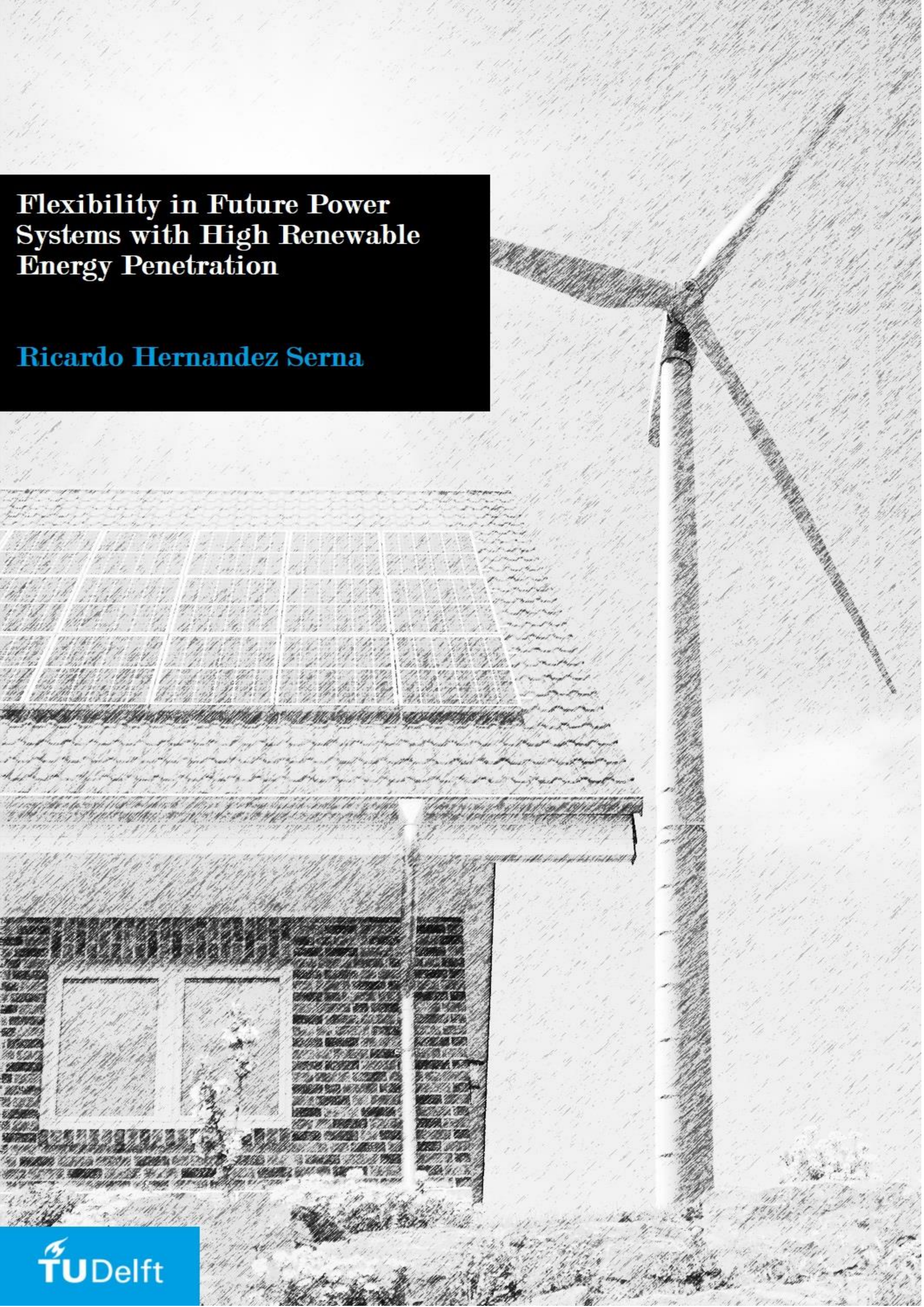
Flexibility in Future Power Systems with High Renewable Energy Penetration

Ricardo Hernandez Serna



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Flexibility in Future Power Systems with High Renewable Energy Penetration

by

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Summary

To achieve the CO2 emission targets set by the European Union and the Paris agreement, the electrical power systems have to change. To achieve the emission targets for 2030 and 2050 is necessary for the system to integrate higher volumes of variable renewable energy sources (VRES) such as solar and wind energy. Once a high amount of VRES is integrated on the system new challenges will be faced by the system operators. Currently, power systems rely on dispatchable power plants to cover the electricity demand. In traditional operations, the system operators will reserve capacity to deal with mismatches between supply and demand. These mismatches present themselves due to several factors, some of them are power plant outages, changes in load consumption patterns and forecasting errors on wind and energy generation. The latter will result in an increasing need for flexibility. Therefore, the widespread implementation of VRES creates the need to asses flexibility reserves which is the topic of this thesis.

Flexibility in energy systems is defined as “the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise”[1]. This property of the system will become essential in the future. This research thesis aims to understand the role of flexibility in future power systems and the effects of increasing penetration of VRES at distribution levels. Some power system assets can provide flexibility if enabled properly. These assets or flexibility sources are traditional power plants, energy storage systems, demand and VRES. Currently, conventional power plants provide the majority of the flexibility required by the system. For the future, there are several strategies available to increase their flexibility. Energy storage systems, specifically battery systems, are becoming a cost-competitive flexibility option. VRES sources are also able to provide flexibility, by introducing market reforms and regulations this flexibility can be unlocked. Additionally, demand-side flexibility has been present in the system, although provided by big industrial loads. In future decentralized systems, the ability of smaller loads to provide flexibility could provide valuable services to the system. Overall, there is a significant number of flexibility providers that require market and regulatory reforms to provide important flexibility services.

Recently, system operators and other stakeholders have recognized the importance of incorporating uncertainties into energy system models. This has resulted in different approaches on how to account for the uncertainty generated by wind and solar energy. This study proposes a method to quantify the uncertainty brought to the system by electric vehicles, household loads and wind and solar energy. To do so, the forecast errors of the aforementioned uncertainty sources were researched. For wind and solar energy and the load, the error depends on the time horizon selected i.e. a one hour forecast will have a smaller error than a day ahead forecast. This error is then presented as a percentage in which the forecast will deviate from actual generation or consumption. For electric vehicles at a neighbourhood level, probabilistic analysis was done to determine the error on EV expected load. EVs are modelled with two sources of uncertainty, the time of arrival to a charging point and the charging duration. To obtain the error of several electric vehicles the standard deviation that is present at every 15 minutes was calculated. Finally, the uncertainty of EVs, loads and wind and solar energy is added to obtain the maximum amount of power deviations that can be present due to these uncertainties. This will allow system operators to know how much flexibility has to be reserved to deal with this deviations. Inertia plays an essential role in ensuring a stable power system. Inertia is inherent to synchronous generators

which release kinetic energy stored on their rotating masses when the frequency drops due to a change in power. This release of kinetic energy slows down frequency deviations. The increase of solar and wind energy can dramatically reduce the inertia of the system since these sources of energy do not provide inertia to the system. Moreover, VRE integration has caused a shift in the merit order curve and its starting to substitute part of the generation provided by conventional power plants, which have higher marginal costs. This will result in a system with a lower inertia and will require faster flexibility to compensate for the inertial response. This is why the concept of enhanced frequency response (EFR) is introduced. Faster flexible sources such as batteries and VRE can provide faster flexibility and compensate for the reduction of inertia.

Furthermore, following current market structures the reserves of flexibility are divided in 4, the previously mention enhanced frequency response, primary, secondary and tertiary reserves. This is done to procure reserves from different flexibility providers. Slower sources of flexibility like traditional generators can provide reserves for longer periods but might not be able to provide faster flexibility. This is why an optimization was formulated to allocate the different sources of flexibility depending on their characteristics. The mathematical formulation of the optimization problem is analyzed with a case study. This case study illustrates a distribution grid in the years 2019, 2030 and 2050 to show the effect of the increase in renewable energy. This results in different allocations of flexibility technologies. It is observed that in current grids conventional power plants provide most of the flexibility whereas in future distribution grids these reserves might come from different sources.

Preface

The basis for this research originated from my passion for renewable energy and the challenges they will face in the future. As the world's electricity systems evolve with higher integration of wind and solar energy, there will be a greater need to understand their effects in the technological part as well as in the sociotechnical one. It is my passion to understand this problem holistically. This is the main reason why I pursued this master.

In truth, I could not have achieved obtaining my master degree without a strong support group. First of all, my family, which has encouraged me to follow this master on the other side of the world and follow my passion. Secondly, to my supervisors whose guidance was essential to develop this thesis. Thirdly, to the committee members, the DCE&S group and TU Delft for providing the necessary resources to conduct this research. Finally, a special thanks to my international friends, which became a family far from home that supported me throughout these two amazing years .

R. Hernandez

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1

Introduction

This chapter provides the context of the thesis and justifies why flexibility in the grid is not an option but a necessity for future energy power systems. Firstly, Section 1.1 presents the background and motivation for this thesis. Section 1.2 sets the scope and goals of this document. The research question is provided in Section 1.3 and developing sub-questions to give a more comprehensive approach. Finally, Section 1.4 presents the outline of this paper.

1.1 Motivation

The EU Energy Road-map 2050 and the Paris agreement in 2015 point towards a carbon-neutral economy in the next decades. Achieving a carbon-neutral economy will result in several changes in today's power system, going through a paradigm shift in the foreseeable future. Traditionally, fossil-fueled power plants generated power. Soon, the system will face new challenges. One of these is due to the rapid integration of variable renewable energy sources (VRES) [37].

The installed capacity of solar and wind is expected to increase in the coming years, due to decreasing costs in these technologies, thus playing a dominant role in power generation. Another factor to take into consideration is the increasing amount of energy demand. It is projected that energy demand will grow in 28% by 2040 [7]. Moreover, the electricity demand will also increase due to the electrification of loads. The latter will result in a significant load increase in sectors such as heat and transportation both in households and industrial applications [9]. Furthermore, the value of storage is being unlocked as more efficient technologies are being brought to the market.

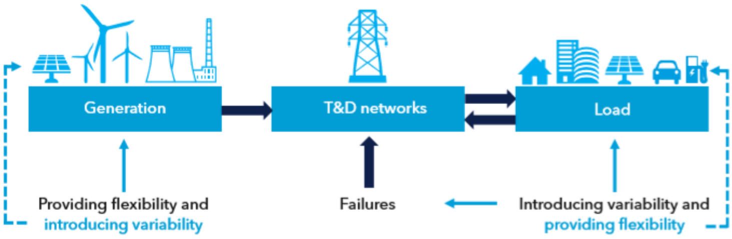


Figure 1.1: Introducing flexibility & variability in future energy systems [15]

Figure 1.1 shows the shift in the traditional power system by adding variability on the generation side caused by VRES and the increasing role of loads as balancing responsible parties. To achieve this integration, the power system of the future is one that shall be able to combine centralized and decentralized generation, allowing active participation of the customers and implementing storage technologies. In other words, a flexible system. The term flexibility can have a variety of definitions, for this investigation, it is a service that provides the capability to the power system to respond to changes and uncertainty in both demand and generation to ensure a reliable operation [15].

The amount of required flexibility will be increased due to the variability of the residual load. The residual load, in this case, indicates the amount of capacity that is left for traditional power plants to cover[34]. A variable residual load is a consequence of the intermittent nature of solar and wind energy. New patterns of consumption related to electric vehicles and heat pumps add even more uncertainty in the load side. New patterns of consumption will cause a mismatch between generation profiles and consumption profiles in a system in which VRES supply a high amount of electricity. Therefore, the need for residual peak load will tend to increase over time. This will present an opportunity for storage options or demand response programs in these periods [18].

The current power system counts with substantial volumes of flexibility already active provided by industry and conventional generation. Demand response has been present in some countries since the early 2000s, although only for industrial loads. The digitization of the grid will allow small loads to participate in demand response programs thanks to smart metering and aggregation [37].

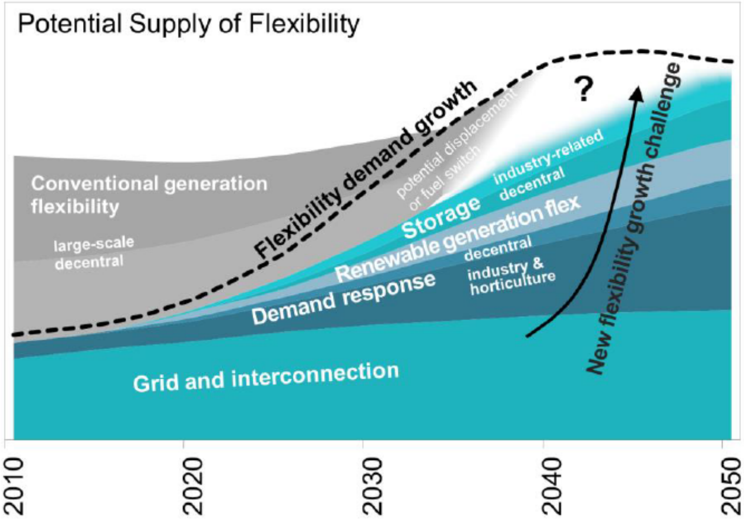


Figure 1.2: Potential supply of flexibility in the Netherlands [37]

Figure 1.2 shows a cumulative chart, which presents Dutch demand, which will be bi-directional and could have more than one purpose. Installed capacity is not considered in the figure. Furthermore, the supply and demand are represented in MWh volume. It is observed that several flexibility options will have to implement to ensure reliable and sustainable energy supply.

Different technologies with different characteristics will interact with each other. This interaction will result in need of a joint deployment in order to ensure an affordable and secure operation. Therefore, there is a necessity to manage these technologies from a system point of view. This will result in higher efficiency and a lower cost in the system. However, there is still a need for a supportive regulatory framework and policies have to be implemented in order to achieve a fully integrated system [34].

Electricity transportation is another vital aspect of this energy transition. Most of the recently implemented sources produce a DC output or have to go through electronic converters (PV, batteries, wind) which will make a low-medium voltage DC grid feasible in the future. Currently, HVDC links are getting in place to connect wind plants to the existing AC grid. Current and future trends have to be considered, such as the presence of storage and generation at the distribution level. This is why this thesis will study flexibility in a DC distribution grid [31].

1.2 Research question

The problem definition of this research leads to one major research question:

How should the flexibility be organized in a distribution grid?

To develop the answer to the previous question, this report addresses several sub-objective questions.

- *What are the available types of flexibility?*
  It is necessary to know what technologies are currently available to have a comprehensive approach. Having a figure with the options arranged according to their timescale response & cost is beneficial to understand possible uses for each technology.
- *How can the flexibility requirements of a power grid be assessed?*
  Having a systematic approach to assess flexibility in a DC grid is beneficial to decision-makers. It can be used to analyze how much the system needs to change to receive high amounts of renewable energy. Furthermore, this assessment will reveal future needs for flexibility in future distribution grids.
- *What are the effects of low inertia in power systems?*
  It is of importance to understand the effects of low inertia in future power systems. The increase of solar and wind energy can dramatically reduce the inertia of the system since these sources of energy do not provide inertia to the system. Furthermore, it has to be understood how the lack of inertia affects the system's flexibility.
- *What is the value of an optimized flexible grid?*
  Variable renewable energy, storage and loads will be modelled. In this context, an optimization problem has to be formulated. This should account for the operational constraints and deal with the uncertainties of these technologies.

1.3 Methodology

In order to answer the proposed research questions of this thesis, a combined approach of statistics, probability theory and optimization were carried out. Furthermore, a GAMS model was created to optimize different scenarios and analyze the results. The following steps detail the used methodology throughout this project:

- **Sources of flexibility**

  Researching literature to classify the technologies that can provide flexibility. Moreover, this research focuses on the technical capabilities of these flexibility sources.
- **Quantification of the required flexibility in a system**

  Illustrating the uncertainty introduced in the system by electric vehicles, household loads and wind and solar energy. Using statistical errors and probability theory to quantify this uncertainty, which determines the required flexibility in a system.
- **Calculation of minimum reaction times**

  Demonstrating the effects of low inertia on the required flexibility. Making use of the system's inertia as an indicator of the minimum reaction time of a flexibility source

- **Optimization**

  Formulating an optimization problem that allocates the required flexibility from different sources. This is formulated in GAMS and use CPLEX to solve the problem.

- **Case study**

  Implementing the optimization in three different years (2019, 2030 and 2050), to find out the required flexibility and which source will be able to provide it.

- **Analysis of results**

  Using the results of the optimization, an analysis is done to examine how the increase of renewable energy on a system affects the required flexibility and the costs.

1.4 Outline

- **Chapter 2** presents the literature review for the topic of this thesis: describing the concept of flexibility and the different sources of flexibility available in power systems. Flexible variable renewable energy, energy storage systems, demand-side flexibility and conventional generation. Moreover, it presents detailed information on their potential applications and benefits.

- **Chapter 3** focuses on the concept of uncertainty in power systems and its quantification. This is done to asses the volume of flexibility that will be required to ensure a stable operation of the power systems. To do so, a method is proposed which accounts for the uncertainty in forecasting household loads, electric vehicles, and solar and wind energy.

- **Chapter 4** describes the role of inertia in power systems and its effects on the flexibility. The equations that determine the reaction time for the flexibility are derived in this chapter. Moreover, this is done for AC and DC grids.

- **Chapter 5** formulates an optimization problem that takes into account the required flexibility calculated in Chapter 3 and the reaction times from Chapter 4. This optimization problem is then applied to a case study which goal is to understand the effects of increasing renewable energy penetration. To achieve this, three scenarios are simulated: 2019, 2030 and 2050

- **Chapter 6** ultimately provides the conclusions of this thesis and reflects on the obtained results. The research questions are answered based on the obtained results. Furthermore, indications of future work are provided.

2

Sources of Flexibility

2.1 Introduction

The future will require a higher volume of flexibility to achieve a proper integration of VREs. Firstly, the term flexibility has to be understood. Power systems require a balance between supply and demand to ensure a reliable, safe and stable operation. Therefore, flexibility is needed to achieve this balance. Flexibility is defined by [15] as a service that provides the capability to the electric power system to respond to fluctuations and uncertainty in supply and demand to maintain and restore stable and safe operation within the limits of the system. There are several ways to measure this system's ability, amongst others:

- Duration of the service.
- Connection's location.
- The period a service can be provided without interruptions.

Flexibility is needed in the system to protect its reliability relative to the variability in time scales and locations in the grid. New international climate and energy plans are creating an increase of VREs and load electrification. Thus, making flexibility key to ensure cost-effective operations. The essential operation of power systems requires flexibility services that are provided at different operational time scales. In traditional AC grids, if the system operator does not maintain a balance, the nominal frequency of the system will deviate, which could potentially lead to outages and instability. Furthermore, flexibility results to be an inherent feature in the design and operation of a power system. Systems are capable of providing up-regulation and down-regulation, meaning that additional power can be provided or reduced respectively, to maintain the balance.

The purpose of this chapter is to understand flexibility in the current system and new options that are currently available but still not widely adopted in power systems. This research will focus on the following sources of flexibility:

- Traditional flexibility.
- Energy storage systems.
- Flexible renewable supply.
- Flexible demand.

This chapter elaborates on the diverse sources of flexibility that can are found in current power systems. Section 2.2 describes the traditional means of flexibility already employed on fossil fuel power plants.Section 2.3 presents the storage options and their means of integration to the grid. Section 2.4 provides background on VREs as a source of flexibility and the challenges in their implementation. Finally, Section 2.5 explains the traditional means of flexibility in the load side and the new possibilities in this sector.

2.1.1 Effects of renewable penetration on conventional generation

The installed capacity of conventional generation was intended to follow a predictable demand profile. Deploying a vertically integrated system caused a high investment on inflexible power plants such as coal, lignite, and nuclear, used as base-load power in 80% of the year [8]. If it is true that renewable energy is essential for reducing CO2 emissions, several countries will still depend on these power plants to achieve a transition. Introducing high levels of VREs will have impacts on traditional plants. Firstly, VRES will take the place of these power plants as base-load generators; this is due to the near-zero marginal cost of generation for wind and solar energy. Reduction of the number of traditional generators will create a need for more flexibility and higher ramping rates to make these plants generate at peak hours with more variability. Furthermore, high wind and solar energy will tend to drive wholesale electricity markets down, making traditional power plants less cost-effective [27]. Lastly, the integration of VREs will have indirect impacts such as an increase in balancing mechanisms and congestion management.

2.2 Flexibility in traditional power plant

Traditional power plants such as coal, gas, nuclear, have historically supplied the power system with flexibility. Currently, the role of these plants is shifting from base loads to load-following due to the integration of VREs. This flexibility means that the plants have to increase or decrease generation when required by the system. Furthermore, this type of plants has the lowest operational cost, although costs rise when starting, stopping or running them at low loading. [24] Systems with low VREs penetration tend to use coal and gas plants to supply the base-load. Alternatively, gas plants are used to cover the demand at peak times due to their fast ramping rates and shortstop and start times. Traditionally, the demand causes variability and uncertainty in the system. Plants with high ramping rates covered this variability and the mismatch of energy. Currently, the system is experiencing variability in the generation side as well due to VRES, which has to be taken into consideration.

2.2.1 Characteristics that influence flexibility

Traditional power plants flexibility depends on three different factors:

- Ramping rates
- Minimum load
- Start-up times

Ramping capabilities refer to the ability of a generator to change demand or supply over some time. Due to the higher variation in residual load than in load itself, the conventional generation has to be faster in modifying their energy output. Ramping in traditional power plants is also considered response time. Power plants have to operate at a minimum load level to ensure higher efficiency. Some periods renewable energy may account for 100% of generation, meaning that traditional power plants might have to lower the operating thresholds. Reducing minimum load requirements proves to be one of the most beneficial, as it aids in the integration of VRES. Starting times are also an indicator of flexibility. At some periods, power plants might find it economically advantageous to shut down completely, having shorter start-up times improve flexibility in a significant way. This time varies from technology, plants like nuclear might take 2 days to perform a cold start with OCGT plants take between 5-11 minutes [13]. Chapter 3 discusses in detail how these three factors add up to quantify flexibility.

The most common types of conventional power plants have differences in operational characteristics. Table 2.1 summarizes costs, ramping rates, start-up times and minimal loads in different power plants. For this investigation, technologies such as open-cycle gas turbines (OCGT), closed-cycle gas turbines (CCGT), and coal were taken into consideration. The table contains current, new and retrofitted plants. The latter suppose a change in operation and in components to achieve more flexibility.

Table 2.1: Ramping capabilities and start up times [13]

Power plant	**Efficiency**	**Ramping (%/min)**			**Cold start (hours)**		
		Exisiting plants	*Technically feasible*	*New installations*	*Exisiting plants*	*Technically feasible*	*Retroffited and New installations*
Coal	up to 48%	1.5	4	6	10	5	4
Lignite	up to 44%	1	2.5	4	10	8	6
CCGT	up to 60%	2	4	8	4	3	2
OCGT	up to 40%	8	12	20	<0.1	-	-

2.2.2 Processes affecting the flexibility in traditional power plants

Conventional power plants supply the grid with different response services that can be applied to serve different purposes. These services offer different benefits to the grid:

- Regulating reserve - Resources that automatically respond to the system operator signals. They provide up and down-regulation that track the real-time imbalances of the system.

- Load following - Provide slower regulation services that are used to bridge between the regulating reserve and energy markets.

- Spinning reserve - a Synchronized generation that can increase its power output. This reserve responds to outages in transmission or generation.

- Non-Spinning Reserve - As well as the spinning reserves this do not respond immediately but can achieve full output within 10 minutes.

- Replacement Reserve - It has a 30-60 minutes response time, is used to restore the reserves to their statues before the contingency.

- Voltage control - This reserve is used to absorb or inject reactive power to the transmission system to keep voltages within an acceptable range.

- Black start - Can start independently from the grid. Furthermore, it has sufficient power to start additional generators.

Table 2.2 shows the response time of each service, the typical duration of it and the costs. It has to be noted that cost fluctuates heavily due to the prices of fuel and that private generation companies have confidential agreements with TSO's.

