdischargel(t)= 0;
            xxx1(t)= 5;
            j1(t)= 0;
        end
        z31(t)= z31(t) - Pdischargel(t);
        z31(t+1)= NLpr(t+1) + Pdischargel(t);
        j11(t+1)= 5;                    % desired discharge time in hours
        xx1(t+1)= xx1(t)- j1(t);
        j1(t+1)= xx1(t+1)/j11(t+1);
        if j1(t+1) <= 0
            j1(t+1)= 0;
        end
        Pdischargel(t+1)= RqEC(t+1) + j1(t+1);
        ssl(t+1)= ((LA11(t+1)*1000000) - (PVout12(t+1) + Pdischargel(t+1)));    %%
incase discharging will cause baseload to be exceeded
        if ssl(t+1) <= Baseload
            Pdischargel(t+1)= 0;
            xxx1(t)= 4;
            j1(t+1)= 0;
        end
        z31(t+1)= z31(t+1) - Pdischargel(t+1);
        z31(t+2)= NLpr(t+2) + Pdischargel(t+1);
        j11(t+2)= 4;                    % desired discharge time in hours
        xx1(t+2)= xx1(t+1)- j1(t+1);
        j1(t+2)= xx1(t+2)/j11(t+2);

```

```

    if j1(t+2) <= 0
        j1(t+2)= 0;
    end
    Pdischargel(t+2)= RqEC(t+2) + j1(t+2);
    ssl(t+2)= ((LAll(t+2)*1000000) - (PVoutl2(t+2) + Pdischargel(t+2))); %%✓
inbase discharging will cause baseload to be exceeded
    if ssl(t+2) <= Baseload
        Pdischargel(t+2)= 0;
        xxxl(t)= 3;
        j1(t+2)= 0;
    end
    z31(t+2)= z31(t+2) - Pdischargel(t+2);
    z31(t+3)= NLpr(t+3) + Pdischargel(t+2);
    j11(t+3)= 3; % desired discharge time in hours
    xxl(t+3)= xxl(t+2)- j1(t+2);
    j1(t+3)= xxl(t+3)/j11(t+3);
    if j1(t+3) <= 0
        j1(t+3)= 0;
    end
    Pdischargel(t+3)= RqEC(t+3) + j1(t+3);
    ssl(t+3)= ((LAll(t+3)*1000000) - (PVoutl2(t+3) + Pdischargel(t+3))); %%✓
inbase discharging will cause baseload to be exceeded
    if ssl(t+3) <= Baseload
        Pdischargel(t+3)= 0;
        xxxl(t)= 2;
        j1(t+3)= 0;
    end
    z31(t+3)= z31(t+3) - Pdischargel(t+3);
    z31(t+4)= NLpr(t+4) + Pdischargel(t+3);
    j11(t+4)= 2; % desired discharge time in hours
    xxl(t+4)= xxl(t+3)- j1(t+3);
    j1(t+4)= xxl(t+4)/j11(t+4);
    if j1(t+4) <= 0
        j1(t+4)= 0;
    end
    Pdischargel(t+4)= RqEC(t+4) + j1(t+4);
    z31(t+4)= z31(t+4) - Pdischargel(t+4);
    z31(t+5)= NLpr(t+5) + Pdischargel(t+4);
    j11(t+5)= 1; % desired discharge time in hours
    xxl(t+5)= xxl(t+4)- j1(t+4);
    j1(t+5)= xxl(t+5)/j11(t+5);
    if j1(t+5) <= 0
        j1(t+5)= 0;
    end
    Pdischargel(t+5)= RqEC(t+5) + j1(t+5);
    z31(t+5)= z31(t+5) - Pdischargel(t+5);
    z31(t+6)= NLpr(t+6) + Pdischargel(t+5);
    if z31(t+6) > GRC
        Pdischargel(t+6)= z31(t+6) - GRC;
        j2(t)= (z31(t+6) - GRC) / xxxl(t); % 6 hours from 14:00 till 20:✓
00
    if ssl(t) > Baseload
        Pdischargel(t)= Pdischargel(t) - j2(t);

```

```

z31(t)= NLpr(t) - Pdischargel(t);
z31(t+1)= NLpr(t+1) + Pdischargel(t);
end
if ssl(t+1) > Baseload
Pdischargel(t+1)= Pdischargel(t+1) - j2(t);
z31(t+1)= z31(t+1) - Pdischargel(t+1);
z31(t+2)= NLpr(t+2) + Pdischargel(t+1);
end
if ssl(t+2) > Baseload
Pdischargel(t+2)= Pdischargel(t+2) - j2(t);
z31(t+2)= z31(t+2) - Pdischargel(t+2);
z31(t+3)= NLpr(t+3) + Pdischargel(t+2);
end
if ssl(t+3) > Baseload
Pdischargel(t+3)= Pdischargel(t+3) - j2(t);
z31(t+3)= z31(t+3) - Pdischargel(t+3);
z31(t+4)= NLpr(t+4) + Pdischargel(t+3);
end
Pdischargel(t+4)= Pdischargel(t+4) - j2(t);
z31(t+4)= z31(t+4) - Pdischargel(t+4);
z31(t+5)= NLpr(t+5) + Pdischargel(t+4);
Pdischargel(t+5)= Pdischargel(t+5) - j2(t);
z31(t+5)= z31(t+5) - Pdischargel(t+5);
z31(t+6)= NLpr(t+6) + Pdischargel(t+5);
z31(t+6)= z31(t+6) - Pdischargel(t+6);
z31(t+7)= NLpr(t+7) + Pdischargel(t+6);
    if z31(t+7) > GRC
        Pdischargel(t+7)= z31(t+7) - GRC;
        j11(t)= j11(t) + 1; % desired discharge time in
hours which increased by an extra hour
        xxx1(t)= xxx1(t) + 1;
        j2(t+1)= (z31(t+7) - GRC) / xxx1(t); % 7 hours from 14:00
till 21:00
    if ssl(t) > Baseload
Pdischargel(t)= Pdischargel(t) - j2(t+1);
z31(t)= NLpr(t) - Pdischargel(t);
z31(t+1)= NLpr(t+1) + Pdischargel(t);
end
if ssl(t+1) > Baseload
Pdischargel(t+1)= Pdischargel(t+1) - j2(t+1);
z31(t+1)= z31(t+1) - Pdischargel(t+1);
z31(t+2)= NLpr(t+2) + Pdischargel(t+1);
end
if ssl(t+2) > Baseload
Pdischargel(t+2)= Pdischargel(t+2) - j2(t+1);
z31(t+2)= z31(t+2) - Pdischargel(t+2);
z31(t+3)= NLpr(t+3) + Pdischargel(t+2);
end
if ssl(t+3) > Baseload
Pdischargel(t+3)= Pdischargel(t+3) - j2(t+1);
z31(t+3)= z31(t+3) - Pdischargel(t+3);
z31(t+4)= NLpr(t+4) + Pdischargel(t+3);
end

```

```

Pdischargel(t+4)= Pdischargel(t+4) - j2(t+1);
z3l(t+4)= z3l(t+4) - Pdischargel(t+4);
z3l(t+5)= NLpr(t+5) + Pdischargel(t+4);
Pdischargel(t+5)= Pdischargel(t+5) - j2(t+1);
z3l(t+5)= z3l(t+5) - Pdischargel(t+5);
z3l(t+6)= NLpr(t+6) + Pdischargel(t+5);
Pdischargel(t+6)= Pdischargel(t+6) - j2(t+1);
z3l(t+6)= z3l(t+6) - Pdischargel(t+6);
z3l(t+7)= NLpr(t+7) + Pdischargel(t+6);
z3l(t+7)= z3l(t+7) - Pdischargel(t+7);
z3l(t+8)= NLpr(t+8) + Pdischargel(t+7);
if z3l(t+8) > GRC
    Pdischargel(t+8)= z3l(t+8) - GRC;
    j1l(t)= j1l(t) + 1; % desired discharge
time in hours which increased by an extra hour
    xxxl(t)= xxxl(t) + 1;
    j2(t+2)= (z3l(t+8) - GRC) / xxxl(t); % 8 hours from
14:00 till 22:00

if ssl(t) > Baseload
    Pdischargel(t)= Pdischargel(t) - j2(t+2);
    z3l(t)= NLpr(t) - Pdischargel(t);
    z3l(t+1)= NLpr(t+1) + Pdischargel(t);
end
if ssl(t+1) > Baseload
    Pdischargel(t+1)= Pdischargel(t+1) - j2(t+2);
    z3l(t+1)= z3l(t+1) - Pdischargel(t+1);
    z3l(t+2)= NLpr(t+2) + Pdischargel(t+1);
end
if ssl(t+2) > Baseload
    Pdischargel(t+2)= Pdischargel(t+2) - j2(t+2);
    z3l(t+2)= z3l(t+2) - Pdischargel(t+2);
    z3l(t+3)= NLpr(t+3) + Pdischargel(t+2);
end
if ssl(t+3) > Baseload
    Pdischargel(t+3)= Pdischargel(t+3) - j2(t+2);
    z3l(t+3)= z3l(t+3) - Pdischargel(t+3);
    z3l(t+4)= NLpr(t+4) + Pdischargel(t+3);
end
Pdischargel(t+4)= Pdischargel(t+4) - j2(t+2);
z3l(t+4)= z3l(t+4) - Pdischargel(t+4);
z3l(t+5)= NLpr(t+5) + Pdischargel(t+4);
Pdischargel(t+5)= Pdischargel(t+5) - j2(t+2);
z3l(t+5)= z3l(t+5) - Pdischargel(t+5);
z3l(t+6)= NLpr(t+6) + Pdischargel(t+5);
Pdischargel(t+6)= Pdischargel(t+6) - j2(t+2);
z3l(t+6)= z3l(t+6) - Pdischargel(t+6);
z3l(t+7)= NLpr(t+7) + Pdischargel(t+6);
Pdischargel(t+7)= Pdischargel(t+7) - j2(t+2);
z3l(t+7)= z3l(t+7) - Pdischargel(t+7);
z3l(t+8)= NLpr(t+8) + Pdischargel(t+7);
z3l(t+8)= z3l(t+8) - Pdischargel(t+8);
z3l(t+9)= NLpr(t+9) + Pdischargel(t+8);
end

```

```

        end
    if z31(t) < (-1*GRC)
        s87(t)= abs(z31(t)) - GRC;
        if Pdischargel(t) >= s87(t)
            Pdischargel(t)= Pdischargel(t) - s87(t);
            j3(t)= s87(t) / j11(t);
            if Pdischargel(t) < s87(t)
                j3(t)= Pdischargel(t) / j11(t);
                Pdischargel(t)= 0;
            end
        end
        z31(t)= z31(t) - Pdischargel(t);
        z31(t+1)= NLpr(t+1) + Pdischargel(t);
        Pdischargel(t+1)= Pdischargel(t+1) + j3(t);
        z31(t+1)= z31(t+1) - Pdischargel(t+1);
        z31(t+2)= NLpr(t+2) + Pdischargel(t+1);
        Pdischargel(t+2)= Pdischargel(t+2) + j3(t);
        z31(t+2)= z31(t+2) - Pdischargel(t+2);
        z31(t+3)= NLpr(t+3) + Pdischargel(t+2);
        Pdischargel(t+3)= Pdischargel(t+3) + j3(t);
        z31(t+3)= z31(t+3) - Pdischargel(t+3);
        z31(t+4)= NLpr(t+4) + Pdischargel(t+3);
        Pdischargel(t+4)= Pdischargel(t+4) + j3(t);
        z31(t+4)= z31(t+4) - Pdischargel(t+4);
        z31(t+5)= NLpr(t+5) + Pdischargel(t+4);
        Pdischargel(t+5)= Pdischargel(t+5) + j3(t);
        z31(t+5)= z31(t+5) - Pdischargel(t+5);
        z31(t+6)= NLpr(t+6) + Pdischargel(t+5);
        Pdischargel(t+6)= Pdischargel(t+6) + j3(t);
        z31(t+6)= z31(t+6) - Pdischargel(t+6);
        z31(t+7)= NLpr(t+7) + Pdischargel(t+6);
        Pdischargel(t+7)= Pdischargel(t+7) + j3(t);
        z31(t+7)= z31(t+7) - Pdischargel(t+7);
        z31(t+8)= NLpr(t+8) + Pdischargel(t+7);
        Pdischargel(t+8)= Pdischargel(t+8) + j3(t);
        z31(t+8)= z31(t+8) - Pdischargel(t+8);
        z31(t+9)= NLpr(t+9) + Pdischargel(t+8);
    end
end
end
end
if x2(t) > x1(t) % Scenario 2 of discharge
    if RqEC(t) > 0 && RqEC(t+1) == 0 % to identify the latest sequence✓
of RqEC
        j4(t)= x1(t);
        Pdischargel(t)= RqEC(t);
        if RqEC(t) > j4(t)
            Pdischargel(t)= j4(t);
        end
        j4(t-1)= x1(t) - Pdischargel(t);
        if j4(t-1) > 0
            Pdischargel(t-1)= RqEC(t-1);
            if RqEC(t-1) > j4(t-1)

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        Pdischargel(t-1)= j4(t-1);
    end
    j4(t-2)= x1(t) - (Pdischargel(t) + Pdischargel(t-1));
    if j4(t-2) > 0
        Pdischargel(t-2)= RqEC(t-2);
        if RqEC(t-2) > j4(t-2)
            Pdischargel(t-2)= j4(t-2);
        end
    end
    j4(t-3)= x1(t) - (Pdischargel(t) + Pdischargel(t-1) + Pdischargel(t-2));
    if j4(t-3) > 0
        Pdischargel(t-3)= RqEC(t-3);
        if RqEC(t-3) > j4(t-3)
            Pdischargel(t-3)= j4(t-3);
        end
    end
    j4(t-4)= x1(t) - (Pdischargel(t) + Pdischargel(t-1) + Pdischargel(t-2) + Pdischargel(t-3));
    if j4(t-4) > 0
        Pdischargel(t-4)= RqEC(t-4);
        if RqEC(t-4) > j4(t-4)
            Pdischargel(t-4)= j4(t-4);
        end
    end
    j4(t-5)= x1(t) - (Pdischargel(t) + Pdischargel(t-1) + Pdischargel(t-2) + Pdischargel(t-3) + Pdischargel(t-4));
    if j4(t-5) > 0
        Pdischargel(t-5)= RqEC(t-5);
        if RqEC(t-5) > j4(t-5)
            Pdischargel(t-5)= j4(t-5);
        end
    end
    j4(t-6)= x1(t) - (Pdischargel(t) + Pdischargel(t-1) + Pdischargel(t-2) + Pdischargel(t-3) + Pdischargel(t-4) + Pdischargel(t-5));
    end
    end
    end
    end
    end
end
end
%Step 4.2.1: apply PV curtailment method first on the afternoon
s7= PVoutl2 + Pdischargel; %% incase there are curtailed energy in the morning from the afternoon curtailment part
netload3= (LAll*1000000) - s7;

