Bachelor Thesis

Bachelor's degree in Industrial Technology Engineering

Analysis of measures to increment the share of renewable energy in distribution grids

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Abstract

The actual power system is undergoing a period of transformation. The introduction of renewable energy power parks in the grid started the transition from a high voltage connected generation model towards a model where part of the generation assets will be connected to medium and even low voltage grids. Furthermore, the fast-changing world of technology is starting to allow passive users to generate and manage electricity, and thus, take a new position towards the grid. This transformation entails new opportunities and challenges for a power system that was initially thought to be vertically integrated and with unidirectional power flows.

Europe is already giving its directives to ease the transition towards a more decentralized power system; however, some member states are faster than others when transposing them. Taking advantage of the different speeds between member states, this thesis aims to analyse and compare those pioneering regulatory frameworks in terms of renewable energy sources connection to distribution grids. This should allow the thesis to identify which kind of measures are the best ones to increase the share of renewable energy sources.

In order to carry out the research, a systematic review of technical and energy policy articles has been carried out consulting the *ScienceDirect*, the *IEEE Xplore*, and the *ResearchGate* databases, together with European directives and regulations in the field of energy policies and member states network codes for connection of generation assets.

The core of the thesis is based on a few institutions and documents which we would like to highlight. To set the technical basis of the impact of renewable energy sources, the book *Integration of Distributed Generation in the Power System* has been used. In terms of conceptualizing the regulatory framework the Florence School of Regulation technical reports *The EU Electricity Network Codes* and the *Clean Energy Package* are essential to this thesis together with the European energy *e-Directive* and *e-Regulation*. The report *The smartEn Map: European Balancing Markets Edition (2018)* published by smartEn has been used as a reference point to study the state of the art of balancing markets. Finally, the network codes for *Low Voltage Grid Connection of Generators* from Italy, Germany and Denmark are the base for the development of the energy storage section.

The European directives and regulations point towards a market-based approach to overcome the challenges and benefit from the opportunities that the transition towards a distributed power system will create. The thesis go from a holistic view, considering the new European guidelines, to a study of those member states that are already half-way on their transition towards a distributed power system based on renewable energy sources. This is will give an overview of the current regulatory framework and find the main outlines of the forthcoming one.

Finally, comment that one of the outcomes of the research carried out during the thesis is the participation in the conference paper "*RESOlvD: ICT services and energy storage for increasing renewable hosting capacity in LV distribution grids*".
The paper has been approved for publication, and it can be partially consulted in the Annex A of the thesis.

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1 Abbreviations

ESS Energy Storage System.

MS Member State.

DER Distributed Energy Resource.

EU European Union.

PGM Power Generating Module.

HV High voltage.

MV Medium voltage.

TSO Transmission Network Operator.

ENTSO-E European Network of Transmission System Operators.

LV Low voltage.

RES Renewable Energy Source.

DSO Distribution System Operator.

EB GL Electricity Balancing Guideline.

DAM Day Ahead Market.

IM Intra-day Market.

ESCO Energy Service Company.

LEM Local Energy Market.

LFM Local Flexibility Market.

DG Distributed Generation.

IEEE Institute of Electrical and Electronics Engineers.

vRES variable Renewable Energy Source.

PCC Point of Common Coupling.

PPE Partial Power Electronics.

BSS Battery Storage System.

SG Smart Grid.

BRP Balancing Responsible Party.

PHES Pumped Hydroelectric Energy Storage.

KPI Key Performance Index.

HC Hosting Capacity.

LHC Locational Hosting Capacity.

CEP Clean Energy Package.

RfG NC Requirements for Generators Network Code.

DCC NC Demand Conection Network Code.

FCR Frequency Containment Reserve.

Ofgem Office of Gas and Electricity Markets.

DSM Demand Side Management.

USEF Universal Smart Energy Framework.

DR Demand Response.

DSF Demand Side Flexibility.

FRR Frequency Restoration Reserve.

RR Replacement Reserve.

SGU Significant Grid User.

IRENA International Renewable Energy Agency.

RO Renewables Obligation.

FiT Feed in Tariff.

VPP Virtual Power Plant.

LFSM-O Limited Frequency Sensitive Mode in Overfrequency.

LFSM-U Limited Frequency Sensitive Mode in Underfrequency.

VPL Virtual Power Line.

2 Introduction

Motivation

The increasing concern about the environment has put traditional fuel-based generators in the spotlight. Day after day, renewable energy sources are establishing themselves as a viable alternative to the actual generation model. Furthermore, societies are slowly realizing of the potential social benefits of renewable energy sources in terms of citizen empowerment. However, the power system operation is very complex and to adequately integrate renewable energy sources there is the need to develop the proper regulatory framework.

The opportunities arising from the new generation model are the primary motivation to carry out the study and analysis of how new regulations should be shaped to integrate a higher share of renewable energy sources without compromising the system operation.
After all, there is a more general motivation underlying this bachelor thesis which is to give some hints on how to create a fairer – from the social and environmental perspective – power system within the European regulatory framework.

Objectives

The general objective of this thesis is to study, analyse, and suggest measures to increment the share of renewable energy sources in distribution grids.

In order to accomplish the main objective there are two sub-objectives. The first one is the study in depth of the recently published European energy regulation, to understand how Europe approaches the promotion of renewable energy sources. Then, knowing that the new European regulation points towards higher integration of renewable energy sources via a market-based approach, the second objective is to identify the key measures and market design variables, that enhance the share of renewable energy sources in distribution grids.
Finally, the sum of both sub-objectives aims to give a holistic perspective of the new European regulatory framework to promote renewable energy sources, together with some suggestions to implement it more easily.

Scope of the Project

The major outcome of this bachelor thesis is the study of those existing regulations that already fulfil the recent European guidelines for the energy sector (Clean Energy Package). Within the Clean Energy Package, the thesis is focused on those master lines that, in one way or another, aim to promote a higher share of renewable energy sources in low voltage grids.

The Clean Energy Package points towards the creation of a safer and more reliable power system via flexibility markets. Within those markets, it focuses its scope on enhancing participation from the distribution side of the grid. When talking about agents and technologies, it highlights the key role of aggregation and energy storage technologies. So, the scope of the bachelor thesis is centred on:

a) Study of the Clean Energy Package e-Directive and e-Regulation.

b) Study of flexibility market designs that enhance participation of distributed energy resources.

c) Study of regulations that define connection requirements for energy storage.

To focus even more the thesis scope, only European member states regulations and flexibility markets have been studied to avoid possible proposals conflicting with the European regulatory framework.

3 Electricity Networks: Structure, evolution and challenges

3.1 The Traditional Grid Scheme

Electricity supply and consumption is something we take for granted nowadays. Over the years, countries have invested vast amounts of money in the development of one of the most complex interconnected systems ever created by humanity. This project aims to search the main European Member States (MSs) legislation on flexibility markets and Energy Storage Systems (ESSs) in order to find those common points that can help to make easier the deployment of distributed energy resources (DERs). However, before going deeper into the grid structure and all the legislation related, it is essential to understand how the grid works. This will allow the reader to understand how and why this forthcoming revolution will affect the power system.

The electricity system is composed of two main agents, the physical infrastructure for generation, transport and use, and the electricity market. These two agents are mutually correlated since generation will be determined by the market but also because real-time generation and demand profiles can make changes on market prices.

3.1.1 Physical Agents

The physical grid involves all the agents related to the generation, transportation and safety of the system to be able to provide all the services offered, plus the loads. It is composed of three main infrastructures and organizations, as shown in Figure 1.

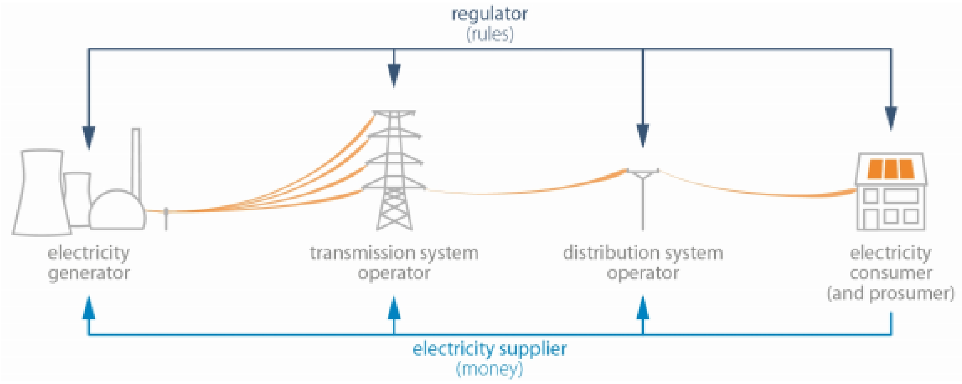


Figure 1: Traditional grid scheme. Source [1].

- **Generators**: In the European Union (EU) and MSs legislation they are classified by their generation capacity (maximum power output). According to it, they must fulfil some minimum requirements in order to guarantee the proper operation of the system. In the classic approach to generation, huge power generating modules (PGMs) are the main agents feeding the grid downstream.
  Large PGMs produce at a range from 6kV to 20kV [2] to then increase the voltage up to 220 kV or more to connect to the high voltage (HV) transmission lines.

- **Transmission system**: It is responsible for electricity transportation over long distances, and it does it at HV level. This way, the losses in transportation are lower while using a cheaper infrastructure. Transportation level voltages range from 220 kV up to 1000 kV [1], and generators and high voltage to medium voltage (MV) transformers are the principal agents connected to the transmission system. However, big loads like the National Railway System or metallurgy plants can also be connected to it. Due to their critical position in the system connecting generation and consumption, transmission grids are meshed to avoid collapsing if there is any failure in one line. Furthermore, the mesh organization also allows distributing evenly (if it is feasible) the loads through different lines in order to avoid congestion and reduce losses.

The transmission networks are operated by Transmission Network Operators (TSOs) which at European level are organized in the European Network of Transmission System Operators (ENTSO-E) founded in 2008. It was created to facilitate the transition and coordination to a new internal European market, as stated in the Third Energy Package **e-Directive** and **e-Regulation** [3, 4].

- **Distribution system**: It is responsible for energy transportation for shorter distances. A grid is considered a distribution grid when it transports electricity at medium (MV) and low (LV) voltages. The voltage levels comprehended inside this definition are: 132 kV, 66 kV, 45 kV, 30 kV, 20 kV, 10 kV, 6 kV, 3 kV, 1 kV, 400 V and 230 V [2].

  The assets connected at distribution level are mainly loads ranging from industrial loads, connected at MV, to residential loads, usually connected at LV. Then, some generation units are also connected at the distribution side of the grid, usually renewable energy sources (RESs). As an exception, Denmark had already in 2007 a significant penetration of generators at MV level [5]. The share of generation in distribution grids is expected to increase during the following years. This will change how they are managed and operated.

  The structure of the local distribution system is not usually redundant as the transmission system structure is. This is partially why, as it will be seen, changing the connection point of generation from HV to MV or LV could be a problem for distribution grids.
  Distribution networks are managed by Distribution System Operators (DSOs), who connect consumers, install electricity meters and communicate the consumption to energy suppliers [1].

Figure 2 gives a schematic, but complete overview of how the power system is organized from the high voltage connection of large generation plants to small consumers.

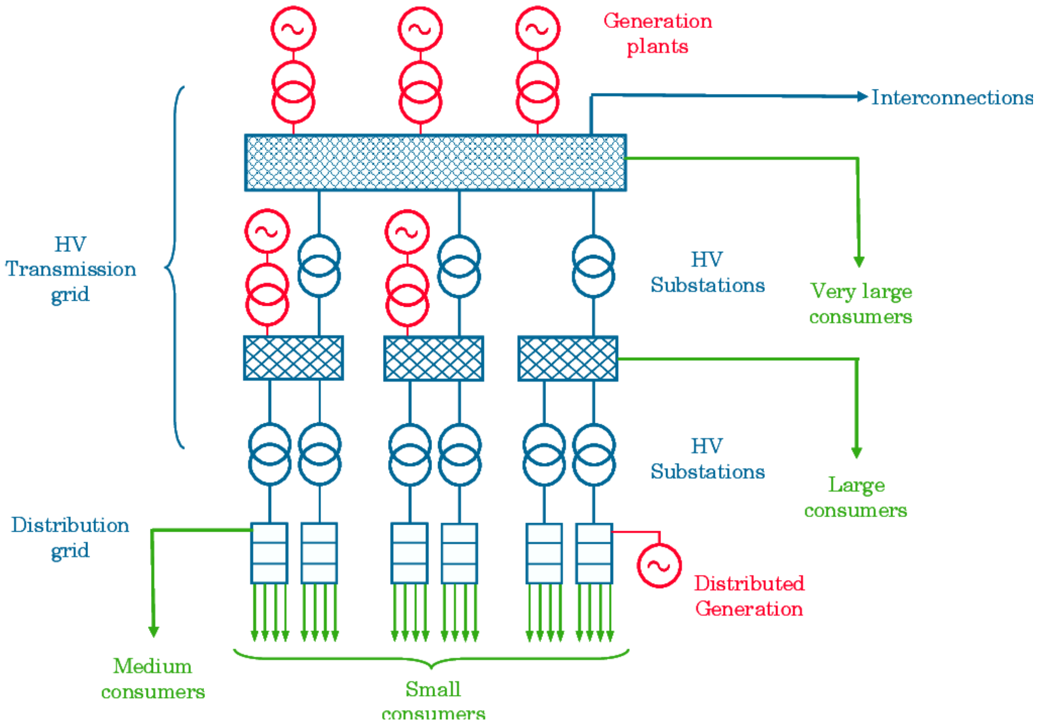


Figure 2: Electric power system configuration and structure. Source [2].

3.1.2 Structure of the Distribution System

Power delivery systems are designed to collect electrical energy produced in large generation centres and transport it to final load points where the demand is [6]. Since the aim of this project is mainly focused at a distribution level, this section goes more in-depth into distribution grid structures and typical configurations.

It is essential to understand the configuration of the distribution network to identify how distributed energy resources penetration can affect or benefit the grid and why this happens.

After the electricity has been moved long distances at HV through the transmission system and is already close to the demand point, it enters the distribution system. The limit between these two systems is the distribution substation where the energy of the transmission system is received, and a voltage reduction is applied from HV to MV. From here there is a divergence between the American and the European power system. In the American one, the distribution network is subdivided into two stages: The Primary Distribution System lines also known as MV feeders, and then when they reach the final voltage reduction from MV to LV (meaning voltages below 1 kV), the system is known as Secondary Distribution System. Each stage of the system has its characteristic designs and structures.
Instead, the European distribution network divides its sub-levels by voltage reductions, not specifying between Primary and Secondary distribution system, which in some cases makes it difficult to identify the grid configuration of a specific level.

From [7], the typical profiles of the European distribution networks can be extracted. European medium voltage feeders are mainly three-phased, and single-phase loads can be connected to one of the phases. The same happens with low voltage feeders, so in the end, HV/MV and

MV/LV transformers are most of them three-phase. From this approach, and if handled properly by the DSOs controlling the connection of new loads, the European distribution network should be naturally phase-balanced (to clarify, in [7] medium voltage level encompasses from 36 to 1 kV, where the low voltage level starts).

Due to the voltage-hierarchical organization of the European distribution systems, it is hard to identify specific network structures within voltage levels. However, there is an arising need to model the main distribution-network structures due to the expected increase in the share of DERs. Knowing the topology of the grid would allow system operators to do a first assessment of the possible impact of new DERs connection via simulations.

The following part of the work is devoted to show which are the main characteristics of European distribution grids. The models are extracted from the article [7], where six distribution feeder structures are proposed together with three large scale models. Article [7] aims to provide new research projects with a more accurate definition of the distribution grid topology in Europe. In this report, they will be used to give an overview and a better understanding of how is structured the European distribution system. This information is helpful to understand how European distribution grids would cope with new DERs embedded at the distribution level.

From the representative feeder structures, four of them are MV, and the other two are LV (all the models are characterized by being balanced and three-phase, and some of them are shown in Figure 3):

a) **Urban MV network with two substations**: Two HV/MV substations with feeder support connecting each other through a normally-open switch. This can also be known as open-loop configuration [6] and aims to solve the reliability problems on the HV/MV transformers at the expense of higher investment costs.

b) **Urban MV network with one substation and one switching station**: Three MV feeders outgoing from a HV/MV substation. The ends of the feeders are connected to a switching station to enable grid reconfiguration in case of failure.

c) **Semi-urban MV network with a substation ring**: Two trunk feeders outgoing from the same HV/MV substation, connected in a closed-loop via a normally-open switch.

d) **Rural MV network**: HV/MV substation with multiple radial feeders. In this case, the lack of redundancy of the design, while decreasing investment costs makes a local feeder failure critical for the loads connected.

e) **Urban LV network**: It is configured by a MV/LV substation with short feeders outgoing from it. It is the typical configuration in networks with a concentrated demand.

f) **Semi-urban LV network**: It is configured by a MV/LV substation with short feeders outgoing from it. It is the typical configuration in networks with a concentrated demand. As it will be seen in 3.3.2, this configuration is particularly challenged by generation assets connected, mainly due to the risk of overvoltage caused by the length of the feeders.