Table 2.2: Properties of key ancillary services [22]

Service	**Response**	**Duration**	**Cost ($/MWh)**
Normal Operation			
Regulating reserve	∼1 min	Minutes	35-40 200-400
Load following	∼10 min	10 min to hours	Obtained form intraday market
Contingency conditions			
Spinning reserve	Seconds to <10 min	10 to 120 min	6-17 100-300
Non-spinning reserve	<10 min	10 to 120 min	3-6 100-400
Replacement reserve	<30 min	2 hours	0.4-2 2-36
Other services			
Voltage control	Seconds	Seconds	1−4/kvar-yr
Black start	Minutes	Hours	-

2.3 Electrical energy storage system's flexibility

Energy storage systems (ESS) will be a crucial part of most energy systems and could be an essential element in achieving a low carbon future. These technologies allow the decoupling of supply and demand for energy, in essence, which provides a valuable resource for system operators. There are many cases in which the deployment of energy storage is competitive or close to competition in the current energy system. However, regulatory and market conditions are often ill-equipped to offset storage for the set of services it can provide. Also, some technologies are still too expensive concerning alternatives (for example, flexible generation and new transmission lines in electricity systems)[1].

Several factors are driving interest in electric energy storage systems. Such as the increased volume on renewable energy, costs for handling grid peak demand, and the necessary investments required to maintain a reliable power system [3]. Currently pumped hydro storage (PHS) is the only mature technology available, accounting for 99% of the world's storage capacity [1]. This technology is used for energy time-shifting, but it is not able to provide services on a short scale and variable power. New research and development in technologies that can provide ancillary services are done to bring them to the market. There are different classes of storage systems according in the form that the energy is kept: electrical, electrochemical, mechanical, chemical and thermal. These different technologies can be seen in Figure 2.1.

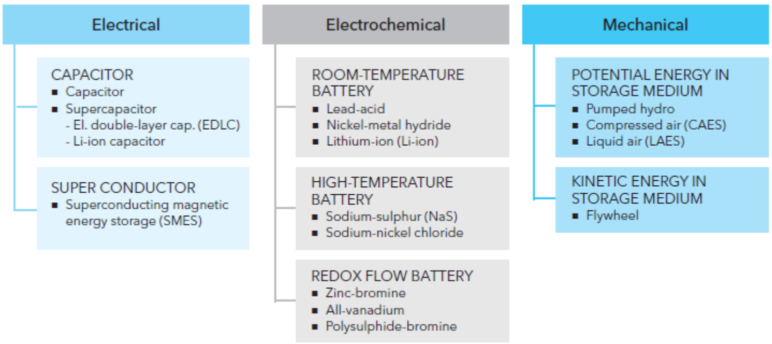


Figure 2.1: Classification of main electrical energy storage systems [15]

2.3.1 ESS characteristics

In contrast with traditional flexibility, ESS has a limited amount of energy, meaning that continuous power output is not achievable. Nonetheless, the different technologies have a variety of discharge duration, pumped hydro storage (PHS), and compressed air energy storage (CAES) can provide energy during long periods, i.e. days or weeks. For electrical applications, discharge period, response time and power rating, are used to determine if a technology is more suited than others to perform a specific task regarding grid management. For thermal storage, output temperature and capacity are two factors that determine suitability. Table 2.3 shows the different power, cost, response time and discharge duration for several storage technologies.

Table 2.3: Energy storage systems characteristics [12] [26]

Technology	**Power range (MW)**	**Energy range(MWh)**	**Discharge duration**	**Response time**	**Cost (Euro/kW)**	**Cost (Euro/kWh)**
Supercapacitor	2,5-15	0-0,3	>1 minute	msec	200-400	500-1000
SMES	0,1-10	0,015		msec	200-300	1000-10000
Lead-acid	0-20	0,001-40	10min to 4h	msec	300-600	200-400
Lithium-ion	0-0,1	0,004-10	10min to 4h	msec	1200-4000	600-2500
Sodium-sulphur	200kW to 50 MW	1.2 MWh to 400 MWh	6h at nominal power	msec	2000-3000	300-500
Sodium-nickel chloride	Several MW	4kWh to several MWh	from 2h to several hours	msec	150 – 1000	
Pumped hydro	100-5000	up to 100 GWh	500-8000	some sec– few min	600-2000	5-100
CAES	5-300	<1000	Some h – some 10h	Some min	400-800	2-50
LAES	10-200	2,5	2 - 24 hours	5 min	900-1900	260-530
Flywheel	0-0,25	0,75	15 sec - 15 min	msec	250-350	1000-5000

To achieve overall flexibility, a hybrid system should be implemented. This is, combining different types of ESS into a system. The objective of a hybrid system is to improve a power system in different ways and to achieve multi-purpose flexibility. A type of combination could be a high-power low-duration technology with a high-energy long-duration. This combination can take care of a broader range of tasks in the power system.

Furthermore, ESS provides different benefits, such as fast response and scalability. Systems can range from small used for local flexibility up to large systems used for central flexibility. There are other advantages in energy storage systems compared to traditional flexibility and grid extension. For example, battery systems present a faster installation and are re-configurable, giving them the adaptability necessary to work in different locations or scales.

2.3.2 ESS applications

Storage energy systems can be applied in the different voltage levels of a power system. Bulk ESS are placed within the transmission level. These systems normally fall in the domain of system operators and power producers. Storage systems at high voltage level offer several benefits:

- Allowing a higher VRES penetration in the system, thus lowering CO2 emissions and reach the goals set by the Paris Agreement and EU's energy road map.
- Ensuring a balance between supply and demand with the provision of ancillary services, such as frequency regulation support.
- Allowing the system the ability to respond faster to contingencies, whether it is an equipment failure or a plat outage.

- Balancing loads and aiding with transmission congestion.
- Supporting conventional power plants by avoiding them to cycle while used for frequency regulation.

ESS in the distribution side can be used near feeders and in local areas such as industrial and residential zones. These systems can work either on the supplier side or on the demand side. Some benefits of these distributed systems are:

- Relieving grid peaks.
- Making the system more reliable
- Decrease capital costs of new electrical infrastructure.
- Cooperate with VRES in the distribution side and electric vehicles.

Table 2.4 show several types of storage technologies and their different applications depending on their operational characteristics. Capacity, discharge time and response time are taken into consideration to classify them.

Table 2.4: Energy storage systems applications

Applications	**SC**	**SMES**	**FW**	**Lead-acid**	**Nickel-metal hydride**	**Lithium-ion**	**Sodium-sulphur**	**PHS**	**CAES**	**LAES**
Ancillary services										
Regulating reserve								x	x	x
Load following	x	x	x	x	x	x	x			
Voltage control	x	x	x	x	x	x	x			
Reactive support	x			x	x	x	x			
Frequency control	x	x	x	x	x	x	x			
Black start						x		x		
Energy management services										
Peak shaving	x			x	x	x	x	x	x	x
Congestion relief									x	
Demand shifting	x		x	x	x	x	x		x	
Seasonal storage								x	x	x
Load leveling			x	x	x	x	x	x	x	x

2.4 Flexible renewable supply

Variable renewable energy sources can be actively controlled. This control refers to the ability to operate these generators in such a way that they can offer flexibility services in different timeframes. Therefore, assisting in congestion management and balancing the system. Wind turbines and photovoltaic systems are capable of supplying a fast response to operating signals. There are two ways these technologies can provide these services. Curtailing power production is one of them; this means down-regulation can be provided. The second option is to maintain power production under its maximum capacity to provide up-regulation when needed. The issue with these two options is that they involve reducing the overall power output of VREs [30].

Curtailing energy provided by PV and wind turbines is becoming a widespread phenomenon in the current power systems due to the new reach of these technologies. Curtailment can directly affect revenues on solar and wind farms projects, and thus reducing the attraction of investment. Quantifying these impacts is complicated due to the different characteristics a grid presents, operation practices and the location's weather. Curtailment happens typically because of congested transmission lines or the lack of access to them. Furthermore, it can be caused by excess generation in low demand periods when traditional generation already reached its minimum power output. This output might be defined by the necessity of maintaining frequency in ac grids, particularly in islanded grids [15].

VRES are the fundamental drivers of a zero-carbon power energy system, also the ones creating the need for flexibility. In a system with high VRES penetration controlling their power output could prove to be a potential flexibility source. Still, several challenges arise from this solution, firstly the stochastic nature of VRES the flexibility that they can provide is associated with uncertainty. In spite of the capacity of VRES of providing these services with the market and policy environment still, present several barriers. This environment varies by market design; some of them use offer-based market mechanisms instead of manual wind energy curtailment [23].

A considerable barrier for renewable energy curtailment comes from the political and social perception of “wasting” clean energy. At first sight, this loss of power should not happen, although curtailment in specific situations provides a solution regarding the total costs of electricity.

2.4.1 Curtailment

Categorizing types of curtailment is necessary to understand the rationale behind the situations that cause it. Two types of curtailment are described, voluntary and involuntary. Curtailment, in this sense, is defined as a moment in which a generation unit produces less power than it could because of its marginal costs. It is important to understand that curtailing energy can be translated into an economic benefit for the generators.

Table 2.5: Curtailment categories [20]

Category	**Voluntary**	**Involuntary**	**Compensation**
Network constraints	Accepted in contracts at the moment of connection.	DSO controlled reduction of generation in short time lapses.	DSO or TSO compensates depending on market prices also depend on policies.
Security	Specialized market. (Flexibility market)	Maximum generation limits, enforced by TSO.	Separate market for compensation from TSO based on policy.
Excessive generation	Low or negative prices present in the market.	Generation limits.	Compensation by TSO only for voluntary curtailment.
Strategic bidding	Manipulating prices	-	-

The lack of infrastructure mainly induces involuntary curtailment caused by network constraints. New wind capacity can be placed in a few years, whereas new transmission lines can take up to 10 years. [ref] This can be solved by placing generation units in a less curtailable area. Voluntary curtailment occurs when investors also have to finance the connection to the grid. This might mean that producing less energy is more economically beneficial than constructing an interconnection line with higher transmission capacity. Usually, VRES curtailment is applied as a temporary solution, to allow new VRES units to be installed and new interconnections between countries. The latter will allow countries with a low percentage of renewable energy in their mix to import energy from countries that overproduce and thus avoiding the need for curtailment. Furthermore, it is a common practice to under-dimension PV inverters to reduce the peak generation of PV installation. By doing this, power peaks can be reduced by 10%, but the annual energy yield lightly decreases [15].

2.4.2 Barriers and drivers

VRES curtailment is mainly driven in the EU by security reasons instead of economic ones. Negative residual loads, i.e. negative prices, are not occurring that often in European markets. In future years the residual load shape will undergo a profound transformation if the targets of VRES are met.

Countries will have to put in place a new market and grid operational procedures to minimize or avoid curtailment. As a result, infrastructure will have to be strengthened to integrate high shares of VRES. Taking into consideration that high peaks that exceed the grid's capacity occur only in small hours in the year, an increased cost of electricity due to new infrastructure can decrease the social acceptance of renewable energy [11].

A considerable barrier for renewable energy curtailment comes from the political and social perception of "wasting" clean energy. At first sight, this loss of power should not happen, although curtailment in specific situations provides a solution regarding the total costs of electricity. For this reason, the future power system has to be one of the diverse flexibility sources which can accommodate different technologies that reduce curtailment. Some examples are demand-side management and storage.

2.5 Flexible demand

Flexible demand in energy power systems is gaining attention in many countries, although it has been present in some countries since the early 2000s for industrial loads. Flexible demand encompasses demand response and demand-side management. Even though these terms are usually interchangeable, they have different characteristics. Demand-side management (DSM) involves the actions taken by the retailer or utility to provide flexibility. On the other hand, when the consumer reacts to operational or price signals, it is referred to as demand response (DR) [15].

The organization of the elastic demand has been present in some countries since the early 2000s, although only for industrial loads. The straight forward way of implementing DR is with time-based electricity tariffs. For example, using day, night, peak and valley tariffs to divide the period's energy is going to be used. With this approach, consumers reduce their consumption to receive an economic benefit. Typically consumers would shift their consumption to the night when electricity is cheaper, although these tariffs are not enforced, the results are uncertain.

Reserve markets can implement demand flexibility via contracts between TSOs or DSOs and the end consumer, which is usually an industrial partner. EU countries introduce flexibility with bilateral contracts or in single buyers' market, where the different parties offer flexible capacity. This flexible capacity is offered in the different imbalance markets and for different time frames. Agents that participate usually are industrial companies that have daily pumping requirements or greenhouse owners. The nature of the industrial processes allows them to shift their demand without interfering with their primary processes. Currently, different industries are exploring new ways to offer flexible demand to reduce their electricity bills. Besides voluntary programs such as hourly tariffs, TSOs can arrange regulated plans for load disconnections in case of a fault in the system. One example is the Belgian electricity system which allows the operator to disconnect loads automatically in case of disruptions or manually in case of insufficient generation. The digitization of the grid will allow small loads to participate in demand response programs thanks to smart metering and aggregation.

2.5.1 Demand side management

Demand side management programs used by utilities aim to change consumption patterns in specific periods of time according to system's needs. These programs change the load curve accordingly to the retailers objective. Figure 2.2 shows the typical load curve objectives.

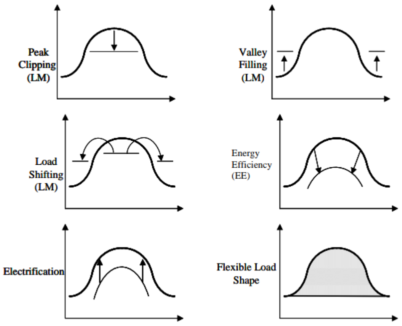


Figure 2.2: Demand side management techniques [4]

- Conversion and energy efficiency involves the use of a different energy carrier than electricity or the installation of new and more efficient appliances.
- Load shifting moves the energy consumption from one period to another, typically when prices of energy are lower.
- Peak clipping refers to the decrease in consumption during peak hours; this brings benefits to users and systems operators. Reducing electricity bills for consumers and decreasing the need for infrastructure and congestion management.
- Valley filling programs shift consumption to periods with the lowest energy demand. Wind energy can provide a base generation during the night or other periods of low demand; these programs aim to utilize this energy and avoid curtailment.
- Flexible load shape involves the use of dynamic response to distribute power requirements over different times.
- Electrification is the opposite of conversion. Currently, new loads are using electricity as their energy carrier. The transportation and heating sector are currently shifting towards an electricity-based operation.

2.5.2 Demand response

Demand response allows commercial and industrial consumers to respond to market signals by increasing or reducing their energy consumption. Increase or decrease in consumption responds to peaks of supply or demand for electricity, allowing greater flexibility and stability of the network and more efficient use of infrastructure and energy resources.

A modulation event is usually articulated in the following phases:

1. The network operator foresees a network stability problem and sends the balance notification to the aggregator.
2. The aggregator receives the balancing order and distributes it (using the optimization algorithms implemented) among the clients in its portfolio to reduce or increase energy consumption.
3. The designated client modulates their consumption/generation (both automatic and manual modes are foreseen).
4. The network operator is made available to modulate the load.
5. After checking the correct supply of the service, the client receives the remuneration agreed in the contract.

Flexible demand is a key factor to undertake important challenges for the operation of the system and will play a fundamental role in the transition towards the future energy model. Furthermore, DSM traditional programs have been focused on industrial demand, being less widespread in other sectors with a greater number of consumers like the residential and service sectors.

In the coming decades, it is expected that the new measures of demand management are oriented to the services and residential, taking advantage of the new role of consumers, with greater participation and knowledge of the electric system. The new management mechanisms of the demand will be developed in within smart grids, the introduction of electric vehicles, storage and almost zero consumption buildings.

One example is the National Grid in the UK that procures balancing services from industrial partners. These services are defined depending on their direction (positive or negative) and on the time response they can be offered. These response services are applied to increase the system's frequency or to decrease it, positive and negative services are used respectively. An upwards regulation service provider will increase its power output if it is capable of doing it, or reduce its load, contrarily as the negative service provider. Furthermore, response services have to be provided within seconds and with the necessary response time. Response services are activated automatically by a frequency read, whereas instructions within minutes of an event trigger reserve services. Figure 2.3 illustrates the time scale in which response services should be activated and its duration.

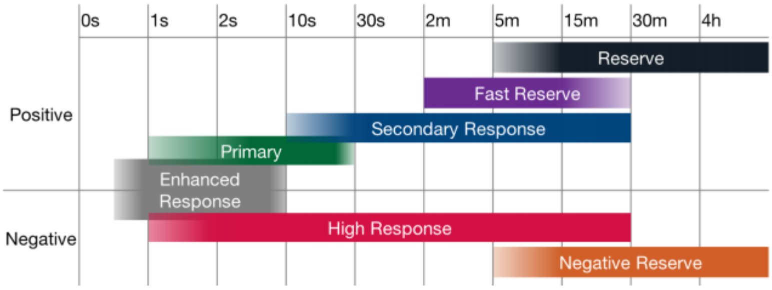


Figure 2.3: Response services time scale [10]

The various services represent the fast end of the DSM timescale. Primary control would resemble the spinning reserve that is offered by rotating masses of traditional generation while the secondary control is in charge of restoring the frequency adding or decreasing the active power. The regulation power plants conventionally took this role, this shift of task to the demand allows it to work as a virtual spinning reserve if the power consumption is related to the grid state with a droop control.

2.5.3 Benefits

Table 2.6 shows the benefits in utilizing flexible demand in different sections.

Table 2.6: Flexible demand benefits [11]

	Operation	**Expansion**	**Market**
Generation	• Reduce energy generation in peak times. • Facilitate the balance of supply and demand. • Reduce operating reserves requirements.	• Avoid investment in peaking units. • Allow more penetration of intermittent renewable sources.	• Reduce risk of imbalances. • Limit market power. • Reduce price volatility.
Demand	• Consumers are more aware of the cost. • Give consumers options to maximize their utility. • Opportunity to reduce electricity bills.	• Take investment decisions with greater awareness of consumption and cost.	• Increase demand elasticity
T&D	• Relieve congestion • Management contingencies. • Reduce overall losses. • Facilitate technical operation.	• Defer investment in network reinforcement or increase longterm network reliability.	-
Retailing	-	-	• Reduce risk of imbalance. • Reduce price volatility. • More consumer choice.

2.6 Conclusions

High penetration of VRES will bring new challenges to the traditional power system. Because of this, the concept of flexibility in the grid has gained more interest from researchers, system operators and industry. The added uncertainty and variability of wind and solar energy enhances the need for a flexible power system. A system that is able to cope with sudden changes in the generation profile in order to maintain the balance between supply and demand. This chapter discussed several flexibility sources like traditional power plants, renewable flexible supply, energy storage systems, and demand.

Traditional flexibility is the one delivered by rotating generating units, either gas, hydro, nuclear or coal-powered plants. In the conventional generation-demand scheme, these plants followed the demand and flexibility was not a significant issue. Currently, with the high integration of VRES, the supply side is bringing new challenges to traditional plants. One consequence of this new shift in generation paradigm is that traditional plants will operate at part load when VRES output is high or not at all when VRES can cover the whole demand. These situations will end up reducing the economic efficiency and reducing the investment on them. To avoid these new policies or markets should be set in place to ensure enough capacity in standby to cover moments in which VRES is not enough.

This chapter defined supply flexibility as the output from variable renewable sources (wind and solar). This power output varies from traditional plants as it depends strictly on weather conditions. Not following the demand pattern is one of the problems that have to be solved to achieve functional integration. One of the most popular options to manage the output of these technologies is curtailment, which involves reducing the power output. This decision faces several issues; one of those is the public perception of wasting green energy. On the other hand, curtailment might be an economically viable option for systems operators when facing congestion or low demand. In the future, new optimization processes shall be placed to avoid curtailment and produce as much renewable source energy if European energy agreements are to be met.

Energy storage systems are currently not being used at a grid-scale except pumped hydro storage, which accounts for 99% of the total storage installed capacity. This means that new technologies are still too expensive to be considered feasible or are not yet at the desired level of maturity. ESS are considered as new systems whereas elastic demand and supply are considered add-ons; this results in a higher expenditure by interested parties. Decreasing costs on batteries are driving its application in distribution and transmission systems. ESS prove to be a source of a wide variety of services to the grid that is traditionally supplied by rotating generators which makes them an exciting option in the future.

Figure 2.4 compares the different flexibility sources in two axes: time response and discharge duration. These two axes are essential to define due to their importance to maintain a balance between demand and supply that ensures proper operation of the power system. Batteries are considered as one block, although several types vary in operation. Demand response can respond in theory in seconds; the barrier is current practices which make operators call industries and can respond in more extended periods. Same phenomena can be observed in curtailment; the flow of information is the main delay in activating control for wind and solar energy.

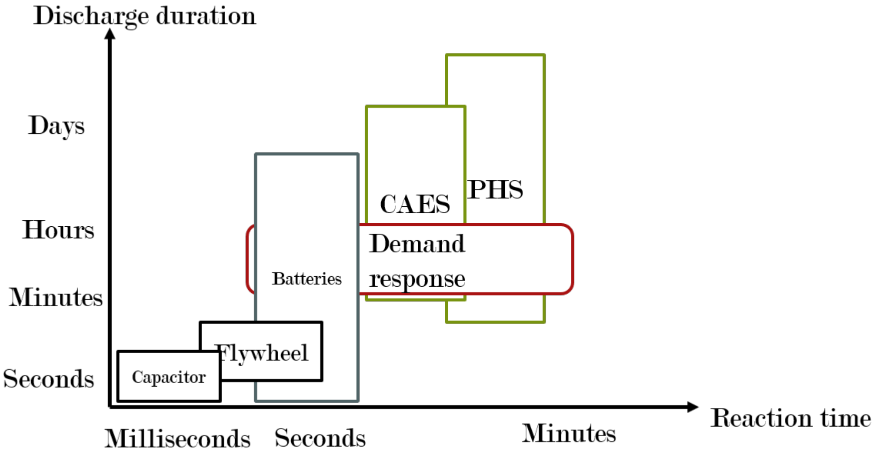


Figure 2.4: Flexible sources response time vs discharge duration

3

Flexibility assessment

3.1 Introduction

Future power systems will face new challenges in their planning and operation, notably, in planning reserve capacities that deal with the uncertainty introduced by VRES. Keeping the balance between supply and demand in the power system will become an even more complicated process than in current systems because of the situations mentioned above. This chapter develops a process in which uncertainty in the system can be translated into the amount of flexibility needed.

Forecasting applications are an essential part of quantifying the amount of uncertainty in the grid in different timescales. These applications serve different purposes for different stakeholders in the systems, i.e. grid operators, wind and solar power producers and other market participants. Traditionally, load forecasts had an essential role in grid operations. However, the introduction of renewable energy forecasts is a recent phenomenon. Multiple forecasts with different time horizons are required, the more extended time frame forecasts (days to weeks), are used to schedule maintenance of transmission lines or resource planning whereas shorter forecast horizons (minutes to days) are used to ensure reliable operation of the system. Uncertainties in the output of VRES are not yet accurately accounted for in industry tools for system management, unit dispatch and market operations [41]. There are several uncertainty sources besides wind and solar energy such as loads, outages, loss of transmission capacity and frequency deviations. These uncertainties cause alterations in the system balance, which could bring upon inefficient and expensive solutions in the real-time operations. Furthermore, the combination of “traditional” source of uncertainties and wind or solar, will cause significant unexpected variations on the supply-demand mismatch.

This chapter introduces the effects of the uncertainty from VRES. Section 3.3 explains newly electrified loads that are electric vehicles. Furthermore, Section 3.4 explains how a flexibility calculation would be done. Finally, Section 3.5 explains current markets practices and proposes a new one.

3.2 Uncertainty

The growing integration of VRES supposes a rise in risks for control performance and reliability of the power system. The lack of assessment of these risks supposes less information about the potential consequences of VRES in the system. Furthermore, uncertainties will make system operators procure higher volumes of balancing mechanisms at costlier prices. There is an increasing need for high accuracy evaluations of uncertainties associated with the integration of VRES. Flexibility needs will increase depending on how much uncertainty is found in a specific system. Ramping capabilities are highly correlated to the variations of wind and solar energy.

Two questions have to be addressed to diminish the impact of uncertainty in the power system: When should extra units have to run to keep up with possible ramps over a time horizon? Is the available online capacity enough to keep the balance during intra-hour and real-time basis? System operators need accurate forecasting in different time frames both from loads and VRES to anticipate variations in either one of them, there are several reasons for the need of these accurate forecasts:

1. Enhancing forecasts will enable TSOs to obtain the required reserve capacity to maintain the balance in the system.
2. Reserving energy and balancing services in the different time frames, i.e. day ahead, intra-hour and real-time.
3. Reducing errors in forecasting would assure that the ramping capacity of the system can handle variations in the supply-demand balance.

As stated before, there are different forecasts for several time frames and with different applications for the power system. Table 3.1 shows the different characteristics of the available forecasting methods.