Sheet10= 10;
PrAll6= xlswrite(Sdata,netload3, Sheet10, Rangel); %% write netload data with storage
PrAll7= xlsread(Sdata, Sheet10, Range2); %% read the power ramp of netload with storage
Sheet11= 11;
PrPV2= xlswrite(Sdata,s7, Sheet11, Rangel);
PrPV3= xlsread(Sdata, Sheet11, Range2); %% read the power ramp of PV output with storage discharged

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z33= PrA117;
RC1= abs(z33) - GRC; %% Grids current ramping capability with storage
discharge
DPRC1= abs(PrPV3) - abs(RC1); %% The difference between PV power ramp with
storage discharge and grids current ramping capability
PVout4= PVout12;
m2= sum(m1);
for t= 1:1:365
    if m2(t) == 0 %% To update x1 capacity
        m2(t)= USC1(t);
    end
end
m3= repmat(m2,24,1); % forming the matrix
for t= 1:1:8760
    if m3(t) < x2(t)
        if z33(t) > GRC && z33(t+1)<= GRC && DPRC1(t) > 0 %% PV down ramping
and netload up ramping evening period to identify the latest case in discharging
period
            c3(t)=1;
            PVout4(t-1)= PVout4(t) + (DPRC1(t) + Pdischargel(t)); % we added
Pdischargel to account for the power ramp change of first sequence of discharging
due to storage
            z33(t)= z33(t) - RC1(t);
            z33(t-1)= z33(t-1) + RC1(t);
            RC1(t-1)= abs(z33(t-1)) - GRC;
            PrPV3(t-1)= PVout4(t-1) - PVout4(t-2);
            DPRC1(t-1)= abs(PrPV3(t-1)) - abs(RC1(t-1));
            if z33(t-1) > GRC
                PVout4(t-2)= PVout4(t-1) + DPRC1(t-1);
                z33(t-1)= z33(t-1) - RC1(t-1);
                z33(t-2)= z33(t-2) + RC1(t-1);
                RC1(t-2)= abs(z33(t-2)) - GRC;
                PrPV3(t-2)= PVout4(t-2) - PVout4(t-3);
                DPRC1(t-2)= abs(PrPV3(t-2)) - abs(RC1(t-2));
                if z33(t-2) > GRC
                    PVout4(t-3)= PVout4(t-2) + DPRC1(t-2);
                    z33(t-2)= z33(t-2) - RC1(t-2);
                    z33(t-3)= z33(t-3) + RC1(t-2);
                    RC1(t-3)= abs(z33(t-3)) - GRC;
                    PrPV3(t-3)= PVout4(t-3) - PVout4(t-4);
                    DPRC1(t-3)= abs(PrPV3(t-3)) - abs(RC1(t-3));
                    if z33(t-3) > GRC
                        PVout4(t-4)= PVout4(t-3) + DPRC1(t-3);
                        z33(t-3)= z33(t-3) - RC1(t-3);
                        z33(t-4)= z33(t-4) + RC1(t-3);
                        RC1(t-4)= abs(z33(t-4)) - GRC;
                        PrPV3(t-4)= PVout4(t-4) - PVout4(t-5);
                        DPRC1(t-4)= abs(PrPV3(t-4)) - abs(RC1(t-4));
                        if z33(t-4) > GRC
                            PVout4(t-5)= PVout4(t-4) + DPRC1(t-4);
                            z33(t-4)= z33(t-4) - RC1(t-4);
                            z33(t-5)= z33(t-5) + RC1(t-4);

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RC1(t-5)= abs(z33(t-5)) - GRC;
PrPV3(t-5)= PVout4(t-5) - PVout4(t-6);
DPRC1(t-5)= abs(PrPV3(t-5)) - abs(RC1(t-5));
if z33(t-5) > GRC
    PVout4(t-6)= PVout4(t-5) + DPRC1(t-5);
    z33(t-5)= z33(t-5) - RC1(t-5);
    z33(t-6)= z33(t-6) + RC1(t-5);
    RC1(t-6)= abs(z33(t-6)) - GRC;
    PrPV3(t-6)= PVout4(t-6) - PVout4(t-7);
    DPRC1(t-6)= abs(PrPV3(t-6)) - abs(RC1(t-6));
    if z33(t-6) > GRC
        PVout4(t-7)= PVout4(t-6) + DPRC1(t-6);
        z33(t-6)= z33(t-6) - RC1(t-6);
        z33(t-7)= z33(t-7) + RC1(t-6);
        RC1(t-7)= abs(z33(t-7)) - GRC;
        PrPV3(t-7)= PVout4(t-7) - PVout4(t-8);
        DPRC1(t-7)= abs(PrPV3(t-7)) - abs(RC1(t-7));
        if z33(t-7) > GRC
            PVout4(t-8)= PVout4(t-7) + DPRC1(t-7);
            z33(t-7)= z33(t-7) - RC1(t-7);
            z33(t-8)= z33(t-8) + RC1(t-7);
            RC1(t-8)= abs(z33(t-8)) - GRC;
            PrPV3(t-8)= PVout4(t-8) - PVout4(t-9);
            DPRC1(t-8)= abs(PrPV3(t-8)) - abs(RC1(t-8));
        end
    end
end
end
end
end
end
end
end
if m3(t) >= x2(t)
    if TMA11(t) == 10 && z33(t) > GRC && z33(t+1)<= GRC && DPRC1(t) > 0    %%
to account the PV curtailed in the unassigned period into RqEC1 part 1
    c3(t)=2;
    PVout4(t-1)= PVout4(t) + (DPRC1(t) + Pdischargel(t));    % we added
Pdischargel to account for the power ramp change of first sequence of discharging
due to storage
    z33(t)= z33(t) - RC1(t);
    z33(t-1)= z33(t-1) + RC1(t);
    RC1(t-1)= abs(z33(t-1)) - GRC;
    PrPV3(t-1)= PVout4(t-1) - PVout4(t-2);
    DPRC1(t-1)= abs(PrPV3(t-1)) - abs(RC1(t-1));
    if z33(t-1) > GRC
        PVout4(t-2)= PVout4(t-1) + DPRC1(t-1);
        z33(t-1)= z33(t-1) - RC1(t-1);
        z33(t-2)= z33(t-2) + RC1(t-1);
        RC1(t-2)= abs(z33(t-2)) - GRC;
        PrPV3(t-2)= PVout4(t-2) - PVout4(t-3);
        DPRC1(t-2)= abs(PrPV3(t-2)) - abs(RC1(t-2));
        if z33(t-2) > GRC

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PVout4(t-3)= PVout4(t-2) + DPRCl(t-2);
z33(t-2)= z33(t-2) - RC1(t-2);
z33(t-3)= z33(t-3) + RC1(t-2);
RC1(t-3)= abs(z33(t-3)) - GRC;
PrPV3(t-3)= PVout4(t-3) - PVout4(t-4);
DPRCl(t-3)= abs(PrPV3(t-3)) - abs(RC1(t-3));
if z33(t-3) > GRC
    PVout4(t-4)= PVout4(t-3) + DPRCl(t-3);
    z33(t-3)= z33(t-3) - RC1(t-3);
    z33(t-4)= z33(t-4) + RC1(t-3);
    RC1(t-4)= abs(z33(t-4)) - GRC;
    PrPV3(t-4)= PVout4(t-4) - PVout4(t-5);
    DPRCl(t-4)= abs(PrPV3(t-4)) - abs(RC1(t-4));
    if z33(t-4) > GRC
        PVout4(t-5)= PVout4(t-4) + DPRCl(t-4);
        z33(t-4)= z33(t-4) - RC1(t-4);
        z33(t-5)= z33(t-5) + RC1(t-4);
        RC1(t-5)= abs(z33(t-5)) - GRC;
        PrPV3(t-5)= PVout4(t-5) - PVout4(t-6);
        DPRCl(t-5)= abs(PrPV3(t-5)) - abs(RC1(t-5));
        if z33(t-5) > GRC
            PVout4(t-6)= PVout4(t-5) + DPRCl(t-5);
            z33(t-5)= z33(t-5) - RC1(t-5);
            z33(t-6)= z33(t-6) + RC1(t-5);
            RC1(t-6)= abs(z33(t-6)) - GRC;
            PrPV3(t-6)= PVout4(t-6) - PVout4(t-7);
            DPRCl(t-6)= abs(PrPV3(t-6)) - abs(RC1(t-6));
        end
    end
end
end
end
end
end
if m3(t) >= x2(t)
    if z33(t) > GRC && DPRCl(t) > 0 && TMA11(t+1) == 10    %% to account the
PV curtailed in the unassigned period into RqEC1 part 1
        c3(t)=3;
        PVout4(t-1)= PVout4(t) + (DPRCl(t) + Pdischargel(t));    % we added
Pdischargel to account for the power ramp change of first sequence of discharging
due to storage
        z33(t)= z33(t) - RC1(t);
        z33(t-1)= z33(t-1) + RC1(t);
        RC1(t-1)= abs(z33(t-1)) - GRC;
        PrPV3(t-1)= PVout4(t-1) - PVout4(t-2);
        DPRCl(t-1)= abs(PrPV3(t-1)) - abs(RC1(t-1));
        if z33(t-1) > GRC
            PVout4(t-2)= PVout4(t-1) + DPRCl(t-1);
            z33(t-1)= z33(t-1) - RC1(t-1);
            z33(t-2)= z33(t-2) + RC1(t-1);
            RC1(t-2)= abs(z33(t-2)) - GRC;
            PrPV3(t-2)= PVout4(t-2) - PVout4(t-3);
            DPRCl(t-2)= abs(PrPV3(t-2)) - abs(RC1(t-2));
        end
    end
end

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        RqEC1(t)= s9(t);    %the addition of any energy curtailed from the
afternoon method if it lies in the desired charging period set
    end
end
z333= PrA119;
s88= SA11 * 0;
for t= 1:1:8760    % To get the required daily MWh required charging storage
capacity to deal with ramping in the morning for each month
    PrA119;
    RqEC1;
    if PrA119(t) < (-1*GRC) && TMA11(t) <= 7 && TMA11(t) >= 1    %% To identify
the first case in the morning of the day ramping is exceeded
        RqEC1(t)= abs(z333(t)) - GRC;
        z333(t+1)= PrA119(t+1) - RqEC1(t);
        s88(t)= 1;
        if z333(t+1) < (-1*GRC)
            RqEC1(t+1)= abs(z333(t+1)) - GRC;
            z333(t+2)= PrA119(t+2) - RqEC1(t+1);
            s88(t)= 1;
            if z333(t+2) < (-1*GRC)
                RqEC1(t+2)= abs(z333(t+2)) - GRC;
                z333(t+3)= PrA119(t+3) - RqEC1(t+2);
                s88(t)= 1;
                if z333(t+3) < (-1*GRC)
                    RqEC1(t+3)= abs(z333(t+3)) - GRC;
                    z333(t+4)= PrA119(t+4) - RqEC1(t+3);
                    s88(t)= 1;
                    if z333(t+4) < (-1*GRC)
                        RqEC1(t+4)= abs(z333(t+4)) - GRC;
                        z333(t+5)= PrA119(t+5) - RqEC1(t+4);
                        s88(t)= 1;
                        if z333(t+5) < (-1*GRC)
                            RqEC1(t+5)= abs(z333(t+5)) - GRC;
                            z333(t+6)= PrA119(t+6) - RqEC1(t+5);
                            s88(t)= 1;
                        end
                    end
                end
            end
        end
    end
end
end
end
end
    if PrA119(t) < (-1*GRC) && TMA11(t) == 10    %% to account the PV curtailed in
the unassigned period into RqEC1
        RqEC1(t)= abs(z333(t)) - GRC;
        z333(t+1)= PrA119(t+1) - RqEC1(t);
        s88(t)= 2;
        if z333(t+1) < (-1*GRC)
            RqEC1(t+1)= abs(z333(t+1)) - GRC;
            z333(t+2)= PrA119(t+2) - RqEC1(t+1);
            s88(t)= 2;
            if z333(t+2) < (-1*GRC)
                RqEC1(t+2)= abs(z333(t+2)) - GRC;
                z333(t+3)= PrA119(t+3) - RqEC1(t+2);
            end
        end
    end
end

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        s88(t)= 2;
        if z333(t+3) < (-1*GRC)
            RqEC1(t+3)= abs(z333(t+3)) - GRC;
            z333(t+4)= PrA119(t+4) - RqEC1(t+3);
            s88(t)= 2;
        end
    end
end
end
end
end
SRqEC1= sum(RqEC1); % To get the required daily MWh required charging storage capacity to deal with ramping in the morning for each month
x3= repmat(SRqEC1,24,1); % forming the matrix
SPVcurt11= sum(PVcurt11); % To get all the required daily PV curtailed energy in MWh due to the Baseload constraint
for t= 1:1:8760 % To get the avliable curtailed PV energy from baseload constraint that is situated in the battery charging period
    if TMA11(t) <= 7 && TMA11(t) >= 1 && PVcurt11(t) > 0
        RqEC2(t)= PVcurt11(t);
    end
    if TMA11(t) == 10 && PVcurt11(t) > 0
        RqEC2(t)= PVcurt11(t);
    end
end
end
SRqEC2= sum(RqEC2); % To get the daily avliable curtailed PV energy from baseload constraint that is situated in the battery charging period
DF= USC1 - SRqEC1;
bb= DF * 0; % The indicator of when to charge from the curtailed PV energy from baseload constraint that is situated in the battery charging period
for t= 1:1:365
    if SRqEC2(t) >= DF(t) && DF(t) > 0 % indicates of when to charge from the curtailed PV energy from baseload constraint
        bb(t)= 1;
    end
end
end
x33= repmat(SRqEC2,24,1); % forming the matrix
x10= repmat(DF,24,1); % forming the matrix
bbb= repmat(bb,24,1); % forming the matrix
%Step 5: (M2 higher charging stress on battery) optimal charging method to deal with ramping constraints
x1=repmat(USC1,24,1);

u11= SA11 * 0;
u111= SA11 * 0;
u22= SA11 * 0;
u222= SA11 * 0;
u33= SA11 * 0;
u44= SA11 * 0;
z55= SA11 * 0;
s55= SA11 * 0;
s66= SA11 * 0;
c333= SA11 * 0;
c3333= SA11 * 0;