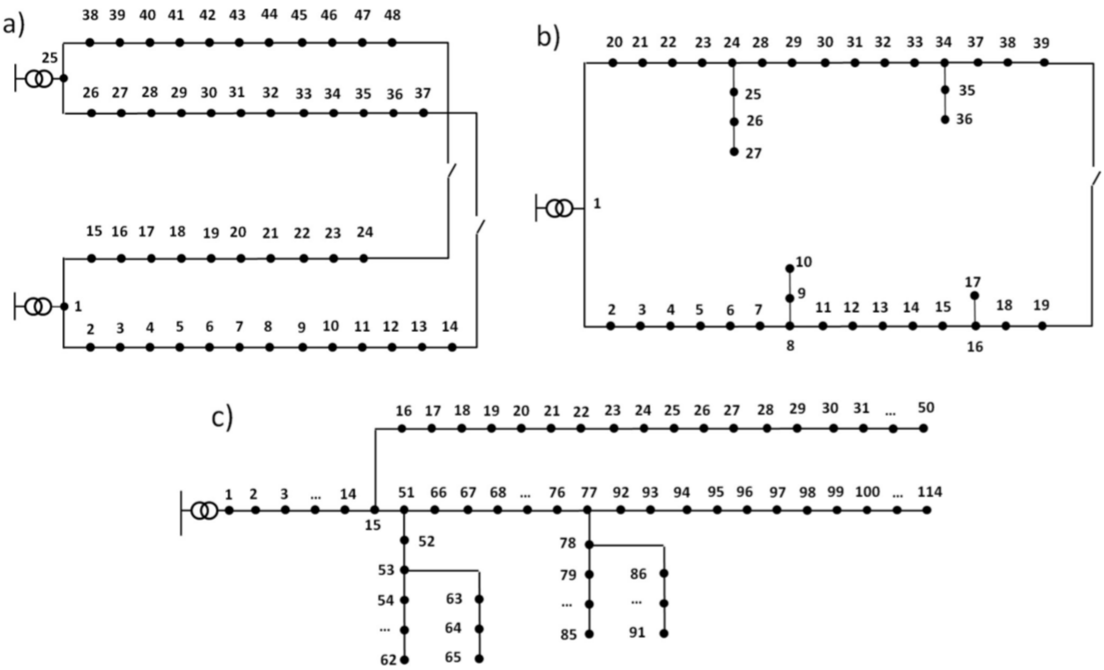


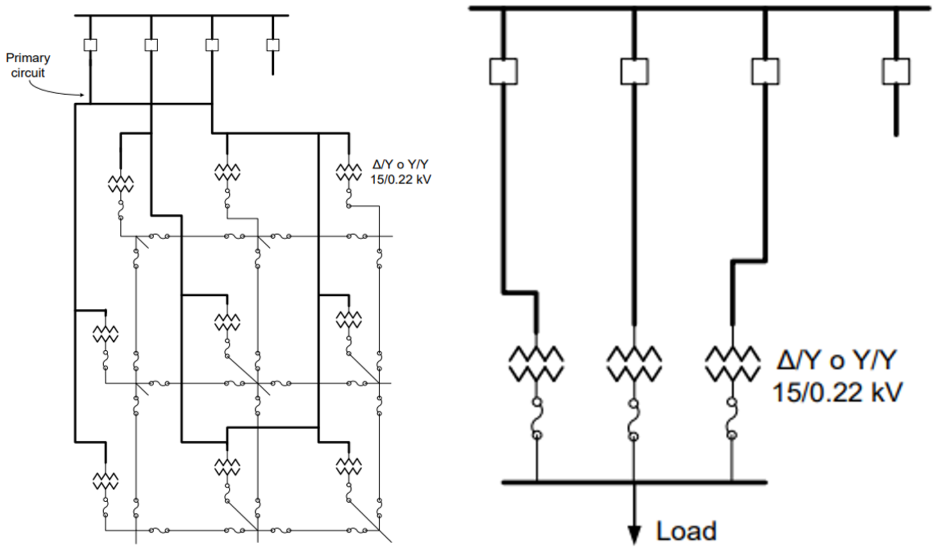
Figure 3: Feeder-type representative networks: (a) urban MV network with two substations interconnected, (b) semi-urban MV network with a substation ring, (c) semi-urban LV network. Source [7].

All of these configurations are characterized by being radial; such design has its perks and disadvantages, some of which are mentioned in [6]. As advantages are mentioned: lower fault currents together with voltage regulation and power flow control methods which are easier to implement in a radial grid. Furthermore, system design is less expensive in terms of equipment. All these benefits make radial designs a good option for networks where most of the parameters are known and controllable. In this configuration, overcurrent is the primary concern in terms of safety.

Radial grids also present some difficulties, being the most important one the lack of redundancy that makes local feeder failure critical for the customers connected. However, this can be solved depending on the configuration chosen, always at the expense of higher investment costs. That is why the following variations of radial designs, also extracted from [6], are mentioned:

- **Network configuration**: This configuration consists of several MV feeders feeding the LV network from multiple step-down distribution transformers. On the secondary side of the transformer, a low voltage meshed grid is responsible for providing the load to the final consumer. This configuration is used to serve commercial and residential loads. Figure 4 **a**) is an schematic representation of this configuration.

- **Spot configuration**: This configuration is designed to provide highly reliable service to a single site, usually with a high-power demand. It consists of two or more (typically three or five [6]) network transformers that are paralleled at the LV level [8]. Figure 4 **b**) is an schematic representation of this configuration.



a) Network Configuration b) Spot Configuration

Figure 4: Spot and Network feeder configurations. Source [6].

3.1.3 The Electricity Market

For decades, the provision of electricity has been characterized by centrally controlled systems with over-capacity ensuring security of supply [9]. Hitherto, electric generation and demand were two concepts that were inevitably correlated. In the present situation and after the liberalization of the system started with the First Energy Package back in 1996 [10, 11], electricity markets play a crucial role in terms of demand prediction to facilitate the planning of generation and the fulfilment of the on-time demand. Due to the bonded nature of generation and demand, a lousy forecast could suppose an unbalance of the system which would endanger the safety and reliability of it.

Regarding the unbundling principle [10] applied to the power grid and the consequent new business models in the electricity sector, article [12] states, "*with restructuring and deregulation of the electricity supply industry, the philosophy of operating the system also changed. While the classical philosophy being to supply all the required demand whenever it occurs, the new philosophy states that the system will be most efficient if fluctuations in demand is kept as small as possible*". The unbundling of the vertically integrated facilities, creating new roles on the system, created the need for a trading platform between agents. Since the main objective of the power system is energy provision to customers; the First and Second Energy packages (1996 & 2003) introduced the idea of competition in the generation market [11]. However, with the liberalization there were, and still are, other needs/concerns of the grid that need to be covered. So, slowly the EU is also trying to regulate and standardize those markets which are related to reliability and safety of the power system, starting in 2017 with the *Electricity Balancing Guideline* (EB GL) [13] and proposing new markets guidelines as the 2019 Clean Energy Package outcomes [14, 15].

From this starting point, the most important differentiation of electricity markets is based on the purpose of the product traded:

a) **Energy Markets**: Comprehend all trading markets where power is traded to be delivered to end consumers via the grid [16]. Depending on the agents involved, there are two types of markets:

- **Wholesale markets**: In these markets, the agents are generators, suppliers and large electricity consumers. These are the markets that determine how the generation will be in the following days, weeks or even years. Depending on the time horizon, electricity contracts and markets can be classified as [1]:
  - Long-term market: Up to 20 years or more.
  - Forward or future market: From years to weeks in advance.
  - Day-ahead market (DAM): Trading of products the day before activation.
  - Intra-day market (IM): Delivery within a specified time period (< 1 day).

  Then, there is also the regulated figure of Physical Bilateral Contracts, also known as Over-the-counter Contracts, which consists of the private trading of electricity without the need of going through a market mechanism [2].

- **Retail markets**: Suppliers and consumers are the two main agents nowadays in the retail market. However, new agents like Energy Services Companies (ESCOs) are starting to appear. Suppliers offer electricity contracts (approved by the competent regulator, for instance in Spain the *Comisión Nacional de los Mercados y la Competencia*) and consumers choose their supplier [1]. The exceptions to a market based approach are considered in the **e-Directive** [14] *Art. 5*. However, it is aimed at the energy-poor and vulnerable household customers and leaves the price regulation as the last option available to avoid market distortions.

b) **Flexibility Markets**: The product can itself be defined as flexibility, and *Eurelectric* [17] defines it as: *"the modification of generation injection and/or consumption patterns* [. . .] *in order to provide a service within the energy system."*

- **Ancillary markets**: The ancillary services market is a figure arising nowadays to provide the grid operators, TSOs and DSOs, with products to secure the efficient and safe operation of the grid. There are two kinds of products that could be traded. Balancing products, already well established by the Electricity Balancing Guidelines, and Congestion management products at the distribution level. The second ones will arise with the forthcoming system transformation.
  Before the existence of such markets balancing products where mandatorily provided by large PGMs and loads, in most cases with a compensation payment but not participating in an open market.

A more in-depth approach to electricity markets, mainly the flexibility ones, will be done when approaching the new European energy legislation. Since, as it will be seen, they are expected to play a crucial role in order to fit new DERs in the distribution grid.

Finally, it is interesting to get an initial idea of a topic currently under debate among the power system research community: Centralized vs Decentralized markets.
The inertia of a crucial infrastructure like the power system dragged the emergence of electricity

markets through the same conceptual framework where everything was initially conceived: a centralized approach where a single agent (TSOs) is the final responsible entity for the correct operation of the grid. The needs of the forthcoming power system with influencing agents distributed throughout all grid levels claims for a reformulation or a revolution of the actual control structure.

Some authors, [9, 18, 19], and even System Operators (e.g. *EnergiNet: Evaluation of market models for new agents* [20]), while accepting the potential of other concepts, are focusing on how the centralized market design should be reconfigured to enhance the inclusion of all the new agents to electricity markets. This is what is happening in the most advanced market designs nowadays, [21, 22]. Other authors [23, 24, 25] instead, think that the natural way to adapt to this new challenging scenario is by changing the management of the markets from a centralized approach towards a decentralized one. In this situation, Local Energy Markets (LEMs) and Local Flexibility Markets (LFMs) would take a prominent role as trading platforms between end-users and system operators

3.2 Towards a New Model

The vertically integrated facilities that composed the traditional grid scheme – where a single company owned all the assets of the grid, from generation, transmission and distribution to energy supply companies– are not viable anymore. European legislation first pointed towards the unbundling of the power system to enhance efficiency via competitiveness. Nowadays, and since the publication of the Second Energy Package in 2003 by the European Commission, the directives and regulations related to electricity aim to create competitive markets to provide all the products and services related to the power grid [10, 11]. Furthermore, when the objective of decarbonization of the energy sector by 2050 was set, a legislative drive was given to promote an increment on the share of RESs and DERs in the power system. This started with the Third Energy Package in 2009 and has been followed by the recent Clean Energy Package outcomes in 2019.

Due to the "distributed" nature of RESs, one of the main drivers of the change, the new paradigm seems to rely on the distribution side of the grid, which up until now has been relegated mainly as an intermediary connecting generation and loads. In this new scheme a lot of new agents and concepts arise out of necessity, and the most general one is Distributed Energy Resource. The following section is organized, starting from the DER concept and going deeper to define new agents and their roles comprehended inside it.

Distributed Energy Resources are the present and especially the future of the power grid [26, 27]. Inside the amplitude of the term, a wide range of electrical systems connected to the distribution side of the network can be encompassed. However, nowadays DER definitions are mainly orbiting towards generation; concepts like distributed generation (DG) or embedded generation are commonly used, although important components like ESSs and inverters face problems because of the narrowness of this generation-focused approach.

In order to address this lack of clarity of the DER concept, the definition by Moskovitz [28] is given: "*Demand-and supply-side resources that can be deployed throughout an electric distribution system (as distinguished from the transmission system) to meet the energy reliability need of the customers served by that system. Distributed resources can be installed on either the customer side or the utility side of the meter.*" This definition overcomes the generation-only approach, and it can encompass all the technologies and agents of the forthcoming grid. As will be seen through the report, adequate definitions are crucial to properly fit new technologies and agents into the grid framework via regulatory updates and thus removing uncertainties and technical hindrances.

On the other hand, there is the utterly generation-focused definition by the Institute of Electrical and Electronics Engineers (IEEE): "*the generation of electricity by facilities that are sufficiently smaller than central generating plants to allow interconnection at any point nearly the load in the power system.*" [26].

From the generator perspective, DERs tend to be divided in two main types:

a) **Renewable Energy Sources**: Maybe due to their crucial role in the energy transition when talking about DERs is common to think of RESs. Unlimited energy availability characterizes RESs. From a grid perspective, they have another key characteristic: the most common RESs have variable generation profiles, which means that they are not always producing at maximum capacity. This brings up a new problem for grid planning and management since the widely used worst-case scenario method for scaling the network

can lead to underused infrastructures and high costs of investment [17].
This kind of RESs is known as Variable RESs (vRESs).

b) **Non-Renewable Energy Sources**: These generators use the same technologies as the traditional PGMs that still sustain the grid, so in these terms, they can not cause any new issue. However, generation profiles within the new scenario may not be a 100% technology dependant. In some cases, they could depend on the owner of the asset decision to stop injecting energy to the grid. This, in the end, could also similarly affect the grid as vRES power generation variability does.

It is also important to define that DG can take place on two distinct levels, local level (utility side of the meter) or end-point level (customer side of the meter). While local-level DG comprises all sizes and kinds of generators, for instance, RES and non-RES (see [5] on Denmark high DG penetration), end-point level tends to be composed by small size generators typically from renewable sources. Another distinction that must be made between the operation modes of DG:

- **Isolated mode**: Only supplying to the local load.

- **Grid Connected mode**: Supplying energy to the load or to the grid depending on the circumstances, this model is the most challenging for the grid.

3.2.1 Distributed Generators

As power generating modules, distributed generators present some inherent characteristics that are seen as advantages respect to conventional PGMs. Article [26] presents the following list:

- **Modular structures**: Aggregation of different DER assets is possible. This characteristic can help to sort out the disadvantages of some technologies, like variable generation, or zero production due to one component failure. It also enhances investments due to scalability it provides to such installations, that can open the generation market for smaller investors.

- **Inter-technology modularity**: Due to their power electronics interfaces some DER technologies can be clustered in the same power park, which can create more efficient installations in terms of generation

- **Installation time**: The short installation time is one unique point of DG. However, the larger the module or installation, the harder it will be to install. Nevertheless, even in the case of large DER power parks, the time needed to be operative is much smaller than in a conventional plant.

- **Immediate start up**: Always depending on the installation design, but in some designs, each asset or cluster of assets, could start operating as soon as installed. This enhances the profitability of the investment compared to traditional technologies that need to be 100% installed to start operating.

- **Cascading new modules overtime**: Some of the technologies, mainly RES, allow cascading on modules later, or even the transportation of modules from one location to another. This allows for flexibility in terms of re-sizing of the power parks if it is needed in the future. Flexibility, in the end, erases barriers for investors.

Moreover from a more holistic perspective, the change of paradigm towards a higher RES implementation, widespread of distributed generation, unbundling of the power system ownership and the democratization of all the levels of the power system, can have some positive impacts, among others some listed in [29] are:

- **Reduction of investment costs**: In terms of generation units (depending on the size of the DER installation, the investment costs can be even covered by individual consumers) and grid reinforcement needs.
- **Reduction of the environmental impact**: DER-RES can reduce power system emissions, and a proper DER integrated approach can avoid additional emissions by reducing the need for emissions-producing backup generation.
- **Optimized distribution grid operation**: Through coordinated control of DERs.
- **System quality and reliability improvement**: If DG is properly connected and managed.

However, as opposed to the positive characteristics of DGs on their own, the ones towards the grid need from proper planning and coherence –from all the stakeholders involved– to be functional and effective. Otherwise, the impacts from high penetration of DG can be negative.
Some possible drawbacks mentioned in [30] are :

- Small generators could be out of the control of the System Operator, and the smaller ones could not be dispatchable like some big power stations, causing unbalancing of the grid, congestion, and an increase of power loses.
- Strongly fluctuation RES production and new consumption habits can make planning and operation of the system harder.
- The distribution system nowadays is designed for power transport only in one-way, reverse power flows can cause safety relays to trip even when there is no faulty condition.
- The uncertainty of the changes related to the actual environmental crisis could delay investments in large RES plants in order to avoid long-term forecasting errors that can challenge the profitability of the investments. In the same direction, large RES power plants that fail at forecasting their average capacity at long-term can entail problems for the power system planning and uncertainties for the markets.

For more information and real cases, see [31] for a technical approach and [29] *Chapter: Germany's Experience* for a real case-study.

3.2.2 Connection of DG to the Distribution Grid

Large synchronous PGMs rule the traditional power generation model. This type of technology is characterized by the coupling between the kinetic energy of the generators and the frequency of the power system. This link is a fundamental pillar of the actual grid, which has its drawbacks in particular cases, but when everything is properly functioning helps to have a well-balanced system. Even in some cases when significant frequency deviations happen, PGMs can help with the balance of frequency in the grid via control of the prime mover input [32].

Most of the new DERs are not synchronous generators, and even some of them do not produce

AC. In order to be connected to the grid, all generators must fulfil a list of requirements established by the TSOs. The list of requirements is comprehended inside the system regulation known as Network Code. DG units without the inherent capability to accomplish these rules need to rely on interfaces with the grid that, via Power Electronics, can fulfil these characteristics. With that said, and to clarify further legislative approaches to DG network codes, it is interesting to study how generators can be connected to the grid.

First of all, it is essential to define the connection point of an energy source to the grid. It is usually referred to as the Point of Connection (PCC) [30]. There are two possible definitions of PCC, depending on if it is before or after the interconnection transformer. In this case and following the choice from [30] the PCC will be assumed to be before the interconnection transformer, see *Figure* 5.