Table 3.1: Forecasting characteristics at different timescales [5]

	Type of forecast	**Time horizon**	**Key applications**	**Methods**
Generation support	Intra-hour	5-60 min	Regulation, real-time dispatch, market clearing	Statistical, persistence
	Short term	1-6 hours ahed	Scheduling, load-following, congestion management	Blend of statistical and NWP models
	Medium term	Day(s) ahead	Scheduling, reserve requirement, market trading, congestion management	NWP with corrections for systematic biases
	Long term	Week(s), seasonal 1 year or more ahead	Resource planning, contingency analysis, maintenance planning, operation management	Climatological forecasts, NWP
Decision support	Ramp forecasting	Continuous	Situational awareness, curtailment	NWP and statistical
	Load forecasting	Day ahead, hour ahead, intra-hour	Scheduling, economic dispatch, congestion management, demand side management	Statistical

Uncertainty within loads and VRES has a difference in the predictability. Loads can be anticipated with small margins of error based on historical events, weather forecasts and specific events from certain regions. VRES generation relies primarily on weather, which does not correlate with demand profiles. Mismatch in generation and demand profiles will cause a change in the use of gas or hydro plants, which would have to be able to keep up with the ramping needs of the system.

Forecasts have to accommodate the two top challenges that uncertainty brings upon the system. Positive ramps during times of low loads and negative ramps in moments of a high demand. In the first case, curtailment can be an option, although not the most efficient one. Obtaining a high degree of accuracy in forecasts would allow system operators to reduce the uncertainty in ramps and deal with them more efficiently. Forecast accuracy can be expressed in several ways. The challenge comes with the different ways of interpreting the obtained data. Different time scale forecast or assumptions can provide different interpretations of accuracy.

There are several sources of uncertainties this section discusses. Currently, VRES are the leading new players in the new power system and the ones that add high levels of uncertainties due to their intermittent nature. Load forecasting has been traditionally the one most used by system operators to ensure available capacity. Currently, new loads are entering the market, such as electric vehicles (EVs) also different systems now are being electrified in the household sector. These sources of uncertainties are under the scope of this research, although many others affect the power system.

3.2.1 Wind uncertainty

High penetration of wind energy will cause system operators to face a new challenge brought by the uncertainty and variability of wind resources. This will affect the decisions made for scheduling and dispatching. Wind power forecast (WPF) is a tool that allows system operators and other stakeholders to make decisions that address uncertainty and variability. Furthermore, applied to the market environment, WPF helps to determine the hourly and daily prices of energy and operating reserves.

WPF is rapidly gaining importance in the research community for the power industry. System operators, generators, traders and regulators require more reliable forecasts. It is beneficial for the different actors in place; wind plant owners will be able to compete in the electricity markets against steady and non-intermittent energy sources. For system operators knowing the amount of wind power output in a specific moment determines several decisions such as maintenance planning, operating reserves, among others.

Defining a time scale for wind predictions is still a debate in the scientific community, several authors propose different frontiers for each period category. Despite differences in proposed time horizon, it is clear that three different are present: very short-term, short-term and medium-term. Depending on these horizons, the forecasting systems have different applications and benefits for generating companies (GENCOs) and system operators (SOs). Table 3.2 shows the benefits of wind forecasting in different timescales for generators and system operators

Table 3.2: Wind forecasting applications [25]

Time Horizons	**GENCOs**	**SO**
Very short-term (Up to 9 hours)	Intraday market Real-time market	Ancillary services management Unit commitment Economic dispatch Congestion management
Short-term (up to 72 hours)	Day-ahead market Maintenance planning of wind farms Wind farm and storage device coordination	Maintenance planning of network lines Congestion management Day-ahead reserve setting Unit commitment and economic dispatch
Medium-term (up to 7 days	Maintenance planning of wind farms Maintenance planning of conventional generation	Maintenance planning of transmission lines

Wind power forecasting has standard error measures, the prediction error given at a time $t+k$ for a forecast made at an origin time t, $e_{t+k|t}$ is defined as the difference between the actual measured power and the wind power at $t+k$ predicted at t.Therefore,

$$e_{t+k|t} = P_{t+k} - \hat{P}_{t+k|t}, \tag{3.1}$$

where e is the error corresponding to time $t+k$ for the prediction made at time t, P_{t+k} is the measured power at time $t+k$, and $\hat{P}_{t+k|t}$ is the power forecast for time $t+k$ made at time t.

There are two criteria that are commonly used throughout literature to measure the errors in the forecasting against the actual production. These are the Mean Absolute Error which is discussed in the introduction of this section and Root Mean Square Error (RMSE). Since the RMSE is given in the same unit as the forecast variable, the information it represents is easier to interpret than the one given by the mean square error. The RMSE is given by

$$NRMSE_k = \sqrt{\frac{\sum_{t=1}^{N} e_{t+k|k}^2}{N}}, \tag{3.2}$$

where N in the number of predictions. It is useful to normalize the errors by dividing the prediction error by the rated capacity of the wind farm. This will give a value that can be easily compared to others obtained from different wind plants regardless of the amount of the installed capacity. To normalize the RMSE and the MAE, the values are divided by the installed capacity or the mean production of the site. This will result in the Normalized Mean Absolute Error (NMAE) and the Normalized Root Mean Square Error (NRMSE).

According to different research reviewed, the typical error measure involved for comparison of results are the NRMSE and the NMAE. For this research and to follow an logic order, wind and solar output error will be measured by the NRMSE.

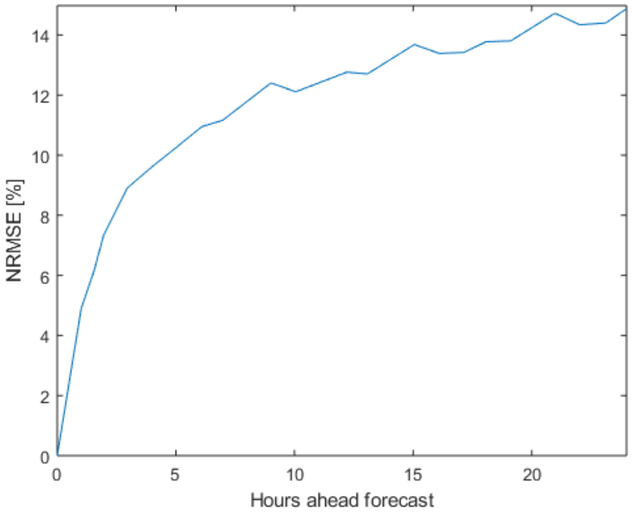


Figure 3.1: NRMSE of forecasted wind power output [33]

Although research and new technological advances are being made in wind forecasting, still there are several challenges to make an accurate prediction. Precise forecasting are related to different characteristics:

- Landscape complexity reflects the slope of the area in which the wind farm is located. It is given by the ruggedness index (RIX)
- Wind farm's installed capacity. Number of turbines and layout.
- Location.
- Data accuracy.
- Type of numerical weather prediction.
- Type of model, it can be physical, statistical or a combination of both.
- Sites climatology characteristics.

3.2.2 Solar PV uncertainty

The integration of a high volume of solar installed capacity into the grid has shown significant challenges to the power system such as stability, reliability, power balance and changes in frequency. Forecasting the power output of such plants has proven to be essential to solving these issues. Figure 3.2 shows the evolution of solar PV installations in a range of 15 years. This growth accelerates the need for more accurate forecasting tools in different time scales just as in wind forecasting.

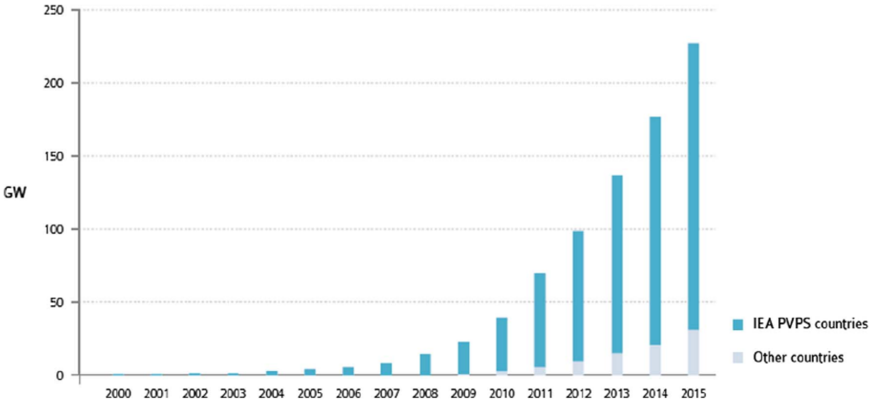


Figure 3.2: Evolution of solar PV installations [36]

Photovoltaic systems energy yield is normally predicted based upon long term averages of solar irradiation. However, the uncertainty has to be classified in different time scales to define the needs of the system to integrate solar production. Long term predictions have to take into consideration the year on year variability. This information can be of use to solar investors for large PV systems and for TSOs to manage their infrastructure and congestions accordingly. This research focuses on the short term variability of solar energy. Short term is defined as a day ahead; this definition is also useful due to the characteristics of the electricity markets, which operated based on day-ahead bids from consumers and producers. This short term uncertainty is especially necessary, as stated before keeping the balance between demand and supply is necessary.

VRES create mismatches between demand and supply, which is not possible to predict with a high degree of certainty in a day ahead timescale. Additional generation capacity normally takes care of the imbalances created from forecasting methods errors. Forecasting algorithms and stochastic optimization tools have been created to include uncertainty in models to make decisions. Stochastic programming can formulate and solve problems that count with unknown parameters; within this context, each uncertainty (solar PV output) can be modelled as a random variable. These new tools are of importance for system operators, traders and producers. The latter makes use of these algorithms to accommodate their power output in a more economically efficient way in the electricity markets. New technologies such as storage and demand response could play an important role in mitigating the negative effects of uncertainty in solar generation. If these measures are not implemented the intermittent nature of VRES could cause periods of high operational costs. For example, in situations in which VRES output has to be curtailed and high costs, fast-starting units have to be started-up. Furthermore, forecasting methods are not yet completely accurate, which means that even though technological advances are being made in this area, still the system has to be flexible enough to face this challenge.

The characteristics of PV solar power uncertainty have been extensively discussed by [2]. These characteristics bring upon the system several challenges for system operators. SOs have to maintain the balance while operating under the systems physical constraints and achieving the lowest cost. Several researchers [32] have studied the way to achieve this. Nevertheless, the majority of these studies are commonly fixed to one timescale resolution. Furthermore, a single or two-stage scheduling is used to commit the generation resources and their proper dispatch. This makes it hard to understand how uncertainty affects the system throughout the different timescales. In real operations, forecasts have to be updated continuously. As the real-time operation approaches the impacts of the forecast will also change, bringing new economic and reliability issues.

An extensive review of current solar forecasting has been done by [32]. This review shows the errors in forecasting the PV output with different methods. Moreover, these studies have been done by taking into account different timescales. At least 70 different methods were reviewed, ranging in different error output measures, timescales, methods and forecast variables. For the purpose of this research, only the ones that measured the error in the PV power output are taken into consideration. From these methods, a second filter was applied, which was the ones that used a standardized forecast error measurement. In this case, the normalized root mean square value (NRMSE) is selected. The normalized value is used to get rid of the differences in installed capacity since the different papers researched use different site locations and installed capacities. Different timescales are chosen to present how uncertainty varies throughout the time forecasts are done.

Figure 3.3 shows a graph that shows the NRMSE at various time scales. A spike exists between the one hour ahead and 5 hours ahead forecasts. This spike is because several methods were reviewed, and most of them had different characteristics, making solar forecasts still a non-standard process.

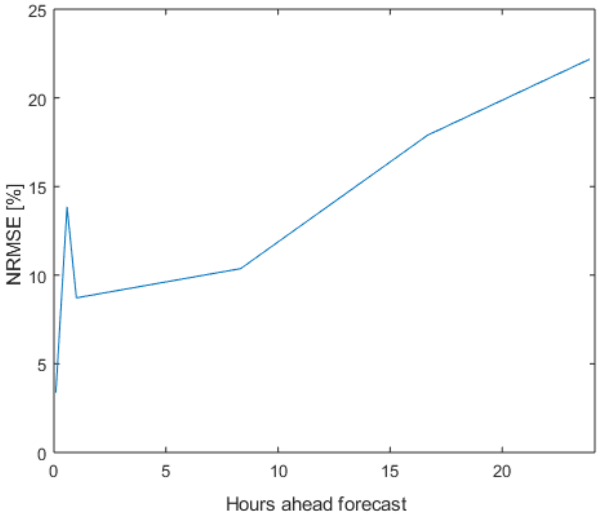


Figure 3.3: NRSME for short term solar forecasting [32]

3.2.3 Household loads uncertainty

Forecasting the load has been an essential part of the planning of electric companies, distribution and transmission operators. With new technological breakthroughs, accurate load forecasting has become more important. Load forecasting gets affected during different time horizon due to different consumer behaviour and other external factors, i.e. holidays, massive events. The uncertainty brought by the loads into the system presents a challenge for utilities. Historically vertically integrated power systems only faced the load uncertainty problem, whereas now loads have also become more intricate and the generation before the meter also conveys a certain amount of complexity in its measurement. A miscalculation of the demand can cause the system to operate in a vulnerable region to disturbances. Therefore, reliable and safe operation of the system relies on load forecasts.

There are several factors that have to be taken into consideration to provide a reliable load forecast. Figure 3.4 shows some factors that add uncertainty to load forecasting. It is seen that there is a complex analysis in calculating the load's variability.

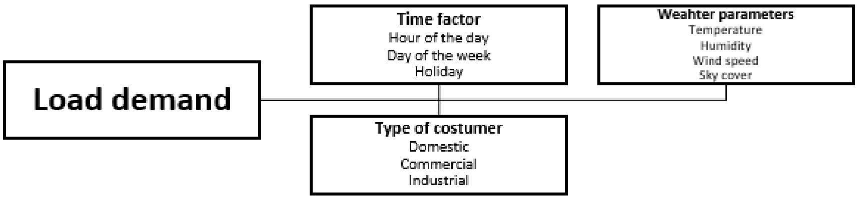


Figure 3.4: Sources of load uncertainty [41]

The evolution of demand in a week varies considerably depending on the month of the year. However, if a week is isolated, it is possible to easily observe certain parameters of periodicity in the demand curve for each day. For this paper, a day-ahead forecast is considered. It has to be noted that load will vary depending on the day of the week.

Load forecast uncertainty can be described by a probability distribution whose parameters can be estimated from experience and future considerations. It's difficult to obtain sufficient historical data to determine the distribution type, and the most common practice is to describe the uncertainty by a normal distribution with a given standard deviation. This research uses the results of an Autoregressive Integrated Moving Average Model (ARIMA), which is a statistical model that uses variations and regressions of statistical data to find patterns for a prediction of the future. It is a dynamic model of time series, that is, the data of the past explain forecasts and not by independent variables.

Figure 3.5 shows the mean absolute percentage error obtained from the ARIMA. The forecast horizon is a day ahead, and it shows how the uncertainty fluctuates regarding the time horizon in which the forecast was made.

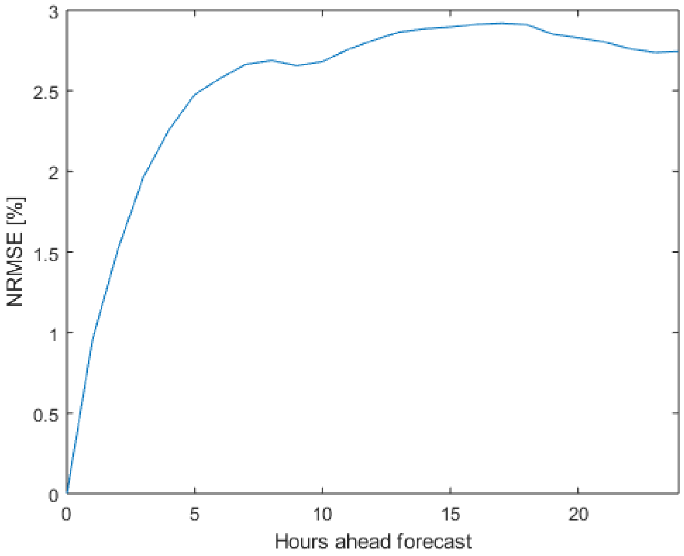
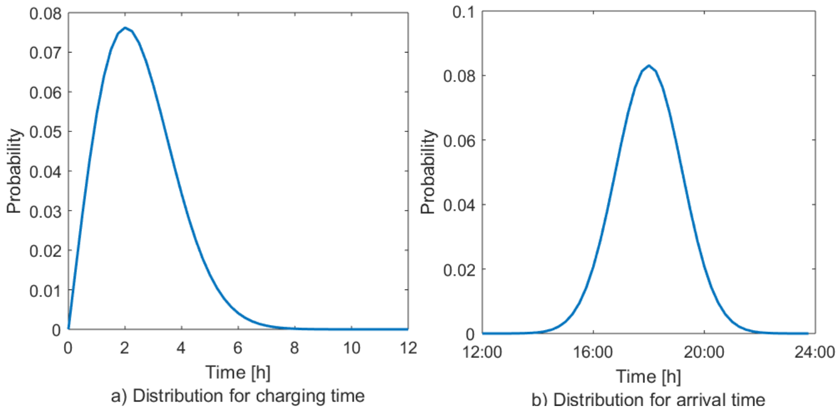


Figure 3.5: Load forecasting mean absolute percentage error [35]

3.2.4 Electric vehicle uncertainty

Achieving sustainable transportation in the future will result in the fast deployment of electric vehicles (EVs). Electrification of loads in transportation will add more demand on the power system that was traditionally covered by fossil fuels. It is expected that EVs will grow from 3 million units in 2018 to 120 million in 2030 [2]. This will bring upon a new challenge to distribution systems where the EVs charging points are connected.

Electric vehicles are distinguished for having two sources of uncertainty. Not knowing the precise moment in which the vehicle will arrive to the charging station and for how long will it need to charge. The probability density function for the arrival time is shown in Figure 3.6b. This graph has a mean that is centered around 18:00 and has a standard deviation on 1.2 hours [40]. Figure 3.6a shows the charging time for a small electric vehicle with a 3 kW charging rate. The latter figure follows a Weibull distribution with k=2.022 and λ=2.837 [40].

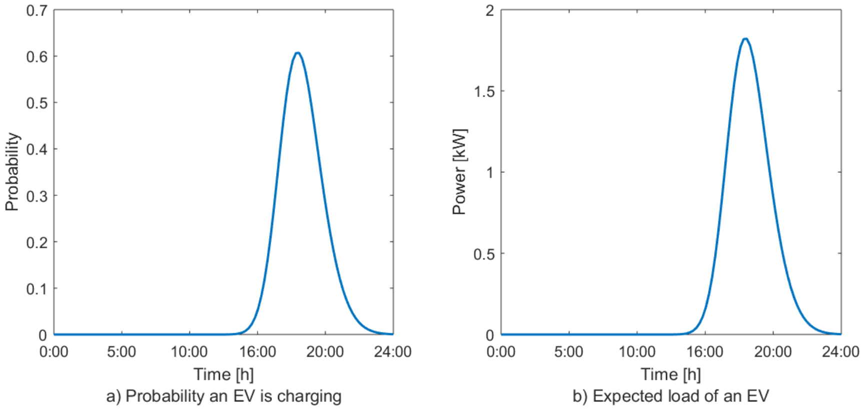


a) Distribution for charging time

b) Distribution for arrival time

Figure 3.6: Probability density distributions for the modeling of electric vehicles [40]

The aforementioned distributions result in the probability that the car is charging at any given hour and the expected load. This two graphs are shown in Figure 3.7.



a) Probability an EV is charging

b) Expected load of an EV

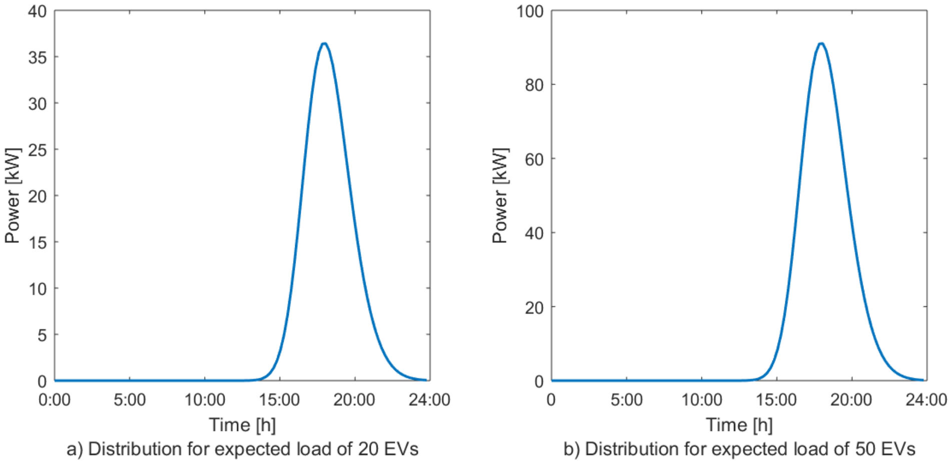
Figure 3.7: Probability density distributions of expected load and charging [40]

To aggregate more electric vehicles and obtain the expected load, these probability distributions are treated as binomial distributions. It is then assumed that a n number of vehicles are present in the distribution network, and they share the same characteristics from Figure 3.7a and 3.7b. It is also assumed that every vehicle is an independent variable in which there can either be a success or failure (meaning the vehicle is charging or not) and the probability of success is the same for each vehicle. A finite number of vehicles is selected to exemplify the aggregation, in this case, 20 and 50 vehicles. The probability there are r successes, is given by

$$P(X = r) = \frac{n!}{r!(n-r)!} p^r (q)^{n-r} \tag{3.3}$$

where X is the number of successful outcomes out of n trials, r is the number of vehicles charging at a certain moment, p is the probability one vehicle is charging, and q is the probability a vehicle is not charging and P is the probability a certain amount of power is delivered at a specific time of the day.

For 20 and 50 vehicles Figures 3.8a and 3.8b show the expected load throughout a day. Changes in this distributions are expected since charging patterns are expected to change. Charging during working hours is becoming more attractive for electric vehicle users.



a) Distribution for expected load of 20 EVs

b) Distribution for expected load of 50 EVs

Figure 3.8: Distributions for different number of EVs [40]

Each time interval presents its standard deviation due to the binomial distribution characteristics. The nature of each data set is different; some approximate normal distribution while others do not. To calculate the confidence value that is required to ensure that in 95% of the time the value is in the selected range, each period distribution was plotted and defined as a normal distribution or not. Once they were classified, the confidence value was selected. For a normal distribution, a 3σ was chosen, which indicates that 99.7% of the values lie within 2 standard deviations from the mean. For the other distributions, a Chebyshev's inequality approach is taken; this rule states that 95% of the values lie within 4σ from the mean [16].

Figure 3.9 shows the different probability distributions between 16:15 and 17:15. This means that at every 15-minute interval, there is a different probability that a certain amount of electric vehicles are charging. It also shows the different shapes of the functions, making it necessary to classify each 15-minute interval as a normal distribution or use the Chebyshev's inequality, this to use the correct confidence interval.

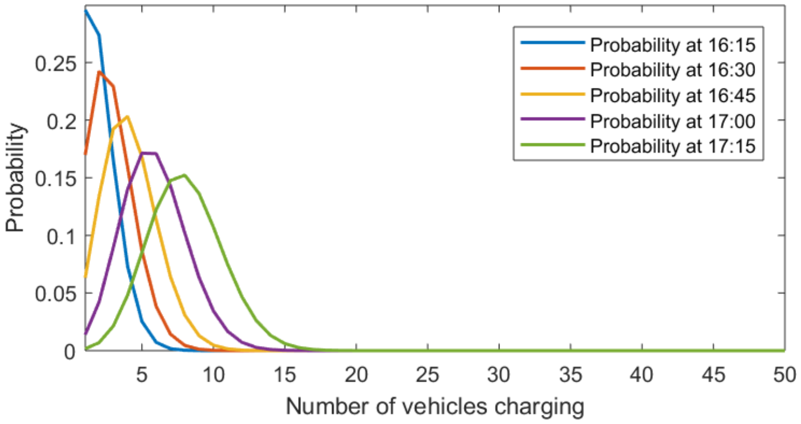


Figure 3.9: Probability distributions at different 15 minutes intervals

To conclude, each 15-minute interval has a different probability distribution. This means that a n amount of vehicles can be charging for a particular duration in a specific time of the day. This probability adds to the uncertainty seen in the system; this chapter expands on how the different sources of uncertainty can be aggregated. Figure 3.10 shows the calculated standard deviation per every 15-minute interval for the example of 50 electric vehicles. It is seen that during hours with more probability of charging the standard deviation is higher.