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ss6= SA11 * 0;

z5= PrA117;
% When there is enough PV curtailed energy to be used in charging process
for t= 1:1:8760
    if TMA11(t) == 1 && bbb(t) == 1
        s6(t)= x1(t);
        ss6(t)= x10(t);
        if RqEC1(t) > 0
            Pchargel(t)= RqEC1(t);
            if Pchargel(t) >= x1(t)
                Pchargel(t)= x1(t);
            end
            u22(t)= x3(t);
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences
                ull(t)= RqEC1(t);    %% also it gives indication
of how much of charging priorety is left to charge from
                u22(t)= x3(t) - ull(t);
            elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
                ull(t)= RqEC1(t) - Pchargel(t);
                u22(t)= x3(t) - ull(t);
            end
            z5(t)= Pchargel(t)+ NLpr(t);
            s6(t)= x1(t) - Pchargel(t);
            z5(t+1)= Pchargel(t) - z5(t+1);
        end
        if RqEC2(t) > 0
            Pchargel(t)= Pchargel(t) + RqEC2(t);
            if Pchargel(t) >= x10(t)
                Pchargel(t)= x10(t) + RqEC1(t);
            end
            if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
                ull1(t)= RqEC2(t);
            elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
                ull1(t)= RqEC2(t) - Pchargel(t);
            end
            s6(t)= x1(t) - Pchargel(t);
            ss6(t)= x10(t) - (Pchargel(t)-RqEC1(t));
        end
    end
end
for t= 1:1:8760
    if TMA11(t) == 2 && bbb(t) == 1
        s6(t)= s6(t-1);
        ss6(t)= ss6(t-1);
        if RqEC1(t) > 0
            Pchargel(t)= RqEC1(t);
            if Pchargel(t) >= s6(t-1)
                Pchargel(t)= s6(t-1);
            end
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences

```

```

        ull(t)= RqEC1(t); % also it gives indication of how much of charging priority is left to charge from
        u22(t)= u22(t-1) - ull(t);
        elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
            ull(t)= RqEC1(t) - Pchargel(t);
            u22(t)= u22(t-1) - ull(t);
        end
        z5(t)= Pchargel(t)+ NLpr(t);
        s6(t)= s6(t-1) - Pchargel(t);
        z5(t+1)= Pchargel(t) - z5(t+1);
        end
        if RqEC2(t) > 0 && ss6(t) > 0
            Pchargel(t)= Pchargel(t) + RqEC2(t);
            if Pchargel(t) >= ss6(t-1)
                Pchargel(t)= ss6(t-1) + RqEC1(t);
            end
            if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
                ull1(t)= RqEC2(t);
            elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
                ull1(t)= RqEC2(t) - Pchargel(t);
            end
            s6(t)= s6(t-1) - Pchargel(t);
            ss6(t)= ss6(t-1) - (Pchargel(t)-RqEC1(t));
        end
    end
end
for t= 1:1:8760
    if TMA11(t) == 3 && bbb(t) == 1
        s6(t)= s6(t-1);
        ss6(t)= ss6(t-1);
        if RqEC1(t) > 0
            Pchargel(t)= RqEC1(t);
            if Pchargel(t) >= s6(t-1)
                Pchargel(t)= s6(t-1);
            end
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t) % incase max charge of
exceeds the remaining RqEC1 of other sequences % also it gives indication of how much of charging priority is left to charge from
                ull(t)= RqEC1(t);
                u22(t)= u22(t-1) - ull(t);
            elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
                ull(t)= RqEC1(t) - Pchargel(t);
                u22(t)= u22(t-1) - ull(t);
            end
            z5(t)= Pchargel(t)+ NLpr(t);
            s6(t)= s6(t-1) - Pchargel(t);
            z5(t+1)= Pchargel(t) - z5(t+1);
            end
            if RqEC2(t) > 0 && ss6(t) > 0
                Pchargel(t)= Pchargel(t) + RqEC2(t);
                if Pchargel(t) >= ss6(t-1)
                    Pchargel(t)= ss6(t-1) + RqEC1(t);
                end
            end
        end
    end
end

```

```

        if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
            ull1(t)= RqEC2(t);
        elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
            ull1(t)= RqEC2(t) - Pchargel(t);
        end
        s6(t)= s6(t-1) - Pchargel(t);
        ss6(t)= ss6(t-1) - (Pchargel(t)-RqEC1(t));
    end
end
end
for t= 1:1:8760
    if TMA11(t) == 4 && bbb(t) == 1
        s6(t)= s6(t-1);
        ss6(t)= ss6(t-1);
        if RqEC1(t) > 0
            Pchargel(t)= RqEC1(t);
            if Pchargel(t) >= s6(t-1)
                Pchargel(t)= s6(t-1);
            end
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences
                ull(t)= RqEC1(t);    %% also it gives indication
of how much of charging priority is left to charge from
                u22(t)= u22(t-1) - ull(t);
            elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
                ull(t)= RqEC1(t) - Pchargel(t);
                u22(t)= u22(t-1) - ull(t);
            end
            z5(t)= Pchargel(t)+ NLpr(t);
            s6(t)= s6(t-1) - Pchargel(t);
            z5(t+1)= Pchargel(t) - z5(t+1);
        end
        if RqEC2(t) > 0 && ss6(t) > 0
            Pchargel(t)= Pchargel(t) + RqEC2(t);
            if Pchargel(t) >= ss6(t-1)
                Pchargel(t)= ss6(t-1) + RqEC1(t);
            end
            if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
                ull1(t)= RqEC2(t);
            elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
                ull1(t)= RqEC2(t) - Pchargel(t);
            end
            s6(t)= s6(t-1) - Pchargel(t);
            ss6(t)= ss6(t-1) - (Pchargel(t)-RqEC1(t));
        end
    end
end
end
for t= 1:1:8760
    if TMA11(t) == 5 && bbb(t) == 1
        s6(t)= s6(t-1);
        ss6(t)= ss6(t-1);
        if RqEC1(t) > 0
            Pchargel(t)= RqEC1(t);

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        if Pchargel(t) >= s6(t-1)
            Pchargel(t)= s6(t-1);
        end
        if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences
            ull(t)= RqEC1(t);    %% also it gives indication
of how much of charging priorety is left to charge from
            u22(t)= u22(t-1) - ull(t);
        elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
            ull(t)= RqEC1(t) - Pchargel(t);
            u22(t)= u22(t-1) - ull(t);
        end
        z5(t)= Pchargel(t)+ NLpr(t);
        s6(t)= s6(t-1) - Pchargel(t);
        z5(t+1)= Pchargel(t) - z5(t+1);
        end
        if RqEC2(t) > 0 && ss6(t) > 0
            Pchargel(t)= Pchargel(t) + RqEC2(t);
            if Pchargel(t) >= ss6(t-1)
                Pchargel(t)= ss6(t-1) + RqEC1(t);
            end
        end
        if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
            ull1(t)= RqEC2(t);
        elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
            ull1(t)= RqEC2(t) - Pchargel(t);
        end
        s6(t)= s6(t-1) - Pchargel(t);
        ss6(t)= ss6(t-1) - (Pchargel(t)-RqEC1(t));
        end
    end
end
for t= 1:1:8760
    if TMA11(t) == 6 && bbb(t) == 1
        s6(t)= s6(t-1);
        ss6(t)= ss6(t-1);
        if RqEC1(t) > 0
            Pchargel(t)= RqEC1(t);
            if Pchargel(t) >= s6(t-1)
                Pchargel(t)= s6(t-1);
            end
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences
                ull(t)= RqEC1(t);    %% also it gives indication
of how much of charging priorety is left to charge from
                u22(t)= u22(t-1) - ull(t);
            elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
                ull(t)= RqEC1(t) - Pchargel(t);
                u22(t)= u22(t-1) - ull(t);
            end
            z5(t)= Pchargel(t)+ NLpr(t);
            s6(t)= s6(t-1) - Pchargel(t);
            z5(t+1)= Pchargel(t) - z5(t+1);
        end
    end
end

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    if RqEC2(t) > 0 && ss6(t) > 0
        Pchargel(t)= Pchargel(t) + RqEC2(t);
    if Pchargel(t) >= ss6(t-1)
        Pchargel(t)= ss6(t-1) + RqEC1(t);
    end
    if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
        ull1(t)= RqEC2(t);
    elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
        ull1(t)= RqEC2(t) - Pchargel(t);
    end
    s6(t)= s6(t-1) - Pchargel(t);
    ss6(t)= ss6(t-1) - (Pchargel(t)-RqEC1(t));
    end
end
end
for t= 1:1:8760
    if TMA11(t) == 7 && bbb(t) == 1
        s6(t)= s6(t-1);
        ss6(t)= ss6(t-1);
        if RqEC1(t) > 0
            Pchargel(t)= RqEC1(t);
            if Pchargel(t) >= s6(t-1)
                Pchargel(t)= s6(t-1);
            end
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences
                ull1(t)= RqEC1(t);    %% also it gives indication
of how much of charging priorety is left to charge from
                u22(t)= u22(t-1) - ull1(t);
            elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
                ull1(t)= RqEC1(t) - Pchargel(t);
                u22(t)= u22(t-1) - ull1(t);
            end
            z5(t)= Pchargel(t)+ NLpr(t);
            s6(t)= s6(t-1) - Pchargel(t);
            z5(t+1)= Pchargel(t) - z5(t+1);
        end
        if RqEC2(t) > 0 && ss6(t) > 0
            Pchargel(t)= Pchargel(t) + RqEC2(t);
        if Pchargel(t) >= ss6(t-1)
            Pchargel(t)= ss6(t-1) + RqEC1(t);
        end
        if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
            ull1(t)= RqEC2(t);
        elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
            ull1(t)= RqEC2(t) - Pchargel(t);
        end
        s6(t)= s6(t-1) - Pchargel(t);
        ss6(t)= ss6(t-1) - (Pchargel(t)-RqEC1(t));
        end
    end
end
for t= 1:1:8760

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if TMA11(t) == 10 && bbb(t) == 1
    s6(t) = s6(t-1);
    ss6(t) = ss6(t-1);
    if RqEC1(t) > 0
        Pchargel(t) = RqEC1(t);
        if Pchargel(t) >= s6(t-1)
            Pchargel(t) = s6(t-1);
        end
        if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences
            ull(t) = RqEC1(t);    %% also it gives indication
of how much of charging priority is left to charge from
            u22(t) = u22(t-1) - ull(t);
        elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
            ull(t) = RqEC1(t) - Pchargel(t);
            u22(t) = u22(t-1) - ull(t);
        end
        z5(t) = Pchargel(t) + NLpr(t);
        s6(t) = s6(t-1) - Pchargel(t);
        z5(t+1) = Pchargel(t) - z5(t+1);
    end
    if RqEC2(t) > 0 && ss6(t) > 0
        Pchargel(t) = Pchargel(t) + RqEC2(t);
        if Pchargel(t) >= ss6(t-1)
            Pchargel(t) = ss6(t-1) + RqEC1(t);
        end
        if RqEC2(t) > 0 && Pchargel(t) >= RqEC2(t)
            ull1(t) = RqEC2(t);
        elseif RqEC2(t) > 0 && Pchargel(t) < RqEC2(t)
            ull1(t) = RqEC2(t) - Pchargel(t);
        end
        s6(t) = s6(t-1) - Pchargel(t);
        ss6(t) = ss6(t-1) - (Pchargel(t) - RqEC1(t));
    end
end
end
% When there isnt enough PV curtailed energy to be used in charging process
for t = 1:1:8760
    if TMA11(t) == 10 && PVout21(t) > 0 && RqEC1(t) > 0 && bbb(t) == 0
%% charging period in the unassigned period
        Pchargel(t) = RqEC1(t);
        if Pchargel(t) >= x1(t)
            Pchargel(t) = x1(t);
        end
        u22(t) = x3(t);
        if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)    %% incase max charge of
exceeds the remaining RqEC1 of other sequences
            ull(t) = RqEC1(t);    %% also it gives
indication of how much of charging priority is left to charge from
            u22(t) = x3(t) - ull(t);
        elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
            ull(t) = RqEC1(t) - Pchargel(t);
            u22(t) = x3(t) - ull(t);
        end
    end
end

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        end
        z5(t)= Pcharge1(t)+ PrAll7(t);
        s6(t)= x1(t) - Pcharge1(t);
        s6(t+1)= s6(t);
        u22(t+1)= u22(t);
        z5(t+1)= Pcharge1(t) - z5(t+1);
    end
end
for t= 1:1:8760
    if TMA11(t) == 7 && PVout21(t) > 0 && bbb(t) == 0    %% last hour of
storage charging period
        u22(t)= x3(t);
        if RqEC1(t+1) > 0 || RqEC1(t+2) > 0
            x1(t)= s6(t+2);
            x3(t)= u22(t+2);
            u22(t)= x3(t);
        end
        if u22(t) < x1(t)    %% To prioritize the charging of the curtailed
energy in the morning first
            c333(t)= 1;
            s5(t)= GRC + z5(t+1);    %% the max charge that does not cuase ramping
constraint to the next hour
            if PVout21(t) <= s5(t)
                Pcharge1(t)= PVout21(t);
            elseif PVout21(t) >= s5(t)
                Pcharge1(t)= s5(t);
            end
            if Pcharge1(t) <= x1(t)
                Pcharge1(t)= Pcharge1(t);
            elseif Pcharge1(t) >= x1(t)
                Pcharge1(t)= x1(t);
            end
            if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)    %% incase max charge of
s5(t) exceeds the remaining RqEC1 of other sequences
                u11(t)= RqEC1(t);    %% also it gives
indication of how much of charging priorety is left to charge from
                u22(t)= x3(t) - u11(t);
                u33(t)= x1(t) - Pcharge1(t);
                if u22(t) >= u33(t)
                    Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
                end
            elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
                u11(t)= RqEC1(t) - Pcharge1(t);
                u22(t)= x3(t) - u11(t);
            elseif RqEC1(t) == 0
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - u11(t);
                u33(t)= x1(t) - Pcharge1(t);
                if u22(t) >= u33(t)
                    Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
                end
            end
        end
        z55(t)= Pcharge1(t)+ NLpr(t);    %% to deal with it in incase

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the charging causes ramping constraint becuae its too large
    s66(t)= x1(t) - Pcharge1(t);           %% this will depend upon next✓
Pcharge1(t-1) at Tmall 6 if it doesnt meet the requirment in which will be reduced✓
further more in next sequence Tmall 6
    s55(t)= GRC + z55(t);
    if s55(t) > s66(t)
        s55(t)= s66(t);
    end
    u44(t)= z55(t) - s55(t);
    if u44(t) > GRC
        c3333(t)= 1;
        Pcharge1(t)= Pcharge1(t) - (u44(t) - GRC);
        z5(t)= Pcharge1(t)+ NLpr(t);
        s6(t)= x1(t) - Pcharge1(t);
    end
elseif u22(t) >= x1(t)
    c333(t)= 2;
    if RqEC1(t) == 0
        u11(t)= 0;
        Pcharge1(t)= 0;
        u22(t)= x3(t) - u11(t);
    elseif RqEC1(t) > 0 && RqEC1(t) > x1(t)
        u11(t)= RqEC1(t) - x1(t);
        Pcharge1(t)= x1(t);
        u22(t)= x3(t) - u11(t);
    elseif RqEC1(t) > 0 && RqEC1(t) == x1(t)
        u11(t)= RqEC1(t);
        Pcharge1(t)= x1(t);
        u22(t)= x3(t) - u11(t);
    elseif RqEC1(t) > 0 && RqEC1(t) < x1(t)
        u11(t)= RqEC1(t);
        Pcharge1(t)= u11(t);
        u22(t)= x3(t) - u11(t);
    end
end
z5(t)= Pcharge1(t)+ NLpr(t);
s6(t)= x1(t) - Pcharge1(t);
s1(t)= z5(t) - GRC;
z5(t+1)= Pcharge1(t) - z5(t+1);
end
end
for t= 1:1:8760
    if TMA11(t) == 6 && PVout21(t) > 0 && s6(t+1) > 0 && bbb(t) == 0
        if u22(t+1) < s6(t+1)           %% To protrizze the charging of the curtialed✓
energy in the morning first
            c333(t)= 1;
            s5(t)= GRC + z5(t+1);
            if PVout21(t) <= s5(t)
                Pcharge1(t)= PVout21(t);
            elseif PVout21(t) >= s5(t)
                Pcharge1(t)= s5(t);
            end
            if Pcharge1(t) <= s6(t+1)