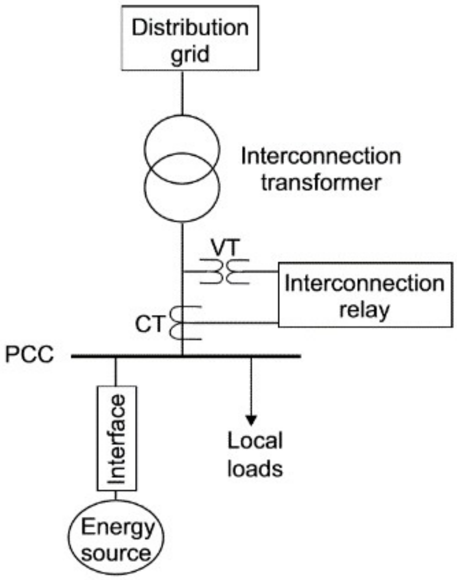


Figure 5: Definition of Point of Connection. Source [30].

The key link between the generator and the PCC is the interfacing technology that adapts the power output of it to the requirements of the grid. There are different interfacing technologies used to connect various types of generators to the grid. The following list, together with Table 1, both extracted from [30], give a quick overview of each interfacing technology existing. Furthermore, Table 1 compares them in terms of control, robustness, efficiency and cost.

- **Direct Machine Coupling**: As the name suggests, no interfacing technology is needed to connect the generator to the grid.

- **Full Power Electronics Coupling**: In this case, there is a fully working interface technology between the generator and the PCC or the grid. This is usually caused by the inability of the generation source to fulfil the grid requirements. The interface can also help to maximize the performance of the energy source.

- **Partial Power Electronics (PPE) Coupling**: In this case, the interfacing technology is not rated for the full potential of the DG source. Instead, other benefits arise. One example of this approach is Double-feed induction generators where the PPE approach allows to decouple mechanical frequency and electrical frequency. It is usually used in wind turbines.

- **Distributed Power Electronics Interfaces**: This is not a technology; it is a way to manage the system consisting of dividing the power plant into sub-modules, each one with its power electronics interface. Then, there is a general interface managing all the sub-modules before the PCC. This approach, despite the higher costs, has also been proved to be better at maximizing efficiency.

Table 1: General comparison of Interfacing Technologies. Source [30].

Interfacing technology	Controllability	Robustness	Efficiency	Cost
Induction generator	-	-	+	-
Synchronous generator	+	+	++	+
Partial power electronics	++	-	+	++
Full-power electronics	+++	-	-	+++
Modular or distributed power electronics	++++	+	+++	++

"-" for Less and "+" for More.

If the technical installation before the PCC is a key point to assure the fulfilment of the minimum requisites to be connected to the grid, the way this interface manages the energy production of the module can also influence the grid. In [33] a general classification on different behaviours of Battery Storage Systems (BSSs) towards the grid, that can also apply to DG, is made:

- **Grid Compatible**: It consists of the fulfilment of the minimal requirements regarding quality, reliability and safety at the distribution grid level (DSO imposed).

- **Grid Supportive**: Besides of the fulfilment of the minimal requirements, the power-generating profile of the DG adapts to the needs of the grid. It has a local component, for instance, adapting the asset generation profile to avoid local over-voltages.

- **System Compatible**:It consists on the fulfilment of the minimal requirements regarding quality, reliability and safety of the whole electrical system. It is a broader approach that may be required for larger DGs connected.

- **System Supportive**: Besides of the fulfilment of the minimal requirements, the power-generating profile of the DG adapts to the needs of the system. In this case, the provision of ancillary services like balancing services could serve as an example.

However, while the *Compatible* approaches are guaranteed by Connection Codes defined by TSOs and DSOs –if existing for new technologies and agents– the *Supportive* approaches, specifically the ones at distribution grid level, nowadays are hard to achieve due to the lack of communication and coordination between agents in the system. It also has to be taken into account that this is not a non-profit system, so the *Supportive* approaches shall be adequately remunerated, preferably via market mechanisms.

For instance, the project CrowdNett [34] is an example of a BSS created by virtual clustering to provide ancillary services, showing that physical or virtual clustering of assets could be the best option for prosumers to reach the minimum requisites to provide supportive services to the grid.

The introduction of instrumentation to monitor and control DGs and loads –as a part of the more extensive Smart Grid (SG) concept– is the most effective way to achieve distribution-level grid-supportive services, due to the locational characteristics of the new power system.

3.2.3 New Agents

In Section 3.1.1, the traditional agents of the power system were introduced. However, the system is constantly evolving since the change started with the introduction of unbundling principle. Nowadays, the prevision of an increased share of DERs is making tremble the foundations of the power system in some countries. This shake of the system is changing the traditional roles of the well-established agents and is producing new agents and roles that can be fundamental to stand such a challenging scenario.

Based on [23], the agents of the following list are the ones that will arise, or change their actual roles, on the forthcoming power system:

- **Transmission System Operator**: The role of the TSO may be the least affected by the change of paradigm. However, since it is responsible for the correct operation of the transmission system, ensuring stability and generation-consumption balance, its role may not change entirely. However, more coordination and active intervention than ever will be needed.

- **Distribution System Operator**: On the one hand, the core-roles of the DSO will remain the same, ensuring the correct operation of the distribution grid and its maintenance via network planning [35]. On the other, the increasing amount of generation connected at distribution level together with the drive directed to the creation of Smart Grids points towards a radical change of DSOs business models; from passive to active managers of the distribution grid in order to minimize costs and maximize the possible operational benefits. The *The EU Clean Energy Package* technical report [35], also define new possible roles for DSOs aside from the grid management such as Data management and EV charging infrastructure.

- **Balancing Responsible Party (BRP)**: It is defined by the **e-Regulation** *Art. 2(2)* [14] as "*a market participant or its chosen representative responsible for its imbalances in the electricity market*". In other words, it is the market agent that –since the liberalization of the system– takes the responsibility to maintain continuous balance in a specific area of the power system, also known as its portfolio. The overall balance responsible is still the national TSO, but BRPs are entities liable in front of the TSO, for the balancing of the area where they operate.
  The change of paradigm where end-users are not passive anymore opens a wide and complex field of responsibilities and interactions between BRPs, Retailers and Aggregators, that will need to be clearly defined. (See [35] for further information on balancing responsibilities)

- **Retailer**: It is a commercial entity that buys electrical energy from the BRP or the market (depending on how they manage balancing responsibilities) to provide it to the end-users. With the change of paradigm, the retailer role may change towards a mix between the already existing one and the aggregator role.

- **Energy Services Company/Aggregator service company**: It is an already existing agent since the liberalization of the system, which acts as an intermediary between smaller entities and the market. In [35] it is defined as follows: "*An aggregator is an energy service provider who can change the electricity consumption of a group of electricity consumers and provide demand-side flexibility to the grid.*" For instance, industrial loads providing DR services have to establish themselves as aggregators (a legal figure) in order to provide services to the grid.
  The role of the aggregator among small loads and generators will arise with the emergence of consumer empowering technologies. For instance, smart meters and remote-controlled generation/demand assets can allow prosumers to overcome the barriers to participate in electricity markets via aggregation. However, it is crucial to define a proper regulatory framework in terms of market participation and technical requirements of the aggregated pool to unleash its full potential [35].

- **Prosumer**: With the expansion of RESs and other generation technologies scalable to smaller sizes, a new role emerges on the energy system, the prosumer. Prosumers can be defined as that end-user which do not act as a passive load anymore because it has capabilities to generate and in some cases, combined with ESSs, to store energy from their plant or the grid.

- **Generating companies**: In the liberalized market before the DER penetration arises, they were entities that produced and sold electrical energy. Again, with the change of paradigm, the definition of Generation Companies could become dim, because some aggregation models could rely on the same revenue model but form a different business perspective.

With the main agents re-defined, it is also worth mention a few technologies or consumers habits that can influence the way the new system evolves:

- **Energy Storage System**: Up until now, if comprehended in the power grid, it was in the form of Pumped Hydroelectric Energy Storage (PHES) which was defined as a generating unit with its embedded requirements. Nowadays, energy storage systems mainly as electro-chemical storage technologies, also known as Battery Storage Systems, are experimenting a boom, either from end-users or other users such as industries and even system operators. In most of the arising use cases its operational definition is not so clear because they can operate as generators but also as loads (see Section 6 for further information).

- **Demand Response**: Demand response can be defined as the changes in electricity usage by loads from their normal consumption patterns in response to changes in the price of electricity over time. Furthermore, DR can also be defined as "*The incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.*" [36]. It is not a new approach to electricity consumption because big industrial loads have been providing it for a long time, and price-variable tariffs are not a new thing. However, the combination of new agents and technologies of the future electricity system will enhance the impact of demand response strategies.

3.3 Challenges and Opportunities Arising from DG

Over the years network planning has been carried out by TSOs and DSOs coordinated, and the power-flow profile was –and still is– mainly uni-directional from Large PGMs (HV) to the final customer (mostly MV and LV) [31]. Before the firsts laws from the EU promoting the liberalisation of the market, the structure of the grid system operators was vertically integrated [30, 10, 11], so the network planning was easier due to higher control of all the variables related to energy production and a proper forecast of demand.

With the liberalisation of the electricity markets all over Europe – due to the promotion of directives such as the ones in the First, Second and Third Energy packages (respectively: [37, 38, 3]) to create a more robust internal market [30, 27] – grid planning faced problems related to generation forecast. Because at that point the generation at the HV side of the grid was not 100% planned anymore. However, the network overcame the problem establishing rules where these new agents must inform of their operations a centralised organisation in order to maintain the balance of the system, and creating a markets-system where TSOs upload their needs and generators their offers.

Nowadays the EU is promoting another change in the structure of the electricity market, imposed by the need to decarbonise the energy sector by 2050 and the willingness to empower the citizen changing its role from pure consumer to a new agent in the market [27]. This is mainly going to be done by promoting the integration of DERs in the distribution grid which supposes an entirely new approach to the grid management. Challenges like reverse power flows and an increase of voltages near the point of coupling, among others, will arise. This structural change of the electricity system has been changing habits in the sector for some years now, and with these new ways to proceed challenges have arisen, from [30] the main changes can be classified as:

- With the liberalization of the generation, system operators are less capable of limiting connections of new generation assets which can drive the grid, at some locations, to its limits.

- Formerly traditional PGMs location was determined considering the interests of the system operator and the constraints related to the construction of such large power plants. Nowadays, the location of new RES power plants is instead related to energy source availability.

- RES generation tends to connect at distribution level instead of transmission level where all the main PGMs were connected.

- Democratization of generation assets which, other than the new cases stated above, can transform traditional passive-customers to active customers and thus increase the variability of the demand.

These four changes in the power system structure can and will be an improvement in terms of clean generation, increased energy efficiency, customer empowerment, and grid reliability, among others. However, the truth is that nowadays most of the European grids are far from being ready to face such challenging opportunities and these new approaches are also making arise new problematic, and not-so-new ones, that can be divided into two main groups:

a) **Generation and load balancing**: If there is no balance between generation and demand, the frequency of the system starts to deviate from the nominal value; this may be a problem for some electric/electronic loads. However, the main concern arises when large PGMs are synchronous machines. In an intense frequency deviation event some PGMs may trip from the grid, causing even a harder frequency deviation. This domino-like problematic is called cascade tripping and can lead to a local or even "global" system blackout. This problematic has been a concern for the system since its beginnings because the load forecast is not always accurate. However, large PGMs can be mandatorily disconnected from the grid for safety purposes [30]. Then, the challenge increased with the liberalization of the generation market. Nowadays, with the introduction of DER and the empowerment of the user via demand-modulation strategies, the future forecast of generation and demand is expected to be more challenging than ever.

b) **Distribution grid congestion**: Grid congestion, mainly at TSO level but also at DSO level, has always existed. However, due to the traditional operation of the grid, the fit-and-forget approach consisting of investing in expanding the infrastructure was the most cost-efficient approach at the distribution level. With the uncontrolled connection, in terms of number but also location and characteristics, of new DER assets to medium and low voltage grids, a new grid structure may be needed from the fit-and-forget perspective. However, this does not seem either rational nor cost-effective viable, and instead, these new congestion challenges will need to be addressed from an active (real-time) management approach.

3.3.1 Balancing Problems

The effects of the balancing problematic caused by the integration of DER can be considered as system incidences because unbalances should not affect the lifespan of the components of the grid. From this perspective, no investment in infrastructure by TSOs and DSOs can solve this problematic.

Two are the main concerns related to balancing within a grid with an increased share of DERs:

- Uncontrolled generation and loads: The widespread of uncontrolled DERs throughout the distribution grid, together with the increased unpredictability of prosumers loads, head the grid towards a new situation where frequency deviations –caused by generation-demand unbalances– will be more frequent than ever before [39].

- Debilitation of the frequency inertia [40]: Most of the DERs that will cause this change in the power system are RESs which need a power electronic interface to be connected to the grid. This kind of generators are known as asynchronous generators and are not sensible to frequency deviations. This means that when a special event occurs they do not naturally react opposing to such deviation. Instead, a synchronous generator would "react" due to its rotating inertia. Consequently, the resulting grid will be more prone to frequency deviations, and the generators composing it will not react opposing to them, at least as a "natural" response.

The forecasting errors are a challenge for the forthcoming grid. Their consequent unbalances instead are possible issues that need to be addressed before anything happens, either via obligations to all generation units (Connection Codes) or via commercialization of the solutions (Market Codes). If this situation is not properly addressed the grid will face serious reliability problems with an increasing number of local or even global blackouts due to the tripping of the safety switches. The debilitation of the frequency inertia can be solved by imposing synthetic inertia obligations to all asynchronous generation units, via their power electronics interface, or creating a market for this kind of products.

3.3.2 Distribution Grid Congestion

The dynamics of the power system are changing towards a new model where large generators on the HV side of the grid are being replaced by smaller generation units placed at the MV and LV side of the grid. This increase of penetration by DG will have a significant impact on how the grid behaves. At the distribution level, technically speaking, DG will make arise some new challenges and, in some cases, problems already solved will rise again. These problems can be classified into four main categories as done in [1] and [30]:

- Overload and losses of feeders and transformers.
- Risk of overvoltage.
- Power quality disturbances.
- Incorrect operation of protection.

Figure 6 gives an schematic idea of where in the distribution grid can be usually located the issues listed above.

From the literature sources reviewed, [30, 31, 26, 29, 40, 41, 42], the main concerns regarding high penetration of embedded generation at distribution level identified are *Risk of overload* and *Risk of overvoltage*, the other two subsections are less of a concern. That is why the following section develops these two topics more in-depth.

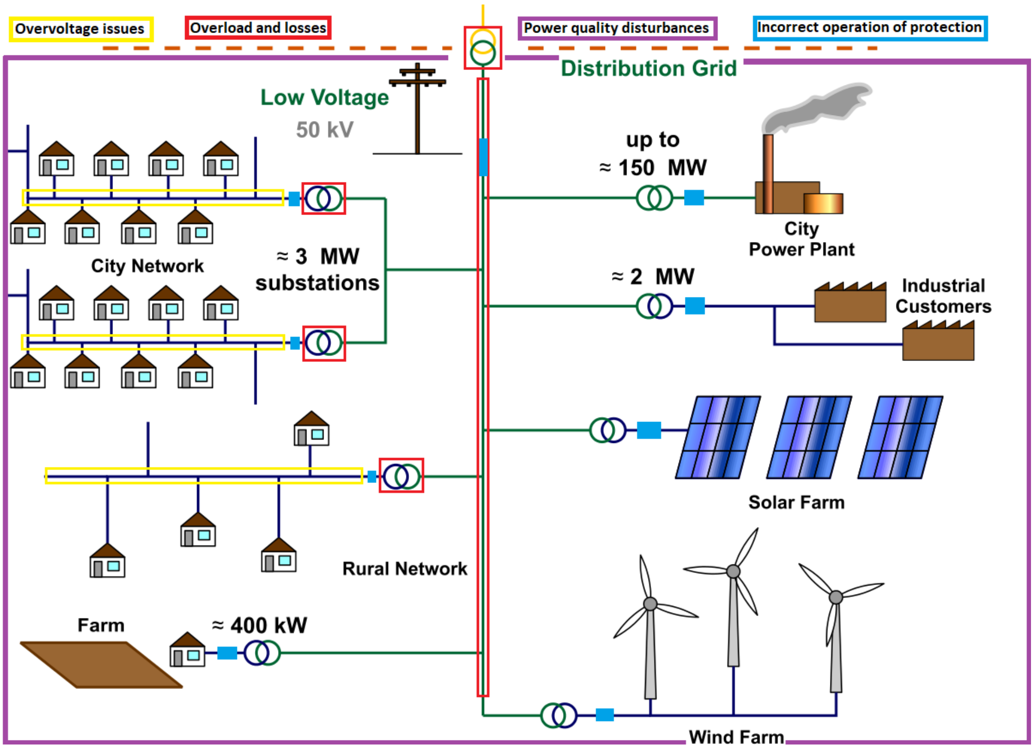


Figure 6: Main component of the distribution grid affected by each congestion problem. Source [43].

Overload and losses of feeders and transformers:

Overload, also known as overcurrent is that situation where a current value above the electrical component limit is passing through it. This situation can lead to a) **Electrical component wear** if the value is not well over the secure operational limit and the situation is not sustained for a long time, or b) **Electrical component failure** if the intensity limit is exceeded substantially. However, once the loadability of a component is exceeded the overload protection should trip the component. This will lead to an interruption of the service [30], but the integrity of the component should be guaranteed.

From the new power system scenario, two are the arising agents that can cause overloads, on the one hand, the increased electric load due to electrification of existing assets like vehicles or heating systems. On the other hand, distributed generators.

From the load perspective, if the feeder is designed to provide X amount of power trough it but the load connected increases, also will increase the power needed to supply it. If not adequately addressed via grid expansion or other methods, this situation can lead to a feeder overload.