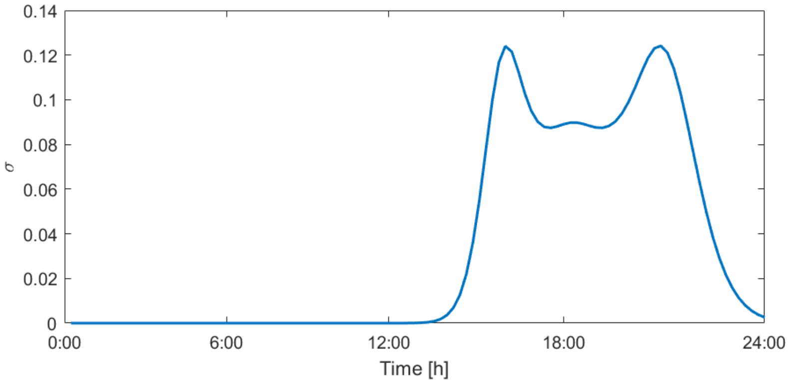


Figure 3.10: Standard deviation of 50 electric vehicles

3.3 Evaluation of flexibility

With wind and solar installed capacity increase in the power systems, system operators are facing the new challenge of the uncertainty in these energy sources. One of the most significant issues is determining the system reserve. Quantifying reserves has been relatively simple in the past and mostly deterministic. This section presents a methodology which quantifies the necessary reserves to deal with the uncertainties of wind and solar energy. Moreover, the uncertainty in loads and electric vehicles is taken into account.

This methodology incorporates a day-ahead forecast for all of the variables to assess the amount of flexibility required on a day-ahead basis. For a more accurate capacity, reserve forecasts with a shorter time-frame must be set in place to reduce the reserves and have a more economically efficient operation.

Forecast errors researched in Section 3.3 are now being used to determine a reliable reserve so the system can always meet the demand even with several sources of uncertainty.able 3.3 Shows the difference in standard deviations on a day ahead and hour ahead forecast.

Table 3.3: Day ahead and hour ahead forecast σ

Forecast	$\sigma_{Day-ahead}$	$\sigma_{Hour-ahead}$
Solar	.14	.06
Wind	.20	.05
Load	.06	.01

Firstly the NRMSE of each source of uncertainty is chosen depending on the time horizon of the forecast. To get the error in an energy measure [Wh] the forecast wind and solar production is multiplied by their respective forecast error. Since it can be assumed that the sources of uncertainty errors are uncorrelated Gaussian stochastic variables, then the total system forecast need of reserve capacity can be obtained by

$$\sigma_T = I\sqrt{(F_W\sigma_W)^2 + (F_S\sigma_S)^2 + (F_L\sigma_L)^2 + (F_{EV}\sigma_{EV})^2}, \tag{3.4}$$

where I is the chosen confidence interval σ_T is the total reserved capacity for a time T, σ_W is the total forecast error of wind output, σ_S is total forecast error of solar output, σ_L is the total forecast error of the load and σ_{EV} is the total forecast error of the electric vehicles load.
F_W is the forecast wind production, F_S is the forecast solar production, F_L is the forecast traditional load and F_{EV} is the forecast electric vehicle demand.

In order to reserve capacity, 24 hour slots are defined. To reserve capacities for shorter periods of time reduces the overall need for reserves commitment. A one hour range has been chosen due to the lack of standardization in traditional markets for flexibility or the lack of them. With shorter time forecasts and the proper way to sell flexibility the need for reserve capacities would decrease substantially.

From 3.4 the standard deviation of the system and in this case of the residual load is used to obtain the variability in the forecast. A confidence interval is chosen to account for the majority of the uncertainty in the system. Traditionally, for regulating reserves, it is not uncommon for the system operator to use confidence intervals equal to 5σ or 6σ. For load following reserves, it ranges from 2σ or 3σ depending on the authors and different geographical areas [17]. A 4σ confidence interval was selected to quantify the needs for reserve in the case study.

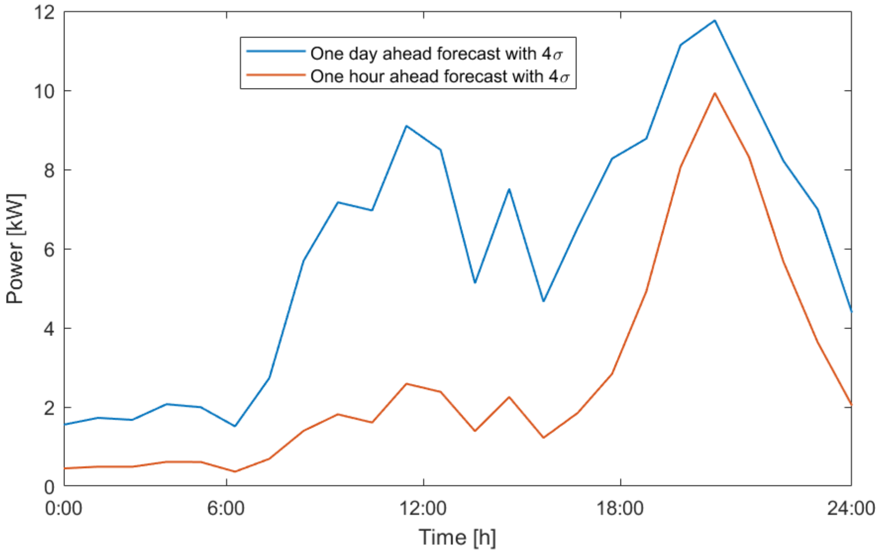


Figure 3.11: Required flexibility using 4σ and σ

Figure 3.11 shows the variability of the required capacity for balancing the mismatch during a day. This will give the required amount of flexibility within 24 hour periods.

3.3.1 Market design

System operators are aware of the necessity of introducing flexibility in power system operations. The potential of connecting flexibility providers and users is being explored by different European system operators [36]. Enabling participation of flexibility providers and participation of demand response will need the introduction of new market rules and products. Balancing markets represent a small part of the energy markets in Europe but are the gateway for new flexibility supply and service providers.

Currently balancing regulations rules are dependent on the different countries. To provide a general explanation, the most popular products offered on European balancing markets by functionality are explained. These are the frequency containment reserve (FCR), automatic frequency restore reserve (aFRR), and the manual frequency restore reserve (mFRR). Traditionally, these reserves have different response times and functions:

- Frequency Containment Reserve (FCR) - Starts in automatically in a matter of seconds, normally 15. It is then fully activated within 30 seconds after the frequency deviation. Its purpose is to hold back the frequency drop and avoid a collapse in the system.

- Automatic Frequency Restore Reserve (aFRR) - These reserves are controlled centrally by the system operators to set the frequency back at its nominal value. These reserves follow the FCR after 30 seconds and have a minimum time duration of 15 minutes.

- Manual Frequency Restore Reserve (mFRR) - These reserves are important to solve major imbalances and congestion issues, they are active after 15 minutes and can last for hours.

Balancing markets are evolving to enable the operation of DR, and other flexibility options and the Netherlands is not an exception. This year TenneT is starting to procure FCR daily, and as of July 2020, it will be procured in 4-hour blocks [36]. Nevertheless, these changes might not be enough in the foreseeable future. As a consequence, this research proposes a different operation method of reserving flexibility.

This type of approach has worked well in power systems in which VRES penetration is still not predominant. In future power systems allocating reserve capacities will face new challenges due to the decrease in traditional generators. Furthermore, the minimum response time of the aforementioned balancing services usually is 15 seconds. When the amount of inertia starts to decrease in the system, the minimum response time will start to decrease, and new technologies will have to provide this service. The scaling of storage technologies and demand response will make them suitable to provide flexibility in shorter time frames. In traditional market practices, a day ahead forecast will be used to realize a unit commitment for the next day. Due to the nature of VRES and current forecast technologies, the actual production on the day will vary and will not match the forecast. This is way shorter forecast horizons have to be made and included in the operations to reduce the required reserves.

If there's a forecast in a time horizon bigger than one hour, then more reserves will be required to cover for the uncertainty of the different sources. With the penetration of VRES, reserve capacities are increasing, bringing upon different actors the need for better ways to allocate these capacities to reduce costs in operation[41].

To reserve capacity, 24-hour slots are defined. Reserving flexibility for shorter periods reduces the overall need for reserves commitment [41]. A one hour range has been chosen due to the lack of standardization in traditional markets for flexibility or the lack of them [36]. With shorter time forecasts and the proper way to sell flexibility, the need for reserve capacities would decrease substantially. As a result of this increase, a one-hour ahead forecast is chosen to operate the future power system. Once the total required flexibility is quantified from the previous steps, the new types of flexibility providers have to be allocated in an economically efficient way.

Figure 3.12: Required flexibility for a one hour ahead forecast

Figure 3.12 shows the amount of capacity required in one hour. The minimum reaction time will be dictated by the amount of inertia/capacitance present in the system. This proposed method to allocate reserves comes from the need for a future example of how new grids will operate. The next chapter will discuss how to allocate the different types of flexibility discussed in the previous chapter in an optimal method.

3.4 Conclusions

System flexibility has to be assessed to reserve enough capacity to deal with the mismatch between generation and demand. The uncertainty of the several intermittent sources has to be determined. Wind, solar and loads have a certain degree of error in their forecasts. This error depends on the time horizon that is selected to make the forecast. This uncertainty can be quantified with the σ of each source. To quantify the error, several forecast techniques were assessed to come up with values that are not dependent on specific characteristics of wind or solar plants. As a result, a normalized root mean square error was chosen as the metric to use in this assessment.

To realize an assessment on how much reserve capacity is needed, an hour ahead forecast is done. Using equation 3.11, the total amount of capacity needed to deal with the variability of the VRES and the load is calculated. Market design plays a significant role in how flexibility is integrated into the systems' operations. Currently, barriers still exist in the integration of new technologies as providers of flexibility.

4

Power systems with low inertia

4.1 Introduction

With the transition towards renewable electricity, a change is taking place in the way these units are connected to the grid. Traditional power systems are mainly powered by synchronous generators that are installed in conventional power plants. The characteristics of these machines have shaped the power systems and the way these are operated.

From a physics standpoint, synchronous machines and coupled drive trains have inherent inertia and thus, can store kinetic energy within their rotating masses. Because these units' terminals are connected to the network, the kinetic energy is exchanged with the system. This allows the system to be less prone to frequency fluctuations during disturbances caused by imbalances between demand and generation [28].

On the other side, renewable energy units such as wind and PV typically transform DC electricity to AC by the use of power converters. The existence of this DC/AC link decouples the generator from the grid, meaning that the kinetic energy that might exist is not exchanged with the grid. As a consequence, there is no energy to limit power imbalances. Because of the change towards renewable energy and the displacement of conventional power plants, the total inertia and energy received by the system will decrease. The decrease in the system's inertia will affect the operations and stability of future power systems. The aim of this chapter is to obtain an equation that shows that the inertia of a system will determine the minimum response time of the flexibility in the system. Meaning that with lower inertia present on the system, the flexibility has to be faster to prevent drops on frequency or voltage for an AC and DC grid, respectively.

The outline of this chapter is the following. First, Section 2 discusses the fundamentals of inertia in AC power systems and how to calculate the minimum response time of flexibility. Section 3 describes how the principles of inertia in a DC distribution grid and how to calculate the minimum response time of flexibility. Finally, Section 4 uses the Netherlands as a case study to calculate minimum response times for flexibility at a Transmission level and carries out the same for a DC distribution grid.

4.2 Inertia in AC systems

First, to understand inertia, it has to be defined. The concept of inertia describes the motion of objects and these objects are affected by applying forces on them. In a broad sense, inertia is the resistance of an object to a change in its state of motion, which includes changes in direction and rotational speed [5].

AC system inertia is related to traditional generators that count with a majority of rotating mass-based generator units. Synchronous inertia in power systems is the rotating mass of generators synchronously connected to the network. The speed of rotating masses changes if the instantaneous supply is not equal to demand (accelerating/decelerating or increasing/decreasing frequency). The total mechanical inertia stored on these machines offers a resistance to the change in speed and serves to counteract changes in the frequency of their inner voltage. As a result, the inertia on synchronous generators is considered essential for the operation of current power systems.

4.2.1 Frequency stability

The stability of power systems refers to the property that allows them to remain in a state of operation in equilibrium under normal operating conditions and recover another state of equilibrium after being subjected to a disturbance.

Power system stability can be classified depending on different parameters. The primary forms of stability are described as rotor angle, frequency and voltage stability. The inertia is an essential parameter of the synchronous generators that belong to a system due to its influence in the system's stability. Decreasing the system's inertia has a direct effect on rotor angle and voltage stability [39]. Nonetheless, inertia plays an essential role in frequency stability. This stability refers to the systems ability to maintain a constant frequency after disturbances between generation and demand. It is said that frequency instability may cause continued frequency fluctuations that lead to tripping of generators or loads. This occurs when the frequency surpasses a specific range or when the rate of change of frequency is too high. Figure 4.1 shows a common profile after a generation outage.

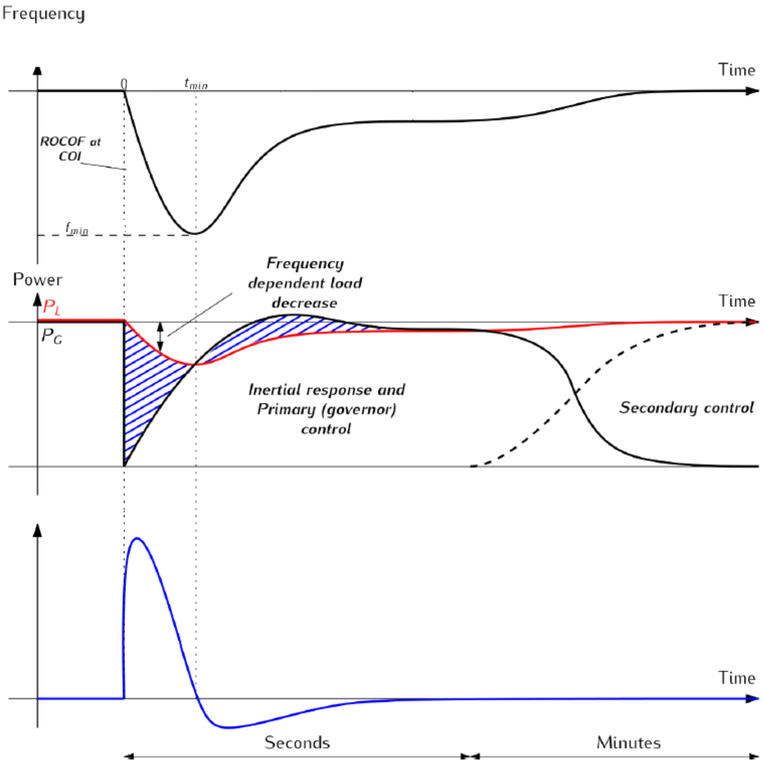


Figure 4.1: Typical frequency response after a generator outage, i.e. drop in PG (A: frequency, B: load and generation power, C: inertial response) [29].

When in steady-state, the generation and load are balanced, resulting in a nominal frequency value (f_0=50 Hz in Europe). When a power imbalance takes place, the frequency starts to change form the nominal value. This changes can occur during normal operating conditions or contingencies.

To stabilize and restore the frequency after an imbalance, a process of different control mechanisms is set in place. This process is divided into four stages:

- Inertial response
- Primary control
- Secondary control
- Tertiary control

As seen in B, in the blue shaded area, after a power imbalance the synchronous generators release their stored kinetic energy into the grid to oppose the frequency change and provide a time delay for the primary control to step in. After the power impact is distributed throughout all the synchronous generators, the nominal frequency of the system is reached. To restore the frequency, the secondary control has to act; this adjusts the power setpoints of some selected generators. This is a slower type of flexibility which acts typically after 10 to 15 minutes. Furthermore, a tertiary control is implemented to restore the secondary control reserves or to provide an economically efficient allocation of reserves in different generating units. This reserves, either in the demand or generation side, have to be allocated to control the frequency. This is contracted by the system operator, which has the task of ensuring frequency stability. The reserves are categorized depending on the type of imbalance they support, the direction of the reserve (upwards or downwards) and on the time frame in which they are activated. In this research, this last serves as a fundamental decision factor.

4.2.2 Minimum response time

Starting from a single machine, the mechanical dynamics are controlled by the swing equation; by taking the rated power and system frequency as base values and assuming small changes in the rated frequency, the swing equation is given by [6]:

$$2H\frac{df}{dt} = P_m - P_e, \tag{4.1}$$

where P_m is the mechanical power, P_e the electrical power, f is the frequency at the machine's terminals and H is the inertia constant. This constant is expressed in seconds and indicates the time that a given generator can serve its rated power using only the kinetic energy stored in its rotating mass. This constant is given by

$$H = \frac{\frac{Jw_0^2}{2}}{S} = \frac{\frac{J(2\pi f_0^2)}{2}}{S} = \frac{E_{kin}}{S}, \tag{4.2}$$

Where S is the rated power, J is the moment of inertia, w_0^2 is the rotational speed and E_{kin} is the kinetic energy of the machine. It is concluded then that the inertia of a synchronous generator gives the resistance to a change in frequency that comes from an imbalance between mechanical and electrical power. At steady-state, all of the synchronous machines operate at the same frequency. Furthermore, if a power imbalance occurs, the generators adopt different motions depending on its imbalance of P_e and P_m as stated in Equation 4.1. Nonetheless, because of the synchronizing forces and damping given by rotor damper windings, the machines will eventually run at the same speed. Because of this implicit synchronization, it can be said that all of the individual machines can be aggregated into one unit. The behaviour of this aggregated unit is given by

$$2H_{sys}\frac{df}{dt} = P_m - P_e, \tag{4.3}$$

Where H_{sys} is the equivalent inertia of an aggregated power system. H_{sys} can be defined as the sum of the inertia constant of the machines that are connected to the system and it is obtained by

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i N_i}{S_{sys}}, \tag{4.4}$$

where H_i is the inertia constant, S_i typical size and N_i spinning units of each generation technology. S_{sys} is the size of the system. Once H_{sys} is determined, by using Equation 4.3, the change in frequency caused by the mismatch of generation and demand. This is derived to be

$$\Delta f = \frac{1}{2H_{sys}} \int_{t_0}^{t_{min}} (P_G - P_L)\, dt, \tag{4.5}$$

Finally, from equation 4.5, the minimum response time for the flexibility can be obtained. This minimum response time, t_{min} is given by

$$t_{min} = \frac{2\Delta f H_{sys}}{P_G - P_L}, \tag{4.6}$$

t_{min} will change over time because the imbalances between load and generation also change during a day.

In Figure 4.3, the frequency as a function of time is given for a power imbalance of 0.1 p.u.. It highlights that for a given imbalance, the frequency drop is much larger and faster if inertia is decreased. For a lower H_{sys} , the governor control therefore needs to react sooner to cease the frequency decline before it reaches critical values

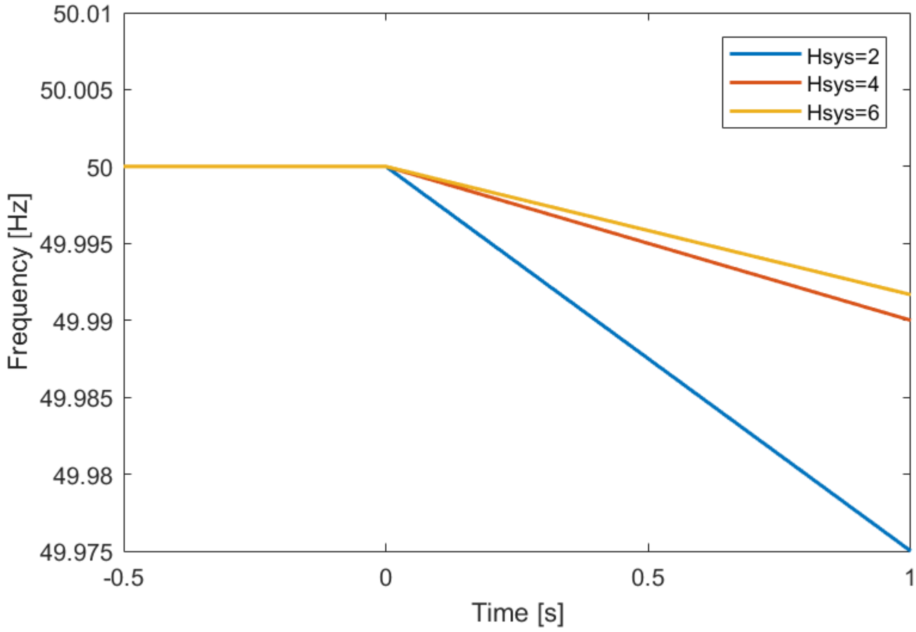


Figure 4.2: Frequency decrease

Furthermore, as the change in frequency and H_{sys} are inversely proportional, low system inertia can result in very low response time for flexibility, see Figure 4.3

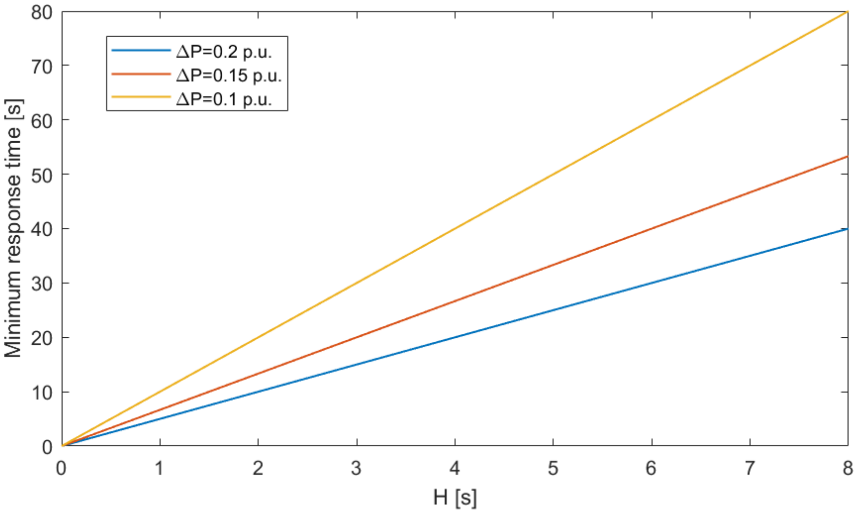


Figure 4.3: Minimum response time

4.2.3 Inertia for the Dutch power grid

This subsection will asses the previously stated equations that calculate the minimum response time of flexibility. To do so, the total inertia of the Netherlands is calculated, and the minimum response times needed. First, the total amount of installed capacity by technology has to be obtained. Table 4.1 shows the installed capacity by technology in the Netherlands in 2019 and projected values for 2030, 2040 and 2050. This values are given by [38] and [29]. Moreover, the table shows the typical size of these plants and their inertia constant.

Table 4.1: Installed capacities in the Netherlands from 2019 to 2050 [29][38]

Technology	**Installed capacity 2019**	**Installed capacity 2030**	**Installed capacity 2040**	**Installed capacity 2050**	**Typical size $[S_i]$**	**Inertia constant $[H_i]$**
Nuclear	486	485	150	0	869	6
Fossil Hard coal	4631	4429	1500	0	361	4.1
Wind Onshore	3669	7674	10000	14000		0
Hydro Run-of-river and poundage	38	0	0	0	59	2.7
Wind Offshore	957	2561	20000	53000		0
Hydro Pumped Storage	0	2066	2066	2066	140	4
Solar	3937	5933	15000	34000		0
Waste	758	433	230	0	208	3.3
Fossil Gas	15570	10379	14000	16000	168	4.3
Fossil Oil	0	2066	1050	0	153	4.3
Hydrogen	0	250	500	1000	168	3.7
Biomass	485	600	700	900	208	3.7
Total installed capacity	***30531***	***36876***	***65196***	***120966***		

Using the data of the previous table and Equation 4.4, the H_{sys} of the Netherlands can be calculated. Resulting in an H_{sys} of 4.24 s. Once this value is obtained, the required minimum response time can be calculated with Equation 4.6. First, the ΔP per unit of the system has to be calculated. The data of generation and demand for a day in July was selected. Furthermore, Δf is taken to be 0.5 Hz; this is due to common operational standards. Figure 4.4 shows how the minimum response time increases when the imbalance between demand and supply is smaller.