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Pcharge1(t)= Pcharge1(t);
elseif Pcharge1(t) >= s6(t+1)
    Pcharge1(t)= s6(t+1);
end
if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
    u11(t)= RqEC1(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
    u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)));
    if u22(t) >= u33(t)
        Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
    end
elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
    u11(t)= RqEC1(t) - Pcharge1(t);
    u22(t)= x3(t) - x3(t) - (u11(t) + u11(t+1));
elseif RqEC1(t) == 0
    u11(t)= RqEC1(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
    u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)));
    if u22(t) >= u33(t)
        Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
    end
end
z55(t)= Pcharge1(t)+ NLpr(t);    %% to deal with it in incase the
charging causes ramping constraint
s66(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)));
s55(t)= GRC + z55(t);
if s55(t) > s66(t)
    s55(t)= s66(t);
end
u44(t)= z55(t) - s55(t);
if u44(t) > GRC
    c3333(t)= 1;
    Pcharge1(t)= Pcharge1(t) - (u44(t) - GRC);
end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;
if RqEC1(t) == 0
    u11(t)= 0;
    Pcharge1(t)= 0;
    u22(t)= x3(t) - (u11(t) + u11(t+1));
elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
    u11(t)= RqEC1(t) - s6(t+1);
    Pcharge1(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
    u11(t)= RqEC1(t);
    Pcharge1(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
    u11(t)= RqEC1(t);
    Pcharge1(t)= u11(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
end
end

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end
z5(t)= Pcharge1(t)+ NLpr(t);
s6(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pcharge1(t) - z5(t+1);
if Pcharge1(t) < s1(t+1)
    u11(t)= 0;
    u22(t)= 0;
    u33(t)= 0;
    u44(t)= 0;
    z55(t)= 0;
    s55(t)= 0;
    s66(t)= 0;
    c333(t)= 0;
    c3333(t)= 0;
    z5(t)= 0;
    s6(t)= 0;
    s1(t)= 0;
    s5(t)= 0;
    Pcharge1(t)= 0;

    Pcharge1(t+1)= Pcharge1(t+1) - s1(t+1);
    z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
    s6(t+1)= x1(t) - Pcharge1(t+1);
    s1(t+1)= z5(t+1) - GRC;
    if u22(t+1) < x1(t)
        if RqEC1(t+1) > 0 && Pcharge1(t+1) >= RqEC1(t+1)
            u11(t+1)= RqEC1(t+1);
            u22(t+1)= x3(t+1) - u11(t+1);
            u33(t+1)= x1(t) - Pcharge1(t+1);
            if u22(t+1) >= u33(t+1)
                Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
            end
        elseif RqEC1(t+1) > 0 && Pcharge1(t+1) < RqEC1(t+1)
            u11(t+1)= RqEC1(t+1) - Pcharge1(t+1);
            u22(t+1)= x3(t+1) - u11(t+1);
        elseif RqEC1(t+1) == 0
            u11(t+1)= RqEC1(t+1);
            u22(t+1)= x3(t+1) - u11(t+1);
            u33(t+1)= x1(t) - Pcharge1(t+1);
            if u22(t+1) >= u33(t+1)
                Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
            end
        end
    elseif u22(t+1) >= x1(t)
        c333(t+1)= 2;
        if RqEC1(t+1) == 0
            u11(t+1)= 0;
            Pcharge1(t+1)= 0;
            u22(t+1)= x3(t+1) - u11(t+1);
        elseif RqEC1(t+1) > 0 && RqEC1(t+1) > x1(t)
            u11(t+1)= RqEC1(t+1) - x1(t);
            Pcharge1(t+1)= x1(t);

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        u22(t+1)= x3(t+1) - u11(t+1);
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) == x1(t)
        u11(t+1)= RqEC1(t+1);
        Pcharge1(t+1)= x1(t);
        u22(t+1)= x3(t+1) - u11(t+1);
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) < x1(t)
        u11(t+1)= RqEC1(t+1);
        Pcharge1(t+1)= u11(t+1);
        u22(t+1)= x3(t+1) - u11(t+1);
    end
end
z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
s6(t+1)= x1(t) - Pcharge1(t+1);
s1(t+1)= z5(t+1) - GRC;
if u22(t+1) < s6(t+1)      %% To protriz the charging of the curtailed
energy in the morning first
    c333(t)= 1;
    s5(t)= GRC + z5(t+1);
    if PVout21(t) <= s5(t)
        Pcharge1(t)= PVout21(t);
    elseif PVout21(t) >= s5(t)
        Pcharge1(t)= s5(t);
    end
    if Pcharge1(t) <= s6(t+1)
        Pcharge1(t)= Pcharge1(t);
    elseif Pcharge1(t) >= s6(t+1)
        Pcharge1(t)= s6(t+1);
    end
    if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
        u11(t)= RqEC1(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1));
        u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)));
        if u22(t) >= u33(t)
            Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
        end
    elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
        u11(t)= RqEC1(t) - Pcharge1(t);
        u22(t)= x3(t) - x3(t) - (u11(t) + u11(t+1));
    elseif RqEC1(t) == 0
        u11(t)= RqEC1(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1));
        u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)));
        if u22(t) >= u33(t)
            Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
        end
    end
end
z55(t)= Pcharge1(t)+ NLpr(t);    %% to deal with it in incase the
charging causes ramping constraint
s66(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)));
s55(t)= GRC + z55(t);
if s55(t) > s66(t)
    s55(t)= s66(t);
end

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u44(t)= z55(t) - s55(t);
if u44(t) > GRC
    c3333(t)= 1;
    Pchargel(t)= Pchargel(t) - (u44(t) - GRC);
end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;
if RqEC1(t) == 0
    u11(t)= 0;
    Pchargel(t)= 0;
    u22(t)= x3(t) - (u11(t) + u11(t+1));
elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
    u11(t)= RqEC1(t) - s6(t+1);
    Pchargel(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
    u11(t)= RqEC1(t);
    Pchargel(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
    u11(t)= RqEC1(t);
    Pchargel(t)= u11(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1));
end
end
z5(t)= Pchargel(t)+ NLpr(t);
s6(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pchargel(t) - z5(t+1);
end
end
end
for t= 1:1:8760
    if TMA11(t) == 5 && PVout21(t) > 0 && s6(t+1) > 0 && bbb(t) == 0
        if u22(t+1) < s6(t+1)    %% To protrize the charging of the curtailed
energy in the morning first
            c333(t)= 1;
            s5(t)= GRC + z5(t+1);
            if PVout21(t) <= s5(t)
                Pchargel(t)= PVout21(t);
            elseif PVout21(t) >= s5(t)
                Pchargel(t)= s5(t);
            end
            if Pchargel(t) <= s6(t+1)
                Pchargel(t)= Pchargel(t);
            elseif Pchargel(t) >= s6(t+1)
                Pchargel(t)= s6(t+1);
            end
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
                u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
                if u22(t) >= u33(t)

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        Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
    end
elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
    u11(t)= RqEC1(t) - Pchargel(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
elseif RqEC1(t) == 0
    u11(t)= RqEC1(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
    u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
    if u22(t) >= u33(t)
        Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
    end
end
end
z55(t)= Pchargel(t)+ NLpr(t);           %% to deal with it in incase
the charging causes ramping constraint
s66(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
s55(t)= GRC + z55(t);
if s55(t) > s66(t)
    s55(t)= s66(t);
end
u44(t)= z55(t) - s55(t);
if u44(t) > GRC
    c3333(t)= 1;
    Pchargel(t)= Pchargel(t) - (u44(t) - GRC);
end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;
if RqEC1(t) == 0
    u11(t)= 0;
    Pchargel(t)= 0;
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
    u11(t)= RqEC1(t) - s6(t+1);
    Pchargel(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
    u11(t)= RqEC1(t);
    Pchargel(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
    u11(t)= RqEC1(t);
    Pchargel(t)= u11(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
end
end
z5(t)= Pchargel(t)+ NLpr(t);
s6(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pchargel(t) - z5(t+1);

if Pchargel(t) < s1(t+1)
    u11(t)= 0;
    u22(t)= 0;

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u33(t)= 0;
u44(t)= 0;
z55(t)= 0;
s55(t)= 0;
s66(t)= 0;
c333(t)= 0;
c3333(t)= 0;
z5(t)= 0;
s6(t)= 0;
s1(t)= 0;
s5(t)= 0;
Pcharge1(t)= 0;

Pcharge1(t+1)= Pcharge1(t+1) - s1(t+1);
z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
s6(t+1)= (x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2)));
s1(t+1)= z5(t+1) - GRC;

if u22(t+1) < s6(t+1)
    if RqEC1(t+1) > 0 && Pcharge1(t+1) >= RqEC1(t+1)
        u11(t+1)= RqEC1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2));
        u33(t+1)= x1(t) - (Pcharge1(t+1) + Pcharge1(t+2));
        if u22(t+1) >= u33(t+1)
            Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
        end
    elseif RqEC1(t+1) > 0 && Pcharge1(t+1) < RqEC1(t+1)
        u11(t+1)= RqEC1(t+1) - Pcharge1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2));
    elseif RqEC1(t+1) == 0
        u11(t+1)= RqEC1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2));
        u33(t+1)= x1(t) - (Pcharge1(t+1) + Pcharge1(t+2));
        if u22(t+1) >= u33(t+1)
            Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
        end
    end
elseif u22(t+1) >= s6(t+1)
    c333(t+1)= 2;
    if RqEC1(t+1) == 0
        u11(t+1)= 0;
        Pcharge1(t+1)= 0;
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) > s6(t+1)
        u11(t+1)= RqEC1(t+1) - s6(t+1);
        Pcharge1(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) == s6(t+1)
        u11(t+1)= RqEC1(t+1);
        Pcharge1(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) < s6(t+1)
        u11(t+1)= RqEC1(t+1);

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        Pchargel(t+1)= u11(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2));
    end
end
z5(t+1)= Pchargel(t+1)+ NLpr(t+1);
s6(t+1)= (x1(t) - (Pchargel(t+1)+ Pchargel(t+2)));
s1(t+1)= z5(t+1) - GRC;
if u22(t+1) < s6(t+1)      %% To protrize the charging of the curtailed
energy in the morning first
    c333(t)= 1;
    s5(t)= GRC + z5(t+1);
    if PVout21(t) <= s5(t)
        Pchargel(t)= PVout21(t);
    elseif PVout21(t) >= s5(t)
        Pchargel(t)= s5(t);
    end
    if Pchargel(t) <= s6(t+1)
        Pchargel(t)= Pchargel(t);
    elseif Pchargel(t) >= s6(t+1)
        Pchargel(t)= s6(t+1);
    end
    if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)
        u11(t)= RqEC1(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
        u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
        if u22(t) >= u33(t)
            Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
        end
    elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
        u11(t)= RqEC1(t) - Pchargel(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
    elseif RqEC1(t) == 0
        u11(t)= RqEC1(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
        u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
        if u22(t) >= u33(t)
            Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
        end
    end
end
z55(t)= Pchargel(t)+ NLpr(t);      %% to deal with it in incase the
charging causes ramping constraint
s66(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
s55(t)= GRC + z55(t);
if s55(t) > s66(t)
    s55(t)= s66(t);
end
u44(t)= z55(t) - s55(t);
if u44(t) > GRC
    c3333(t)= 1;
    Pchargel(t)= Pchargel(t) - (u44(t) - GRC);
end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;

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    if RqEC1(t) == 0
        u11(t)= 0;
        Pchargel(t)= 0;
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
    elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
        u11(t)= RqEC1(t) - s6(t+1);
        Pchargel(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
    elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
        u11(t)= RqEC1(t);
        Pchargel(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
    elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
        u11(t)= RqEC1(t);
        Pchargel(t)= u11(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2));
    end
end
z5(t)= Pchargel(t)+ NLpr(t);
s6(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pchargel(t) - z5(t+1);
end
end
end
for t= 1:1:8760
    if TMA11(t) == 4 && PVout21(t) > 0 && s6(t+1) > 0 && bbb(t) == 0
        if u22(t+1) < s6(t+1)    %% To protrizze the charging of the curtaled
energy in the morning first
            c333(t)= 1;
            s5(t)= GRC + z5(t+1);
            if PVout21(t) <= s5(t)
                Pchargel(t)= PVout21(t);
            elseif PVout21(t) >= s5(t)
                Pchargel(t)= s5(t);
            end
            if Pchargel(t) <= s6(t+1)
                Pchargel(t)= Pchargel(t);
            elseif Pchargel(t) >= s6(t+1)
                Pchargel(t)= s6(t+1);
            end
            if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
                u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+
Pchargel(t+3)));
                if u22(t) >= u33(t)
                    Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
                end
            elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
                u11(t)= RqEC1(t) - Pchargel(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
            elseif RqEC1(t) == 0

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        u11(t)= RqEC1(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
        u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)));
        if u22(t) >= u33(t)
            Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
        end
    end
    z55(t)= Pcharge1(t)+ NLpr(t);           %% to deal with it in incase
the charging causes ramping constraint
    s66(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1
(t+3)));
    s55(t)= GRC + z55(t);
    if s55(t) > s66(t)
        s55(t)= s66(t);
    end
    u44(t)= z55(t) - s55(t);
    if u44(t) > GRC
        c3333(t)= 1;
        Pcharge1(t)= Pcharge1(t) - (u44(t) - GRC);
    end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;
    if RqEC1(t) == 0
        u11(t)= 0;
        Pcharge1(t)= 0;
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
    elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
        u11(t)= RqEC1(t) - s6(t+1);
        Pcharge1(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
    elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
        u11(t)= RqEC1(t);
        Pcharge1(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
    elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
        u11(t)= RqEC1(t);
        Pcharge1(t)= u11(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
    end
end
z5(t)= Pcharge1(t)+ NLpr(t);
s6(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1
(t+3)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pcharge1(t) - z5(t+1);
if Pcharge1(t) < s1(t+1)
    u11(t)= 0;
    u22(t)= 0;
    u33(t)= 0;
    u44(t)= 0;
    z55(t)= 0;
    s55(t)= 0;