Whereas, from the distributed generator perspective, the electricity is not consumed but fed into the grid. In this situation, the overload problematic can arise if the total power flow after DG connection, supposing no other power source providing energy, exceeds the value before the connection. This problematic will depend on how close the feeder to its maximum capacity is. For instance, if the feeder was working at 50% of its capacity, more significant amounts of distributed generation will be needed to overload the feeder than if it is working at 95% of its capacity.

Also, it has to be considered that feeder capacity varies along the feeder. This is because at the beginning of the line the power that needs to be provided is the sum of all the loads. Instead, closer to the end of the line the power that needs to be delivered is the one of the loads remaining. So, feeder capacity to allocate DG can vary depending on the location of the generator connection point.

Some interesting simplified capacity indexes are given in [30] to assess if the DG penetration may cause feeder overload. However, a more profound study will be needed to address adequately this multi-variable problematic. In the following section, some indexes proposed on the reviewed literature are given.

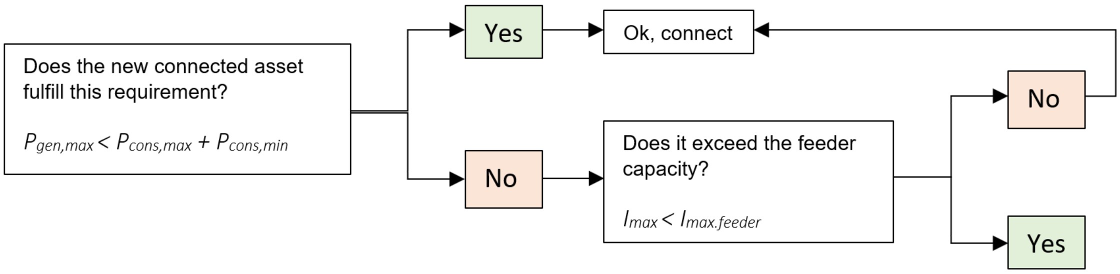


Figure 7: Simplified algorithm for a first evaluation of DG connection to a feeder. Based on: [30].

On the other hand, power losses tend to be reduced by the implementation of distributed generation, even at the distribution level, because generation tends to be closer to the load. The higher reduction is obtained when the generation or DER is installed behind the meter [30], meaning zero power is borrowed from the grid.
However, things change when there is an unbalance between demand and generation caused by DG current injection to the grid, then reverse power flows can cause an increase of transmission losses.

If appropriately used, DG can help to reduce overloads due to new loads connected. Strategically placed DERs can reduce the need of higher power flows upstream the feeder, which eventually can suppose staying inside the feeder limits [5].

Overvoltage:

Overvoltage is that situation that occurs when the voltage value is over the nominal one expected from the grid. If the real voltage value goes much higher than the nominal value, it can ruin the electric loads connected.
Voltage magnitudes variations have always been a concern for system operators. However, before the high share of DERs scenario, it was mainly a concern in terms of Undervoltage.

Undervoltage can deteriorate the overall system quality perception but cannot harm the components connected to the grid. These under voltages happen due to the inherent impedance of the transmission and distribution lines. Hitherto the grid planning for voltage control has gone as follows: From the transformer at the substation to the last user connected, the voltage output of the transformer was set to stay within acceptable values. The initial voltage value was determined to account for the voltage drop along the feeder. To maintain the voltage onto its limits, despite load variations, usually off-load tap changers (transformers with different turn ratios) were used.

From this approach the representative stationary picture of voltage profile in a feeder is like the one in *Figure* 8.

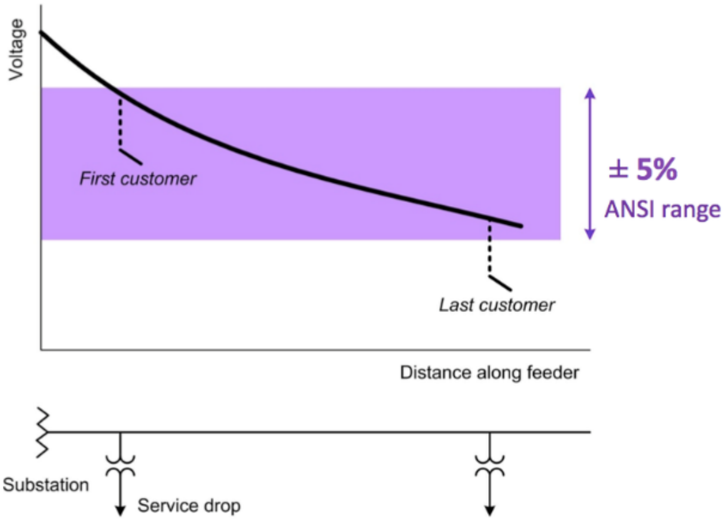


Figure 8: Voltage profile along a feeder without DG. Source [43].

If a generation unit is connected at the feeder, the voltage profile will rise at the PCC of the asset and thus down the feeder (assuming that it is injecting 100% active power). This, in some cases, can lead to an overvoltage.
Approximate formulas to assess the voltage rise are given in [30] and [31]:

$$\boxed{\frac{\Delta U}{U}=\frac{P_{gen}\cdot R_{PCC}}{U_{nom}^{2}}} \longrightarrow \boxed{\Delta U_{gen,max}=P_{gen,max}\cdot R-Q_{cons,max}\cdot X}$$

Figure 9: Voltage variation formulas. Based on: [30, 31]

If the asset is capable of reactive power consumption, it will have the capability to provide more power to the system without endangering it. However, most of DG technologies are asynchronous generators, so naturally, they do not consume reactive power. An exception are induction generators that in the DER-RES group are represented by some specific types of wind turbines. It is also true that power electronics interfaces, mainly inverters, have the technical capacity to "generate" reactive power from the 100% DG active power sources. Furthermore, new options start to arise with new technologies allowing for aggregation. For instance, if the asset connected behind the PCC is an aggregation of a DG plus a capable of consuming reactive power asset, this can create an interesting mix for the grid.
Nevertheless, it has to be taken into account that feeder composition also plays a crucial role [30]. For small X/R ratios (small cross-sectional wires) the possible impact of reactive power

consumption on the overall voltage variation will be less significant than in those feeders with big X/R ratios.

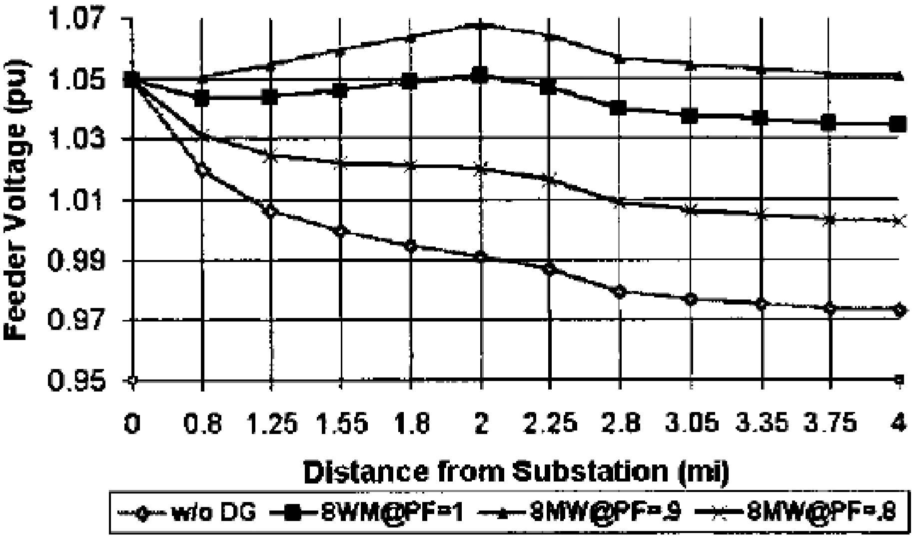


Figure 10: Voltage profiles with different DG penetration. Source [44].

Finally, it is important to mention that all the cases commented on these sections are simplified versions of the real scenario, because only one-asset at a time connected to the grid is considered. However, the increased share of DG expected for the following years leads to an uncertain scenario where active grid management will be a prominent operation strategy to enhance.

Power quality disturbances and incorrect operation of protections:

Power quality disturbances is a term that encompasses all the problems related to the deviations from the nominal values of the power system. It encompases voltage and current deviations, together with unbalances. However, due to their high probability and impact, a deeper insight of Overload, Overvoltage and Unbalances is considered to be important. Instead, the other power quality disturbances are not so related to DG penetration and therefore, will only be mentioned. Sourced from [30], these are some of those disturbances:

- **Fast voltage fluctuations**: “Voltage flickering” these voltage fluctuations are concern usually for vRES like wind power or PV. However, they can be solved usually via the aggregation of single assets into a power park with a common PCC.

- **Low-frequency harmonics**: The introduction of new DG assets fully power-electronic-interfaced can lead to the rise of some harmonic values that up until now were not considered. The problematic regarding the effects of these harmonics over electronic devices are not clear yet.

- **High-frequency harmonics**: In this case, the cause is the same. Caused by voltage source converters, high-frequency harmonics can lead to system resonance that can end with a high-voltage distortion. Germany has established guidelines to limit the frequency emission of new RES assets connected to the grid since 2011 (see [45, 46]).

- **Voltage Dips**: DER generation behave equally to standard generation units or in most cases even better due to their mostly asynchronous nature.

Incorrect operation of protection mechanisms is also a relevant concern for the grid.This is caused mainly due to the new situations created with the connection of generation at distribution level. Two type of faults can happen:

a) **Unwanted operation**: Trip of the safety switch where there is no fault.

b) **Failure to operate**: Switch do not act when there is a faulty condition.

3.4 Hosting Capacity Index

Technically speaking, but also from a regulatory point of view, to make the transition easier for the grid and the new agents, new tools will be needed to assess whether or not DG should be connected to the grid and where. In fact, while investors are looking forward to more and more DG integration, DSOs are concerned about the increase of problems caused by high DG penetration [47]. So, there is a need of appropriate indicators that determine the capacity of the local distribution grid to integrate new sources of energy, This should be based on Key Performance Indexes (KPIs) to assess the benefits and disadvantages of each new DG coupled to the grid. For instance, in Table 2 there are some examples of KPIs to evaluate the performance of a distribution feeder with embedded generation and DERs.
The definition of KPIs could also benefit, by promoting their spread, those new technologies that have the potential to help with grid stability and security, such as batteries.

From this need to quantify the potential of DG that can be integrated into the grid, a new concept appeared: *Hosting Capacity*. Hosting capacity (HC) was described by Bollen et al. [48] as "*the maximum DER penetration at which the power system operates satisfactorily*". Performance limits will determine when the power system is operating satisfactorily and when it is not. These limits are the ones mentioned in Section 3.3.

From all the indexes studied to evaluate HC, there are a high amount of articles –among others [49, 48, 50, 51]– highlighting overvoltage as the main limiting KPI in terms of feeder HC, when considering a high amount of DG penetration. However, not always overvoltage will be the factor limiting the HC of a feeder. Furthermore, overvoltage per se is not a KPI. *Table* 2 based on [52] gives other relevant indicators to assess DG penetration together with the correspondent evaluation method:

Table 2: KPIs to asses the Hosting Capacity of a distribution feeder.

Feeder limitation	*KPI*
Overload and Overvoltage	a) Highest 1h/10 min average current/apparent power/ active power. b) Maximum temperature of the component during a time period. c) Probability of overload-protection tripping
Losses	a) Feeder generation mean (It should be less than twice the load mean)
Fast Voltage Fluctuations	a) Short term and Long term flicker indices (standardized by IEC 61000-4-15)
Harmonics	a) IEC has stablished threshold values for interharmonics b) For superharmonics not a clear HC index is yet defined, research is on course.
Number of events	a) Overload-tripping protection

The Hosting Capacity concept is a relatively recent term, defined for the first time in 2011 [31] by Math Bollen et al. in [30]. However, when developing the concept during recent years, some researchers have identified that the original HC concept lacks from flexibility and simplicity, plus in order to provide a correct evaluation of the grid capacity, it needs to be applied multiple times along the feeder with a lot of KPIs involved. From this perspective, a lot of HC indexes have appeared in order to make the feeder HC calculation more accurate and more accessible. Regarding all the new HCs in existence, the Locational Hosting Capacity (LHC) and its illustrative application proposed in [31] seems to us one of the best options to make the HC concept accessible for all the agents in the power system. LHC could improve the transparency of the network and make it easier for the prosumers and other grid stakeholders to understand the grid and even cooperate with the DSOs to help in the grid management.

Figure 11 shows how the LHC index could be applied to provide information about the hosting capacity of the distribution grid at a given time. This kind of representation of the HC could give a quick assessment of where it is possible to connect DGs with no restrictions and where some further evaluations are needed.

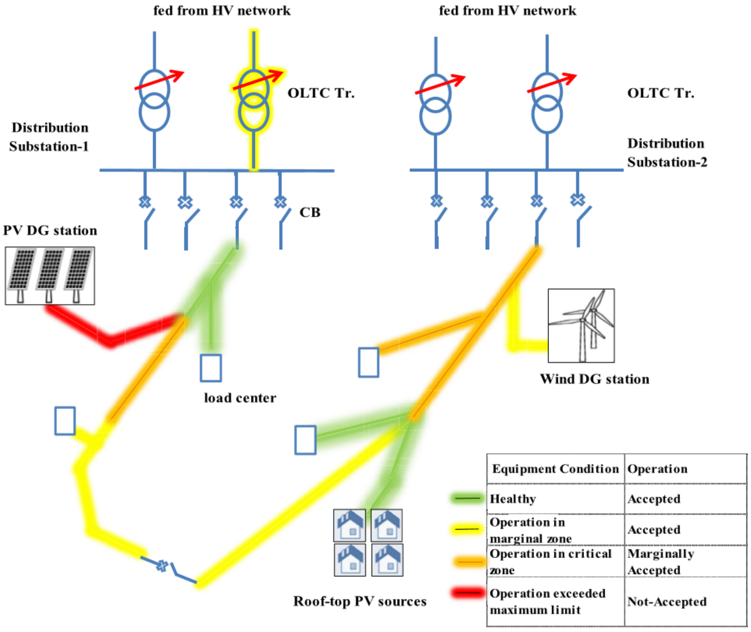


Figure 11: Locational Hosting Capacity illustrative map. Source [31].

Overall, and as already said, HC is neither an index that can be calculated with only one variable of the local distribution grid, nor a constant value through the grid. So, HC should be regularly calculated for various performance indices, such as voltage and frequency variations, power quality, etc. And then taking the worst index value at each node of the grid to estimate the overall system's HC. This approach to HC calculations is given in [31] and [49], and although the complexity it implies, it seems to us a good way to assess the real HC of distribution feeders.

Figure 12 is a graphic representation of the proposed HC procedure applied to one node of the gird.

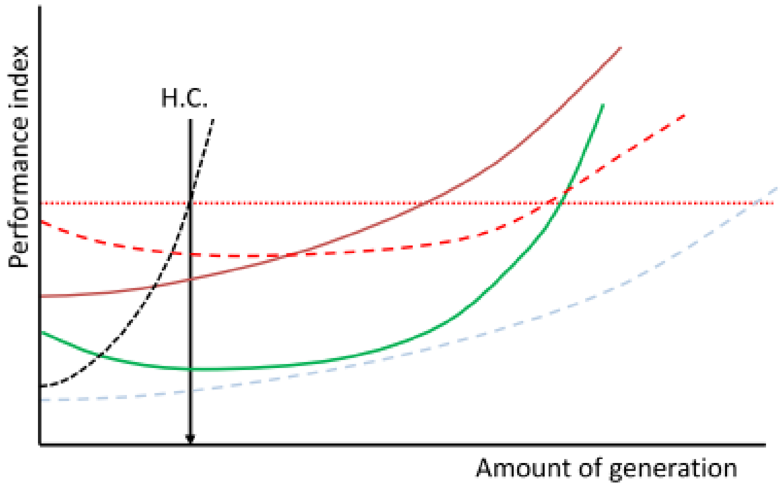


Figure 12: Multple KPIs in the Hosting Capacity calculation for a node. Source [49].

The HC concept was defined to assess the grid capacity of DG connection at any given time. The next logic step, after the HC definition, is to study, which are some of the strategies to improve the HC of a grid. Some HC enhancement methods are proposed in [31]:

- **Network reconfiguration and reinforcement**: It is the classical approach to improve network capacity, also known as "fit-and-forget". However, in the case of DG, it could be not worth from a cost-effective point of view, due to the high variability of vRES power output. The classic approach to grid reinforcement (worst-case scenario) can lead to infrastructure with a low utilisation rate [33].

  There are two approaches possible, Static or Dynamic reconfiguration. The first can be defined as investing in infrastructure, while the second one consists of the use of remotely controlled switches to manage the power flows. However, the Dynamic reconfiguration operation strategy can wear the switches since the current ones are only thought to operate under certain conditions. Some of the following techniques are comprehended inside a broader concept known as Active Grid Management, inside which Dynamic reconfiguration is comprehended too, but with the appropriate assets to do it.

  It is relevant to notice that, while it may not be the best long-term option, network reconfiguration can be efficient for HC enhancement for grids with low DG penetration [31].

- **Reactive Power Control**: These techniques are believed to be the most effective methods for relieving overvoltage problems [31].
  Table 3 shows the most common techniques classified by the market agent that will use it the most.

Table 3: Reactive Power Control methods.

Method/User	*DSO*	*Prosumer*	*Interactive*
Shunt/Series Capacitor bank	X		
Static VAR	X		
STATCOM	X		
Local generation asset + Power electronics interface		X	X

- **Voltage control using On-Load Tap Changers**: On-Load Tap Changers are one of the most practical tools providing automatic compensation for the voltage profile in the network. It consists of a transformer able to change its winding while power is passing through it. This allows the system operator to give a response to the grid needs in terms of power and safety by managing the transformer at the beginning of the feeder.