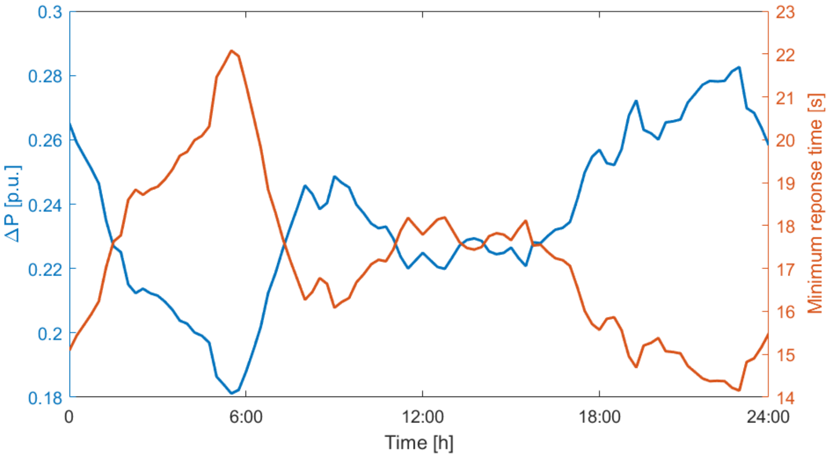


Figure 4.4: Frequency decrease

Values obtained in Figure 4.4 range between 14 and 23 seconds. Meaning that, a flexibility source with this minimum response time has to be present to prevent a change of more than 0.5 Hz on the nominal frequency of the system.

4.2.4 Inertia in DC power grids

DC distribution grids are becoming attractive to implement since they present different advantages to the AC distribution system. The control of DC distribution grids do not need synchronization of frequency, reactive power control and are not affected by harmonic currents [40]. Moreover, DC grids present advantages over AC grids regarding efficiency. Nevertheless, further research is needed for these power systems. This section aims to present an approach to calculate how high penetration of renewable energy determines the response time of flexibility in DC distribution grids. Different from Section 4.3.2, which aimed to calculate the inertia on a transmission level. Because DC transmission systems are out of the scope of this research, a DC distribution grid was selected to show the effects of an increased volume of VRES in the change on voltage. Consequently, calculating the minimum response time is required. The minimum response time dictates the types of flexibility required to avoid significant variations in voltage.

In the case of a DC distribution grid, the voltage is equivalent to the frequency in the AC system. Voltage reacts to the imbalances in the supply and demand, following the behaviour of the frequency. To quantify the rate of change in voltage, the capacitance of the system acts as the inertia of the AC systems. The amount of capacitance present on the system determines the rate of change of voltage on a distribution system. The voltage through a capacitor at a certain time is given by

$$u_s = \frac{1}{C}\int i_c\,dt, \tag{4.7}$$

where C is the capacitance and i_c is the instantaneous current going through the capacitor.

Derived from 4.7 a new equation can be obtained that integrates the power imbalance of the grid. The change in voltage of the system can be approximated by

$$\Delta u_s = \frac{1}{Cu_0}\int_{t_0}^{t_{min}} \Delta P\,dt, \tag{4.8}$$

Where u_0 is the nominal voltage of the system, C is the total system's capacitance, Δu_s is the maximum allowed change in voltage and ΔP is the imbalance of power demand and supply over some time. This period can be defined by different market operation standards or by system operators common practices.

Flexibility in future power systems will require faster response times due to uncertainty brought by VRES. Increase in power imbalances will reduce the response time. This response time is approximated by

$$t_{min} = \frac{\Delta u_s \cdot C \cdot u_s}{\Delta P}, \tag{4.9}$$

4.3 Conclusions

System flexibility has to be assessed to reserve enough capacity to deal with the mismatch between generation and demand. This chapter first explained the consequences of a lack of inertia in the system. The effects of decommissioning traditional plants to give way to new VRES plants will reduce the inertia in the power systems. As a consequence, the time in which flexibility has to act will decrease. To asses this minimum response time, an equation was derived, which can quantify the rate of change of the frequency when a fault occurs. This will give the minimum response time in which the flexibility has to be activated in order to avoid complications on the system. This same procedure was done to asses the minimum response time in future DC grids in which the capacitance of the system will act as the inertia of traditional AC systems.

5

Flexibility Optimization

This chapter gives mathematical formulation that optimizes the required flexibility and the origin of the same. Moreover, utilize this tool to analyze several case studies. Traditionally, optimization on power systems was aimed to solve with the lowest cost of electricity, considering fuels and technical constraints of generators and the systems itself. Nevertheless, the increasing concerns in environmental issues are driving new technologies to have more significant shares in the energy mix. As a consequence, mathematical formulations of optimization problems will change accordingly.

Conventional optimization problems use a day-ahead market clearing mechanism. There is a wide variety of market designs across Europe and the world [33]. To run these markets, unit commitment problems are developed to clear energy and reserves simultaneously. This problem results in the most economically efficient way to clear the day-ahead market. Furthermore, the unit commitment approach schedules the sources with the lowest cost while the technical constraints are satisfied at all times. The Transmission System Operators do this. Even though these optimization problems arrive at optimal solutions, they lack to integrate future challenges in scheduling reserves. These are, quantifying the actual needs for upwards and downwards flexibility and its reaction time. Currently, to establish the required reserve capacity, historical analysis are done. This will not be sufficient in the coming decades. Reserving flexibility becomes more complex as the requirements vary with the seasons, days and even hours. Higher uncertainty in generation will cause that previous historical analysis to become unable to keep a balance in the system in an economically feasible way. Overshooting the needs or reserves or under reserving might be an issue.

The new approach is used to deal with the uncertainty of VRES closer to real operation time. Furthermore, this approach neglects the unit-commitment problem, assuming this was already done one-day before operation by the TSO. The purpose of this research and especially this chapter is to provide with a new tool to schedule flexibility at a distribution level as explained in the market design Section 3.7. Moreover, the optimization problem reserves the required amount of flexibility for upwards and downwards regulation by reducing the cost at a systems perspective. This chapter presents an approach driven by the increase of non-dispatchable energy sources, that do not provide the system with inertia. From Chapter 3 it was concluded that a new type of reserve mechanism should be implemented due to the reduction in the inertia of the system, this means that the minimum response times of the flexibility decrease over time.

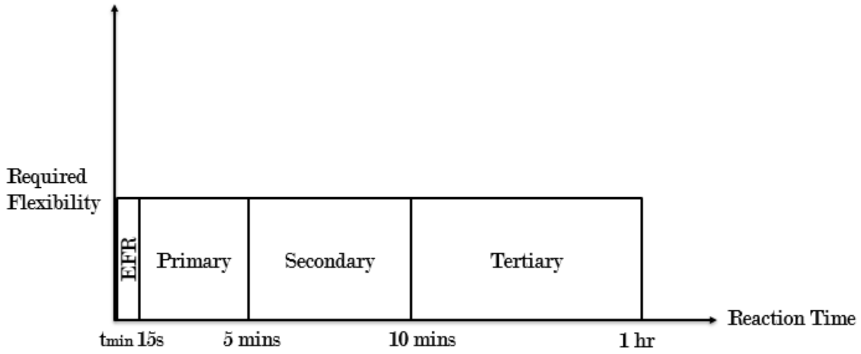


Figure 5.1: Types of flexibility reserves

Figure 5.1 shows the proposed types of flexibility reserves for this optimization problem. The enhanced frequency response (EFR), aims to compensate for the lack of inertia in the system and the increasing imbalances in the system caused by high volumes of VRES. It has a t_{min} of reaction time that is determined by the inertia or capacitance of the system and the installed capacity of VRES. The primary, secondary and tertiary reserves are slower reserves that are procured to regulate imbalances in the system. This paper chapter an LP formulation of the flexibility reserve problem is presented. The presented flexibility reserve problem is deterministic, and with inelastic demand, the stochastic nature of the problem is accounted for in the previous stage of optimization. The LP is implemented in GAMS and MATLAB R2017b, using the MATLAB-GAMS from [39]. The model is solved with CPLEX. Figure 5.2 is a flow chart of the steps that are taken to reach the optimal value.

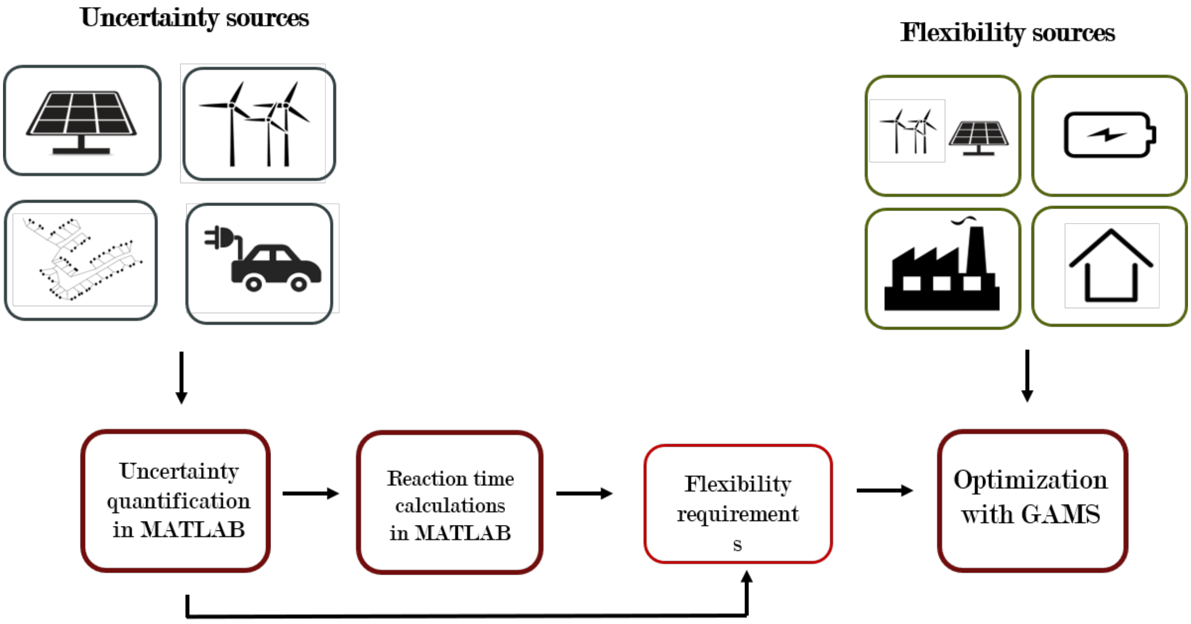


Figure 5.2: Description of the chosen methodology to optimize the flexibility in a distribution network

In Figure 5.2, the method that is followed throughout this research is explained. The uncertainty sources and inertial calculations are explained in Section 3.2. After the flexibility requirements are calculated from the previous steps, these values are implemented in the optimization problem. Moreover, the flexibility sources, i.e. VRES, storage systems, traditional units and demand response are modelled and incorporated in GAMS.

The following section describes the mathematical formulation of the flexibility problem. In Section 5.2, a case study is developed to demonstrate the effects of an increase in renewable energy in reserving flexibility. To conclude, Section 5.3 presents the results obtained from applying the optimization to different scenarios.

5.1 Mathematical formulation

In this section, a linear programming (LP) problem is presented for flexibility management in distribution systems.

5.1.1 Linear Programming

This LP problem aims to minimize the total flexibility operating costs and meet the overall demand considering the uncertainty of VRES, loads and electric vehicles over a period. The aforementioned solves this problem while taking into consideration the systems and units constraints.

To do so, an optimization problem that uses the available resources is developed. Optimization brings together a set of mathematical modelling techniques that allows answering problems of allocation or optimal planning of scarce resources. Furthermore, it supports the decision-making process in an efficient way. For example, optimization problems are done to find the minimum or maximum of a specific function, taking into consideration certain parameters or constraints that have to be satisfied. There are several types of optimization problems that can be classified depending on the nature of the variables, constraints and the function. They are classified as linear programming (LP), non-linear programming (NLP), mixed-integer linear programming (MILP), mixed-integer non-linear programming (MINLP), including others.

An LP formulation has been chosen to optimize the flexibility that deals with the uncertainty of the loads, VRES and electric vehicles existing in future power energy systems. Different mathematical formulations for these flexibility problems can be used. This results in different levels of complexity and feasibility. This type of programming is used due to the characteristics of the problem.

5.1.2 Objective function

This LP problem aims to minimize the total flexibility operating costs and meet the overall demand considering the uncertainty of VRES, loads and electric vehicles over a period. The aforementioned solves this problem while taking into consideration the systems and units constraints. The objective function is defined as follows.

$$min\Bigg(\sum_{j}\sum_{t}\sum_{z} E^{+}_{j,t,z}C^{+}_{j} + E^{-}_{j,t,z}C^{-}_{j}\Bigg) \tag{5.1}$$

where, $E^{+}_{j,t,z}$ is the total energy reserved in unit j for upward flexibility expressed in kWh, C^{+}_{j} is the cost of running unit j expressed in €/h, $E^{-}_{j,t,z}$ is the total energy reserved in unit j for downwards flexibility expressed in kWh, C^{-}_{j} is the cost that unit j incurs by decreasing it's generation or increasing their consumption expressed in €/h. Additionally, the sets $t \in T$ depicts the number of time steps, running from 1 to t, $j \in J$ the number of flexibility sources running from 1 to J and $z \in Z$ the type of flexibility, i.e. EFR, primary, secondary or tertiary.

5.1.3 System reserve constraints

The provision of the system's flexibility is guaranteed by the following constraints. They ensure that at every moment, t, there is enough reserve capacity with the corresponding response times that are required. These reserves are then able to account for the needs of upward and downward flexibility.

Upwards flexibility

In case of a deficit of energy in the system, the transmission system operator compensates the deficit by activating bids for upward regulation on the regulating power market. As a consequence, the player increases his production or reduce his consumption and sell the equivalent volume to the system operator [6].

$$\sum_j P^+_{j,t,z} \geq P^{\sigma+}_t \qquad \forall j,t,z \tag{5.2}$$

where $P^+_{j,t,z}$ is a variable that expresses the required upwards flexibility form unit j at time t and with a minimum reaction time of z expressed in seconds and $P^\sigma+_t$ is the required upwards flexibility at period t also in kW. The upwards flexibility comes from sources that can increase their generation or decrease their consumption.i

To define $P^+_{j,t,z}$ two conditional equations are described as follows

$$P^+_{j,t,z} \leq \begin{cases} 0, & \text{if } R_j > r_z \qquad \forall j,t,z \\ P^{max}_j, & \text{if } R_j < r_z \qquad \forall j,t,z \end{cases} \tag{5.3}$$

$$P^+_{j,t,z} \geq 0 \qquad \forall j,t,z \tag{5.4}$$

where R_j is the minimum response times of unit j and $r_(z)$ is the minimum required response time of the flexibility z. These conditional equations describe how the flexibility is reserved in the different flexibility types described in Figure 5.1. These two conditional statements describe the following behaviours of the optimization problem:

- If the minimum reaction time of unit j is bigger than the reaction time required by the type of reserve z, then no capacity can be reserved.
- on the contrary, if the minimum reaction time of unit j is smaller than the reaction time required by the type of reserve z, then this unit can provide flexibility up to its P^+_{max}.

Downwards flexibility

In the case of surplus energy, the system operator neutralizes the surplus by activating bids for downward regulation on the regulating power market. As a consequence, the player reduces his production or increase his consumption and buy the equivalent volume from the transmission system operator [6]. The formulation of the downwards flexibility follows the same logic as the upwards flexibility.

$$\sum_j P^-_{j,t,z} \geq P^{\sigma-}_t \qquad \forall j,t,z \tag{5.5}$$

where $P^-_{j,t,z}$ is a variable that expresses the required downwards flexibility form unit j at time period t and with a minimum response time of z expressed in kW and $P^{\sigma-}_t$ is the required flexibility at period t also in kW.

To define $P^+_{j,t,z}$ two conditional equations are described as follows

$$P^-_{j,t,z} \leq \begin{cases} 0, & \text{if } R_j > r_z \qquad \forall j,t,z \\ P^{max}_j, & \text{if } R_j < r_z \qquad \forall j,t,z \end{cases} \tag{5.6}$$

$$P^-_{j,t,z} \geq 0 \qquad \forall j,t,z \tag{5.7}$$

5.1.4 Energy constraint

As reserves can contain a finite amount of energy, this has to be considered by the provider of flexibility when scheduling. Electrical storage systems are mostly affected by this as their ability to store energy is limited. Generators such as gas or coal plants are considered to be infinite due to their operation in which only more fuel has to be burned, which is assumed to be enough to cover the uncertainty. Although it is said that the fuel they have is enough to provide flexibility for as much as they want, it is also known that their minimum response time is slower than other types of flexibility. Demand response programs are normally set to have a maximum amount of time that the load can be shifted, reduced or increased. These programs are defined by contracts between aggregators or big industrial loads and system operators.

Upwards regulation energy constraint

The various types of flexibility sources behave differently when providing upwards regulation. The dynamics that govern upwards regulation of a generator show differences with others like demand response. In this case, conventional generators can provide up to their maximum output of power, whereas demand response can only provide it for a certain time.

$$\sum_t \sum_z E^+_{j,t,z} \leq E_j \qquad \forall j, t, z \tag{5.8}$$

where $E^+_{j,t,z}$ is the upwards regulating energy that unit j is providing at time period t expressed in kWh and E^+_j is the total upwards regulating energy that unit j is able to provide in one day. $E^+_{j,t,z}$ is given by

$$E^+_{j,t,z} = \Delta t_z \cdot P^+_{j,t,z} \qquad \forall j, t, z \tag{5.9}$$

where δt_z is the duration of the type of flexibility z.

Downwards regulation energy constraint

$$\sum_t \sum_z E^-_{j,t,z} \leq E_j \qquad \forall j, t, z \tag{5.10}$$

where $E^-_{j,t,z}$ is the downwards regulating energy that unit j is providing at time period t expressed in kWh and E^-_j is the total downwards regulating energy that unit j is able to provide in one day. $E^-_{j,t,z}$ is given by

$$E^-_{j,t,z} = \Delta t_z \cdot P^-_{j,t,z} \qquad \forall j, t, z \tag{5.11}$$

Battery energy

To model a storage system, in this case, a battery, the energy over time is stored into state variables. Moreover, the energy in the battery is constrained by the capacity, the discharge and charge rate.

$$E^b_t = E^b_{t-1} + \eta_c P^{b+}_{t,z} \Delta t_z - \frac{1}{\eta_d} P^{b-}_{t,z} \Delta t_z \qquad \forall t, z \tag{5.12}$$

where E^b_t is the energy in the battery at time t, η_c is the charging efficiency and η_d the discharging efficiency. The battery model is also constrained by the following

$$P^{b+}_{t,z} \leq P^{b+}_{max} \qquad \forall t, z \tag{5.13}$$

$$P^{b-}_{t,z} \leq P^{b-}_{max} \qquad \forall t, z \tag{5.14}$$

5.2 Case study

The EU Energy Road-map 2050 and the Paris agreement in 2015 point towards a carbon-neutral economy in the next decades. This requires higher investments in renewable energy and a higher rate of penetration. This means that fast changes in the power system are coming up, and this research aims to tackle some of them. These would be assessing the changes in reaction times of flexibility; the increase in volume and cost of flexibility requirements a case study is presented in this section. To illustrate the changes in the penetration of renewable energy and EV adoption, three different years are taken into consideration. Data form ENTSO-e and TenneT.

In this section, the distribution grid under a substation in a neighbourhood is treated. The location of this distribution grid is in the Netherlands. It has 55 households, photovoltaic systems and electric vehicles. Figure 5.3 illustrates the 55 household system under which the case study will be analyzed.

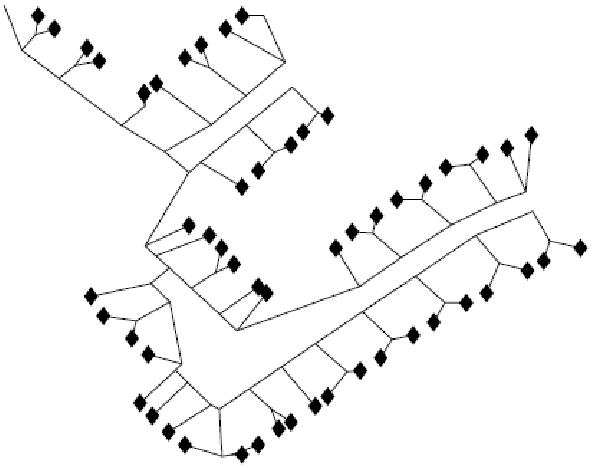


Figure 5.3: IEEE European Low Voltage Test Feeder household loads [19]

Furthermore, it is assumed that there is a percentage of PV installed energy, electric vehicles and wind energy that will be increased according to the ENTSO-e EUCO30 scenario and the TenneT Infrastructure outlook 2050. Firstly, the input data will be described i.e. the relevant information presented by Entso-e and Tennet presented in [29] and [38] respectively. Subsequently, the photovoltaic production, wind production, household load consumption and electric vehicles are described.

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5.2.1 2019

To gain insight into how future flexibility reserves should be planned, flexibility optimization is applied in a current scenario. For this scenario, the distribution grid is investigated without the presence of any new flexibility sources, i.e. storage systems or flexible loads. Considering that the system in 2019 counts with traditional means of flexibility, which are conventional generators and curtailment of renewable energy. The latter is tried to be avoided, to do so, the price of curtailment is set higher than the cost of procuring traditional reserves. Furthermore, 5 electric vehicles are assumed to be present to understand the effect of an increase in demand uncertainty.

To analyze the flexibility reserve planning, firstly the required reserves have to be calculated. In this case, the enhanced frequency response is not required. This is a result of the presence of rotating masses in the system and their ability to provide real inertia. Regardless of a connection through power converter to a DC grid, these generators are able to regulate the voltage of the grid throughout its own control. Therefore it is understood that there is no requirement for the newly introduced "fast flexibility". The upward regulation and downward regulation needs are evaluated for the specific amount of wind energy that is assumed provide energy for the system, the installed PV systems in the rooftops of the households, and the number of EVs.

5.2.2 EUCO2030 Scenario

The EUCO30 policy scenario was created as part of the European Commission's impact assessment work in 2016. The scenario models the achievement of the 2030 climate and energy targets as agreed by the European Council and includes an energy efficiency target of 30 The EUCO30 scenario describes a decarbonization scenario that is compatible with European goals and the Paris Agreements. From this scenario, the primary information is the estimated installed electricity capacity in the Netherlands per source.

5.2.3 Tennet Infrastructure Outlook 2050

This scenario outlines a design on an integrated energy system that is based on supply and demand requirements that are in line with the greenhouse gas emission reductions in the Paris Agreement. The goal of this study is to get an insight into the limitations of electricity and gas infrastructure of the Netherlands in 2050. Furthermore, this scenario has a strong aim for energy independence relying on centralized RES supply and decentralized supply of solar energy.

As outlined in the last section, the relevant data from this scenario is the estimated installed electricity capacity per source.

5.2.4 System parameters based on scenarios

Photovoltaic generation

To simulate the effect of PV generation, household PV systems are placed in the distribution grid. To simplify this modelling, only one type of module was chosen for simulation. Each household PV system has 10 modules installed. The selected PV panel has a peak production of 260 Watts. The number of houses with PV systems change throughout the years. Starting from 2019 with 6 households and finishing in 2050 with a 24% adoption rate (55 households).

	2019	**2030**	**2050**
No. of households with PV panels	5	7	13
Installed capacity [kWp]	7.8	10.4	17

Table 5.1: Increase in solar PV installed capacities

The power generated by the PV systems is calculated using the panel characteristics found in Appendix C and the external parameters that affect it. The weather conditions taken into consideration are the wind speed, solar irradiation and temperature. For the power production of PV panels, meteorological data for summer days in Nijmegen, the Netherlands is used. This data was obtained from Meteonorm. The data was obtained was retrieved in a 10-minute range and randomized to be adapted in the minute basis. This data is used in the fluid-dynamic model to obtain an accurate output from the solar modules.

The overall generation of PV throughout the years can be seen in Figure 5.4. For this output, it is assumed that the forecast is the same in each year. This figure illustrates the growth of PV generation going from 10 households to 55 households. This rate of increase in installed capacity follows the data given by the EUCO2030 and Tennet Infrastructure Outlook predictions.