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s66(t)= 0;
c333(t)= 0;
c3333(t)= 0;
z5(t)= 0;
s6(t)= 0;
s1(t)= 0;
s5(t)= 0;
Pcharge1(t)= 0;
Pcharge1(t+1)= Pcharge1(t+1) - s1(t+1);
z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
s6(t+1)= (x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)));
s1(t+1)= z5(t+1) - GRC;
if u22(t+1) < s6(t+1)
    if RqEC1(t+1) > 0 && Pcharge1(t+1) >= RqEC1(t+1)
        u11(t+1)= RqEC1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3));
        u33(t+1)= x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3));
        if u22(t+1) >= u33(t+1)
            Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
        end
    elseif RqEC1(t+1) > 0 && Pcharge1(t+1) < RqEC1(t+1)
        u11(t+1)= RqEC1(t+1) - Pcharge1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3));
    elseif RqEC1(t+1) == 0
        u11(t+1)= RqEC1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3));
        u33(t+1)= x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3));
        if u22(t+1) >= u33(t+1)
            Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
        end
    end
elseif u22(t+1) >= s6(t+1)
    c333(t+1)= 2;
    if RqEC1(t+1) == 0
        u11(t+1)= 0;
        Pcharge1(t+1)= 0;
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) > s6(t+1)
        u11(t+1)= RqEC1(t+1) - s6(t+1);
        Pcharge1(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) == s6(t+1)
        u11(t+1)= RqEC1(t+1);
        Pcharge1(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) < s6(t+1)
        u11(t+1)= RqEC1(t+1);
        Pcharge1(t+1)= u11(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3));
    end
end
z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
s6(t+1)= (x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)));

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    s1(t+1)= z5(t+1) - GRC;
    if u22(t+1) < s6(t+1)    %% To protrize the charging of the curtailed
energy in the morning first
        c333(t)= 1;
        s5(t)= GRC + z5(t+1);
        if PVout21(t) <= s5(t)
            Pcharge1(t)= PVout21(t);
        elseif PVout21(t) >= s5(t)
            Pcharge1(t)= s5(t);
        end
        if Pcharge1(t) <= s6(t+1)
            Pcharge1(t)= Pcharge1(t);
        elseif Pcharge1(t) >= s6(t+1)
            Pcharge1(t)= s6(t+1);
        end
        if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
            u11(t)= RqEC1(t);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
            u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)));
            if u22(t) >= u33(t)
                Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
            end
        elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
            u11(t)= RqEC1(t) - Pcharge1(t);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
        elseif RqEC1(t) == 0
            u11(t)= RqEC1(t);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
            u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)));
            if u22(t) >= u33(t)
                Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
            end
        end
        z55(t)= Pcharge1(t)+ NLpr(t);    %% to deal with it in incase the
charging causes ramping constraint
        s66(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1
(t+3)));
        s55(t)= GRC + z55(t);
        if s55(t) > s66(t)
            s55(t)= s66(t);
        end
        u44(t)= z55(t) - s55(t);
        if u44(t) > GRC
            c3333(t)= 1;
            Pcharge1(t)= Pcharge1(t) - (u44(t) - GRC);
        end
    elseif u22(t+1) >= s6(t+1)
        c333(t)= 2;
        if RqEC1(t) == 0
            u11(t)= 0;
            Pcharge1(t)= 0;

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        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
    u11(t)= RqEC1(t) - s6(t+1);
    Pcharge1(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
    u11(t)= RqEC1(t);
    Pcharge1(t)= s6(t+1);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
    u11(t)= RqEC1(t);
    Pcharge1(t)= u11(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3));
end
end
z5(t)= Pcharge1(t)+ NLpr(t);
s6(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1
(t+3)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pcharge1(t) - z5(t+1);
end
end
end
for t= 1:1:8760
    if TMA11(t) == 3 && PVout21(t) > 0 && s6(t+1) > 0 && bbb(t) == 0
        if u22(t+1) < s6(t+1)    %% To protrizze the charging of the curtailed
energy in the morning first
            c333(t)= 1;
            s5(t)= GRC + z5(t+1);
            if PVout21(t) <= s5(t)
                Pcharge1(t)= PVout21(t);
            elseif PVout21(t) >= s5(t)
                Pcharge1(t)= s5(t);
            end
            if Pcharge1(t) <= s6(t+1)
                Pcharge1(t)= Pcharge1(t);
            elseif Pcharge1(t) >= s6(t+1)
                Pcharge1(t)= s6(t+1);
            end
            if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
                u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)));
                if u22(t) >= u33(t)
                    Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
                end
            elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
                u11(t)= RqEC1(t) - Pcharge1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
            elseif RqEC1(t) == 0
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
            end
        end
    end
end

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        u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+
Pchargel(t+3)+ Pchargel(t+4)));
        if u22(t) >= u33(t)
            Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
        end
    end
    z55(t)= Pchargel(t)+ NLpr(t);           %% to deal with it in incase
the charging causes ramping constraint
    s66(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel
(t+3)+ Pchargel(t+4)));
    s55(t)= GRC + z55(t);
    if s55(t) > s66(t)
        s55(t)= s66(t);
    end
    u44(t)= z55(t) - s55(t);
    if u44(t) > GRC
        c3333(t)= 1;
        Pchargel(t)= Pchargel(t) - (u44(t) - GRC);
    end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;
    if RqEC1(t) == 0
        u11(t)= 0;
        Pchargel(t)= 0;
        u22(t)=x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
        u11(t)= RqEC1(t) - s6(t+1);
        Pchargel(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
        u11(t)= RqEC1(t);
        Pchargel(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
        u11(t)= RqEC1(t);
        Pchargel(t)= u11(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    end
end
z5(t)= Pchargel(t)+ NLpr(t);
s6(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel(t+3)+
Pchargel(t+4)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pchargel(t) - z5(t+1);
if Pchargel(t) < s1(t+1)
    u11(t)= 0;
    u22(t)= 0;
    u33(t)= 0;
    u44(t)= 0;
    z55(t)= 0;
    s55(t)= 0;
    s66(t)= 0;
    c333(t)= 0;

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c3333(t)= 0;
z5(t)= 0;
s6(t)= 0;
s1(t)= 0;
s5(t)= 0;
Pcharge1(t)= 0;
Pcharge1(t+1)= Pcharge1(t+1) - s1(t+1);
z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
s6(t+1)= (x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+
Pcharge1(t+4)));
s1(t+1)= z5(t+1) - GRC;
if u22(t+1) < s6(t+1)
    if RqEC1(t+1) > 0 && Pcharge1(t+1) >= RqEC1(t+1)
        u11(t+1)= RqEC1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4));
        u33(t+1)= x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+
Pcharge1(t+4));
        if u22(t+1) >= u33(t+1)
            Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
        end
    elseif RqEC1(t+1) > 0 && Pcharge1(t+1) < RqEC1(t+1)
        u11(t+1)= RqEC1(t+1) - Pcharge1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t+1) == 0
        u11(t+1)= RqEC1(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4));
        u33(t+1)= x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+
Pcharge1(t+4));
        if u22(t+1) >= u33(t+1)
            Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
        end
    end
elseif u22(t+1) >= s6(t+1)
    c3333(t+1)= 2;
    if RqEC1(t+1) == 0
        u11(t+1)= 0;
        Pcharge1(t+1)= 0;
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) > s6(t+1)
        u11(t+1)= RqEC1(t+1) - s6(t+1);
        Pcharge1(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) == s6(t+1)
        u11(t+1)= RqEC1(t+1);
        Pcharge1(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) < s6(t+1)
        u11(t+1)= RqEC1(t+1);
        Pcharge1(t+1)= u11(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4));
    end
end
end
z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);

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        s6(t+1)= (x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+
Pcharge1(t+4)));
        s1(t+1)= z5(t+1) - GRC;
        if u22(t+1) < s6(t+1)    %% To protrize the charging of the curtailed
energy in the morning first
            c333(t)= 1;
            s5(t)= GRC + z5(t+1);
            if PVout21(t) <= s5(t)
                Pcharge1(t)= PVout21(t);
            elseif PVout21(t) >= s5(t)
                Pcharge1(t)= s5(t);
            end
            if Pcharge1(t) <= s6(t+1)
                Pcharge1(t)= Pcharge1(t);
            elseif Pcharge1(t) >= s6(t+1)
                Pcharge1(t)= s6(t+1);
            end
            if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
                u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)));
                if u22(t) >= u33(t)
                    Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
                end
            elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
                u11(t)= RqEC1(t) - Pcharge1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
            elseif RqEC1(t) == 0
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
                u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)));
                if u22(t) >= u33(t)
                    Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
                end
            end
            z55(t)= Pcharge1(t)+ NLpr(t);    %% to deal with it in incase
the charging causes ramping constraint
            s66(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1
(t+3)+ Pcharge1(t+4)));
            s55(t)= GRC + z55(t);
            if s55(t) > s66(t)
                s55(t)= s66(t);
            end
            u44(t)= z55(t) - s55(t);
            if u44(t) > GRC
                c3333(t)= 1;
                Pcharge1(t)= Pcharge1(t) - (u44(t) - GRC);
            end
        elseif u22(t+1) >= s6(t+1)
            c333(t)= 2;
            if RqEC1(t) == 0

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        u11(t)= 0;
        Pcharge1(t)= 0;
        u22(t)=x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
        u11(t)= RqEC1(t) - s6(t+1);
        Pcharge1(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
        u11(t)= RqEC1(t);
        Pcharge1(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
        u11(t)= RqEC1(t);
        Pcharge1(t)= u11(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4));
    end
end
z5(t)= Pcharge1(t)+ NLpr(t);
s6(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1(t+3)+ Pcharge1(t+4)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pcharge1(t) - z5(t+1);
end
end
end
for t= 1:1:8760
    if TMA11(t) == 2 && PVout21(t) > 0 && s6(t+1) > 0 && bbb(t) == 0
        if u22(t+1) < s6(t+1)    %% To protriz the charging of the curtailed
energy in the morning first
            c333(t)= 1;
            s5(t)= GRC + z5(t+1);
            if PVout21(t) <= s5(t)
                Pcharge1(t)= PVout21(t);
            elseif PVout21(t) >= s5(t)
                Pcharge1(t)= s5(t);
            end
            if Pcharge1(t) <= s6(t+1)
                Pcharge1(t)= Pcharge1(t);
            elseif Pcharge1(t) >= s6(t+1)
                Pcharge1(t)= s6(t+1);
            end
            if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
                u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)));
                if u22(t) >= u33(t)
                    Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
                end
            elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
                u11(t)= RqEC1(t) - Pcharge1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+

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u11(t+5));
elseif RqEC1(t) == 0
    u11(t)= RqEC1(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
    u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)));
    if u22(t) >= u33(t)
        Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
    end
end
z55(t)= Pcharge1(t)+ NLpr(t); %% to deal with it in incase the
charging causes ramping constraint
s66(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1
(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)));
s55(t)= GRC + z55(t);
if s55(t) > s66(t)
    s55(t)= s66(t);
end
u44(t)= z55(t) - s55(t);
if u44(t) > GRC
    c3333(t)= 1;
    Pcharge1(t)= Pcharge1(t) - (u44(t) - GRC);
end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;
    if RqEC1(t) == 0
        u11(t)= 0;
        Pcharge1(t)= 0;
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
    elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
        u11(t)= RqEC1(t) - s6(t+1);
        Pcharge1(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
    elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
        u11(t)= RqEC1(t);
        Pcharge1(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
    elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
        u11(t)= RqEC1(t);
        Pcharge1(t)= u11(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
    end
end
z5(t)= Pcharge1(t)+ NLpr(t);
s6(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1(t+3)+
Pcharge1(t+4)+ Pcharge1(t+5)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pcharge1(t) - z5(t+1);

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if Pcharge1(t) < s1(t+1)
    u11(t)= 0;
    u22(t)= 0;
    u33(t)= 0;
    u44(t)= 0;
    z55(t)= 0;
    s55(t)= 0;
    s66(t)= 0;
    c333(t)= 0;
    c3333(t)= 0;
    z5(t)= 0;
    s6(t)= 0;
    s1(t)= 0;
    s5(t)= 0;
    Pcharge1(t)= 0;
    Pcharge1(t+1)= Pcharge1(t+1) - s1(t+1);
    z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
    s6(t+1)= (x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+↵
Pcharge1(t+4)+ Pcharge1(t+5)));
    s1(t+1)= z5(t+1) - GRC;
    if u22(t+1) < s6(t+1)
        if RqEC1(t+1) > 0 && Pcharge1(t+1) >= RqEC1(t+1)
            u11(t+1)= RqEC1(t+1);
            u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11↵
(t+5));
            u33(t+1)= x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+↵
Pcharge1(t+4)+ Pcharge1(t+5));
            if u22(t+1) >= u33(t+1)
                Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
            end
        elseif RqEC1(t+1) > 0 && Pcharge1(t+1) < RqEC1(t+1)
            u11(t+1)= RqEC1(t+1) - Pcharge1(t+1);
            u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11↵
(t+5));
            elseif RqEC1(t+1) == 0
                u11(t+1)= RqEC1(t+1);
                u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11↵
(t+5));
                u33(t+1)= x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+↵
Pcharge1(t+4)+ Pcharge1(t+5));
                if u22(t+1) >= u33(t+1)
                    Pcharge1(t+1)= Pcharge1(t+1) - (u22(t+1) - u33(t+1));
                end
            end
        elseif u22(t+1) >= s6(t+1)
            c333(t+1)= 2;
            if RqEC1(t+1) == 0
                u11(t+1)= 0;
                Pcharge1(t+1)= 0;
                u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11↵
(t+5));
            elseif RqEC1(t+1) > 0 && RqEC1(t+1) > s6(t+1)
                u11(t+1)= RqEC1(t+1) - s6(t+1);

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        Pcharge1(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(
(t+5));
        elseif RqEC1(t+1) > 0 && RqEC1(t+1) == s6(t+1)
            u11(t+1)= RqEC1(t+1);
            Pcharge1(t+1)= s6(t+1);
            u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(
(t+5));
        elseif RqEC1(t+1) > 0 && RqEC1(t+1) < s6(t+1)
            u11(t+1)= RqEC1(t+1);
            Pcharge1(t+1)= u11(t+1);
            u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(
(t+5));
        end
    end
    z5(t+1)= Pcharge1(t+1)+ NLpr(t+1);
    s6(t+1)= (x1(t) - (Pcharge1(t+1)+ Pcharge1(t+2) + Pcharge1(t+3)+
Pcharge1(t+4)+ Pcharge1(t+5)));
    s1(t+1)= z5(t+1) - GRC;
    if u22(t+1) < s6(t+1)    %% To protrize the charging of the curtailed
energy in the morning first
        c333(t)= 1;
        s5(t)= GRC + z5(t+1);
        if PVout21(t) <= s5(t)
            Pcharge1(t)= PVout21(t);
        elseif PVout21(t) >= s5(t)
            Pcharge1(t)= s5(t);
        end
        if Pcharge1(t) <= s6(t+1)
            Pcharge1(t)= Pcharge1(t);
        elseif Pcharge1(t) >= s6(t+1)
            Pcharge1(t)= s6(t+1);
        end
        if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
            u11(t)= RqEC1(t);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
            u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)));
            if u22(t) >= u33(t)
                Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
            end
            elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
                u11(t)= RqEC1(t) - Pcharge1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
            elseif RqEC1(t) == 0
                u11(t)= RqEC1(t);
                u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
                u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)));
                if u22(t) >= u33(t)