- **Active power curtailment**: It occurs when DGs are asked to decrease their power output to match the demand requirements. RESs are the primary agents affected by Active power curtailment strategies, due to the "easiness" – lower costs and even risks– of the curtailment operation. In [31] and [49] the following two curtailment strategies are listed:
  - **Soft curtailment**, the generator is forced to reduce the output to adapt to the grid HC limit.

  - **Hard curtailment**, the generator is forced to disconnect from the grid.

  In some cases, curtailment strategies can be a problem for the grid agents, because curtailed energy has to be paid [53]. Hence, it increases the final costs of generation, and this is passed to electricity tariffs.

- **Energy Storage Technologies**: Can provide a wide range of ancillary services to the grid thanks to their main characteristic, as stated in [31], "*it allows demand and generation to be mutually decoupled which is a new scenario in the energy sector*". ESSs can provide robustness and flexibility to the distribution grid, and in fact, some DSOs are starting to experiment with the flexibility provided by energy storage to provide ancillary services for a better operation of the grid. As an example the Project CrowdNett by an "affiliate company" of ENECO a Dutch DSO [34] (some similar projects can also be seen at [54]).
  One major problem with BSSs, which is one of the scopes of this project is that there is, not yet, neither a clearly defined specific regulatory framework nor a proper market framework to benefit from all their potentialities.

- **Harmonic mitigation techniques**: DG will introduce in the power system harmonics that have traditionally been residual (even harmonics, inter-harmonics, . . .). Some regulatory-permissible values for this kind of harmonics are low nowadays because traditional generators do not emit them. [30]. So, in order to avoid unnecessary HC limitations from this perspective, the real impact of these harmonics on electric and electronic devices should be evaluated. Then the limits of emission of the DG interface with the grid should be re-established.

4 European Energy Policies: Towards a new power system

For the last 15 years or so, climate change, global warming, and generally a more rational approach to production and consumption habits have been an increasing concern for societies with a firmly established welfare state. Related to this new approach to the production system, from the first-day electricity markets have been the target of criticism due to their massive contribution to the emission of greenhouse effect gases [27]. Within the European energy policy context, the chosen way to carry out this reduction of emissions by the energy sector is enhancing a higher penetration of DERs –particularly RESs– in distribution networks. This positioning, while has multiple potential benefits for the grid and its agents, also sets out new challenges. All the perks and disadvantages of a higher share of DERs need to be adequately regulated in order to keep secure the functioning and operation of the grid.

It also has to be noted that inside the EU energy policies, the environmental concern is nowadays one of the main drivers. However, there are also other key objectives to achieve, which in some cases will present synergies, but in other cases, could collide among them.

From another perspective, "not-so-concerned-with-the-environment" countries due to major problems, are also looking to a transition in the generation model. In this case, many factors can drive the decision. However, an important one may be the economic easiness of developing a DG network involving smaller stakeholders instead of making the needed substantial public investments in developing a traditional schemed grid [55].

4.1 History of EU Energy Policies

Even before the concern for environmental protection reached legislative E.U levels, some directives were unintentionally securing the foundations of further changes in the energy sector. The creation of an internal market along the E.U was a thing back in 1996 with the introduction of the First Energy Package e-Directive (96/92/EC [37]). Nowadays, the internal market is one of the pillars of the reliable operation of the power system, and interconnection mechanisms are vital agents to balance the power grid. From the First Energy Package publication on, regulations have been continually evolving. The Second Energy Package e-Directive (2003/54/EC [38]) arrived in 2003 as a "recast" of the First, and implementing more measures towards the unbundling of the power sector and the creation of a common internal market for energy [10, 11]. Finally, the emission of the Third Energy Package in 2009 [3] was the point at which the sustainability concern was added to energy regulations.

The environmental concern showed up in the energy policy agenda in 2007 with the publication of "*An energy policy for Europe*", a document focused on describing the main targets of the European energy policy: security of supply, competitiveness, and –the new one– sustainability [56]. With the publication of the Third Energy Package in 2009, the new internal market started to be also a mean for the new, at least from a public point of view, objective: decarbonization of the electricity market by 2050.

As mentioned above, all these legislation and directives do not only aim to create an environmentally friendly energy sector, all of them are part of the European Union Energy Strategy which is based on five aspects, as listed in [57]:

- **Fully integrated internal energy market**

- **Safer and more trustful energy market**
- **Energy efficiency**
- **Climate action**
- **Research, innovation and competitiveness**

There are other objectives like the empowerment of the consumer to participate in this transition that underlie these five main points, but also will entail challenges.

After the emission of the *Third Energy Package* and its outcomes, the *Winter Package* [27] was published in 2016 as an initiative to “recast” the first one, amending and defining some aspects that were lacking before. The outcomes of the guidelines settled in the *Winter Package* were published on the 5 of June 2019, and this pack of regulations and directives now are known as the *Clean Energy Package* (CEP). The most important laws electricity-wise are: Directive 2019/944 [14] and Regulation 2019/943 [15], also known as **e-Directive** and **e-Regulation** respectively.

From now on, during this report, when referring to **e-Direcive** and **e-Regulation**, we will be talking about Directive 2019/944 and Regulation 2019/943.

Meanwhile, from 2009 to 2019, other legislation and network codes to promote a higher and easier penetration of DG have been published as outcomes of the Third Energy Package. Among others, Requirements for Generators Network Code (RfG NC) [58], Demand Connection Network Code (DCC NC) [59] and Electricity Balancing Guideline (EB GL) [13] standout as critical agents for the creation of a European regulatory framework to enhance the widespread of RESs.

Table 4 contains the evolution of European energy policies started in 1996 with the First Energy Package. On the table, the main objectives and regulatory outcomes are mentioned, together with a column devoted to BSSs. This column indicates if there is any specific regulation or mention of battery storage during the regulatory document. Adding it is not a random choice; we considered it would be interesting to see how previous legislation has regulated towards one of the most promising technologies for the success of the forthcoming "distributed" grid (as it will be seen in Section 6).

Table 4: History of EU legislation on the energy sector. Based on [27, 57]

Directive/Regulation	***Objective***	***Based on***	***BSS***
e-Directive 96/92/EC (1996)	Proposed common rules for the creation of an internal market, to create a stronger and safer electricity grid for all E.U citizens.	No predecessor	No
e-Directive 2003/54/EC (2003)	Updated rules of 96/92/EC (recast) + Enabling new electricity suppliers to enter mss markets.	D. 96/92/EC	No
Third Energy Package (2009): a) Directive 2009/72/EC b) Regulation EC 715/2009 c) Regulation EC 713/2009	a) Liberalization via unbundling supply, generation and networks. + Definition of new agents in the market. b) Reinforcement of cross-border exchanges in electricity. c) Stablishes the Agency for the cooperation of Energy Regulators (ACER).	a) D. 2003/54/EC b) No 1228/2003 c) Blank	No
Regulation EC 714/2009 (2009)	Stablished the ENTSO-E.	No predecessor	No
Renewable Energy Directive (RED 2009/28/EC)	Open the mss power grids to RES.	D. 2003/30/EC	No
Energy Efficient Directive (EED 2012/27/EC)	Common framework of measures for the promotion of energy efficiency.	Mix of old directives: - 2009/125/EC - 2010/30/eu - 2001/8/EC - 2006/32/EC	No
Regulation EC 2016/631 (RfG NC, 2016)	It is the final document of ENTSO-E requirements for generators connected to the grid.	Objective proposed in Regulation EC 714/2009.	No
Electric Balancing Guidelines EC 2017/2195 (EB GL, 2017)	Stablishing the harmonized framework for new balancing energy markets in mss.	Objective proposed in Regulation EC 714/2009	No
Clean Energy Package: are the binding legislations and regulations issued from the Winter Package guidelines (2019). a) Directive 2019/944/EC b) Regulation EC 2019/942 c) Regulation EC 2019/943 d) Regulation EC 2019/941	Final recast of the Third Energy Package: a) Directive about internal market regulation. b) Regulation stablishing the ACER (recast) c) Regulation aimed at improving eu regulatory framework of the internal market. d) Regulation prevention, preparation for and management of electricity crisis situations.	a) D. 2009/72/EC b) R. 713/2009 c) R.715/2009 d).D. 2005/89/EC	Yes

4.2 The Third Energy Package

4.2.1 The Current Regulatory Framework

After this brief overview of energy policies throughout Europe's history, it is important to focus on the scope of this work: assessing the integration of DERs in distribution grids.
While the current regulation and directives in force are the CEP **e-Directive** and **e-Regulation**, it is also true that it takes time to shape each MSs regulations into the new European standards. Meanwhile, the power grid is still conformed by the outcomes of the previous energy package, in this case, the Third Energy Package. So, which has been the influence of the Third Energy Package during these years?

The Third Energy Package supposed an inflection point in the EU energy policy due to the identification of network codes and guidelines as a crucial element to stimulate the completion of the internal energy market. As defined by [60], network codes are "*a detailed set of rules pushing for the harmonization of previously more nationally oriented electricity markets and regulations*". So, from the Third Energy Package on, the electricity regulations of each MSs must be a transposition (with some flexibility) of the European regulations, also known as network codes.

Once the need for network codes was stated in the Third Energy Package, a development process started. During this development process, three main groups of network codes were identified [60]:

a) **Connection codes**: They set the requirements for the connection of different users and technologies. The ones proposed on the Third energy package aim at:

    - The secure integration of decentralized resources and demand response.

    - Harmonize the playing field of grid users across MSs.

  - Increase competition among equipment providers by harmonizing the requirement they need to comply within different markets.

b) **Market codes**: Their main objective is the creation of an ambitious new European internal energy market to reflect and enhance the changing technical features of electricity production systems [27], via:

  - The standardization of market products in order to create a stronger internal market, where all products can be traded across MSs if needed.
  - Regulate at TSO level how cross-zonal capacity allocation and congestion management are determined at long and short-term (Forward and Spot markets), which consequently will affect the offer on balancing markets.

c) **Operation codes**: Composed by the System Operation Guidelines and the Emergency and restoration network codes, they set the minimum requirements for TSOs and DSOs concerning operational security and set rules and responsibilities for the coordination system operators at the national level and across the Internal Electricity market.

Due to them being the first version of an iterative process, some of the Third Energy Package planned network codes ended up being considered guidelines. The main difference between them is that, while network codes are highly defined, only accepting some specific characterizations, guidelines include processes where the TSOs must develop the methodology. However, both of them carry the same legal weight and are directly applicable to MSs [60].

Table 5 shows the outcomes of the third energy package classified in the three categories mentioned above and with a specific column for their final format. As can be seen, after an eight years process, from 2009 to 2017, all the proposals of the Third Energy Package have been developed.

Table 5: Third Energy Package network codes. Based on [61], [62] and [63]

	Third Energy Package proposals:	***Developed?***	**Network Code\ Guideline**
Market Guidelines for mss network codes	Capacity allocation and congestion management.	Yes (eu) 2015/1222	GL
	Forward capacity allocation.	Yes (eu) 2016/1719	GL
	Electricity balancing.	Yes (eu) 2017/2195	GL
Connection guidelines for mss network codes	Requirements for grid connection of generators (RfG NC).	Yes (eu) 2016/631	NC
	Demand connection (DC NC).	Yes (eu) 2016/1388	NC
	High-voltage DC.	Yes (eu) 2017/2196	NC
Operation guidelines for mss network codes	Emergency and restoration.	Yes (eu) 2016/1447	NC
	Electricity system operation.	Yes (eu) 2017/1485	GL

From these three categories of network codes, this work is focused on the regulatory outcomes of connection codes and market codes. They are the ones that will directly determine how DER assets shall be connected to the grid and their potential business models. Thus, a clear definition of connection requirements, together with promising market opportunities, is the only way to enhance private investors to invest in DERs.

4.2.2 The Harmonization Process: Requirements for Generators network codes

In this section, one of the most mentioned network codes during the project, Requirement for Generators Network Code, will be slightly developed to understand how it is structured and to show some of its requirements. The section has the objective to give the reader the possibility to evaluate during the following chapters the impact of network codes in the harmonization process and understand how network codes can be crucial for a fast and easy widespread of DERs in distribution grids across Europe.

The **Requirements for Generators Network Code** aims to establish legally binding EU extensive harmonization of grid interconnection to ensure and increase the system security with a growing share of RES.
With the scope clarified, the next step is to understand how the RfG NC defines a framework to develop further requirements. The core of the RfG NC framework consists of defining the basis of how generators are classified. The crucial consideration is that RfG NC approaches generation from a technology-neutral perspective. Instead of legislating for each asset technology, the connection code establishes general requirements applicable, or not, to generator types. Then, it defines specific requirements differentiating between synchronous generators and non-synchronous generators' capabilities.

The criteria used to classify generation assets is their maximum power capacity, which is completely independent of the technology of the generator. Table 6, extracted from [64], shows the different categories and their capacity range. The fact that each synchronous area has a different definition of categories is related to the profile of generation assets

Table 6: RfG NC Generator type classification

Synchronous area	**Type A**	**Type B**	**Type C**	**Type D**
Continetal Europe and Great Britain	0.8kW-1MW	1MW-50MW	50MW-75MW	>75MW
Nordic	0.8kW-1.5MW	1.5MW-10MW	10MW-30MW	>30MW
Ireland	0.8kW-0.1MW	0.1MW-5MW	5MW-10MW	>10MW
Baltic	0.8kW-0.5MW	0.5MW-10MW	10MW-15MW	>15MW

The technology-neutral approach and its outcome –the asset classification– may not seem the most crucial thing in the network code. However, it sets a strong basis for non-technologically discriminatory regulations through all MSs. Nowadays more than ever, with the opening of the power system to new technologies with new capabilities, it is crucial to have a regulatory framework able to encompass all those new agents in a fair and non-discriminatory manner.

After the framework definition, there are the specific requirements. We consider that requirements, while will also be crucial to the widespread of RESs, at this point in the work do not need to be fully developed. However, the first glance of some voltage and frequency requirements is given in Table 7 extracted from [65]. More specifically, it gives an overview of Frequency and Voltage Stability requirements in the RfG NC, together with the asset type that must fulfill the requirement. The selection of these specific two requirements is not arbitrary. It is strongly bonded with further sections of this project. However, if the reader has further interest in RfG NC requirements, the article [65] develops an overview of all the RfG NC requirements, and even compares them to national LV and MV connection codes. For a more comprehensive but also more in-depth approach to network codes consult the technical report: *The EU Electricity Network Codes (2019 ed.)* [60]

Table 7: RfG NC overview of Frequency and Voltage stability requirements. Source [64, 65]

	Requirement	**A**	**B**	**C and D**
Frequency Stability	Operating frequency ranges	X	X	X
	RoCoF withstand capability	X	X	X
	Limited Frequency Sensitive Mode - Overfrequency	X	X	X
	Automatic connection	X	X	X
	Remote ON/OFF	X	X	
	Active power reduction remote control		X	
	Additional frequency requirements			X
	Provision of synthetic inertia			X
Voltage Stability	Reactive power capability		X	X
	Fast reacting reactive power injection		X	X
	Additional power requirements for reactive power capability and control models			X

Finally, it is essential to highlight that while network codes specify requirements such as the ones in Table 7, sometimes those requirements are non-exhaustive [60]. That means that further requirement specification is needed at the national level. We consider that it is also on this flexible side of the regulation where it is interesting to study how MSs have regulated towards higher integration of DERs.

During the development of further sections, specifically Section 6 on battery storage systems, similar classifications of assets and technology-neutral approaches (as far as it is possible) will be seen in National requirements for generators. Something similar is happening and will be observed in Section 5, with the harmonization effect of the Electricity Balancing Guidelines on balancing markets across Europe.

4.3 Clean Energy Package

4.3.1 The Future of the Regulatory Framework

The creation of the Winter Package the year 2016 – also known as Clean Energy Package for all Europeans – started after the European Commission had evaluated the performance of the Third Energy Package established in 2009. It concluded that, overall, it had increased competition within and across MSs borders and strengthened the position of customers. These achievements were amongst the main ones proposed, however, they also found some objectives that were not achieved and needed to be addressed in the following proposals. The main ones, listed on [66], are:

- Barriers to cross-border trade persists.
- Interconnector capacities are under-utilised.
- Retail markets competition could be enhanced.

Then after assessing the outcomes of the previous energy package, the Clean Energy Package also defined new objectives. In the technical report *The EU Clean Energy Package* [35] the objectives are comprehended inside three main groups:

- Adapting to the decentralization of the power system
- Empowering customers and citizens
- Ensuring the internal market level playing field

This sub-section aims to dig deeper on The Clean Energy Package with the intention to show which are those guidelines that will shape the future of the power system. The idea is the same one done in the previous section when studying the Third Energy Package, but in this case it is even more important since the CEP has just entered into force so the next decade of energy policies will be shaped by it.

About the CEP itself, first it has to be known that it is a set of regulations and directives published in June 2019 to promote the energy transition started with the Third Energy Package back in 2009. Among the CEP regulations and directives, the ones that address the electric sector are the **e-Directive** (EC 2019/944; [14]) and the **e-Regulation** (EC 2019/943; [15]), whose subject matter and scope is centred in "*setting the basis for an efficient achievement of the objectives of the Energy Union and in particular the climate and energy framework for 2030*" (**e-Regulation**), " *via the creation of common rules for all the assets connected to the power system, with a view to creating truly integrated, competitive, consumer-centred, flexible, fair and transparent electricity markets in the Union*" (**e-Directive**). Besides, they also aim to create models for system operators to cooperate and set fair rules for cross-border exchanges, with the final aim to strengthen the European internal electricity market

The **e-Directive** and **e-Regulation** are mainly focused towards the creation of market models to promote the energy transition. In terms of market design there is a group of markets, flexibility markets, that can be crucial to promote the widespread of new agents and technologies [67]. A subgroup of these Flexibility markets, the balancing markets, have been promoted on the European road-map since start of the unbundling strategy, and the Third Energy Package promoted such path via slowly opening the participation on the market to new agents. In the **e-Directive** the role of aggregators and Energy Storage Systems, among others, is enhanced being considered, frequently, as important agents and technologies to regulate for. Also, the **e-Regulation** states, "*safe and sustainable generation, energy storage and demand response shall participate on equal footing in the market* [. . .]" (*Art. 3 (j)*), pointing on the same direction.