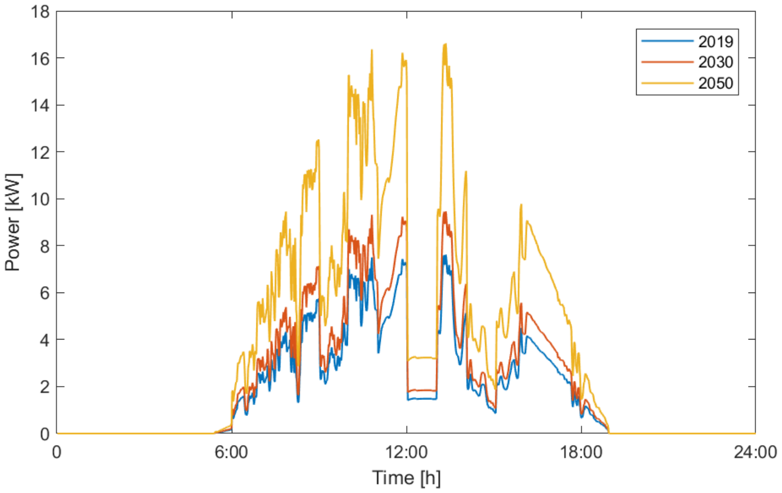

Figure 5.4: Increase in photovoltaic generation

Wind generation

To simulate the effect of wind generation, an onshore wind turbine is placed in the distribution grid. Having wind energy present in the system serves as an uncertainty source. It is assumed that only one wind turbine represents the share of the generation mix that comes from wind energy. Starting from 2019 where it can provide 7 kW to the system and finishing in 2050 with an increase of 120 % resulting in a penetration of 15.5 kW. This rate of increase in installed capacity follows the data given by the EUCO2030 and Tennet Infrastructure Outlook predictions. For wind production, the meteorological data used was the same that was used for the PV generation.

	2019	**2030**	**2050**
Maximum power provided by wind (kW)	7	11.5	15.5

Table 5.2: Increase in wind installed capacity

Figure 5.5 shows the generation profile of a wind turbine in different years, for this case, the same meteorological data but the turbine parameters were adjusted to represent a higher capacity throughout the years.

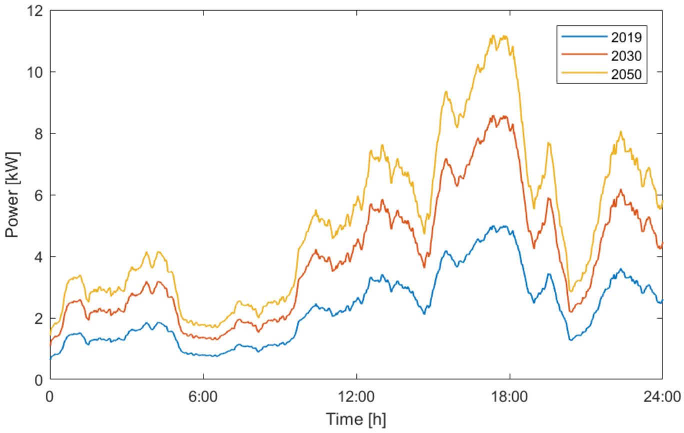

Figure 5.5: Increase in wind generation

Household load

The distribution grid includes 55 households. In this research, it is assumed that a load of a household cannot be forecasted. The data of the household consumption comes from the IEEE European Low Voltage Test Feeder used in [19]. This test feeder contains 100 representative household load profiles. For the simulations, the load values are considered by selecting one of the aforementioned load profiles. For the sake of simplicity, the load is assumed to remain constant throughout the years. The associate increases in load demand due to electrification are assumed to be created by the adoption of electric vehicles.

Figure 5.6 shows the aggregated load profile of 55 households selected from the IEEE European Low Voltage test feeder.

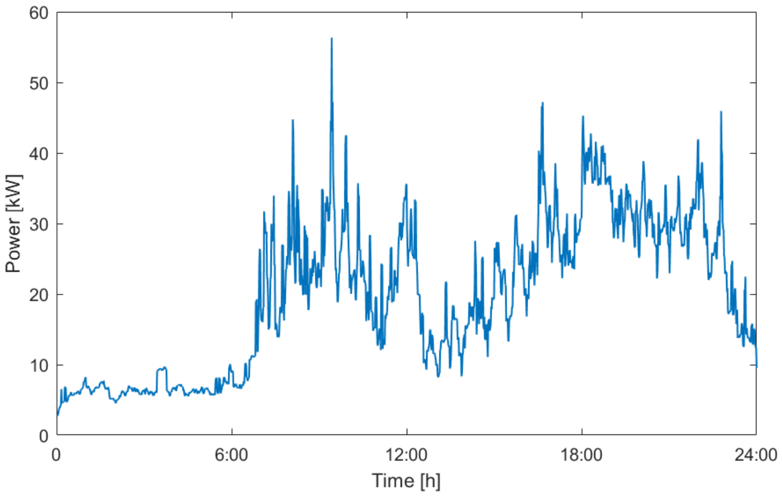

Figure 5.6: Expected power for the load profiles

Electric Vehicles

The electric vehicles are modelled in Section 3. To summarize, EVs are considered to have two different sources of uncertainty. Firstly, it is not known at which time of the day the car will start to charge. Secondly, it is uncertain for how long the EV is charging at the station. Figure 5.7 shows the expected load that takes into account the aforementioned probabilities. Furthermore, it shows the expected load in the three selected years for this case study. The adoption of electric vehicles is expected to grow in the coming decades [2]. It is assumed that in the distribution grid all the EV owners will have the option to charge their cars i.e. there is no constraint in charging points.

	2019	**2030**	**2050**
No. of EVs	2	15	25
Expected load [kW]	6	27	45.25

Table 5.3: Increase in EVs

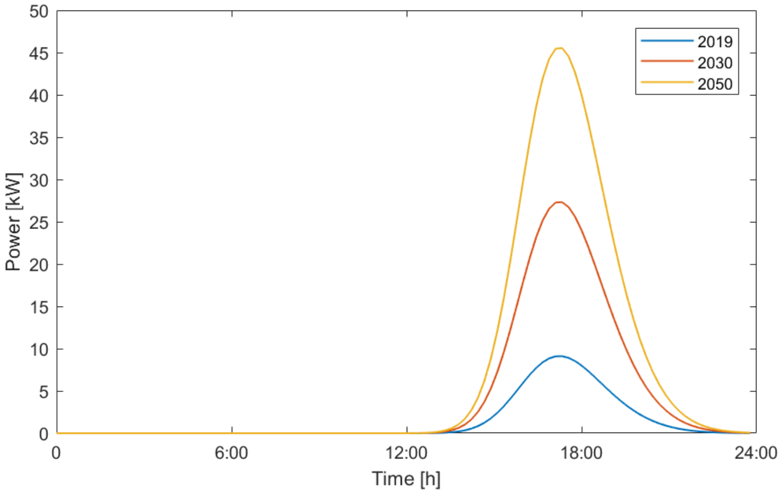

Figure 5.7: Expected load from electric vehicles

5.3 Simulation and optimization

In this section, the caste study, which was illustrated in the previous section, is analyzed. Firstly, the required amount of flexibility is obtained. Secondly, the reaction times are calculated. This calculation is done using the method proposed in Section 3.6. Thirdly, optimization in GAMS is implemented to obtain the value of the flexibility.

5.3.1 Required flexibility

To asses, the required reserves of upwards and downwards flexibility, the method proposed in Section 3.4 is followed. By using one hour ahead, forecast the flexibility of one day throughout the selected years is calculated. Figure 5.8 shows the amount of flexibility that has to be reserved to ensure that even with the forecasting errors, the system can operate reliably and securely.

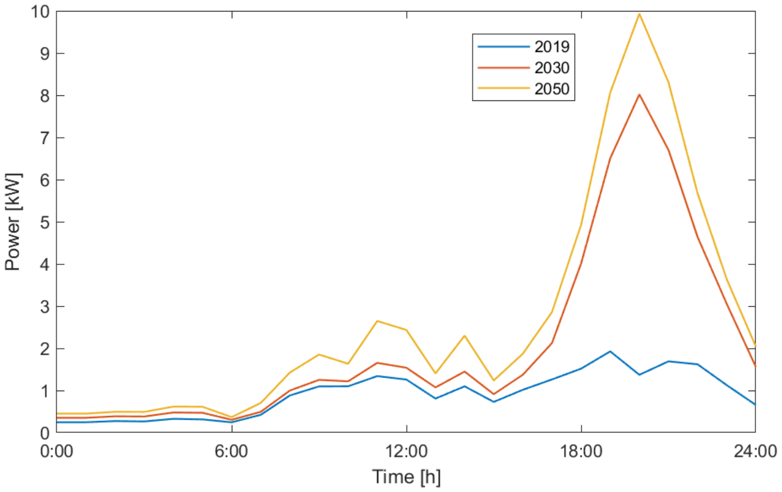

Figure 5.8: Increase of required flexibility

5.3.2 Reaction time

To analyze how the increase of integration of renewable affect the time response for flexibility, a case study was done. In this section, it is assumed that the distribution grid is a DC grid. Firstly, the installed capacities throughout the years following the scenarios from [29] and [37] are calculated. Secondly, using the models of a solar PV plant, a wind plant and electric vehicles are employed to obtain the required flexibility (see Chapter 3). Thirdly, using Equation 4.9 and a capacitance of 25 μF per installed kW of power converters, the total capacitance of the system is obtained. Lastly, the minimum response times required in a DC distribution grid can be estimated.

	2019	**2030**	**2050**
Solar plant [kWp]	7.8	10.4	17
Wind plant [kW]	6.72	11.648	15.68
Average load [kW]	19.8	19.8	19.8
Evs expected load [kW]	6	25	45.25
Evs [no. vehicles]	2	15	25
Evs [no. chargers]	2	15	25
EV Charger rated power [kW]	7.4	55.5	92.5
Conventional generator [kW]	60	60	60
Total VRES [kW]	13.944	20.608	31.36

Table 5.4: Installed capacities in a DC distribution grid from 2019 to 2050

Table 5.4 shows the installed capacities per technology and year, electric vehicles rate of adoption and increase in imbalances The capacitance increases throughout the years but the variability of wind and solar energy increases at a higher rate.

Figure 5.9 illustrates the increase of capacitance and imbalances for a given day in different years. Even though the capacitance will increase with the number of converter coupled units, this will not suffice to maintain an high minimum reaction time.

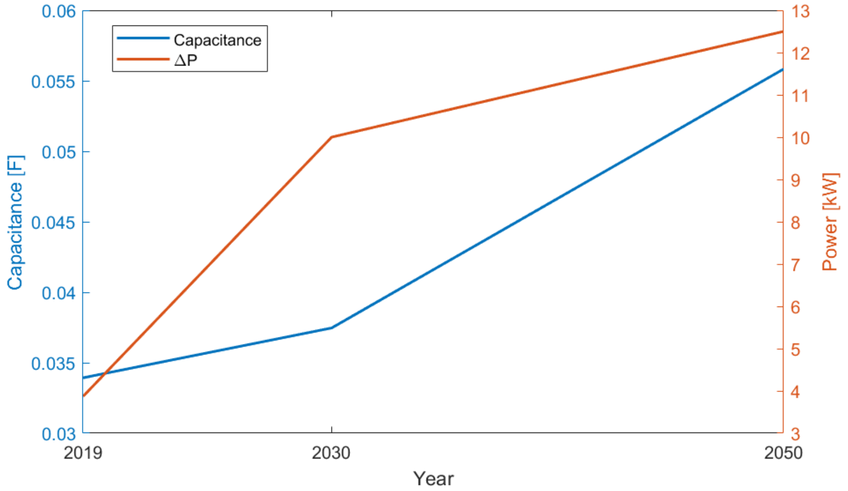

Figure 5.9: Capacitance and imbalance increase

Figure 5.10 shows how the increase of installed capacity of VRES reduces the minimum response time required to avoid a 5V variation in the system. A Δu_o of 5V was selected due to common practices.

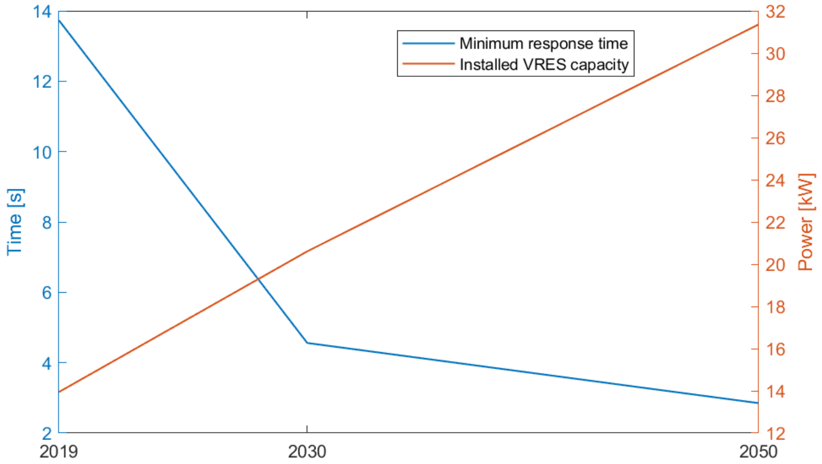

Figure 5.10: Minimum response time and VRES installed capacity

5.4 Optimization results

In this section, the previously illustrated case study is analyzed. Firstly, the optimization framework described in Figure 5.2 is applied to the current year. Secondly, using data from EUCO2030, the year 2030 is analyzed. Thirdly, the optimization framework is applied to the future power system in 2050 based on [38]. Lastly, a comparison is made between the three years to illustrate the changes in reserve planning and the integration of new flexible technologies in a distribution grid.

5.4.1 Current scenario

To gain insights into how current flexibility reserves are planned, flexibility optimization is applied to the current scenario of 2019. For this scenario, the distribution grid is investigated without the presence of any new flexibility sources, i.e. storage systems or flexible loads. Considering that the system in 2019 functions with traditional means of flexibility, which is achieved by conventional generators and curtailment of renewable energy. The latter is to be avoided and to do so, the price of curtailment is set higher than the cost of procuring traditional reserves. Furthermore, 5 electric vehicles are assumed to be present to understand the effect of an increase in demand uncertainty.

For this scenario, a time interval of one day is chosen, and it is established that the 5 electric vehicles are completely charged every day. Furthermore, the data used to create the generation profiles for wind and solar energy are from a summer day. This is done with the purpose of adding more uncertainty from the PV systems. Tables 5.5 and 5.6 show the available units that can provide upwards and downwards flexibility. These tables are used as inputs to the optimization problem discussed. In the case of curtailment of energy, it is assumed that wind turbines operate at their maximum operational output and can decrease their generation if needed.

Upwards regulation				
Unit	**Pmax [kW]**	**Cost [euro/kwh]**	**Reaction time [s]**	**Total energy [kw-day]**
Conventional	100	0.035	15	2400
Wind curtailment	0	NA	NA	0

Table 5.5: Units able to provide upward regulation in 2019

Downwards regulation				
Unit data	**Pmax [kW]**	**Cost [euro/kwh]**	**Response time [s]**	**Total energy [kw-day]**
Conventional	100	0.035	15	2400
Wind curtailment	0.3	0.095	0.1	7.2

Table 5.6: Units able to provide upward regulation in 2019

To analyze the flexibility reserve planning, firstly the required reserves have to be calculated. In this case, the enhanced frequency response is not required because of the presence of rotating masses in the system and their ability to provide real inertia. Regardless of a connection through power converter to a DC grid, these generators can regulate the voltage of the grid throughout its control. Therefore it is understood that there is no requirement for the newly introduced "fast flexibility". The upward regulation and downward regulation needs are calculated for the specific amount of wind energy that is assumed to provide energy for the system, the installed PV systems in the rooftops of the households, and the number of EVs. Secondly, the required flexibility is used as an input for the optimization algorithm. This is carried out in GAMS software using CPLEX, as it is a linear programming solver. AS seen in the optimization methodology discussed above in Figure 5.2, on implementing the algorithm, the optimal allocation of reserves at different time intervals are obtained. The results of this allocation, based on the required flexibility shown in Figure 5.11, are described in Figure 5.12.

The average required flexibility per hour can be seen in Figure 5.11. These values represent the flexibility in one direction, i.e. upwards or downwards. As explained in Section 3.3, a ±4σ confidence interval was selected. Resulting in the same required flexibility for upwards and downwards regulation. For simplicity, Figure 5.11 shows the required reserves with a $+4\sigma$ confidence interval. The flexibility requirements are divided into primary, secondary and tertiary reserves, which are the same in power requirements. Nevertheless, the response times and duration of dispatch are different for each reserve type.

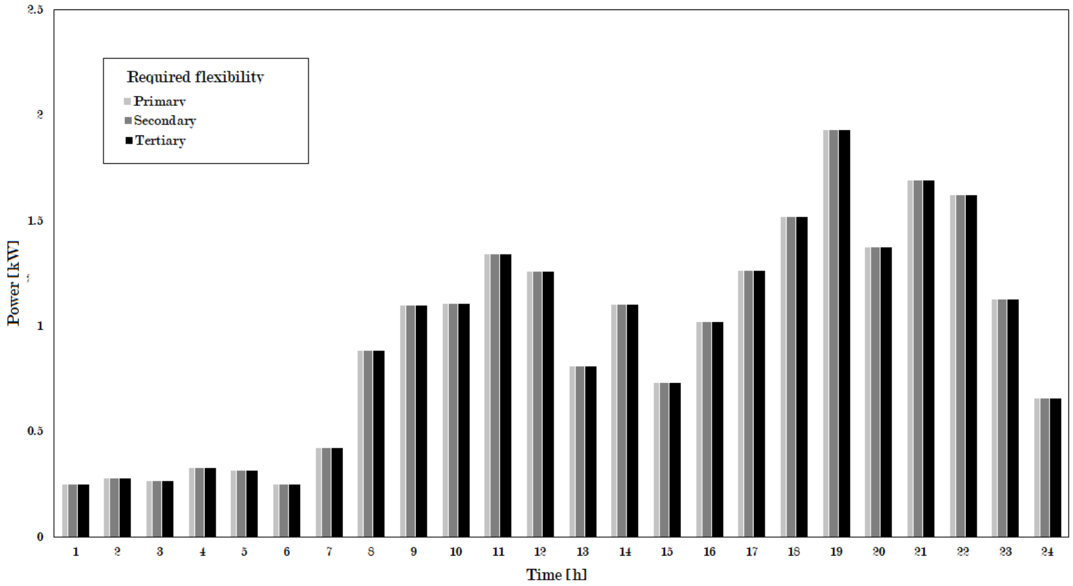

Figure 5.11: Required upwards and downwards flexibility 2019

After the optimization is carried out on GAMS, the results are shown in Figure 5.12. Taking into consideration the input parameters from Table 5.5 and Table 5.6 it is seen that the conventional generator provides all of the flexibility requirement throughout the day. One important factor that determines that curtailment is not an option is its cost. Currently, cost of wind curtailment can reach 95 $euro/MW$ [21]. This reflects how current operations are carried out, where conventional rotating generation units are currently providing the majority of the flexibility in the system. Because of the minimum required reaction times and the cheap marginal costs of increasing or decreasing a generator output, conventional units prove to be the first choice.

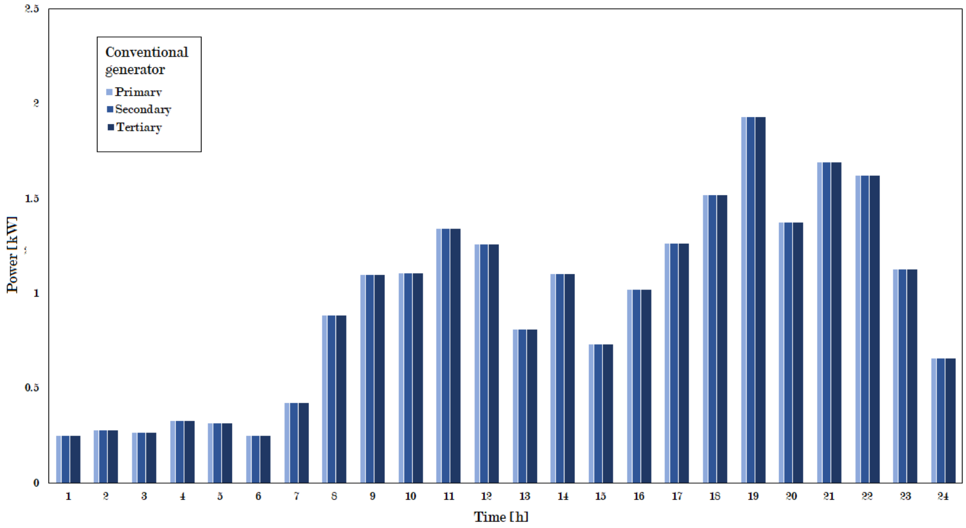

Figure 5.12: Allocated upwards and downwards flexibility 2019

Figure 5.13 shows the costs of procuring the required flexibility reserves. In this scenario, only the conventional generator is providing flexibility. Thus the cost of upwards and downwards regulation is taken from the generator's data. It is assumed that the upwards regulation and downwards price is not the same for a traditional generator because one requires an extra input of fuel.

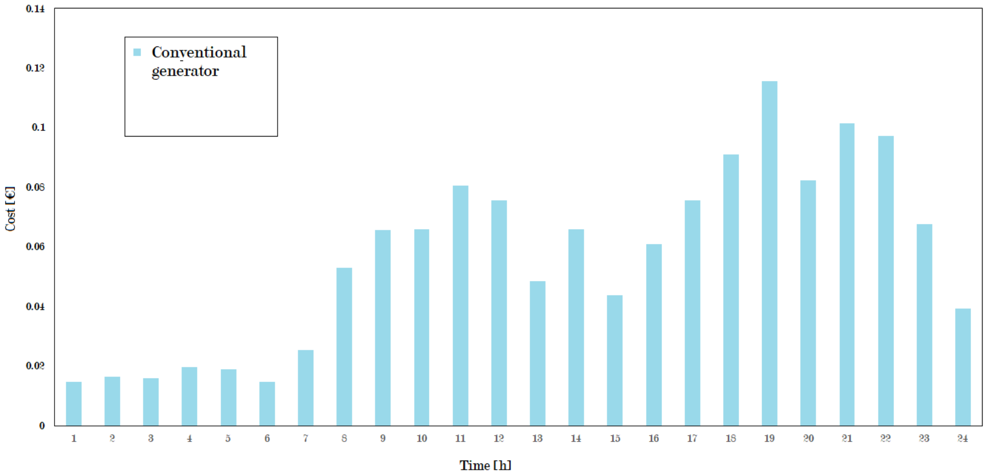

Figure 5.13: Cost for upwards and downwards flexibility per source in 2019 scenario

5.4.2 EUCO2030 Scenario

Future flexibility planning requires more flexibility sources due to the increased uncertainty. Furthermore, the decrease in the system's inertia results on minimum reaction times of flexibility as seen on Figure 5.10. For this scenario, the same distribution grid is investigated, however now with an increase in a number of electric vehicles, and solar and wind energy. In addition to that, flexible demand is now set into place. This flexible demand is assumed to be dependent on the load. A 20% reduction of the load can be expected during peak demand hours. This reduction follows the logic that consumers will be more willing to decrease their power consumption during peak times when the electricity prices are higher. Resulting in a bigger benefit for those households who engage in a demand response program. In this scenario, it is assumed that all of the households are aggregated as one and used as a flexibility source.

Due to the reduction of required reaction times, faster flexibility is required, this can be the case of flexible demand, which can be able to respond in 3 seconds. To achieve this, communication infrastructure has to be set in place. Another source of fast flexibility is batteries. As explained in Chapter 2, ESS such as batteries can provide fast flexibility (reaction time of milliseconds) and other ancillary services to the grid. For this distribution grid, it is assumed that capacity equivalent to 2 Tesla Powerwalls is installed, to provide the enhanced frequency response as explained in Figure 5.1.

Tables 5.7 and 5.8 show the available units that can provide upwards and downwards flexibility. These tables are used as inputs to the optimization problem discussed. In the case of curtailment of energy, it is assumed that wind turbines operate at their maximum operational output and can decrease their generation if needed. Furthermore, the flexible demand can decrease their consumption on a 20% of the load at a time t.

Upwards regulation				
Unit	**Pmax [kW]**	**Cost [euro/kwh]**	**Response time [s]**	**Total energy [kw-day]**
Battery	14	0.040	0.1	27
Demand response	20% of the load at peak times	0.025	3	$\sum_{t=11}^{t=17}\sum_z P^L_{t,z}$
Conventional	40	0.035	15	960
Wind curtailment	0	NA	NA	0

Table 5.7: Upwards regulation parameters 2030

Downwards regulation				
Unit data	**Pmax [kW]**	**Cost [euro/kwh]**	**Response time [s]**	**Total energy [kw-day]**
Battery	14	0.040	0.1	27
Conventional	40	0.035	15	960
Wind curtailment	10% of the generation at time t	0.095	0.1	$\sum_t\sum_z P^w_{t,z}$

Table 5.8: Downwards regulation parameters 2030

After the optimization is carried out, the results are presented in Figures 5.14, 5.15 and 5.17. The first figure shows the calculated required flexibility for a $+4\sigma$ confidence interval. In this case, similar to the previous case, the magnitude of upwards and downwards required flexibility is the same. Nonetheless, the parameters for optimization of flexibility reserves are different in 2030 because of the addition of flexible demand and an energy storage system. As a result, Figure 5.15 shows the allocated flexibility for upwards regulation and Figure 5.17 shows the one allocated for downwards regulation.