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        Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
    end
    end
    z55(t)= Pchargel(t)+ NLpr(t);    %% to deal with it in incase the
charging causes ramping constraint
    s66(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel
(t+3)+ Pchargel(t+4)+ Pchargel(t+5)));
    s55(t)= GRC + z55(t);
    if s55(t) > s66(t)
        s55(t)= s66(t);
    end
    u44(t)= z55(t) - s55(t);
    if u44(t) > GRC
        c3333(t)= 1;
        Pchargel(t)= Pchargel(t) - (u44(t) - GRC);
    end
    elseif u22(t+1) >= s6(t+1)
        c3333(t)= 2;
        if RqEC1(t) == 0
            u11(t)= 0;
            Pchargel(t)= 0;
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
        elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
            u11(t)= RqEC1(t) - s6(t+1);
            Pchargel(t)= s6(t+1);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
        elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
            u11(t)= RqEC1(t);
            Pchargel(t)= s6(t+1);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
        elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
            u11(t)= RqEC1(t);
            Pchargel(t)= u11(t);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5));
        end
    end
    z5(t)= Pchargel(t)+ NLpr(t);
    s6(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel(t+3)+
Pchargel(t+4)+ Pchargel(t+5)));
    s1(t)= z5(t) - GRC;
    z5(t+1)= Pchargel(t) - z5(t+1);
    end
end
end
for t= 1:1:8760
    if TMA11(t) == 1 && PVout21(t) > 0 && s6(t+1) > 0 && bbb(t) == 0
        if u22(t+1) < s6(t+1)    %% To protrizze the charging of the curtaled
energy in the morning first
            c3333(t)= 1;

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    s5(t)= GRC + z5(t+1);
    if PVout21(t) <= s5(t)
        Pcharge1(t)= PVout21(t);
    elseif PVout21(t) >= s5(t)
        Pcharge1(t)= s5(t);
    end
    if Pcharge1(t) <= s6(t+1)
        Pcharge1(t)= Pcharge1(t);
    elseif Pcharge1(t) >= s6(t+1)
        Pcharge1(t)= s6(t+1);
    end
    if RqEC1(t) > 0 && Pcharge1(t) >= RqEC1(t)
        u11(t)= RqEC1(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
        u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)+ Pcharge1(t+6)));
        if u22(t) >= u33(t)
            Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
        end
    elseif RqEC1(t) > 0 && Pcharge1(t) < RqEC1(t)
        u11(t)= RqEC1(t) - Pcharge1(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
        elseif RqEC1(t) == 0
            u11(t)= RqEC1(t);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
            u33(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+
Pcharge1(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)+ Pcharge1(t+6)));
            if u22(t) >= u33(t)
                Pcharge1(t)= Pcharge1(t) - (u22(t) - u33(t));
            end
        end
        z55(t)= Pcharge1(t)+ NLpr(t);           %% to deal with it in incase
the charging causes ramping constraint
        s66(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1
(t+3)+ Pcharge1(t+4)+ Pcharge1(t+5)+ Pcharge1(t+6)));
        s55(t)= GRC + z55(t);
        if s55(t) > s66(t)
            s55(t)= s66(t);
        end
        u44(t)= z55(t) - s55(t);
        if u44(t) > GRC
            c3333(t)= 1;
            Pcharge1(t)= Pcharge1(t) - (u44(t) - GRC);
        end
    elseif u22(t+1) >= s6(t+1)
        c3333(t)= 2;
        if RqEC1(t) == 0
            u11(t)= 0;
            Pcharge1(t)= 0;
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+

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u11(t+5)+ u11(t+6));
    elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
        u11(t)= RqEC1(t) - s6(t+1);
        Pchargel(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
    elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
        u11(t)= RqEC1(t);
        Pchargel(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
    elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
        u11(t)= RqEC1(t);
        Pchargel(t)= u11(t);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
    end
end
z5(t)= Pchargel(t)+ NLpr(t);
s6(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel(t+3)+
Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6)));
s1(t)= z5(t) - GRC;
z5(t+1)= Pchargel(t) - z5(t+1);
if Pchargel(t) < s1(t+1)
    u11(t)= 0;
    u22(t)= 0;
    u33(t)= 0;
    u44(t)= 0;
    z55(t)= 0;
    s55(t)= 0;
    s66(t)= 0;
    c333(t)= 0;
    c3333(t)= 0;
    z5(t)= 0;
    s6(t)= 0;
    s1(t)= 0;
    s5(t)= 0;
    Pchargel(t)= 0;
    Pchargel(t+1)= Pchargel(t+1) - s1(t+1);
    z5(t+1)= Pchargel(t+1)+ NLpr(t+1);
    s6(t+1)= (x1(t) - (Pchargel(t+1)+ Pchargel(t+2) + Pchargel(t+3)+
Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6)));
    s1(t+1)= z5(t+1) - GRC;
    if u22(t+1) < s6(t+1)
        if RqEC1(t+1) > 0 && Pchargel(t+1) >= RqEC1(t+1)
            u11(t+1)= RqEC1(t+1);
            u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11
(t+5)+ u11(t+6));
            u33(t+1)= x1(t) - (Pchargel(t+1)+ Pchargel(t+2) + Pchargel(t+3)+
Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6));
            if u22(t+1) >= u33(t+1)
                Pchargel(t+1)= Pchargel(t+1) - (u22(t+1) - u33(t+1));
            end
        end
    end
end

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elseif RqEC1(t+1) > 0 && Pchargel(t+1) < RqEC1(t+1)
    u11(t+1)= RqEC1(t+1) - Pchargel(t+1);
    u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
elseif RqEC1(t+1) == 0
    u11(t+1)= RqEC1(t+1);
    u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    u33(t+1)= x1(t) - (Pchargel(t+1)+ Pchargel(t+2) + Pchargel(t+3)+ Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6));
    if u22(t+1) >= u33(t+1)
        Pchargel(t+1)= Pchargel(t+1) - (u22(t+1) - u33(t+1));
    end
end
elseif u22(t+1) >= s6(t+1)
    c333(t+1)= 2;
    if RqEC1(t+1) == 0
        u11(t+1)= 0;
        Pchargel(t+1)= 0;
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) > s6(t+1)
        u11(t+1)= RqEC1(t+1) - s6(t+1);
        Pchargel(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) == s6(t+1)
        u11(t+1)= RqEC1(t+1);
        Pchargel(t+1)= s6(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    elseif RqEC1(t+1) > 0 && RqEC1(t+1) < s6(t+1)
        u11(t+1)= RqEC1(t+1);
        Pchargel(t+1)= u11(t+1);
        u22(t+1)= x3(t+1) - (u11(t+1) + u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    end
end
z5(t+1)= Pchargel(t+1)+ NLpr(t+1);
s6(t+1)= (x1(t) - (Pchargel(t+1)+ Pchargel(t+2) + Pchargel(t+3)+ Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6)));
s1(t+1)= z5(t+1) - GRC;
if u22(t+1) < s6(t+1)    %% To protrize the charging of the curtailed
energy in the morning first
    c333(t)= 1;
    s5(t)= GRC + z5(t+1);
    if PVout21(t) <= s5(t)
        Pchargel(t)= PVout21(t);
    elseif PVout21(t) >= s5(t)
        Pchargel(t)= s5(t);
    end
    if Pchargel(t) <= s6(t+1)
        Pchargel(t)= Pchargel(t);

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elseif Pchargel(t) >= s6(t+1)
    Pchargel(t)= s6(t+1);
end
if RqEC1(t) > 0 && Pchargel(t) >= RqEC1(t)
    u11(t)= RqEC1(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel(t+3)+ Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6)));
    if u22(t) >= u33(t)
        Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
    end
elseif RqEC1(t) > 0 && Pchargel(t) < RqEC1(t)
    u11(t)= RqEC1(t) - Pchargel(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
elseif RqEC1(t) == 0
    u11(t)= RqEC1(t);
    u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    u33(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel(t+3)+ Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6)));
    if u22(t) >= u33(t)
        Pchargel(t)= Pchargel(t) - (u22(t) - u33(t));
    end
end
end
z55(t)= Pchargel(t)+ NLpr(t);           %% to deal with it in incase
the charging causes ramping constraint
s66(t)= (x1(t) - (Pchargel(t)+ Pchargel(t+1)+ Pchargel(t+2)+ Pchargel(t+3)+ Pchargel(t+4)+ Pchargel(t+5)+ Pchargel(t+6)));
s55(t)= GRC + z55(t);
if s55(t) > s66(t)
    s55(t)= s66(t);
end
u44(t)= z55(t) - s55(t);
if u44(t) > GRC
    c3333(t)= 1;
    Pchargel(t)= Pchargel(t) - (u44(t) - GRC);
end
elseif u22(t+1) >= s6(t+1)
    c333(t)= 2;
    if RqEC1(t) == 0
        u11(t)= 0;
        Pchargel(t)= 0;
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    elseif RqEC1(t) > 0 && RqEC1(t) > s6(t+1)
        u11(t)= RqEC1(t) - s6(t+1);
        Pchargel(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+ u11(t+5)+ u11(t+6));
    elseif RqEC1(t) > 0 && RqEC1(t) == s6(t+1)
        u11(t)= RqEC1(t);

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        Pcharge1(t)= s6(t+1);
        u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
        elseif RqEC1(t) > 0 && RqEC1(t) < s6(t+1)
            u11(t)= RqEC1(t);
            Pcharge1(t)= u11(t);
            u22(t)= x3(t) - (u11(t) + u11(t+1)+ u11(t+2)+ u11(t+3)+ u11(t+4)+
u11(t+5)+ u11(t+6));
        end
    end
    z5(t)= Pcharge1(t)+ NLpr(t);
    s6(t)= (x1(t) - (Pcharge1(t)+ Pcharge1(t+1)+ Pcharge1(t+2)+ Pcharge1(t+3)+
Pcharge1(t+4)+ Pcharge1(t+5)+ Pcharge1(t+6)));
    s1(t)= z5(t) - GRC;
    z5(t+1)= Pcharge1(t) - z5(t+1);
end
end
end
% The power charge to store by conventional generation incase the max possible PV
power charging is not enough
a1= sum(Pcharge1); % available energy stored from the morning
a12= repmat(a1,24,1); % forming the matrix
x5= a1 * 0;
for t= 1:1:8760
    if PVout12(t) > 0 && PVout12(t-1) == 0 && s6(t) > 0 && x1(t) > 0
        c33(t)= 1;
    end
end
a3= sum(c33);
for t= 1:1:365
    if a3(t) == 1 %% To identify cases needing light load charging
        x5(t)= (USC1(t) - a1(t))/ 4; %% The power charge to store by
conventional gen and 4 is the number of charging hours in light load times
    end
end
x55= repmat(x5,24,1); % forming the matrix
x555= SA11 * 0; % forming the matrix
for t= 1:1:8760
    if TMA11(t) == 8 && TMA11(t+1) == 1
        x555(t)= z5(t+1) + GRC;
        if x55(t) <= x555(t)
            Pcharge1(t)= x55(t); %% The overall power stored from both PV and
conventional gen
            Pcharge1(t-1)= x55(t-1);
            Pcharge1(t-2)= x55(t-2);
            Pcharge1(t-3)= x55(t-3);
        elseif x55(t) > x555(t) %% to deal with incase it causes ramping
constraint being exceeded
            Pcharge1(t)= x555(t);
            Pcharge1(t-1)= ((x1(t) - a12(t)) - x555(t))/ 3;
            Pcharge1(t-2)= Pcharge1(t-1);
            Pcharge1(t-3)= Pcharge1(t-2);
            x555(t-3)= Pcharge1(t-3) + NLpr(t-3);
        end
    end
end

```

```

        if x555(t-3) > GRC
            Pcharge1(t-3)= (Pcharge1(t-3) - (x555(t-3) - GRC));
        end
    end
end
end
all= sum(Pcharge1);    % available energy stored from the morning
a2= repmat(all,24,1); % forming the matrix
alert= all * 0;        % to show if we dont satisfy the required charged capacity in
the morning using the optimal method of charging
for t= 1:1:365
    if all(t) < USC1(t)
        alert(t)= 1;
    end
end
a2= (a2 * (BSSEff/100));
% Step 6: the optimal discharging methodology of stored energy to deal with ramping
% in evening period
Pcharge2= Pcharge1 * (-1);
for t= 1:1:8760 % To only include Pcharge that it is drawn from the non PV
curtailed energy
    if RqEC1(t) > 0 || bbb(t) == 0
        Pcharge2(t)= Pcharge2(t);
    else
        Pcharge2(t)= 0;
    end
end
s100= PVout12 + Pcharge2;
netload55= (LAll*1000000) - s100;
Sheet15= 15;
PrAll12= xlswrite(Sdata,netload55, Sheet15, Rangel); %% write netload data with
storage charging only
PrAll13= xlsread(Sdata, Sheet15, Range2); %% read the power ramp of netload with
storage charging only
z311= PrAll13;
j111= SAll * 0;
j1111= SAll * 0;
j22= SAll * 0;
j33= SAll * 0;
j44= SAll * 0;
Pdischarge2= SAll * 0;
s877= SAll * 0;
ss2= SAll * 0;
aa2= SAll * 0;
aaa2= SAll * 0;
for t= 1:1:8760
    if x2(t) <= a2(t)
        if TMA11(t) == 10 && RqEC(t) > 0 %% to account of the pdischarge2 in the
unassigned period
            Pdischarge2(t)= RqEC(t);
            ss2(t)= ((LAll(t)*1000000) - (PVout12(t) + Pdischarge2(t))); %% incase
discharging will cause baseload to be exceeded
            if ss2(t) <= Baseload

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        Pdischarge2(t)= 0;
    end
    z311(t)= z311(t) - Pdischarge2(t);
    a2(t+1)= a2(t+1) - Pdischarge2(t);
    a2(t+2)= a2(t+2) - Pdischarge2(t);
    a2(t+3)= a2(t+3) - Pdischarge2(t);
    a2(t+4)= a2(t+4) - Pdischarge2(t);
    a2(t+5)= a2(t+5) - Pdischarge2(t);
    a2(t+6)= a2(t+6) - Pdischarge2(t);
    a2(t+7)= a2(t+7) - Pdischarge2(t);
    end
end
if TMA11(t) == 9 && TMA11(t-1) == 10    %% To identify the first sequence of
desired set discharge hours in the afternoon of the day
    if x2(t) <= a2(t)    % Scenario 1 of discharge
        j1111(t)= 6;    % desired discharge time in hours
        aaa2(t)= j1111(t);
        aa2(t)= a2(t) - x2(t);
        j111(t)= aa2(t)/j1111(t);    %% the excess energy distributed to 6 hours of
of desired set discharge hourse from 14:00 till 20:00
        Pdischarge2(t)= RqEC(t) + j111(t);
        ss2(t)= ((LA11(t)*1000000) - (PVout12(t) + Pdischarge2(t)));    %% incase
discharging will cause baseload to be exceeded
        if ss2(t) <= Baseload
            Pdischarge2(t)= 0;
            aaa2(t)= 5;
            j111(t)= 0;
        end
        z311(t)= z311(t) - Pdischarge2(t);
        z311(t+1)= NLpr(t+1) + Pdischarge2(t);
        j1111(t+1)= 5;
        aa2(t+1)= aa2(t) - j111(t);
        j111(t+1)= aa2(t+1)/j1111(t+1);
        if j111(t+1) <= 0
            j111(t+1)= 0;
        end
        Pdischarge2(t+1)= RqEC(t+1) + j111(t+1);
        ss2(t+1)= ((LA11(t+1)*1000000) - (PVout12(t+1) + Pdischarge2(t+1)));    %%
incase discharging will cause baseload to be exceeded
        if ss2(t+1) <= Baseload
            Pdischarge2(t+1)= 0;
            aaa2(t)= 4;
            j111(t+1)= 0;
        end
        z311(t+1)= z311(t+1) - Pdischarge2(t+1);
        z311(t+2)= NLpr(t+2) + Pdischarge2(t+1);
        j1111(t+2)= 4;
        aa2(t+2)= aa2(t+1) - j111(t+1);
        j111(t+2)= aa2(t+2)/j1111(t+2);
        if j111(t+2) <= 0
            j111(t+2)= 0;
        end
        Pdischarge2(t+2)= RqEC(t+2) + j111(t+2);