When talking about flexibility, the **e-Regulation** starts to focus on smaller loads via the aggregator figure, while at the same time promotes the long-term investments that will still be important for the development of the market (**e-Regulation**: *Art. 3* (*e*, *g*)). This change of scope can also be seen in the **e-Directive** *Art. 8* (*2* (*k*)) where a requirement before authorising the construction of new capacity is to take into account alternatives such as demand response and energy storage.

The **e-Directive** provision (39) says: "*Market participants engaged in aggregation are likely to play an important role as intermediaries between customer groups and the market*". Thus, the right of all customers to be free to purchase aggregation services is clearly defined on **e-Directive**: *Art. 13* (*1*) & *Art. 15* (*2 a*). The same happens with fair participation of aggregators in the balancing markets in **e-Regulation**: *Art. 3* (*j*), and demand response through aggregation is promoted together with a defined framework which clearly states that aggregators have the right to enter electricity markets without the consent of other market participants.

Article 32 (2) of the **e-Directive** starts to define flexibility markets for congestion management, an incipient market for distribution-level ancillary products that shall be ruled by DSOs. This markets will be the ones responsible of trading the flexibility needed by the distribution grid in order to allow a higher share of RESs connected. Furthermore,in this kind of flexibility markets MV and LV aggregation together with ESSs will play prominent role.

ESS-wise, the CEP addresses some of the concerns attributed by stakeholders and researchers to previous directives (see Section 6.2.2). One important advance is the official definition of **Energy Storage** from a technology neutral approach (**e-Directive**: *Art. 2* (*59*)).Furthermore, DSO network planning shall include the use of energy storage (among others) to use as an alternative to system expansion. This is said in **e-Directive** *Art. 32* (*3*) and points towards the need for ESSs and other technologies to provide stability to the power system.
However, while some steps in the right direction are done in the CEP, some "recent regulations" still do not define mandates for ESSs leaving them in an uncertain field. For instance, the **Electricity Balancing guidelines** [13] do not give indications for the creation of standardized Frequency Containment Reserve (FCR) products, the ones in balancing markets where ESSs can stand out the most due to their technical capacities, and **RfG NC** excludes energy storage from its field of application.

One of the most relevant articles concerning the future of energy storage, is Article 36 of the **e-Regulation** which states that "*Distribution system operators shall not own, develop, manage or operate energy storage facilities*" to provide services that can be obtained via existing electricity markets. Such statement follows the willingness of the EU to unbundle the electricity market, and therefore provide a level playing field for all participants, which should lead to a fairer electricity system.
As already seen, these statements may lose entity when observing the reality of flexibility market regulations: other than the FCR indeterminacy commented before, non-frequency ancillary services shall be also an important market for ESSs. However, it was not until the CEP that a first step towards a defined and harmonized market for these products was set as an objective. And until the mandatory outcomes of the CEP are applied will still pass a significant amount of time

From an active consumer (prosumer) viewpoint, **e-Directive** *Art. 15* (*5*) addresses one important problem related to ESSs due to their double nature of generator and load. It states on point (b) that MSs shall ensure active customers owning ESSs that won't be subject to any double taxation. Furthermore point (d) allows the same storage facility owned by an active customer to provide several services simultaneously, if technically feasible. Statements as this last one are important for the spread of ESSs – and new technologies overall – because they remove uncertainty and allow to take advantage of their full potential.

However, while new directives and some regulations point towards a higher integration and need of ESSs on the power grid, the actual **Generation** [58] (EC 2016/631) and **Demand Connection** [59] (EC 2016/1388) network codes, which determine the technical requisites for generators and loads to connect to the grid, clearly state on *Art. 3 (2)*: *"This Regulation shall not apply to: (d) storage devices except for pump-storage power-generating modules* [. . .]". This may lead ESSs in limbo on connection requirements, a crucial step towards eneregy storage integration in the power system. Consequently, if this is not solved it will remain creating uncertainty for investors.

Finally, besides some possible criticism, it is remarkable that the creation of network codes for energy storage and aggregation, is pointed as a future outcome of the **e-Regulation** in *Art. 59 1(e)*. These new network codes could suppose an important drive for energy storage and aggregation, and thus allow the distribution grid to cope with a higher share of RESs. This new drive could be similar to the one that the Electricity Balancing guidelines have given to the harmonization of balancing markets throughout Europe, partially due to their obligatory nature and partially thanks to the clear definition of how to proceed.

4.3.2 Network Codes Proposals

Once the main guidelines concerning DERs integration in the power grid have been shown, the next logical step is to see which is the position of the CEP in terms of network codes. This is important because they will shape the future connection and market rules in the power systems across Europe.

The CEP **e-Regulation** leaves the door open on *Art. 59* to a new set of network codes that shall be developed in order to ensure a uniform European regulatory framework. The following list shows all the proposed fields where new network codes shall be developed, emphasizing those network codes that would have a higher impact on increasing DERs share in the power grid. The emphasis on those network codes that could have a higher impact on DER penetration will be done in Table 8 by referencing the articles of the **e-Directive** that are mentioned as the basis for their development. We consider that, showing the foundations of the network codes could give hints about how they will be developed. The areas where network codes shall be developed are:

- Network security and reliability rules, including rules for technical transmission reserve capacity for operational network security as well as interoperability rules.
- Capacity-allocation and congestion-management rules.
- Rules in relation to the provision of non-frequency ancillary services: As will be seen in Section 5, the opening of a non-frequency ancillary services market could be a big drive for DERs thanks to the also distributed nature of some of the non-frequency ancillary services. The development of this network code aims to create a non-discriminatory, transparent provision of non-frequency ancillary services, including rules on steady-state voltage control, inertia, fast reactive current injection, inertia for grid stability, short circuit

current, black-start capability and island operation capability.

- Rules concerning demand response, including rules on aggregation, energy storage, and demand curtailment rules. With no further development of the description in the **e-Regulation** *Art. 59*, this is the network code that could have a higher impact on DER widespread in the power systems.

As an introductory comment to Table 8, most of the articles that will set the basis for the future network codes are from the **e-Directive**. This is basically because the **e-Directive** is aimed to set the path to follow for MSs, but it is up to the individual countries to devise their laws, while the **e-Regulation** is already a binding legislative act.

Table 8: Articles of the e-Directive that will be the base for the further development of those network codes with a higher direct impact on DERs penetration into the power grid.

Network Code Proposal	**Base Articles of the e-Directive**
Rules in relation to provision of non-frequency ancillary services	- Article 36: Ownership of energy storage facilities by DSOs - Article 40: Tasks of transmission system operators - Article 54: Ownership of energy storage facilities by TSOs
Rules in relation to demand response, including rules on aggregation, energy storage, and demand curtailment	- Article 57 (e-Regulation): Cooperation between DSOs and TSOs - Article 17: Demand response through aggregation - Article 31: Tasks of distribution system operators - Article 32: Incentives for the use of flexibility in distribution networks - Article 36: Ownership of energy storage facilities by DSOs - Article 40: Tasks of transmission system operators - Article 54: Ownership of energy storage facilities by TSOs

5 Flexibility Services in Power Systems

5.1 The Role of Flexibility into the Power System

In the traditional organization of the power grid, large PGMs were forced to be able to provide flexibility. Some of these requirements for large PGMs are still considered in the new RfG NC. However, most of the requisites are not mandatory for smaller PGMs, and in some MSs legislation, RES power parks that fit in the large PGMs definition are excluded from the fulfillment of these requirements. With the new paradigm decreasing the number of synchronous PMGs and more difficulties than ever to forecast demand and generation, the large PGMs remaining may not be able to handle the flexibility required to keep the grid working correctly. This will suppose an increased need for flexibility [35]. Also, the penetration of DG into the MV and LV grid will suppose some challenges, as seen in Section 3.3, which will need to be addressed by the DSOs via active grid management. Finally, the provision of local flexibility will help not only to secure the grid operation but also to improve grid efficiency efficiency during normal operation time [18].

For these reasons, improved flexibility markets are being recognized in the **e-Directive** as a pillar to support the safer and more efficient use of the existing grids, and to enhance the HC of distribution feeders. Since the scope of this work is to research those regulations that enhance RESs penetration while guaranteeing safe operation of the power grid, it is interesting to study how flexibility markets could be designed in order to promote DERs participation.

5.1.1 Flexibility Definition

The electricity system has one intrinsic flaw; the generation-consumption link which, aside from ESSs, is not breakable and in the DG new paradigm supposes a big challenge for the grid operators in terms of system safety. From a time-perspective this problematic has two sides:

- **Long-term reliability (Capacity adequacy)**: Defined in [68] as "*the ability of the electric system to supply the aggregated electrical demand and energy requirements of costumers at all times.*"

- **Short-term reliability (Flexibility)**: Defined in [68] as:"*the ability of the electric system to withstand sudden disturbances.*"

After this generic definition of Flexibility, more partial approaches showing the value of flexibility for diverse grid stakeholders, extracted from literature are given:

a) **Consumer approach**: The *Office of Gas and Electricity Markets* (Ofgem) of UK defines flexibility [69] as "*modifying generation and/or consumption patterns in reaction to an external signal (such as a change in price) to provide a service within the energy system.*" Furthermore, they define as new flexibility methods Demand-Side Management (DSM), Energy Storage and Distributed Generation.

b) **Transmission system approach**: One definition of flexibility given by the EU [70] is: "*the capability of the power system to cope with the short/mid-term variability of generation (like renewable energy) and demand so that the system is kept in balance.*"
The *Universal Smart Energy Framework* (USEF) points out that TSOs can benefit from flexibility services to cope with different problematic: from ancillary services for balancing

purposes to constraint management and adequacy services [71].

c) **Distribution system approach**: The new DG paradigm creates the need of a new approach to flexibility from the distribution part of the grid. Using as reference the definition of grid-oriented services given in [25], distribution system flexibility can be defined as the capability of the distribution system to cope with locational short-term congestion of feeders and also for distribution grid balancing purposes. Furthermore, as USEF points out in the report *Flexibility Value Chain* [71] , it also can be used to increase performance and efficiency by using demand-side flexibility which helps defer or avoid the costs of grid reinforcements

So, it is inherent to all the perspectives seen that flexibility is something that provides margin to the grid to maintain instantaneous stable and safe operation, and in some cases during normal operation periods it can improve the way the grid is working.

5.2 Flexibility Provision

One way to approach the power system is by dividing it into generation and consumption, two antagonist concepts that are nowadays merging due to DERs and ESSs. Both sides can provide flexibility:

- Generation-Side Flexibility
- Demand-Side Management (DSM) or Demand Response (DR)

The new DG and Smart Grid paradigm turn the spotlight towards the DR concept. Hitherto, it was only provided by large loads with the ability to modify their consumption habits. From now on, DR will be enhanced by the technological advances and the introduction of DG at MV and LV level. In this new paradigm, even prosumers will be able to adapt their load profiles towards the grid. However, the Generation-Side Flexibility will still be a key agent on the flexibility markets.

Demand-side Management can be approached from two perspectives defined in [72]:

- **Explicit Demand-Side Flexibility**: "*Dispatchable flexibility that can be traded (similar to generation flexibility) on the different energy markets (wholesale, balancing, system support and reserves markets). This is usually facilitated and managed by an aggregator that may be an independent service provider or a supplier.*"
- **Implicit Demand-Side Flexibility**: "*Consumer's reaction to price signals. Where consumers can choose hourly or shorter-term market pricing, reflecting variability on the market and the network, they can adapt their behavior to save on energy expenses. This type of Demand-Side Flexibility (DSF) is often referred to as "price-based" DSF.*"

While both kinds of DR are considered in the new European framework, Explicit Demand-Side flexibility, together with Generation-side flexibility, are the ones towards the EU is legislating. This is mostly because of their product nature that makes them market sellable, which supposes a step forward on the predictions of capacity balancing of future power grids. At the same time, if consumers can provide services to the grid operators, this will suppose empowerment for them and possibly a push for the widespread of small RES installations.

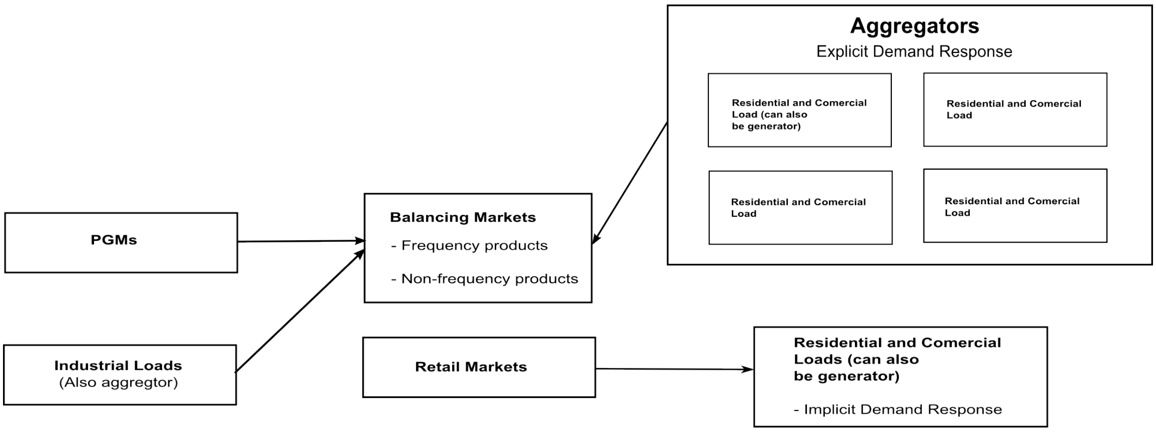


Figure 13: Agents providing flexibility services to the grid.

5.2.1 EU Guidelines on Flexibility

There are several approaches to add flexibility to the grid; the following list enumerates them and evaluates them from the prosumer perspective:

a) **Compulsory provision**: Technical and operational requirements for all the generators and loads is the traditional approach before the creation of the European balancing markets. It is still a thing today on some legislations, but mainly for large PGMs. Imposing these requirements to the smaller generators/loads nowadays seems technically impossible due to the impossibility to control and monitor all the assets, plus it may be unfair for prosumers, and could collide with their interests.

b) **Bilateral contracts**: TSO agrees with some capacity provider on an over-the-counter contract to acquire capacity provision. These kinds of contracts are long-term ones, and the capacity provided is well over anything a prosumer can provide. It is the least transparent way to provide flexibility, but it can be a way to provide safety to some significant investments focused on earning money from energy/capacity provision.

c) **Flexibility provision by TSO or DSO**: DSO and TSO as responsible for the grid management may seem to be one of the prominent agents interested in flexibility provision. However, due to the objectives of market liberalization and unbundling of the power grid settled by the EU, DSOs and TSOs shall not be allowed to own either PGMs or ESSs (other than justified exemptions; see section 4.3.1). Summarizing, this leads to the impossibility of the system operators to provide such services.

d) **Flexiblity Markets**: Since the publication of the First Energy Package, the creation of an European internal electricity market has been the main objective. From this perspective, nowadays the EU is promoting the use of flexibility markets as the primary capacity mechanism (**e-Regulation** *Art. 22*), and also the creation of a standardized portfolio of products to enhance the transnational exchange of capacity. The main argument to discourage other options is that Europe as a whole is nowadays in over-capacity, and traditional capacity mechanisms tend to be highly inefficient [19, 27, 35].

The Third Energy Package follows the path established by the EU in terms of the creation of an internal European market, promoting the unbundling of the electric system structures and therefore opening the system to private investors. Then, there was the Energy Efficiency Directive (2012/27/EC), which is the first one to look forward to the use of "leveled-for-all-users" energy flexibility markets as the primary agents for the transformation to a more efficient energy system on the *Article 18*. Lately, the publication of the Electricity Balancing Guidelines (EB GL; 2017/2195) has been an enormous step forward in terms of standardization of balancing products and guidelines for MSs to establish their own balancing markets. Finally, the publication of the CEP outcomes is a new boost for flexibility markets, amending problematic not treated in previous directives and facing new challenges.

However, it is important to consider that up until the CEP publication, when Europe was talking about flexibility markets it was focused on ancillary services related to frequency provision. This kind of product aims to balance generation and demand so TSOs centrally operate this market. Recently in the **e-Directive** (*Art.59*), the need for network codes related to non-frequency ancillary services is stated for the first time. This will suppose the opening of a new, but also unexplored, decentralized market for congestion management at DSO level.

5.3 Flexibility Markets

Flexibility Markets overall are a subgroup of Electricity markets; therefore, their operation mechanisms are similar. That is why this section is organized firstly explaining the general operation and organization of electricity markets and then studying how flexibility markets work.

5.3.1 Market Structure

Firstly, the European directives and regulations have been pushing towards an unbundling of the electricity markets, so the model used in most of them changed from monopolistic to retail competitive [23], which lead TSOs and DSOs as system operators not able to own neither PGMs nor retailing companies.
Electricity markets can be divided from a delivery-time perspective into:

a) **Forward and future market**: It runs from years before until two days (D-2) before delivery. It is classified as a secondary market giving the agents less risk on operations.

b) **Short-term or Spot market**: Electric products sold closer to delivery time are offered on the short-term markets; this implies more volatility of prices. Inside this category, there are three types of market: the Day-ahead market, the Intra-day market, and the Real-time balancing market.