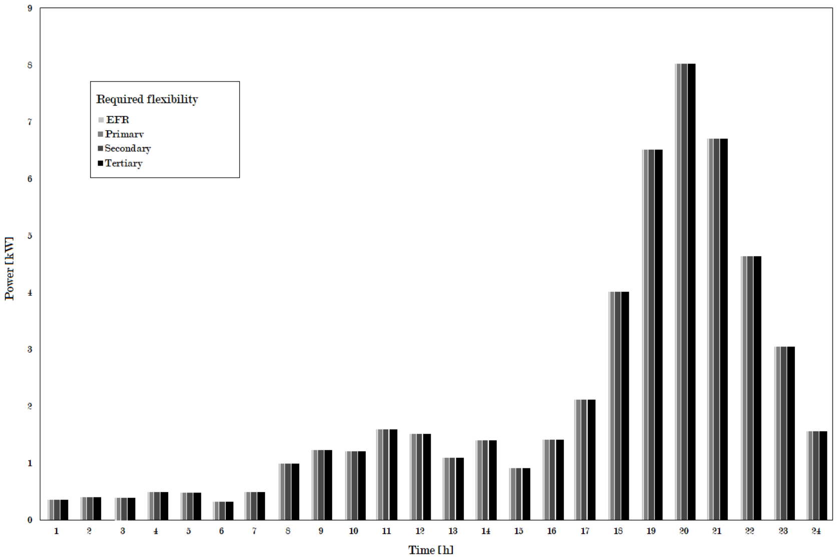

Figure 5.14: Required upwards and downwards flexibility 2030

The following figure shows the allocation carried out for the upwards regulation requirements. It is seen that due to the reduction in minimum reaction time, the conventional generator is not able to offer the enhanced frequency response. To procure it, the optimization allocates the fastest flexibility source, which is the energy storage system. When the flexible load is able to reduce its consumption, i.e. from 11.00 hrs to 17.00 hrs, all of the reserves are allocated to the load.

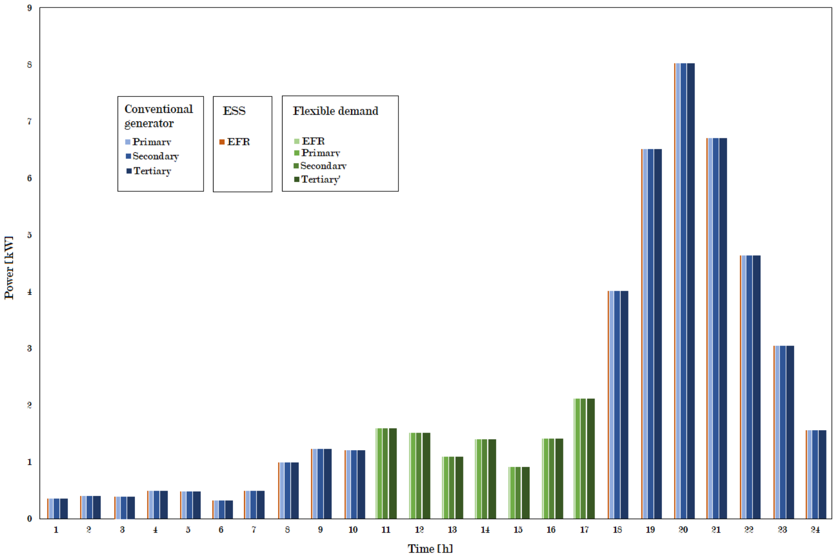

Figure 5.15: Allocated upwards flexibility 2030

The cost of reserving flexibility in the 2030 scenario is illustrated in Figure 5.16. In this case, the cost per source is stacked together in each time period. There is no distinction in between

EFR, primary, secondary and tertiary reserves, only the total cost that each flexibility source incurs. It is observed that procuring EFR only accounts for a small fraction of the total costs; this is due to the short amount of time it is needed.

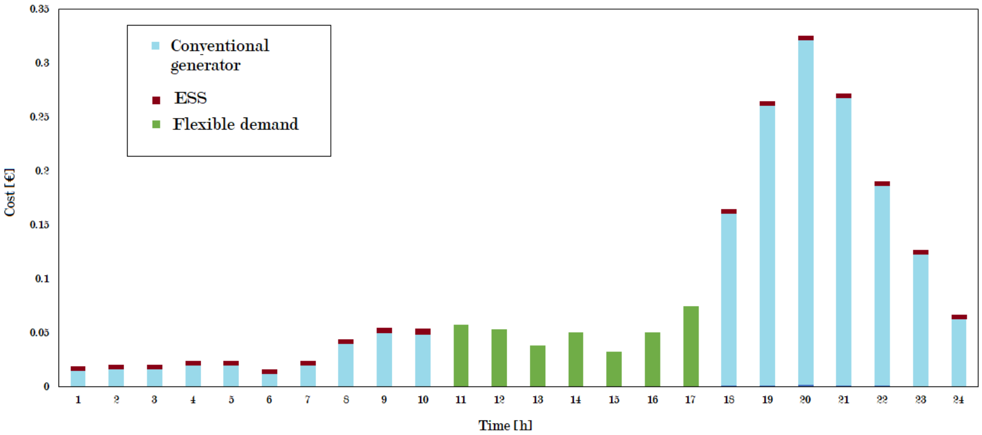

Figure 5.16: Cost of upwards flexibility per source in 2030 scenario

For downwards regulation, the optimization allocates all of the primary, secondary and tertiary reserves to the conventional generator. The same as in the upwards regulation the ESS is required to provide the EFR. Due to the inability of the demand to increase its consumption in this scenario, there is no flexibility provided by other sources. It is interesting to note that new advances will enable the demand to provide higher levels of downwards flexibility. Furthermore, 5.18 shows the costs of procuring the aforementioned flexibility.

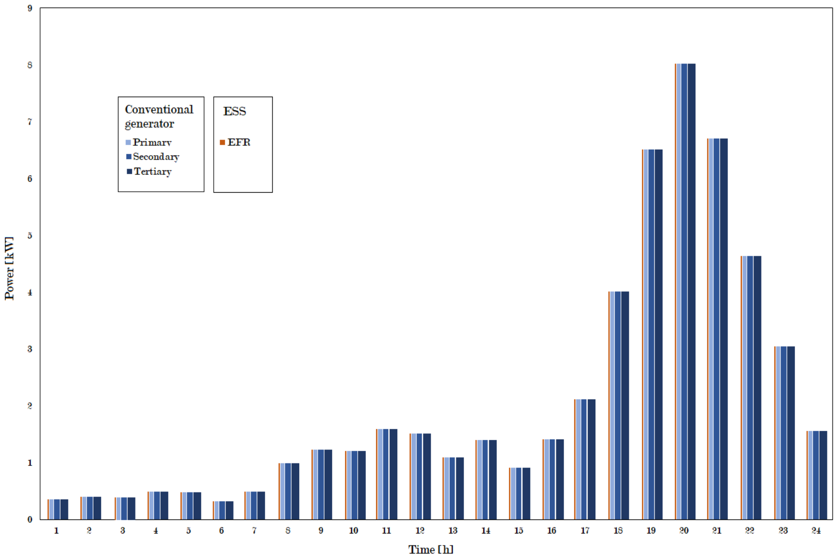

Figure 5.17: Allocated downwards flexibility 2030

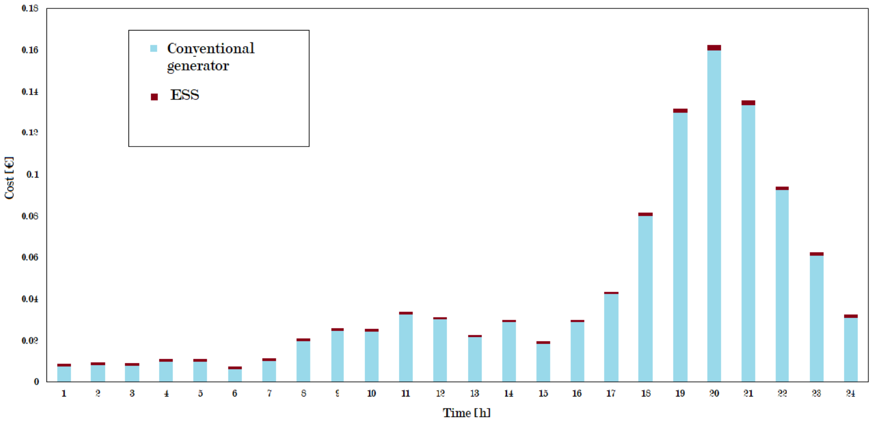

Figure 5.18: Cost of downwards flexibility per source in 2030 scenario

5.4.3 2050

The increase of installed VRES showed in 4.1 will have its consequences in the distant future. The increased variability in the system, added to the electrification of loads will have to be accounted for, when reserving distributed flexibility. For the 2050 scenario outlined by Tennet in its energy infrastructure, the required flexibility is calculated. In relation to the past scenarios, this one integrates a higher amount of renewable energy and most importantly describes a system in which the minimum reaction time of flexibility reduces even more. Regarding the flexible load, the amount this can be reduced by is assumed to be 40%. This number is taken from [14] which describes the theoretical maximum potential for load reduction in European countries, more specifically for Dutch households. While it is true that achieving this percentage of load decrease can seem impractical right now, future advances in house automation and control might allow achieving this number. Same as in the 2030 scenario, it is assumed that the load will be part of a program that provides flexibility during peak hours, i.e. from 11.00 hrs to 17.00 hrs. The curtailment of renewable energy is tried to be avoided due to its social importance. Nevertheless, its fast reaction times become useful when its necessary to provide the enhanced frequency response in times when the flexible load is not able to do so. Tables 5.9 and 5.10 show the input parameters for upwards and downwards regulation selected for this scenario. 5.1.

Upwards regulation				
Unit data	**Pmax [kW]**	**Cost [euro/kwh]**	**Response time [s]**	**Total energy [kw-day]**
Battery	14	0.040	0.1	27
Demand response	40% of the load at peak times	0.025	3	$\sum_{t=11}^{t=17} \sum_z P^L_{t,z}$
Conventional	40	0.035	15	960

Table 5.9: Upwards regulation parameters 2050

Downwards regulation				
Unit data	**Pmax [kW]**	**Cost [euro/kwh]**	**Response time [s]**	**Total energy [kw-day]**
Battery	14	0.040	0.1	27
Conventional	40	0.035	15	960
Wind curtailment	10% of generation at time t	0.095	0.1	$\sum_t \sum_z P^w_{t,z}$

Table 5.10: Downwards regulation parameters 2050

After the simulation for the 2050 scenario is done, the results are presented in Figures 5.19, 5.20 and 5.22. Following the same methodology as the past scenarios. The first figure shows the required flexibility in one day. Compared to the required flexibility in 2019, and 2030, it is seen that in increases in the hours where the electric vehicles would be charging if they follow the probability distributions described in Section 3.3.1.

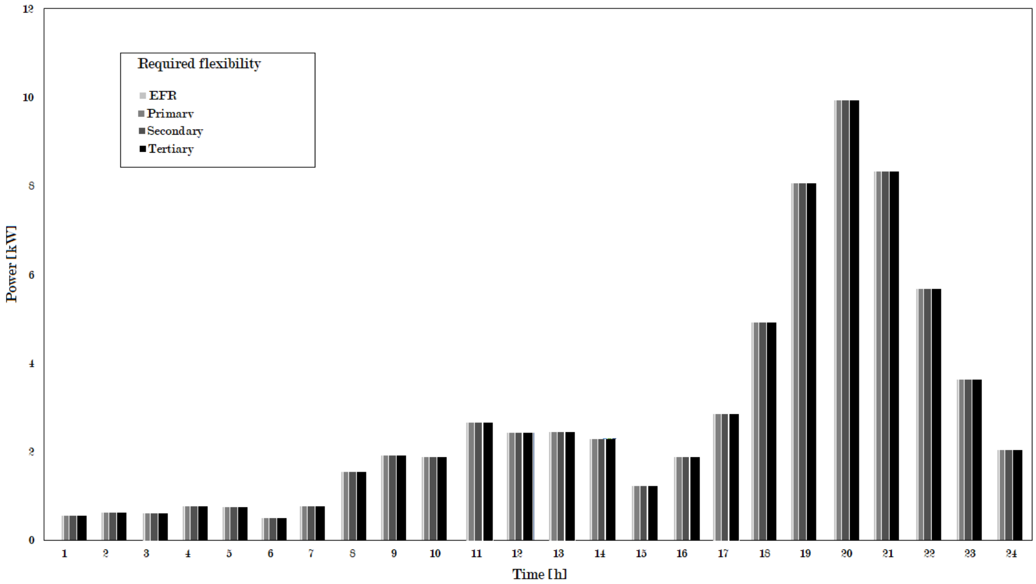

Figure 5.19: Required upwards and downwards flexibility 2050

The upwards flexibility reserves are mainly provided by the conventional generator, which can procure primary, secondary and tertiary reserves due to its reaction time. As in the case of the 2030 scenario, the flexible demand in 2050 scenario is not able to provide the EFR. Due to the assumptions taken in this scenario, the load's flexibility does not meet the reaction time requirements. Instead, the EFR is provided by the ESS.

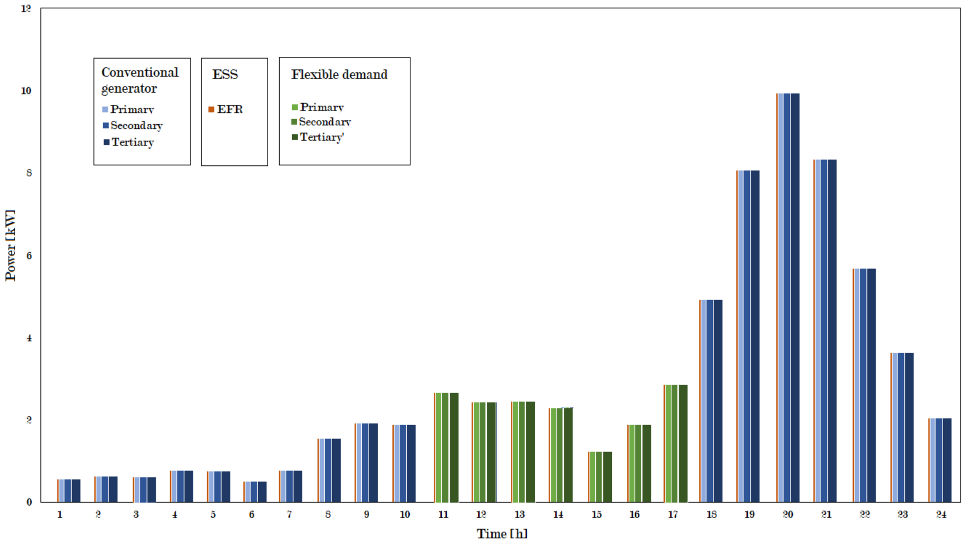

Figure 5.20: Allocated upwards flexibility 2050

In the 2050 scenario, the required EFR is higher compared with the previous scenarios. As a consequence, the costs are more elevated. Figure 5.21 illustrates the share of costs for procuring upwards regulation in 2050.

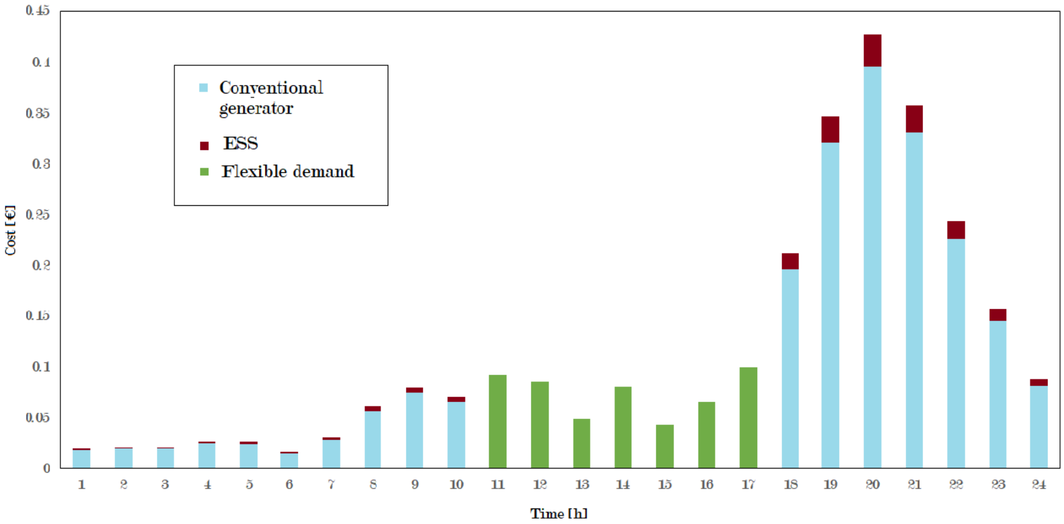

Figure 5.21: Cost of upwards flexibility per source in 2050 scenario

As a consequence of the energy used by the ESS to provide upwards flexibility and its constraints showed in the mathematical formulation of the optimization problem, there is a need for more EFR in the system. This EFR is now provided by both the ESS and curtailment of wind energy. This share of EFR varies in time due to the change in wind output and the 10% maximum allowed wind curtailment. Moreover, Figure 5.23 shows the stacked costs for reserving downwards flexibility. It is shown that wind curtailment is now incurring in costs, which are still small compared to the rest of the flexibility options. Nevertheless, as explained in Section 2.4, curtailment should be avoided due to social reasons.

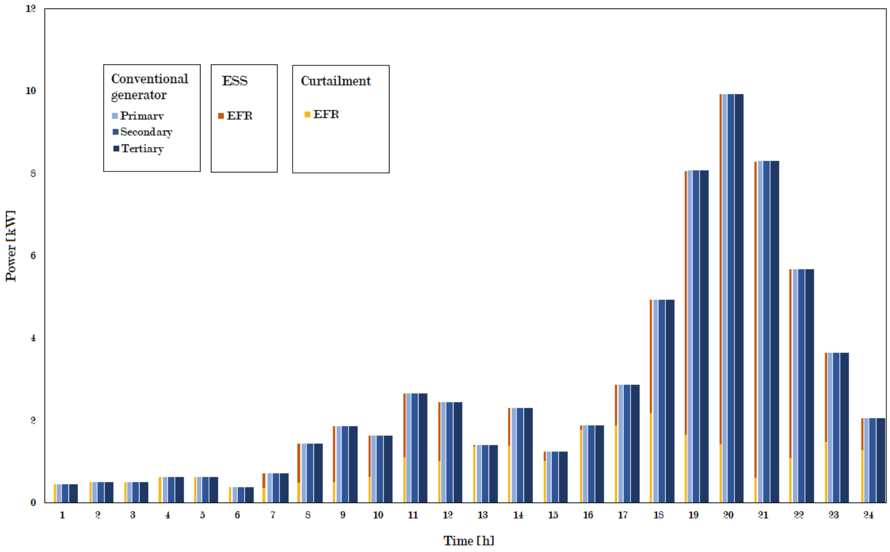

Figure 5.22: Allocated downwards flexibility 2050

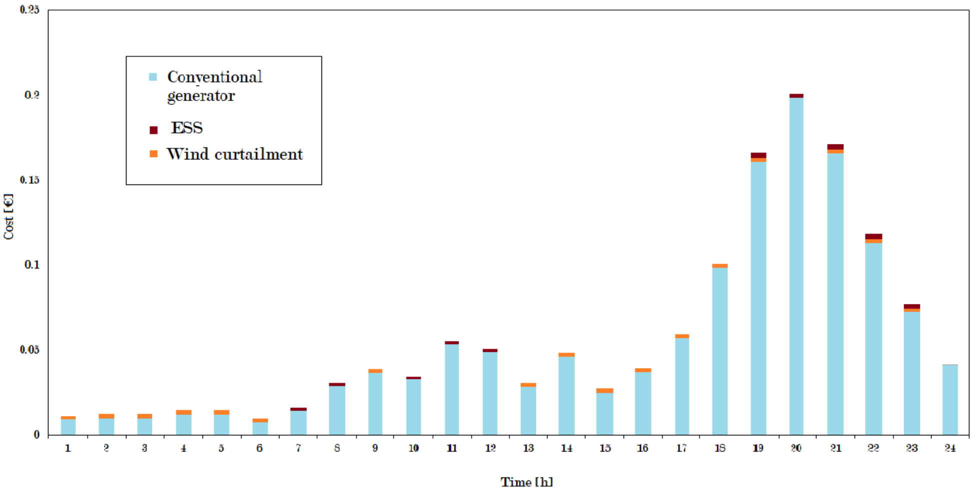

Figure 5.23: Cost of downwards flexibility per source in 2050 scenario

5.4.4 Decrease time step

In the previous sections, the allocation of flexibility was done in 24-time steps, meaning that the flexibility is chosen for each hour of the day. In this subsection, the previous steps to calculate the required flexibility and its allocation is done for 15 minutes time steps to show how reducing the time steps affect the flexibility requirements. To illustrate this, the year 2050 was taken as an example, the processes was done for 24 and 96 time steps accordingly. Figure 5.24 shows how the classification of flexibility changes.

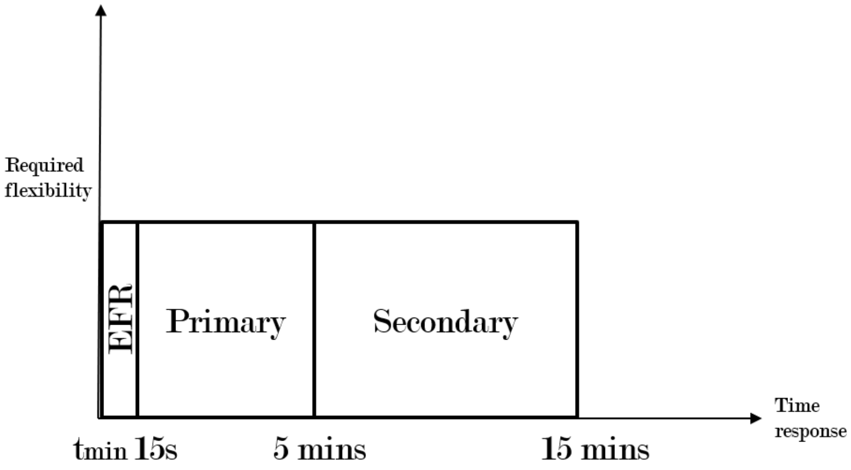

Figure 5.24: Flexibility reserves classification for 15 minutes steps

Once the optimization is run for this case the results in the optimal allocation for flexibility is seen on Figure 5.25.

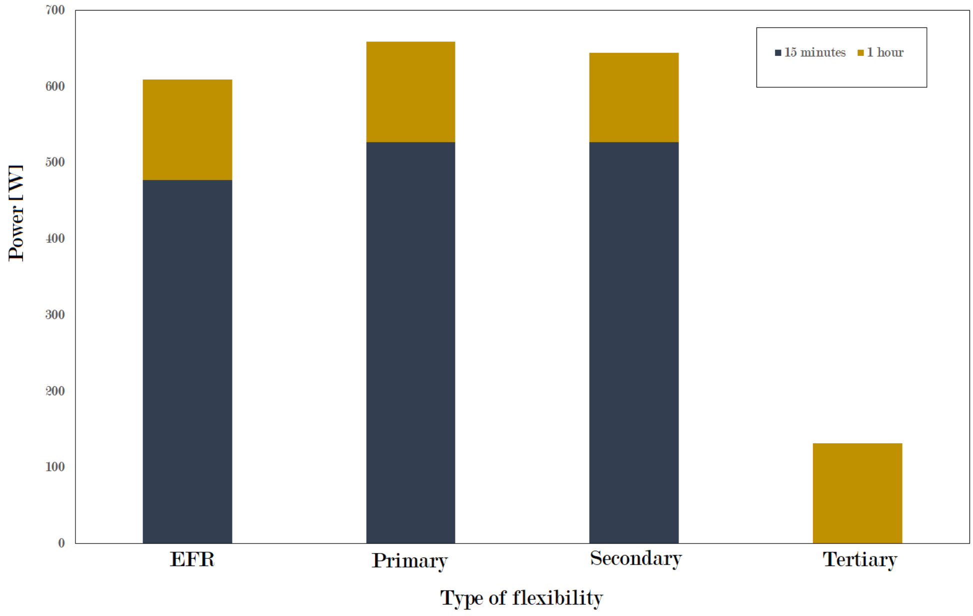

Figure 5.25: Allocated flexibility per type of reserve

In this image it is observed that the amount of allocated flexibility using 15 minutes time steps increases compared to a one hour step. Table 5.11 shows that the costs of allocating the flexibility in these two different steps is almost the same.