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        ss2(t+2)= ((LA11(t+2)*1000000) - (PVout12(t+2) + Pdischarge2(t+2)));    %%✓
incase discharging will cause baseload to be exceeded
    if ss2(t+2) <= Baseload
        Pdischarge2(t+2)= 0;
        aaa2(t)= 3;
        j111(t+2)= 0;
    end
    z311(t+2)= z311(t+2) - Pdischarge2(t+2);
    z311(t+3)= NLpr(t+3) + Pdischarge2(t+2);
    j1111(t+3)= 3;
    aa2(t+3)= aa2(t+2) - j111(t+2);
    j111(t+3)= aa2(t+3)/j1111(t+3);
    if j111(t+3) <= 0
        j111(t+3)= 0;
    end
    Pdischarge2(t+3)= RqEC(t+3) + j111(t+3);
    ss2(t+3)= ((LA11(t+3)*1000000) - (PVout12(t+3) + Pdischarge2(t+3)));    %%✓
incase discharging will cause baseload to be exceeded
    if ss2(t+3) <= Baseload
        Pdischarge2(t+3)= 0;
        aaa2(t)= 2;
        j111(t+3)= 0;
    end
    z311(t+3)= z311(t+3) - Pdischarge2(t+3);
    z311(t+4)= NLpr(t+4) + Pdischarge2(t+3);
    j1111(t+4)= 2;
    aa2(t+4)= aa2(t+3) - j111(t+3);
    j111(t+4)= aa2(t+4)/j1111(t+4);
    if j111(t+4) <= 0
        j111(t+4)= 0;
    end
    Pdischarge2(t+4)= RqEC(t+4) + j111(t+4);
    z311(t+4)= z311(t+4) - Pdischarge2(t+4);
    z311(t+5)= NLpr(t+5) + Pdischarge2(t+4);
    j1111(t+5)= 1;
    aa2(t+5)= aa2(t+4) - j111(t+4);
    j111(t+5)= aa2(t+5)/j1111(t+5);
    if j111(t+5) <= 0
        j111(t+5)= 0;
    end
    Pdischarge2(t+5)= RqEC(t+5) + j111(t+5);
    z311(t+5)= z311(t+5) - Pdischarge2(t+5);
    z311(t+6)= NLpr(t+6) + Pdischarge2(t+5);
    if z311(t+6) > GRC
        Pdischarge2(t+6)= z311(t+6) - GRC;
        j22(t)= (z311(t+6) - GRC) / aaa2(t);    % 6 hours from 14:00 till 20:00
        if ss1(t) > Baseload
            Pdischarge2(t)= Pdischarge2(t) - j22(t);
            z311(t)= NLpr(t) - Pdischarge2(t);
            z311(t+1)= NLpr(t+1) + Pdischarge2(t);
        end
        if ss1(t+1) > Baseload
            Pdischarge2(t+1)= Pdischarge2(t+1) - j22(t);

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z311(t+1)= z311(t+1) - Pdischarge2(t+1);
z311(t+2)= NLpr(t+2) + Pdischarge2(t+1);
end
if ssl(t+2) > Baseload
Pdischarge2(t+2)= Pdischarge2(t+2) - j22(t);
z311(t+2)= z311(t+2) - Pdischarge2(t+2);
z311(t+3)= NLpr(t+3) + Pdischarge2(t+2);
end
if ssl(t+3) > Baseload
Pdischarge2(t+3)= Pdischarge2(t+3) - j22(t);
z311(t+3)= z311(t+3) - Pdischarge2(t+3);
z311(t+4)= NLpr(t+4) + Pdischarge2(t+3);
end
Pdischarge2(t+4)= Pdischarge2(t+4) - j22(t);
z311(t+4)= z311(t+4) - Pdischarge2(t+4);
z311(t+5)= NLpr(t+5) + Pdischarge2(t+4);
Pdischarge2(t+5)= Pdischarge2(t+5) - j22(t);
z311(t+5)= z311(t+5) - Pdischarge2(t+5);
z311(t+6)= NLpr(t+6) + Pdischarge2(t+5);
z311(t+6)= z311(t+6) - Pdischarge2(t+6);
z311(t+7)= NLpr(t+7) + Pdischarge2(t+6);
if z311(t+7) > GRC
Pdischarge2(t+7)= z311(t+7) - GRC;
j1111(t)= j1111(t) + 1; % desired discharge time in hours which
increased by an extra hour
aaa2(t)= aaa2(t) + 1;
j22(t+1)= (z311(t+7) - GRC) / aaa2(t); % 7 hours from 14:00 till
21:00

if ssl(t) > Baseload
Pdischarge2(t)= Pdischarge2(t) - j22(t+1);
z311(t)= NLpr(t) - Pdischarge2(t);
z311(t+1)= NLpr(t+1) + Pdischarge2(t);
end
if ssl(t+1) > Baseload
Pdischarge2(t+1)= Pdischarge2(t+1) - j22(t+1);
z311(t+1)= z311(t+1) - Pdischarge2(t+1);
z311(t+2)= NLpr(t+2) + Pdischarge2(t+1);
end
if ssl(t+2) > Baseload
Pdischarge2(t+2)= Pdischarge2(t+2) - j22(t+1);
z311(t+2)= z311(t+2) - Pdischarge2(t+2);
z311(t+3)= NLpr(t+3) + Pdischarge2(t+2);
end
if ssl(t+3) > Baseload
Pdischarge2(t+3)= Pdischarge2(t+3) - j22(t+1);
z311(t+3)= z311(t+3) - Pdischarge2(t+3);
z311(t+4)= NLpr(t+4) + Pdischarge2(t+3);
end
Pdischarge2(t+4)= Pdischarge2(t+4) - j22(t+1);
z311(t+4)= z311(t+4) - Pdischarge2(t+4);
z311(t+5)= NLpr(t+5) + Pdischarge2(t+4);
Pdischarge2(t+5)= Pdischarge2(t+5) - j22(t+1);
z311(t+5)= z311(t+5) - Pdischarge2(t+5);

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z311(t+6)= NLpr(t+6) + Pdischarge2(t+5);
Pdischarge2(t+6)= Pdischarge2(t+6) - j22(t+1);
z311(t+6)= z311(t+6) - Pdischarge2(t+6);
z311(t+7)= NLpr(t+7) + Pdischarge2(t+6);
z311(t+7)= z311(t+7) - Pdischarge2(t+7);
z311(t+8)= NLpr(t+8) + Pdischarge2(t+7);
    if z311(t+8) > GRC
        Pdischarge2(t+8)= z311(t+8) - GRC;
        j1111(t)= j1111(t) + 1;    % desired discharge time in hours
which increased by an extra hour
        aaa2(t)= aaa2(t) + 1;
        j22(t+2)= (z311(t+8) - GRC) / aaa2(t);    % 8 hours from
14:00 till 22:00

    if ssl(t) > Baseload
        Pdischarge2(t)= Pdischarge2(t) - j22(t+2);
        z311(t)= NLpr(t) - Pdischarge2(t);
        z311(t+1)= NLpr(t+1) + Pdischarge2(t);
    end
    if ssl(t+1) > Baseload
        Pdischarge2(t+1)= Pdischarge2(t+1) - j22(t+2);
        z311(t+1)= z311(t+1) - Pdischarge2(t+1);
        z311(t+2)= NLpr(t+2) + Pdischarge2(t+1);
    end
    if ssl(t+2) > Baseload
        Pdischarge2(t+2)= Pdischarge2(t+2) - j22(t+2);
        z311(t+2)= z311(t+2) - Pdischarge2(t+2);
        z311(t+3)= NLpr(t+3) + Pdischarge2(t+2);
    end
    if ssl(t+3) > Baseload
        Pdischarge2(t+3)= Pdischarge2(t+3) - j22(t+2);
        z311(t+3)= z311(t+3) - Pdischarge2(t+3);
        z311(t+4)= NLpr(t+4) + Pdischarge2(t+3);
    end
    Pdischarge2(t+4)= Pdischarge2(t+4) - j22(t+2);
    z311(t+4)= z311(t+4) - Pdischarge2(t+4);
    z311(t+5)= NLpr(t+5) + Pdischarge2(t+4);
    Pdischarge2(t+5)= Pdischarge2(t+5) - j22(t+2);
    z311(t+5)= z311(t+5) - Pdischarge2(t+5);
    z311(t+6)= NLpr(t+6) + Pdischarge2(t+5);
    Pdischarge2(t+6)= Pdischarge2(t+6) - j22(t+2);
    z311(t+6)= z311(t+6) - Pdischarge2(t+6);
    z311(t+7)= NLpr(t+7) + Pdischarge2(t+6);
    Pdischarge2(t+7)= Pdischarge2(t+7) - j22(t+2);
    z311(t+7)= z311(t+7) - Pdischarge2(t+7);
    z311(t+8)= NLpr(t+8) + Pdischarge2(t+7);
    z311(t+8)= z311(t+8) - Pdischarge2(t+8);
    z311(t+9)= NLpr(t+9) + Pdischarge2(t+8);
end
end
if z311(t) < (-1*GRC)
    s877(t)= abs(z311(t)) - GRC;
    if Pdischarge2(t) >= s877(t)
        Pdischarge2(t)= Pdischarge2(t) - s877(t);

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j33(t)= s877(t) / j111(t);
if Pdischarge2(t) < s877(t)
j33(t)= Pdischarge2(t) / j111(t);
Pdischarge2(t)= 0;
end
end
z311(t)= z311(t) - Pdischarge2(t);
z311(t+1)= NLpr(t+1) + Pdischarge2(t);
Pdischarge2(t+1)= Pdischarge2(t+1) + j33(t);
z311(t+1)= z311(t+1) - Pdischarge2(t+1);
z311(t+2)= NLpr(t+2) + Pdischarge2(t+1);
Pdischarge2(t+2)= Pdischarge2(t+2) + j33(t);
z311(t+2)= z311(t+2) - Pdischarge2(t+2);
z311(t+3)= NLpr(t+3) + Pdischarge2(t+2);
Pdischarge2(t+3)= Pdischarge2(t+3) + j33(t);
z311(t+3)= z311(t+3) - Pdischarge2(t+3);
z311(t+4)= NLpr(t+4) + Pdischarge2(t+3);
Pdischarge2(t+4)= Pdischarge2(t+4) + j33(t);
z311(t+4)= z311(t+4) - Pdischarge2(t+4);
z311(t+5)= NLpr(t+5) + Pdischarge2(t+4);
Pdischarge2(t+5)= Pdischarge2(t+5) + j33(t);
z311(t+5)= z311(t+5) - Pdischarge2(t+5);
z311(t+6)= NLpr(t+6) + Pdischarge2(t+5);
Pdischarge2(t+6)= Pdischarge2(t+6) + j33(t);
z311(t+6)= z311(t+6) - Pdischarge2(t+6);
z311(t+7)= NLpr(t+7) + Pdischarge2(t+6);
Pdischarge2(t+7)= Pdischarge2(t+7) + j33(t);
z311(t+7)= z311(t+7) - Pdischarge2(t+7);
z311(t+8)= NLpr(t+8) + Pdischarge2(t+7);
Pdischarge2(t+8)= Pdischarge2(t+8) + j33(t);
z311(t+8)= z311(t+8) - Pdischarge2(t+8);
z311(t+9)= NLpr(t+9) + Pdischarge2(t+8);
end
end
end
if x2(t) > a2(t) % Scenario 2 of discharge
if RqEC(t) > 0 && RqEC(t+1) == 0 % to identify the latest sequence of
RqEC
j44(t)= a2(t);
Pdischarge2(t)= RqEC(t);
if RqEC(t) > j44(t)
Pdischarge2(t)= j44(t);
end
j44(t-1)= a2(t) - Pdischarge2(t);
if j44(t-1) > 0
Pdischarge2(t-1)= RqEC(t-1);
if RqEC(t-1) > j44(t-1)
Pdischarge2(t-1)= j44(t-1);
end
j44(t-2)= a2(t) - (Pdischarge2(t) + Pdischarge2(t-1));
if j44(t-2) > 0
Pdischarge2(t-2)= RqEC(t-2);