In those markets several types of products can be sold:

- Energy
- Transmission capacity
- Reserves - Flexibility

From the energy-capacity point of view there are two market types:

- **Balancing Capacity Markets**: It is a Forward and future market aimed at guaranteeing the long-term reliability of the power grid by securing the provision of flexibility to fulfill the demand variations.

- **Real-time balancing market for energy**: This market is the closest to real-time operation and nowadays is used by TSOs to balance last minute faults on the system. In the forthcoming paradigm, DSOs may also need to buy these kinds of products to secure the safe operation of feeders.

Since the safe and reliable operation of the grid is the responsibility of the TSO, the balancing markets are operated by themselves, and they are the single buyers.

Usually, contestants to provide ancillary services must first go through the balancing capacity market to be able to publish their offers on the balancing energy markets. However, this is not always the case; for instance, Spain has been applying a system of capacity payments for a long time. On the other hand, in some energy balancing markets through Europe, participants are free to publish their offers as long as they fulfill the minimum requisites.

Europe since the Third Energy Package has been pushing to achieve the harmonization of balancing markets throughout the internal electricity market. One of the crucial regulations published in this direction is the EB GL [13], which establishes guidelines for the harmonization of the bidding, clearing, and payment mechanisms of frequency-related ancillary services markets and provides rules to harmonize the different products on the markets portfolio.
From a market perspective, three are the main points in terms of auction design [23]:

1. **Bidding**: The bidding process can be the first and the most limiting barrier for some market participants. Transparent, fair, and non-discriminatory prerequisites is one of the main concerns on the new European directives and regulations.

2. **Clearing**: Clearing methods can be discriminatory in some cases. However, the common method through Europe is the Sealed Bid method [23]. In this method contestants upload their offers secretly, then, the system operator crosses the demand and offers curves and buys all the offers needed to fulfill the forecasted needs or real-time needs.

3. **Payment**: The payment method is also a key point to enhance participation in the markets. Two are the common methods used across Europe: Paid-as-cleared and Paid-as-bid. Both methods have their perks and disadvantages; however, the EB GL *Art.30* promotes the Paid-as-cleared method if any other method cannot be proved more cost-efficient.

5.3.2 Flexibility Market Design Variables

This section is intended to showcase the main market design parameters to have a complete overview of the market design complexity. It is important to note that it is not possible to select those relevant market design parameters without any bias. The election of a market model to provide flexibility to the power grid is an already biased bet done by the European Union to adapt to the new embedded generation scenario. Europe has selected a market-based competitive model that should open the flexibility system to new participants, including end-users. For these reasons, the following design parameters are specially chosen in terms of participation enhancement and breaking barriers for new agents. However, this has to be achieved without compromising the reliability of the system. On this basis, literature research has been done. Its outcomes are summarized in Table 9

In Table 9 the market design variables are grouped in four categories, from a wider and abstract approach to a more defined and concrete one. The first one is *Market Framework*, and it encompasses those concepts and regulations of the power system where the market is operating. Then, there are the *Pre-requisites*. These are already related to the market itself but have nothing to do with the final product. In this group there are requisites such as *Bid Size* or *Pre-qualifiaction method*. Finally, there are the *Product Definition* variables, strongly bonded with the nature of the market product, and *Other requisites*, a section for those requisites that do not fit in any of the other categories. The bidding phase of the market is the one that can establish more limiting barriers for smaller participants. The following table shows the relevant characteristics extracted from the literature reviewed selected in terms of open the markets to emerging agents in the new DG paradigm.

Table 9: Market Design characteristics that can affect smaller assets participation.

Market Design	*Variables*
Market Frameworks: The first step of a market design, which is partially aside of the market itself, is the definition of frameworks.	**New products markets** [21]: A low number of markets for ancillary services can be a hindrance for market participants, due to the wider specifications of each product which can be harder to fulfil for smaller assets.
	Aggregator framework [21, 22]: The lack of a framework can hinder or even imposibilite end-users to participate directly to balancing markets.
	Definition of balancing responsibilities: Definition of balancing responsibilities is the basis of the balancing markets, to promote transparency and participation, clear responsibilities of all possible participants must be defined.
	Timing of ancillary service markets [19]: Shorter contract-duration or very time specific contracts can help promote the participations of smaller assets.
Pre-requisites: Market pre-requisites are the first "real/requirement" boundary for participants in order to be able to take part on the market.	**Pre-qualification method** [21, 22]: It can be Pooled, when the BSP can fulfil the technical requirements of the product independently of each pooled asset capacity, or Asset level, when each asset used by the BSP have to fulfil the technical requirements.
	Bid Size [21, 22]: This is the minimum size of the offer participants have to provide in order to be able to enter the tender. This is a key prerequisite to enhance or hinder participation.
Product definition: The European guidelines on Electricity Balancing 2017/2195 promotes the harmonization of products stablishing minimum criteria for product definition.	**Preparation period**: Period between the request by the contracting TSO in case of TSO-BSP model and the start of the ramping period.
	Ramping period: Period between activation of the resource and full delivery of power.
	Full activation time: Period between the activation request by the contracting TSO and corresponding full delivery of the concerned product.
	Deactivation Period.
	Minimum duration of delivery.
	Maximum duration of delivery.
	Mode of activation: It can be automatic or manual.
	Validity period: Period when the balancing energy bid offered by the balancing service provider can be activated, where all the characteristics of the product are respected.
Other requisites:	**Number of activations per validity period** [22]: If not defined can cause uncertainty to all participants. However, this design point is one where revenue-focused assets interests can collide with end-user assets because the limitation of activations which can be a way to enhance smaller users, can hinder the investment of larger assets.
	Direction of the service: Balancing services can be provided upward (producing more or consuming less) or downward (producing less or consuming more). On the EU 2017/2195 FRR and RR products are mandatorily unidirectional.

Together with the Market Design Variables, the Clearing and Payment phases of a market can also affect the participation in markets. From the Clearing perspective, and as already said before the Sealed-Bid method is the predominant one across Europe. The Payment phase can be reduced to the payment method of the market. From this view point two are the common options in the European energy markets:

- **Payment method**: European regulations push towards energy payments, in this path two are the common methods across Europe:
    a) **Paid as bid**: If the energy bid is activated, it will be paid at the price defined by the service provider.
    b) **Paid as cleared**: Also known as Marginal Pricing, this is the case when all activated energy bids will be paid as much as the last one needed to cover the imbalance

Lastly, there is one interesting topic nowadays when talking about new flexibility markets with new aggents participating, Penalties. In this sense, it is not clear yet how to proceed. European guideline 2017/2195 establishes the obligation of TSO to develop rules that define responsibilities. However, there are not specific guidelines on how to apply penalties. On [21], some MSs mechanisms can be seen, but it is hard to find a pattern.

5.4 Flexibility Products

From the ENTSO-E perspective, and so the EU perspective, nowadays, there are two types of flexibility products; those related to energy balancing, also known as balancing services or frequency ancillary services, and the ones related to congestion and grid management also known as non-frequency ancillary services.

Going a step further, there are some characteristic attributes of these products that can help to understand how they work and why they are designed the way they are. On the one hand, balancing mechanisms are a natural component of the power system, so they have existed since day zero. They are operated by the entity responsible for securing the transmission system reliability. Nowadays, the TSO is not anymore the only entity monopolizing the balancing mechanisms. Nevertheless, as final-responsible of unbalances, the EU has given TSOs the role of market operators. This approach to balancing markets is known as centralized.

On the other hand, there are congestion management/non-frequency products. This kind of market is behind-schedule, in terms of regulation, when compared to the balancing ones. Therefore, their characteristics are not harmonized yet. However, the thing here is: as seen in Section 3.3, significant penetration of DERs can lead to exceeding the feeders' capacity mainly due to over-voltages. Feeder congestion is a problem related to each DSO, and therefore, the first directives aiming the creation of a non-frequency ancillary services market are pointing towards the creation of harmonized but decentralized markets managed by the DSOs.

Furthermore, there is an ongoing discussion about the ownership and management of balancing markets. Some authors believe in a transition from centralized to decentralized management of these markets because it would lead to more open markets for end-customers and small-users aggregators.This is justified by the possibility to adapt product characteristics to each DSO spcific load and generation profile. On the other hand, as a criticism, a decentralized market model may increase the complexity of the operation of the power system.

5.4.1 Balancing Products

The *Electricity Transmission System operation NC* (EU 2017/1485) defines three balancing products categories which are: Frequency Containment Reserve, Frequency Restoration Reserve and Restoration Reserve [60]. Table 10 summarizes the characteristics of the three groups of balancing products.

Table 10: Balancing products types. Classification and definition.

	Frequency Containtment process	**Frequency Restoration process**		**Reserve Replacement process**
Sytem Operation Guidelines definition	Frequency Containment Reserve (FCR)	Automatic Frequency Restoration Reserves (aFRR)	Manual Frequency Restoration Reserves (mFRR)	Replacement Reserve (RR) Non mandatory product.
ENSTO-E UCTE definition	Primary Control	Secondary Control	Tertiary Control	
Activation mode[2]	Automatic and Local	Automatic and Central	Manual and Central	
Objective	Instantaneous response (usually <30s) to stabilize frequency deviations	Once the spike/drop is stabilized, the frequency restoration process (FRR) starts to bring frequency back to the nominal value. aFRR is the first product to be activated, the mFRR. The operational range is from seconds, up to 15 min.		RR is the slowest reaction reserve (usually >15min) and is used to support or replace FRR in long term stabilizing operations.

1.- The exact definition of the characteristics of each product has to be determined by the corresponding TSO responsible of each balancing market.
2.- Local = the generator detects the spike/dip and activates itself; Central = TSO command.

The Electricity Balancing Guideline only establishes a compulsory framework for harmonization of Frequency Restoration Reserves (FRR) and Replacement Reserves (RR) on *Art. 25*.The nature of Frequency Containment Reserves make them critical and maybe not so all-users-liberalized-market friendly. Furthermore, starting from these outlines some MSs are developing particular balancing products adapted to new participants in the market (always fitting inside the European given framework).

5.4.2 Non-frequency Ancillary Products

The definition given on the **e-Directive** is the following: *"service used by a transmission system operator or distribution system operator for:*

a) Steady state voltage control

b) Fast reactive current injections

c) Inertia for local grid stability

d) Short-circuit current

e) Black start capability

f) Island operation capability

PGMs already provide most of these services at the TSO level. However, the expected high penetration of generation at distribution level has already been creating operational issues that need a solution that can only be provided locally. Take as an example the German case [73].

One of the differentiating characteristics between frequency and non-frequency ancillary products is that the non-frequency related ones are strongly bonded to the location of the service provided. Also, some products have particular technical needs. That is partially why on [74] it is mentioned that while the first option from the EU perspective is the creation of markets for these kinds of products, maybe not all of them are well suited for market-based approaches.

Since there are not yet European guidelines or network codes on non-frequency ancillary services, the MSs outlook of these products varies from some countries without any liberalized market to others that are currently developing pilot projects. Services like the Cornwall Local Energy Market or the PicloFlex trading platform are good examples of LFM projects.

5.5 Aggregation

In terms of demand response, the already existing market-player role of the aggregator [75] is starting to emerge as an essential figure to enhance. The aggregator, as said before, is not a new role; industrial-sized loads have been providing flexibility services to the grid since the liberalization of the market in some countries like France and the UK [18]. However, the Aggregator figure is strongly emerging nowadays for two main reasons. The first one has to do with the widespread of the technology needed to implement an aggregation based business model among grid users. Secondly, it may be the only way for most prosumers to participate in flexibility markets.

A definition of Aggregation is given in the report *Value of Aggregators in Electricity Systems, MIT* [76]. There, it is defined like: "*the act of grouping distinct agents in a power system (i.e. consumers, producers, prosumers, or any mix thereof) to act as a single entity when engaging in power system markets (both wholesale and retail) or selling services to the system operator(s).*"

Due to the problems caused by embedded generation, more flexibility than ever will be needed. Furthermore, local flexibility provision (DSO level) will emerge as a critical product to provide the grid with stability and reliable operation. So there is a complementary duality in aggregation, on the one hand, can be seen as an economic incentive for customers, and on the other hand, it is also a need of the grid to overcome the problems caused higher shares of RESs.

5.6 Flexibility Market Design Analysis

The purpose of this section is to find relevant market design variables to enhance market participation. Two will be the perspectives given, firstly the Market Framework holistic approach, indicating those approaches and characteristics that would make a market prone to enhance participation. Secondly, Product Design will be considered, focusing on how to remove barriers for all market participants. Since balancing markets are the ones widely spread, this second approach will focus on balancing product design.

From both perspectives, a review of MSs actual situation will be done. Those countries' frameworks and products that fulfill some of the indicators stated will be mentioned trying to show how future flexibility markets and products should be in order to enhance participation.

5.6.1 Market Framework

There is an ongoing theoretical discussion about how the new market designs should be. Whether they provide energy or flexibility, two are the positions. Some authors believe that the actual centralized model should be maintained but constantly evolving to adapt to new agents, trends, and needs of the power system. Others instead wager for a new decentralized model which, with its perks and disadvantages, would suppose a revolution on how the traditional agents of the grid interact in order to keep its operation safe and reliable.

The European Commission energy policies point towards a change of the generation model from a high voltage centralized approach towards a medium/low voltage approach, which by its nature will be a decentralized. Furthermore, the fast-evolving world of technology innovations is already opening new opportunities in terms of renewable energy investments, remote-control of assets, constant monitoring of the grid, etc. This inevitably is merging into the Smart Grid concept, which in the end, encompasses a grid with more capabilities for a decentralized control of all the assets and proper data-exchange.
So, if everything is going towards decentralized management of energy, why electricity markets should not do the same?

Other than the technological and political influences pointing towards the decentralization of the grid, there is one aspect of the forthcoming power system that will only be addressable from a local approach: **Congestion and Grid Management at Distribution Level**. From this crucial starting point and based on literature research, this report will defend a decentralized framework for electricity market design.

Starting with the main driver for this work positioning, it is crucial to understand how grid congestion problems (see section 3.3.2) and their management are one of the most significant consequences related to the transition towards a distributed generation model. This is not only from an innovative and empowering perspective but from the basic operating principles of the grid: safe operation, reliability, and, therefore, energy provision to customers.

There is extended literature – from electrical policy journals [77, 78], to technical reports [79], going through all kind articles and books [23, 25] – pointing out the DSO role transformation from a passive manager of the grid to an active manager in order to cope with local congestion problems. This means a transition from long term planning and grid investment towards real-time flexibility management of the grid.

Within Europe, regulating authorities have committed to a market-based approach and facilitate a competitive electricity market to provide effective price signals to electricity dispatch [67]. This means that if DSOs change their grid management approach to an active one, all the services they would need should be provided via a market mechanism. From this positioning emerges one of the crucial elements to support a position favorable to a Decentralized Market model: **congestion problems can only be addressed at a local level** [67]. Therefore, congestion products can only be provided by assets close to the congested point. With that said, it seems at least questionable to approach a locational-product from a centralized perspective, so the following question arises: Is there any advantage to maintain the centralized approach?

On the one hand, centralized approaches indeed tend to reduce the complexity of the overall market ecosystem [25]. However, when the location of the asset becomes a pre-requisite to entering the bid, the TSO would need to create new specific products each time a new issue arises in the distribution grid. This would suppose a much higher workload for the TSO as a market operator, plus an extra intermediary for the DSOs each time they need to solve a congestion problem.

Another frequently mentioned problematic is TSO-DSO coordination in a decentralized energy-market model [25]. However, nowadays, without any LFM in sight, the European Commission is stating the need to enhance coordination between grid agents with proposals such as the ones in the System Operation Regulation (2017/1485). There, on *Article 1* when defining the subject matter, the regulation states "*For the purpose of safeguarding operational security, frequency quality and the efficient use of the interconnected system and resources, this Regulation lays down detailed guidelines on b) rules and responsibilities for the coordination and data exchange between TSOs, between TSOs and DSOs, and between TSOs or DSOs and SGUs, in operational planning and in close to real-time operation.*"

So, while it is evident that challenges like proper coordination between agents will arise in the new scenario, it seems also true that they will do it no matter which is the market design. Going one step further, and as it will be seen in the following section, when talking about product design, local markets have the characteristic to allow specific product design to adapt to the possibilities/needs of the market agents. This adaptability enhances participation reducing entrance barriers [24, 67].

Once the decentralized market model has been shown as a viable approach to Congestion management, if not the most rational one, another question can arise: Does it make sense to have local flexibility markets also providing balancing products? Or is the centralized model still the best option?

Here this question can only be answered partially because it is strongly bonded with the problematic of participation barriers that markets may apply to the agents participating (see Section 5.6.2). However, what can be done is to show that at least, with its drawbacks accounted, it is still a viable, if not interesting, option.

Nowadays, balancing markets are centralized and operated by TSOs. The nature of the grid where the system must be balanced and imbalances can be compensated by any asset independently of its location makes a centralized approach of balancing markets a more than a reasonable option. The traditional grid scheme has well-defined agents with their well-defined roles and responsibilities. One of these roles is the balancing responsible party, which is defined in the EB GL [13] as: "*a market participant or its chosen representative responsible for its imbalances*". BRPs can be generation assets, industrial loads, and retailers, among others. To sum up, anyone connected to the grid accounting for their generation or load profile and providing it to the TSO the day n-1 in order to balance the system in advance. The BRP figure is nowadays a crucial agent of the grid because it is the figure accountable for imbalances of the system, the one on which the TSO delegates its primary responsibility: balancing. New arising agents like Aggregators, if not appropriately defined, may dilute the BRP figure since they could aim to provide flexibility services. At the same time, this may unbalance the portfolio of the BRP accounting for the Aggregator client's energy profile. A compensation payment needs to be arranged between independent aggregators and BRPs [25].