Table 5.11: Flexibility costs for one hour and 15 minutes time steps.

	Flexibility cost (euros)
2050 with one hour time steps	3.66
2050 with 15 minutes time steps	3.67

This is explained because the cost of flexibility is being done by calculating the reserved energy, not the reserved capacity. This will mean that systems will reserve the capacity from the same units more times throughout the day, this can increase economic benefits for the overall system because different units can now provide flexibility for shorter times instead of reserving an amount of capacity for an extended time.

5.5 Conclusions

This chapter aimed to develop a mathematical formulation that allocates the different sources of flexibility in different reserves types. These reserves types are defined as primary, secondary, tertiary and enhanced frequency response. The latter aims to account for the lack of inertia in the system and its result of quicker required reaction times of flexibility.

In order to achieve this, the problem was mathematically formulated so it would take into account the different characteristics of the flexibility sources. These were modelled to illustrate how the reaction times will affect the allocation of flexibility in future power systems. A system is described in order to test the optimization. This system contains a distribution grid, solar PV systems, wind energy, electric vehicles and household loads.

A case study was proposed in order to demonstrate the effects of an increased amount of VRES and electric vehicles. Three different years were chosen to depict this effect, 2019, 2030 and

2050. The last two years were modelled using data from [29] and [38]. These two entities forecast the installed renewable capacity in those years, and with that information, the optimization was carried out. By using GAMS software and the CPLEX solver for linear programming, the results are shown for each year. As the years go by, it is seen that reserving the required flexibility gets more complex and different sources of flexibility are required to ensure proper system operation. Furthermore, two operations are proposed, one with a one hour time steps, and then this is decreased to 15 minutes time steps. This reflects on how the system reserves the capacity and bring more competition. Moreover, reducing the time steps can result in a more stable system since in that case, the reserved amount of EFR will be able to cover more power imbalances closer to real-time operation.

6

Conclusions and recommendations

This final chapter provides the conclusions of this research, as well as some recommendations for future work. The objective was to understand the role of flexibility in future power systems with high penetration of renewable energy. To address the conclusions clearly, the research questions proposed at the beginning of this paper are answered.

6.1 Conclusions

What are the available types of flexibility?

It is necessary to know what technologies are currently available to have a comprehensive approach. Chapter 2 provides Figure 2.4, which organizes the flexibility sources according to their timescale response and discharge duration. This figure is beneficial to understand possible uses for each technology. There are different flexibility sources available in a power system — such as traditional power plants, flexible renewable energy, energy storage systems, and flexible demand.

Traditional flexibility is provided by rotating generating units, either gas, hydro, nuclear or coal-powered plants. These types of plants are providing flexibility in current systems. The major drawback is their reaction time since their ramp-up rates can be considered slow compared to other technologies. Variable renewable energy is also able to provide flexibility in form curtailment, which involves reducing the power output. This way of operating faces several issues; one of those is the public perception of wasting green energy. On the other hand, curtailment might be an economically viable option for systems operators when facing congestion or low demand. Another option is to under-produce energy and increase generation when necessary. These two options can be implemented by introducing market reforms and regulations to unlock them.

There is still high potential to deploy energy storage systems like batteries since pumped hydro storage accounts for 99% of the total storage installed capacity. The decreasing prices of batteries are driving its application in distribution and transmission systems. Energy storage systems prove to be a source of a wide variety of services to the grid that is traditionally supplied by rotating generators which makes them an interesting option in the future. Flexible demand is another option that is present on the system. Demand-side flexibility has been present in the system for several years, although provided by big industrial loads. In future decentralized systems, the ability of smaller loads to provide flexibility can provide frequency response services to the system operators. Furthermore, they might result in an economic benefit for the users. Consumers that now become prosumers is one key aspect that will shape the future of power systems.

How can the flexibility requirements of a power grid be assessed?

It is necessary to have an approach that assesses how much flexibility is required in a grid to ensure that the balance between generation and demand is kept at all times. The requirements of flexibility have to be analyzed when high amounts of VRES are integrated into the system.

Firstly, the uncertainty that is brought to the system by loads, electric vehicles and solar and wind energy has to be determined. Wind, solar and loads have a certain degree of error in their forecasts. The forecast errors of the aforementioned uncertainty sources were researched. For wind and solar energy and the load, the error depends on the time horizon selected, i.e. a one hour forecast has a smaller error than a day ahead forecast. This error is then presented as a percentage in which the forecast deviates from actual generation or consumption. For electric vehicles, a probabilistic analysis was done to determine the error on EV expected load. EVs are modelled with two sources of uncertainty, the time of arrival to a charging point and the charging duration. To obtain the error of several electric vehicles, the standard deviation that is present at every 15 minutes was calculated. Finally, the uncertainties of EVs, loads and wind and solar energy were added to obtain the maximum amount of power deviations that can be present due to these uncertainties. This will allow system operators to know how much flexibility has to be reserved for dealing with this deviations.

What are the effects of low inertia in power systems?

Inertia plays an essential role in ensuring a stable power system. Inertia is inherent to synchronous generators which release kinetic energy stored in their rotating masses when the frequency drops due to a change in generation or load. This release of kinetic energy slows down frequency deviations. The increase of solar and wind energy can dramatically reduce the inertia of the system since these sources of energy do not provide inertia to the system. This will result in a system with a lower inertia and will require faster flexibility to compensate for the inertial response.

To avoid fast frequency drops in the system, the concept of enhanced frequency response (EFR) is introduced. This service is designed to contain the frequency after a deviation in the system until additional flexibility returns the frequency to its nominal value. When a system presents low inertia, its reaction time decreases, as shown in Chapter 4. This decrease in reaction time means that future power systems need to have fast flexibility sources such as batteries and allow curtailment of VRES. These minimum reaction times can be calculated with the formulas described in Chapter 4 for AC and DC system. To use this approach, information on the available amount of rotating generators and the number of power converters in the system is required.

How to select and plan flexibility for a day in a distribution grid?

To answer this question, first, different reserve types are defined. These are primary, secondary, tertiary and the previously mentioned enhanced frequency response. These reserves are classified by minimum reaction time and duration. This relates to Figure 5.1, that divides the sources of flexibility in the same way. Once these reserves are defined, and the minimum reaction time of the EFR is calculated, an optimization problem is formulated. This problem allocates the different flexibilities present in a system depending on their technical characteristics and costs. This optimization reserves the required flexibility to deal with imbalances on the system. Furthermore, upwards and downwards flexibility has to be reserved. This means for upwards regulation that generators have to produce more and consumers reduce their demand for downwards regulation, the opposite for generators and consumers.

The different sources of flexibility have to be modelled correctly to illustrate how they operate in real conditions, making special emphasis on their real reaction time and the operational boundaries they are subject. For example, demand response programs can achieve different results, such as peak shaving or load shifting, which means different behaviours and mathematical modelling. Every source has its constraints, and these have to be modelled properly.

What are the effects of increased renewable energy in flexibility?

It is essential to foresee how flexibility changes over the years. In the future power system, the amount of renewable energy and electric vehicles will increase, and thus the level of uncertainty. Furthermore, the complexity of quantifying the reserves and how to procure them will become higher. A system is described to test the optimization. This system contains a distribution grid, solar PV systems, wind energy, electric vehicles and household loads. A case study was proposed to demonstrate the effects of an increased amount of VRES and electric vehicles.

Three different years were chosen to describe this effect, 2019, 2030 and 2050. The last two years where modelled using data from Entso-e and TenneT. These two entities forecast the installed renewable capacity in those years, and with that information, the optimization was carried out. For the year 2019, it can be seen how flexibility is currently allocated, meaning that conventional generators are the primary source of flexibility. As the years pass by and the required flexibility increases, other options emerge. ESS will have a more significant role in balancing at distribution levels due to cost reductions and their ability to provide faster flexibility. Finally, the results for 2050 show that procuring flexibility in a distribution grid is more complicated. They are showing that for a reserve type two sources of flexibility might have to be stacked up to have enough flexibility. For example, curtailment and a battery might be reserved to procure EFR in one hour period. Curtailment can be avoided by investing in more battery systems, although a more in-depth economic analysis has to be done.

6.2 Recommendations

In this section, recommendations on further research on the topic flexibility in future power systems are presented.

- The importance that reaction times have in the future make interesting retrofitting old technologies and improving new ones. The actualization of technologies has to be accounted for in the modelling of future power grids.
- It is necessary to have more information on short-time forecast errors. At the time this research was conducted, there was little information on NRMSE for forecasts with a horizon shorter than one hour. If shorter forecasts horizons are used, the required flexibility decreases.
- The approach taken required using statistical errors for the uncertainty sources that have literature on this, for EVs a probabilistic approach was taken. It would be ideal to have a standardized approach to account for errors in the forecast.
- This research conducted calculations for reaction times based on a single day data. This can be improved by making these calculations for an entire year and comparing summer and winter profiles. Furthermore, to calculate the minimum response times for a DC distribution grid, a fixed value for capacitance was used. To ensure the values of capacitance are correct actual values have to be measured for a specific system.
- Normally a unit commitment problem is done, and reserves are allocated in this problem. The difference with the proposed formulation in this research is that more emphasis is done in the reserves of flexibility. For further work, a unit commitment formulation that accounts for the effects of reduced inertia and that reserves flexibility depending on reaction times will be required.

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A

Flexibility characteristics

In this first appendix the properties of the different types of flexibility available are shown. This includes traditional flexibility, energy storage systems and demand response. Table A.1 shows the properties of the key ancillary services provided by traditional power plants to the grid.

Table A.1: Properties of key ancillary services [22]

Service	**Response**	**Duration**	**Cost ($/MWh)**
Normal Operation			
Regulating reserve	∼1 min	Minutes	35-40 200-400
Load following	∼10 min	10 min to hours	Obtained form intraday market
Contingency conditions			
Spinning reserve	Seconds to <10 min	10 to 120 min	6-17 100-300
Non-spinning reserve	<10 min	10 to 120 min	3-6 100-400
Replacement reserve	<30 min	2 hours	0.4-2 2-36
Other services			
Voltage control	Seconds	Seconds	1−4/kvar-yr
Black start	Minutes	Hours	-

Table A.3: Traditional power plants costs [13]

Power plant	**Investment costs (€/kW)**	**Variable costs (€/MWh)***	**Cold start costs (€/MW) ****	**Minumum Load (%)**	**Lifetime (years)**
Coal	1300-1750	22-30	78-110	20-40	35-45
Lignite	1600-1850	3-5	-		45
CCGT	685- 1250	40-60	60	15-50	30-40
OCGT	380-700	60-76	24	20-50	25-5-

* Highly dependent on fuel costs. Price indications for the current European market.

** In the EU additional CO2 costs have to be included.

Table A.4: Characteristics of ESS for particular applications in the power system, [1]

Application	**Output (Electricity, Thermal)**	**Size(MW)**	**Discharge duration**	**Cycles (Typical)**	**Response time**
Seasonal storage	e,t	500 to 2000	Days to months	1 to 5 per year	day
Arbitrage	e	100 to 2000	8 hours to 24 hours	0.25 to 1 per day	<1 hour
Frequency regulation	e	1 to 2000	1 min to 15 min	20 to 40 per day	1 min
Load following	e,t	1 to 2000	15 min to 1 day	1 to 29 per day	<15 min
Voltage support	e	1 to 40	1 second to 1 min	10 to 100 per day	milisecond to second
Black start	e	0.1 to 400	1 hour to 4 hours	<1 per year	<1 hour
Transmission and distribution congestion relief	e,t	10 to 500	2 hours to 4 hours	0.14 to 1.25 per day	>1 hour
T&D infrastructure investement deferral	e,t	1 to 500	2 hours to 5 hours	0.75 to 1.25 per day	>1 hour
Demand shifting and peak reduction	e,t	0.001 to 1	Minutes to hours	1 to 29 per day	<15 min
Off-grid	e,t	0.001 to 0.01	3 hours to 5 hours	0.75 to 1.5 per day	<1 hour
Variable supply resource integration	e,t	1 to 400	1 minute to hours	0.5 to 2 per day	<15 min
Waste heat utilization	t	1 to 10	1 hour to 1 day	1 to 20 per day	<10 min
Combined heat-power	t	1 to 5	Minutes to hours	1 to 10 per day	<15 min
Spinning reserve	e	10 to 2000	15 minutes to 2 hours	0.5 to 2 per day	<15 min
Non-spinning reserve	e	10 to 2000	15 minutes to 2 hours	0.5 to 2 per day	<15 min

B

Inertia characteristics

In this first appendix the inertial properties of the different types of available power plants are shown. Table B.1 shows the properties of the different power plants types/

Table B.1: Inertial properties of different generation technologies

[29]

Generation technology	**Typical rating [MW]**	**Typical inertia constant H [s]**
Biofuel	208	3.3
Hard coal	361	4.1
Gas	168	4.3
Lignite	310	3.9
Nuclear	869	6
Oil (THN)	153	4.3
Hydro-pump	140	4
Hydro-run 59 2.7	59	2.7
Hydro-dam 140 4	140	4
Other non-RES 104 3.7	104	3.7
Solar-thermal 150 3	150	3

Table B.2 shows the expected installed capacities in the Netherlands. This are obtained from [29] for the year 2030 and [38] for 2050.

Table B.2: Installed generation capacities in the Netherlands for 2019, 2030 and 2050

Netherlands installed capacity 2019	**Entso-e 2019**	**Entso-e EUCO2030**	**TenneT Infrastructure Outlook 2050**
Technology	*Installed capacity 2019*	*Installed capacity 2030*	*Installed capacity 2050*
Nuclear	486	485	0
Fossil Hard coal	4631	4429	0
Wind Onshore	3669	7674	14000
Hydro Run-of-river and poundage	38	0	0
Wind Offshore	957	2561	53000
Hydro Pumped Storage	0	2066	2066
Solar	3937	5933	34000
Waste	758	433	0
Fossil Gas	15570	10379	16000
Fossil Oil	0	2066	0
Hydrogen	0	250	1000
Biomass	485	600	900

C

Optimization code in GAMS

This appendix describes the code utlized in the GAMS software. It has to be noted that variables $psig_t$, $pmaxdr_t$ and $pmaxv_t$ are variables that are the input of the user. This variables come from the MATLAB calculations in which the uncertainty is calculated and the load and wind profiles.

```
Set
t 'time' / t1*t24 /
j 'conventional generator' / j1 /
z 'minim response time segments' / z1*z3 /
w 'demand response' /w1/
b 'battery' /b1/
v 'windcurtailment' /v1/;
Parameter 'Max power of unitj for upward[kW]' Pmaxup(j) /j1 100/;
Parameter 'Max power of unit for downward[kW]' Pmaxdown(j) /j1 80/;
Parameter 'Cost of flexibility upward [€/kWh]' Cup(j) /j1 0.04/;
Parameter 'Cost of flexibility downwards[€/kWh]' Cdown(j) /j1 0.02/;
Parameter 'Response time of units [s]' R(j) /j1 14/;
Parameter 'Total Energy for upwards flex [kWh]' Eup(j) /j1 2400/;
Parameter 'Total Energy for downward flex [kWh]' Edown(j) /j1 1700/;
Parameter 'Minimum response times [s]' minresponse(z)
/z1 .1
z2 15
z3 300
z4 600/;
Parameter 'Duration of each reserve [hour]' res(z)
/z1 0.0025
z2 0.079166667
z3 0.1666667/;
Parameter 'Required flexibility per hour[kW]' psig(t)
/t1 psig(1)
t2 psig(2)
t3 psig(3)
t4 psig(4)
t5 psig(5)
t6 psig(6)
t7 psig(7)
t8 psig(8)
t9 psig(9)
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t10 psig(10)
t11 psig(11)
t12 psig(12)
t13 psig(13)
t14 psig(14)
t15 psig(15)
t16 psig(16)
t17 psig(17)
t18 psig(18)
t19 psig(19)
t20 psig(20)
t21 psig(21)
t22 psig(22)
t23 psig(23)
t24 psig(24)/;
Parameter ’Demand response time response’ resp(w) /w1 .2/;
Parameter ’Total energy in demand response program’ Edr(w) /w1 382 /;
Parameter ’Cost for demand response’ Cdr(w) /w1 .02/;
Parameter pmaxdr(t)/
t1 pmaxdr(1)
t2 pmaxdr(2)
t3 pmaxdr(3)
t4 pmaxdr(4)
t5 pmaxdr(5)
t6 pmaxdr(6)
t7 pmaxdr(7)
t8 pmaxdr(8)
t9 pmaxdr(9)
t10 pmaxdr(10)
t11 pmaxdr(11)
t12 pmaxdr(12)
t13 pmaxdr(13)
t14 pmaxdr(14)
t15 pmaxdr(15)
t16 pmaxdr(16)
t17 pmaxdr(17)
t18 pmaxdr(18)
t19 pmaxdr(19)
t20 pmaxdr(20)
t21 pmaxdr(21)
t22 pmaxdr(22)
t23 pmaxdr(23)
t24 pmaxdr(24)/;
Parameter ’Curtailment response time’
resp1(v) /v1 .1/;
Parameter ’Curtailment available energy’
Ev(v) /v1 12 /;
Parameter ’Curtialment cost’ Cv(v) /v1 .05/;
Parameter
pmaxv(t)
/t1 pmaxv(1)
t2 pmaxv(2)
t3 pmaxv(3)
t4 pmaxv(4)
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t5 pmaxv(5)
t6 pmaxv(6)
t7 pmaxv(7)
t8 pmaxv(8)
t9 pmaxv(9)
t10 pmaxv(10)
t11 pmaxv(11)
t12 pmaxv(12)
t13 pmaxv(13)
t14 pmaxv(14)
t15 pmaxv(15)
t16 pmaxv(16)
t17 pmaxv(17)
t18 pmaxv(18)
t19 pmaxv(19)
t20 pmaxv(20)
t21 pmaxv(21)
t22 pmaxv(22)
t23 pmaxv(23)
t24 pmaxv(24)/;
Parameter effc(b)'charging efficiency' /b1 .95/;
Parameter effd(b) 'discharging efficiency'/b1 .85/;
Parameter Cbmax(b) 'maximum energy [kwh]'/b1 12/;
Parameter Cbmin(b) 'minimum capacity [kwh]'/b1 1/;
Parameter costup(b)'cost charging'/b1 .06/;
Parameter costdown(b)'cost discharging' /b1 .06/;
Parameter resptime(b)'response time'/b1 0.1/;
Parameter Pmaxb(b) 'maximum power' /b1 7/;
Parameter Eb0(b) 'initial energy' /b1 9/;
Variable OF;
Positive VariablePup(j,t,z),Pdown(j,t,z),energyup(j,t,z),energydown(j,t,z),Pdr(w,t,z),energydr(w,t,z),
Pdr(w,t,z),energydr(w,t,z),Eb(b,t,z),Pbup(b,t,z),Pbdown(b,t,z),energyupb(b,t,z),energydownb(b,t,z),pbup1(b,t,z),
pbdown1(b,t,z),Pdr1(w,t,z),energyv(v,t,z),Pv(v,t,z),Pv1(v,t,z);
Equations cost, totalenergyup,totalenergydown, activation1up,activation2up,activation1down,activation2down
balanceup,balancedown,energyconstraintdown, energyconstraintup,dr1,dr2,dr3,dr4,dr5, ebcons,ebcons2,ebcons3,
ebcons4,activationb1up,activationb2up,activationb1down,activationb2down,totalenergyupb,totalenergydownb,
eb1,eb2,eb3,eb4,power,power1,dr5,dr6,energyb1,wc1,wc2,wc3,wc4,wc5;

    *conditionals upwards
activation1up(j,t,z).. Pup(j,t,z) $ (R(j)>minresponse(z))=e=0;
activation2up(j,t,z).. Pup(j,t,z) $(R(j)<minresponse(z))=l= Pmaxup(j);
power(j,t,z).. Pup(j,t,z)=l=Pmaxup(j);
power1(j,t,z)..Pdown(j,t,z)=l=Pmaxdown(j);

    *conditionals downwards
activation1down(j,t,z).. Pdown(j,t,z) $ (R(j)>minresponse(z))=e=0;
activation2down(j,t,z).. Pdown(j,t,z) $(R(j)<minresponse(z))=l= Pmaxdown(j);

    *energy calculation
totalenergyup(j,t,z).. energyup(j,t,z)=e= res(z)*Pup(j,t,z);
totalenergydown(j,t,z).. energydown(j,t,z)=e=res(z)*Pdown(j,t,z);

    *energy constraints
energyconstraintup(j).. sum((t,z),energyup(j,t,z))=l=Eup(j);
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energyconstraintdown(j).. sum((t,z),energydown(j,t,z))=l=Edown(j);

    *demand response only peak hours
dr1(w,t,z).. Pdr(w,t,z) $ (resp(w)>minresponse(z))=e=0;
dr2(w,t,z).. Pdr(w,t,z) $(resp(w)<minresponse(z))=l= pmaxdr(t);
dr3(w,t,z).. energydr(w,t,z)=e= res(z)*Pdr(w,t,z);
dr4(w).. sum((t,z),energydr(w,t,z))=l=Edr(w);
dr5(w,t,z).. Pdr(w,t,z)=l=pmaxdr(t);

    *10 percent wind curtailment
wc1(v,t,z).. Pv(v,t,z) $ (resp1(v)>minresponse(z))=e=0;
wc2(v,t,z).. Pv(v,t,z) $(resp1(v)<minresponse(z))=l= pmaxdr(t);
wc3(v,t,z).. energyv(v,t,z)=e= res(z)*Pv(v,t,z);
wc4(v).. sum((t,z),energyv(v,t,z))=l=Ev(v);
wc5(v,t,z).. Pv(v,t,z)=l=pmaxv(t);

    *Battery conditionals
activationb1up(b,t,z).. Pbup(b,t,z) $ (resptime(b)>minresponse(z))=e=0;
activationb2up(b,t,z).. Pbup(b,t,z) $(resptime(b)<minresponse(z))=l=Pmaxb(b);
activationb1down(b,t,z).. Pbdown(b,t,z) $ (resptime(b)>minresponse(z))=e=0;
activationb2down(b,t,z).. Pbdown(b,t,z) $(resptime(b)<minresponse(z))=l= Pmaxb(b);

    *battery energy
totalenergyupb(b,t,z).. res(z)*Pbup(b,t,z) =e= energyupb(b,t,z);
totalenergydownb(b,t,z).. res(z)*Pbdown(b,t,z)=e= energydownb(b,t,z);

    *Battery constraints
energyb1(b,t,z)..Eb(b,t,z)=e= Eb0(b)$(ord(t)=1) + Eb(b,t-1,z)$(ord(t)>1) +effc(b)*Pbdown(b,t,z)*res(z)-
(1/effd(b))*Pbup(b,t,z)*res(z);
ebcons(b,t,z).. Eb(b,t,z)=l=Cbmax(b);
ebcons2(b,t,z)..Eb(b,t,z)=g=Cbmin(b);
ebcons3(b,t,z).. Pbup(b,t,z)=l=Pmaxb(b);
ebcons4(b,t,z).. Pbdown(b,t,z)=l=Pmaxb(b);

    *Battery energy constraints
eb1(b).. sum ((t,z), energyupb(b,t,z))=l=Cbmax(b);
eb2(b).. sum ((t,z), energydownb(b,t,z))=l=Cbmax(b);
eb3(b,t,z).. Pbup(b,t,z)=l=Pmaxb(b);
eb4(b,t,z).. Pbdown(b,t,z)=l=Pmaxb(b);

    *system balance
balanceup(t,z).. sum ((j,w,b), Pup(j,t,z)+Pbup(b,t,z)+Pdr(w,t,z))=e= psig(t);
balancedown(t,z).. sum ((j,b,v), Pdown(j,t,z)+Pbdown(b,t,z)+Pv(v,t,z))=e= psig(t);

    *objective function
cost.. OF =e= sum((v,w,b,j,t,z), energyup(j,t,z)*Cup(j)+energydown(j,t,z)*Cdown(j)+energydr(w,t,z)*Cdr(w)
+energyupb(b,t,z)*costup(b)+energydownb(b,t,z)*costdown(b)+energyv(v,t,z)*Cv(v));

    Model flexbinary /all/;
Solve flexbinary us MIP minimizing OF;
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