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if a2(t) < x2(t) || a2(t) < x3(t)
    if z3333(t) > (GRC +1) && z3333(t+1) <= GRC && DPRC2(t) > 0    %% PV
down ramping and netload up ramping evening period
    PVout5(t-1)= PVout5(t) + (DPRC2(t) + Pdischarge2(t));    % we added
Pdischarge1 to account for the power ramp change of first sequence of discharging
due to storage
    z3333(t)= z3333(t) - RC2(t);
    z3333(t-1)= z3333(t-1) + RC2(t);
    RC2(t-1)= abs(z3333(t-1)) - GRC;
    PrPV5(t-1)= PVout5(t-1) - PVout5(t-2);
    DPRC2(t-1)= abs(PrPV5(t-1)) - abs(RC2(t-1));
    c8(t)=1;
    if z3333(t-1) > GRC
    PVout5(t-2)= PVout5(t-1) + DPRC2(t-1);
    z3333(t-1)= z3333(t-1) - RC2(t-1);
    z3333(t-2)= z3333(t-2) + RC2(t-1);
    RC2(t-2)= abs(z3333(t-2)) - GRC;
    PrPV5(t-2)= PVout5(t-2) - PVout5(t-3);
    DPRC2(t-2)= abs(PrPV5(t-2)) - abs(RC2(t-2));
    if z3333(t-2) > GRC
    PVout5(t-3)= PVout5(t-2) + DPRC2(t-2);
    z3333(t-2)= z3333(t-2) - RC2(t-2);
    z3333(t-3)= z3333(t-3) + RC2(t-2);
    RC2(t-3)= abs(z3333(t-3)) - GRC;
    PrPV5(t-3)= PVout5(t-3) - PVout5(t-4);
    DPRC2(t-3)= abs(PrPV5(t-3)) - abs(RC2(t-3));
    if z3333(t-3) > GRC
    PVout5(t-4)= PVout5(t-3) + DPRC2(t-3);
    z3333(t-3)= z3333(t-3) - RC2(t-3);
    z3333(t-4)= z3333(t-4) + RC2(t-3);
    RC2(t-4)= abs(z3333(t-4)) - GRC;
    PrPV5(t-4)= PVout5(t-4) - PVout5(t-5);
    DPRC2(t-4)= abs(PrPV5(t-4)) - abs(RC2(t-4));
    if z3333(t-4) > GRC
    PVout5(t-5)= PVout5(t-4) + DPRC2(t-4);
    z3333(t-4)= z3333(t-4) - RC2(t-4);
    z3333(t-5)= z3333(t-5) + RC2(t-4);
    RC2(t-5)= abs(z3333(t-5)) - GRC;
    PrPV5(t-5)= PVout5(t-5) - PVout5(t-6);
    DPRC2(t-5)= abs(PrPV5(t-5)) - abs(RC2(t-5));
    if z3333(t-5) > GRC
    PVout5(t-6)= PVout5(t-5) + DPRC2(t-5);
    z3333(t-5)= z3333(t-5) - RC2(t-5);
    z3333(t-6)= z3333(t-6) + RC2(t-5);
    RC2(t-6)= abs(z3333(t-6)) - GRC;
    PrPV5(t-6)= PVout5(t-6) - PVout5(t-7);
    DPRC2(t-6)= abs(PrPV5(t-6)) - abs(RC2(t-6));
    if z3333(t-6) > GRC
    PVout5(t-7)= PVout5(t-6) + DPRC2(t-6);
    z3333(t-6)= z3333(t-6) - RC2(t-6);
    z3333(t-7)= z3333(t-7) + RC2(t-6);
    RC2(t-7)= abs(z3333(t-7)) - GRC;
    PrPV5(t-7)= PVout5(t-7) - PVout5(t-8);

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DPRC2(t-7)= abs(PrPV5(t-7)) - abs(RC2(t-7));
if z3333(t-7) > GRC
    PVout5(t-8)= PVout5(t-7) + DPRC2(t-7);
    z3333(t-7)= z3333(t-7) - RC2(t-7);
    z3333(t-8)= z3333(t-8) + RC2(t-7);
    RC2(t-8)= abs(z3333(t-8)) - GRC;
    PrPV5(t-8)= PVout5(t-8) - PVout5(t-9);
    DPRC2(t-8)= abs(PrPV5(t-8)) - abs(RC2(t-8));
end
end
end
end
end
end
end
end
end
end
for t= 1:1:8760
    if a2(t) < x3(t)
        if z3333(t) < ((-1*GRC)-1) && DPRC2(t) > 0 && z3333(t-1) >= (-1*GRC) %% PV
up ramping and netload down ramping morning period
        PVout5(t)= PVout5(t-1) + DPRC2(t);
        z3333(t)= z3333(t) + RC2(t);
        z3333(t+1)= abs(z3333(t+1)) + RC2(t);
        RC2(t+1)= abs(z3333(t+1)) - GRC;
        PrPV5(t+1)= PVout5(t+1) - PVout5(t);
        DPRC2(t+1)= abs(PrPV5(t+1)) - abs(RC2(t+1));
        if z3333(t+1) > (GRC)
            PVout5(t+1)= PVout5(t) + DPRC2(t+1);
            z3333(t+1)= z3333(t+1) - RC2(t+1);
            z3333(t+2)= abs(z3333(t+2)) + RC2(t+1);
            RC2(t+2)= abs(z3333(t+2)) - GRC;
            PrPV5(t+2)= PVout5(t+2) - PVout5(t+1);
            DPRC2(t+2)= abs(PrPV5(t+2)) - abs(RC2(t+2));
            if z3333(t+2) > (GRC)
                PVout5(t+2)= PVout5(t+1) + DPRC2(t+2);
                z3333(t+2)= z3333(t+2) - RC2(t+2);
                z3333(t+3)= abs(z3333(t+3)) + RC2(t+2);
                RC2(t+3)= abs(z3333(t+3)) - GRC;
                PrPV5(t+3)= PVout5(t+3) - PVout5(t+2);
                DPRC2(t+3)= abs(PrPV5(t+3)) - abs(RC2(t+3));
                if z3333(t+3) > (GRC)
                    PVout5(t+3)= PVout5(t+2) + DPRC2(t+3);
                    z3333(t+3)= z3333(t+3) - RC2(t+3);
                    z3333(t+4)= abs(z3333(t+4)) + RC2(t+3);
                    RC2(t+4)= abs(z3333(t+4)) - GRC;
                    PrPV5(t+4)= PVout5(t+4) - PVout5(t+3);
                    DPRC2(t+4)= abs(PrPV5(t+4)) - abs(RC2(t+4));
                    if z3333(t+4) > (GRC)
                        PVout5(t+4)= PVout5(t+3) + DPRC2(t+4);
                        z3333(t+4)= z3333(t+4) - RC2(t+4);
                        z3333(t+5)= abs(z3333(t+5)) + RC2(t+4);

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RC2(t+5)= abs(z3333(t+5)) - GRC;
PrPV5(t+5)= PVout5(t+5) - PVout5(t+4);
DPRC2(t+5)= abs(PrPV5(t+5)) - abs(RC2(t+5));
if z3333(t+5) > (GRC)
    PVout5(t+5)= PVout5(t+4) + DPRC2(t+5);
    z3333(t+5)= z3333(t+5) - RC2(t+5);
    z3333(t+6)= abs(z3333(t+6)) + RC2(t+5);
    RC2(t+6)= abs(z3333(t+6)) - GRC;
    PrPV5(t+6)= PVout5(t+6) - PVout5(t+5);
    DPRC2(t+6)= abs(PrPV5(t+6)) - abs(RC2(t+6));
end
end
end
end
end
end
end
end
% Step8: calculate the saved PV curtailed energy with storage
totalPVcurt1= sum(PVcurt333);           %% The amount of PV power curtailed in MWh due to
to ramping constriant
PVcurt55= PVout12 - PVout5;           %% The amount of hourly PV power curtailed in
MW in the both morning and afternoon with storage due to ramping constriant
for t= 1:1:8760           %% to get the pv curtailed energy excluding the charged power
from the battery
    if PVcurt55(t) == PVcurt333(t) && Pcharge2(t) < 0 && PVcurt55(t) > 0
        PVcurt55(t)= PVcurt55(t) + Pcharge2(t);
    end
end
PVcurt555= sum(PVcurt55);           %% The sum of PVcurt55 in MWh
PVout6= PVout12 - PVcurt55;           %% PV power after applying curtailment with
excluding charged power from battery
SV1= totalPVcurt1 * 0;
SV2= totalPVcurt1 * 0;
for t= 1:1:365
    SV1(t)= totalPVcurt1(t) - PVcurt555(t);           %% To get total PV curtailed energy in
MWh saved in the day with storage
    SV2(t)= 100 - ((PVcurt555(t) / totalPVcurt1(t)) * 100);           %% To get total prcentage
of PV curtailed energy saved in the day with storage
end
SV3= (sum(SV1)/ 10^6);
s11= PVout6 + Pdischarge2 + Pcharge2;
netload6= (LAll*1000000) - s11;           %% to get final netload with storage and
curtailment if storage capacity is not enough
c101= SAll * 0;
c102= SAll * 0;
for t= 1:1:8760
    if netload3(t) < Baseload
        c101(t)= 1;
    end
    if netload6(t) < Baseload && RqEC(t) > 0
        c102(t)= 1;
    end
end

```

```

end
PVcurt111= (PVcurt11 - (Pcharge1 + Pcharge2));           %% The new amount of PV
power that is curtailed due to baseload constraint exluding the utlised one due to
charging the battery
PVcurt1111= PVcurt11 - PVcurt111;                       %% The ustlised amount of
PV power due to charging the battery from the curtailed PV energy due to baseload
constraint
FPVcurt= PVcurt55 + PVcurt111;                          %% To get all the amount of
PV power curtailed with storage for both ramping and baseload
PVout7= (PVout1 - (Pcharge1 + FPVcurt));                 %% To get final PV power
with storage
s12= (Pdischarge2 + (Pcharge1 * (-1)));                  %% To get Battery charging
and discharging
for t= 1:1:8760
% To verify that the optimal charging method fills the storage to the max without
causing ramping constraints in morning period
    if PrA1111(t) < ((-1*GRC)-1)
        c44(t)= 1;
    end
    if PrA1111(t) > (GRC +1)
        c44(t)= 1;
    end
end
end

```

5. *Optimal sizing and energy management strategy for seasonal storage*

```

%% Optimal Sizing and Energy Management Strategy for Seasonal Storage %%
% Step1: Peak Load calculation and setting desired peak load
PLR= SAll * 0;
for t= 1:1:8760
    if (LAll(t)*1000000) == netload2(t)    %% To identify loads at PV available
times for peak load reduction monitoring
        PLR(t)= 0;
    else
        PLR(t)= netload2(t);
    end
end
PkL= max(PLR(:));    %% peak load with only applying PV curtailment meaning no
storage is applied only showing hours altered by the PV availability or curtailment
PkLL= max(netload2(:));    %% peak load with only applying PV curtailment meaning no
storage is applied showing all hours
PkLl= max(netload6(:));    %% peak load with applying the batteries to deal with
ramping constraint
PkLR= (100 - ((PkLl / Peakload) * 100));    %% peak load reduction in percentage
without seasonal storage
PkLT= ((Peakload / 100) * (100 - Tper));    %% Desired peak load with seasonal
storage
Tperl= Tper - PkLR;    %% Required percentage target of peak load reduction
using seasonal storage including the peak load reduction from batteries and PV
system
for t= 1:1:1
    if Tperl(t) <= 0    %% Incase we get the targeted peak load without
seasonal storage
        Tperl(t)= 0;
    end
end
% Step2: Calculating the required Capacity of seasonal storage to achieve the
desired peak load
RqEC3= SAll * 0;    %% The required energy of to be discharged by seasonal
storage to get targeted peak load
b3= SAll * 0;
for t= 1:1:8760
    if netload6(t) > PkLT
        b3(t)= 1;    %% To indicate the hours that needs to be targeted to
achieve desired peak load
        RqEC3(t)= netload6(t) - PkLT;
    end
end
SRqEC3= sum(RqEC3(:));    %% To get the required seasonal storage capacity to achieve
targeted peak load
RqEC3l= (RqEC3 / (Sseff/100));    %% over sizing capacity of seasonal storage due to
roundtrip efficiency loss
SRqEC3l= sum(RqEC3l(:));    %% To get the required seasonal storage capacity with
roundtrip efficiency loss to achieve targeted peak load
b33= sum(b3(:));    %% The number of hours where the seasonal storage should be
applied in
RqEC32= (RqEC3 * (Sseff/100));    %% seasonal storage energy with roundtrip
efficiency loss
SRqEC32= sum(RqEC32(:));

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SSc= (SRqEC3 * (x6/100)); %% seasonal storage capacity

% Step3: Charging seasonal storage
% Step3.1: Estimating max available energy to be stored by seasonal storage
Sheet16= 16; %% excel sheet number for timing
TMA111= xlsread(Sdata, Sheet16, Range1); %% data for All months

RqEC4= SA11 * 0; %% The curtailed PV energy due to baseload constraint from Jan till end of Apr
EEExp= SA11 * 0; %% Energy exported to neighbouring grids
for t= 1:1:8760
    if PVcurt111(t) > 0 && TMA111(t) == 1
        RqEC4(t)= PVcurt111(t); %% charging from PV curtailed due to baseload constraint excluding the utilised one due to charging the battery to deal with ramping constraint
    end
    if RqEC4(t) <= RegExp
        RqEC4(t)= 0;
    end
    if RqEC4(t) > RegExp
        RqEC4(t)= RqEC4(t) - RegExp;
    end
end
SRqEC4= sum(RqEC4(:)); %% To get the maximum energy that can be used to be stored in the seasonal storage with regional export restriction or limit factor applied
RqEC41= (RqEC4 * (SSeff/100)); %% seasonal storage energy with roundtrip efficiency loss
SRqEC41= sum(RqEC41(:));
for i= 1:1:1
    if SSc(i) >= SRqEC4(i) %% incase when seasonal storage capacity set is larger than SRqEC4
        SSc(i)= SRqEC4(i);
    end
end
% Step3.2: Charging process of seasonal storage
Pcharge3= SA11 * 0; %% The power stored each hour for seasonal storage
Pcharge4= reshape(Pcharge3,8760,1);
b5= Pcharge4;
RqEC44= reshape(RqEC4,8760,1);
for i= 1:1:1
    b5(i)= SSc;
end
for t= 1:1:8760
    if b5(t) == 0
        if RqEC44(t) >= 0
            Pcharge4(t)= b5(t);
        end
    end
    if b5(t) > 0
        if RqEC44(t) > 0
            Pcharge4(t)= RqEC44(t);
        end
        if Pcharge4(t) > b5(t)
            Pcharge4(t)= b5(t);
        end
    end
end

```

```

end
end
if RqEC44(t) == 0
Pcharge4(t) = RqEC44(t);
end
end
b5(t+1) = b5(t) - Pcharge4(t);
end
end
Pcharge5 = reshape(Pcharge4, 24, []); %% seasonal storage hourly charging from PV
curtailed energy due to baseload constraint
% Step4: Discharging seasonal storage
a4 = sum(Pcharge5(:)); %% Sum of available energy to be discharged by seasonal
storage
a44 = (a4 * (SSeff/100)); %% Sum of available energy to be discharged by seasonal
storage with roundtrip efficiency loss
a444 = (RqEC3/SRqEC3); %% Ratio of discharge
Pdischarge3 = SA11 * 0; %% Power discharged by seasonal storage
for t = 1:1:8760
Pdischarge3(t) = a44 * a444(t);
end
PVcurt1110 = PVcurt111 - Pcharge5; %% The new amount of PV power that is curtailed
due to baseload constraint excluding the utilised one due to charging the seasonal
storage
netload7 = netload6 - Pdischarge3;
PkL2 = max(netload7(:))/10^6; %% peak load with applying the batteries to deal with
ramping constraint and seasonal storage

Sheet17 = 17;
PrAll14 = xlswrite(Sdata, netload7, Sheet17, Range1); %% write netload data with
seasonal storage
PrAll15 = xlsread(Sdata, Sheet17, Range2); %% read the power ramp of netload with
seasonal storage
% Step5: calculating exported energy to neighbouring grids
PVcurt99 = PVcurt55 + PVcurt1110; %% Curtailed PV energy with both diurnal
and seasonal storage
for t = 1:1:8760
if PVcurt99(t) > 0 && TMA111(t) == 1 %% To show the exported energy to
neighbouring grids
EExp(t) = PVcurt99(t);
if EExp(t) > TransCap
EExp(t) = TransCap;
end
end
if PVcurt99(t) > 0 && TMA111(t) == 0
EExp(t) = PVcurt99(t);
if EExp(t) > TransCap
EExp(t) = TransCap;
end
end
end
end
end

```