With that said, it is important to point out that the challenge of accounting for responsibilities in the new grid design is not related to the market centralized or decentralized approach. It is related to an appropriate framework definition, as USEF stated and tried to solve by proposing a new model for system responsibilities [79]. Some countries with centralized balancing markets have already started regulating this problematic. France and Switzerland are two examples of it [25].

So far, the position in favor of a Local Flexibility Market for Congestion products has been justified; then it has been shown that some of the main encumbrances of a decentralized power system, such as TSO-DSO coordination or balancing responsibilities, have nothing to do with the centralized/decentralized approach to the power system and its markets.

Finally, it is also worth mentioning the publication of the CEP **e-Directive** and **e-Regulation** where a strong drive to empower DER-related agents and technologies is given. Furthermore, it leaves the door open to decentralized market models when stating the need for NC for non-frequency ancillary services provision in **e-Regulation** *Art. 59*, even if it holds responsible TSOs for it when referring to *Article 40* of the **e-Directive**.
On the non-mandatory side of the European legislation, the **e-Directive** states *Art. 32*: "*Member States shall provide the necessary regulatory framework to allow and provide incentives to distribution system operators to procure flexibility services, including congestion management in their areas, in order to improve efficiencies in the operation and development of the distribution system. In particular, the regulatory framework shall ensure that distribution system operators are able to procure such services from providers of distributed generation, demand response, or energy storage and shall promote the uptake of energy efficiency measures*[. . .]." These kinds of statements leave the door open to the creation of LFMs. However, it is also true that it is very dim and may need further development on network codes (see Section 4.3.2).

Apart from the market approach discussion, one key enabler of DER participation in all the markets is the clear definition of the roles and responsibilities of the Aggregator agent. This positioning is clearly stated as a need by the European Commission in the **e-Directive** and **e-Regulation**. For instance, **e-Directive** *Article 17* is particularly focused on responsibilities definition. Furthermore, one of the common points in the literature reviewed about the topic was the need for a clear framework for aggregators. The USEF in [79] puts the aggregator as the central agent of the forthcoming power system. Then, they propose a framework to make the new power system operable from a responsibilities perspective. Besides, EnnergiNet [20] has been studying possible market models for aggregators with the final objective to improve the overall framework for consumption flexibility. Articles [22, 80] conclude that even with aggregation services being the most promising agent of the new grid, the lack of framework is, nowadays, the main hindrance aggregation is facing. On the same line, the article [18] points out the need for policies to define roles and responsibilities for aggregators and even goes a step further by glimpsing the possible need for a framework definition for LFM. Finally, the smartEn in the report *European Balancing Markets* (Edition 2018; [21]) approaches the assessment of existing MSs flexibility market designs based on how aggregation is allowed. (The report was developed with the external contribution of power system stakeholders like ACER, ENTSO-E, REE, RTE France, and Swissgrid.)

5.6.2 Specific Market and Product Design

This section is an assessment of the market and product design, which enhances the participation of the maximum number of agents into the grid. It is important to notice that most of the proposals that will be investigated do not change the status of the current agents of the market, they only intend to lower market barriers that may hinder the participation of new agents. Before going on, we consider that it is important to clarify that the frontier between market and product is vague, as said in [67]: *"In reality, any single product or service defined by the system operator or market operator can be considered as an independent market in the electricity sector."*

To develop this section, the research has been based on those MSs already existing balancing-markets considered by the literature reviewed as the ones with more convenient market and product designs to allow wider participation. Articles [21, 22] have been the starting point to develop all the tables that will be used through this section in order to give an overview of the most advanced balancing markets in the EU.

The structure of this section is based on two out of the three perspectives related to market access limitation of [67]: Market entry pre-qualification and Product specifications. Plus, a brief review of Remuneration mechanisms.

Market entry pre-qualification:

When proposing a decentralized local flexibility model, congestion services may be the primary driver of the proposal. However, it is not the only one. Another important aspect of decentralization is the possibility to adapt market products to the profile of the participants. This adjustment to specific capacities should enhance participation by lowering entrance barriers.

As quoted in [67]: "***Specific Market Design** creates corresponding incentives for market agents to react*". Also, the International Renewable Energy Agency (IRENA) on its report [81], points out the importance of *Specific and Innovative* products to unlock the potential of new agents and technologies. Besides, the article [22] highlights the importance of this approach when talking about the UK balancing market. Table 11 shows some of the products on the large list of specific designs by National Grid ESO, United Kingdom's TSO. When observing the table it can be seen how diversifying the portfolio, products of the same family can differ vastly. For instance, **Dynamic FRR** (**Secondary**) and **Dynamic FRR** (**High**) differ not only in *Full activation time*, but mainly in *Duration of delivery* ,being the **Secondary** more accessible to small-loads aggregators due to the limited duration of the service, plus the maximum activations per year.

Finland and Denmark (see Tables 12 and 14) also are worth to be mentioned, because they have more than one product to provide FCR with clearly differentiated technical requirements.

Table 11: National Grid ESO balancing products portfolio.

United Kingdom [21, 22, 82]						
Product	*Minimum bid [MW]*	*Full activation time*	*Prequalification process*	*Product resolution*	*Symmetrical*	*Duration of delivery*
Non-Dynamic FRR (FCR)	1	30s	Pooled	Monthly auctions	Yes	30 min
Dynamic FRR (Primary) (FCR)	1	2s to 10s	Pooled	Monthly auctions	Yes	20s
Dynamic FRR (Secondary) (FCR)	1	30s	Pooled	Monthly auctions	Yes	30 min 11 act/year
Dynamic FRR (High) (FCR)	1	10s	Pooled	Monthly auctions	Yes	Indefinitely/ agreed
Enhanced Frequency Response (EFR-FCR)	1	<1s	N/A	4 year tendered bilateral contract	N/A	15 min
Fast Reserve (FR-aFRR)	50	2 to 4 min	Pooled	Monthly auctions	N/A	15 min
Demand Response (DR)	N/A	N/A	Pooled	N/A	N/A	N/A
Demand Turn Up (DTU)	1 (assets should be >0.1MW)	Up on agreement (6h 30 min average)	Pooled	Bilateral contract	Downward	Up on agreement

Another important characteristic of the market design is **Product Resolution** [60]. It can be defined as the duration of the capacity agreement once a capacity bid has won the capacity auction. During the capacity agreement period, each time there is a need for flexibility, the capacity offered will enter the bid. If it wins, then the energy provision will be activated.

Too long product resolution would hinder the participation of agents whose facilities are not entirely focused on revenue-making due to the uncertainty related to the sudden change of generation/load pattern if their asset is activated. This is stated as an important enabler mainly for aggregators' participation in [22]. From this perspective, Finland out-stands of the rest with 1h Product Resolution (see Table 12). One step below, Denmark also has very low resolutions (see Table 14). Then countries like the Netherlands are pointing towards the right direction by continually addressing product design and compromising to lower product resolutions. Very short product resolutions, erases the utility of capacity auctions, instead the assets can enter directly to the balancing market for energy if they fulfill the minimum requirements.

Table 12: Fingrid balancing products portfolio.

Finland [22, 83, 84]						
Product	*Minimum bid [MW]*	*Full activation time*	*Prequalification process*	*Product resolution*	*Symmetrical*	*Duration of delivery*
FCR-N	0.1	3 min	Pooled	1h	Yes	1h(except limited capability units 30 min)
FCR-D	1	30s	Pooled	1h	No; It is an only upward regulation product	1h(except limited capability units 30 min)
aFRR	5	2 min	Only generation	1h	Yes	1h (maximum)
mFRR	5/10	15 min	Pooled	1h	Yes	15 min to unlimited (activations: once a year)

The previous characteristics are a kind of prequalification bias but underling in the market design. Now it is time to analyse the two more relevant explicit prequalification burdens that may discourage weaker participants from entering to flexibility markets.

First and foremost, there is **Asset Prequalification Method**. It has been identified as the most restricting variable – in terms of participation enhancement – if it is not designed properly. If no pooling of assets were allowed in the prequalification phase, it would be impossible for aggregators of small users to enter the markets. This is a crucial barrier that needs to be erased from all MSs markets in order to make participation non-discriminatory and egalitarian, as stated in [21, 22, 60]. In fact, due to its restrictiveness, most of the market products of MSs in this section do accept pooling of assets which emphasises this characteristic for being one of the pillars of non-discriminatory participation in flexibility markets.

On the other hand, there is the **Minimum Bid** volume requirement which has been identified as an essential product design to address in order to facilitate market participation [16, 21, 22, 25, 67, 60, 81]. Currently a lot of TSOs have already reduced the minimum bid sizes of their products. The examples given in this section are representative of the best MSs balancing markets designs. Instead, nowadays, the average minimum volume oscillates between 5 MW to 20 MW [21]. Still, the positively mentioned above UK market tends to stay half-way from fully engaging participation. For instance, the **Fast Reserve** (**FR-aFRR**) has a *minimum bid size* of 50 MW, also the danish product for **FCR** (**DK1**) has a minimum bid of 20 MW. To be fair with the danish market, in this case, it has approached participation enhancement via *Specific Market Design*. It is also true that currently there is a trend to reduce minimum bid volumes mainly driven by the European regulations and directives. **Product Specifications**

From here on, we will be focusing on product characteristics, giving a general pattern of product-design market-friendly variables, and explaining the reasons for the proposals.

As developed in article [67], and also mentioned in [81], one of the roles of the Aggregator is to group smaller users to overcome the barriers in flexibility or energy markets. Hence, many, if not most, of the following concerns can be overcome by an aggregation service; however, this is not the point. It is important to remember that the EU **e-Directive** points towards a market framework that eases participation for all the possible market participants.

- **Direction of the service**: Products should not require bi-directional energy provision, because it hinders the participation of those agents not able to act as generators and loads at the same time [22, 67]. Even for large Aggregators with a diversified portfolio of assets connected, it can hinder their participation in some markets [81]. To show the impact and importance of the removal of such requirement, the report [60] cites the *Art. 32(3)* of the EB GL which requires that the procurement of upward and downward balancing capacity for at least FRR and RR shall be carried out separately.

Table 13: Elia balancing products portfolio.

Belgium [85]						
Product	*Minimum bid* [*MW*]	*Full activation time*	*Prequalification process*	*Product resolution*	*Symmetrical*	*Duration of delivery*
FCR	1	30s (2 sec response time)	Pooled	Weekly auction (constant activation possibility)	No (R1 Up/R1 Down, specific products)	Unlimited (25 min for assets defined as limited energy reservoirs.)
mFRR (non-reserved volumes)	1	30s up to 15min	Pooled	15 min auction	No	Minimum 15 min up to availability reported by the provider 40 act/year
mFRR (reserved volumes)	1	30s up to 15min	Pooled	Mothly auctions	No	R3 standard: up to 8h/day . (unlimited activations) R3 Flex: up to 2h/day (twice a day; max 8 a month)
mFRRsa (scheduled activation)	1	Due to its scheduled nature it wil be notified 15 to 30 minutes before real activation.	Pooled	N/A	No	One or more supply periods (15 min)

From this perspective, an interesting approach is the one of the Belgian TSO (see Table 13), where the product for FCR is divided in R1 Up and R1 Down maintaining all the other requisites. Besides, other markets require market participants to state their Upwards or/and Downwards capabilities on their offers. This approach may seem very similar to creating two products, but in terms of transparency, one of the EU objectives of the market-based approach, it is a step below.

- **Product Definition**: For these mandatory-defined product characteristics selected in Section 5.3.2, an assessment of their optimal design is carried out.
  On the one hand, there are those characteristics that ease participation when the time requirement is lengthened:
  - Preparation Period
  - Ramping Period
  - Deactivation Period
  - Full Activation Time

  It is important to notice that setting a high minimum threshold viable to fulfil by the weakest participants will not harm other market agents. Table 14, can be useful to see how the "same" product can be defined in different ways.

Table 14: Energinet balancing product portfolio

Denmark [86]						
Product	*Minimum bid [MW]*	*Full activation time*	*Prequalification process*	*Product resolution*	*Symmetrical*	*Duration of delivery*
FCR (DK1)	0.3	30s full activation	Pooled	4 h period	No	Minimum 15 min
Frequency- controlled normal operation reserve: FCR-N (DK2)	0.3	150 s	Pooled	1h, 3 h or 6h periods	Yes	Unlimited
Frequency- controlled disturbances reserve: FCR-D (DK2)	0.3	30s full activation (50% within 5s)	Pooled	1 h, 3 h or 6h periods	No; It is an only upward regulation product.	Until restoration of balance or mFRR takes over
aFRR (DK1-DK2)	1	5/15 min	Pooled	N/A	Yes	N/A
mFRR	5	15 min	Pooled (not mixed technologies generation and consumption)	1h	Yes	Unlimited

The Danish example is useful because it provides an insight into different product designs inside the same market, FCR can be provided via three products in Denmark: FCR, FCR-N and FCR-D. From a product definition perspective, and focusing only on *Full activation time*, the FCR-N product is the one more “end-user friendly/aggregator friendly” due to the higher activation time (150s). However, the Finnish (see Table 12) definition of FCR-N is even more convenient than the Danish one with an activation time of 180s.

On the other hand, there are those characteristics in which shorter time requirements mean higher participation enhancement:

- Minimum Duration of Service
- Maximum Duration of Service

In [22] long duration of delivery is used to criticize some product designs because it can become a barrier for the majority of prosumers. Also in [21], some balancing products from all MSs are criticized for the same reason. For instance, when defining the Austrian mFRR product is stated: *“The duration of the activation is still 4 hours, which excludes aggregators that are pooling small residential customers* [. . .]”.

Interesting approaches in MSs balancing markets are for instance are the ones from the Belgian TSO Elia, the Finnish Fingrid and the Dutch Tennet.

On the one hand, what is interesting of the Belgian approach is the creation of differentiated mFRR reserved products (see Table 13) that have two possibilities in terms of service duration:

- **R3 Standard**: focused on 100% centred on flexibility provision assets (8h/day maximum; no limit of activations)
- **R3 Flex**: aimed at agents like end-user aggregator (2h/day, twice per day maximum; with a limit of 8 activations per month).

Another interesting approach, maybe no so egalitarian form a market-based perspective, is the one of the Dutch TSO Tennet (see Table 15). In this case, instead of defining different products for FCR, what they do is differentiate between *Normal Energy Resources* and *Limited Energy Resources*, thereby setting lower requirements for the limited ones. The same does Elia in Belgium with FCR products.

Table 15: Tennet balancing products portfolio

Netherlands [87]						
Product	*Minimum bid [MW]*	*Full activation time*	*Prequalification process*	*Product resolution*	*Symmetrical*	*Duration of delivery*
FCR (**no contract needed BSP-BRP**)	1	30 s	Pooling allowed <150 MW (each asset <1,5 MW)	Daily, to be 4h periods by 1 July 2020	Yes	15 min for limited energy resources (2h max before next activation avaliability)
aFRR	1	Ramp up or down at least 7% of the bid volume per minute.	Pooled (inside the same region)	Weekly bids for 15 min periods	No	15 min
mFRRda (**direct activation**)	20	Upwards: 15 min Downwards: 10 min	Pooled	Quarterly and monthly tenders.	No	Full activation time plus 60 minutes at least. (Max 6h required between deployments)
mFRRsa (**scheduled activation**)	1	Due to its scheduled nature it wil be notified 15 to 30 minutes before real activation.	Pooled	N/A	No	One or more supply periods (15 min)

Finally, another possible approach is the one where the bidder sets its availability in the offer. This approach may be less convenient because it can create inequalities related to assets capabilities. One example of this behaviour is the Belgian mFRR non-reserved volumes product, in which the capabilities of the asset/s have to be stated in the offer.

- **Activations per Validity Period**: The activation per validity period only concerns to those products that, before going to the real-time balancing market for energy, participants have to enter to a balancing capacity market. In this case, activations per validity period refer to the existence/or not of a maximum amount of activations during the Product Resolution period.

  Nowadays, it is usually not defined [21]; in some cases, TSOs provide information related to the average number of activations in order to remove uncertainty. The article [22] argues that the specification of a maximum number of activations can be crucial to allow customers to decide whether they want to enter the market or not. However, from all the characteristics studied this is the only one that can create a conflict between market participants since those assets 100% focused on providing balancing services are interested in providing as many services as possible. To address this situation it is interesting to see how the Belgian TSO has proceeded to create 2 mFRR products, **R3 Standard** with unlimited activations and **R3 Flex** with limited activations (see Table 13). Another example are UK FCR products (see Table 11), precisely the **Dynamic FRR (secondary)** with a maximum of 11 activations per year. Another option already seen is reducing Validity Periods to values where the boundary between capacity product and energy product is diluted. The Finnish TSO is an excellent example when applying this approach.

Remuneration Mechanisms

Appropriate remuneration schemes and pricing mechanisms are the core to allow decentralized flexibility to evolve [67]. From a European regulatory approach everything seems settled, because *Article 30* of the EB GL says referring to payment methods in balancing markets: "*Such methodology shall: (**a**) be based on marginal pricing (pay-as-cleared).* "

However, it is interesting to have a broader sight of the situation. As discussed in Section 5.4.2, Congestion management products have a strong locational link, which may make marginal pricing not the best remuneration method. Article [67] sets out the need for a suitable pricing model for distributed flexibility services at the distribution level. It uses Cornwall Local Energy Market as an example of a pilot project researching in this direction. Another interesting example could be the PicloFlex trading platform also operating in the UK.

6 Battery Storage Systems

6.1 Introduction

For many years energy storage technologies, except for PHES, were relegated from the power system. Partially due to their high-costs which made them noncompetitive, but also and mainly due to the structure of the power system which was designed from a centralized and controllable approach, which removes the need of provision of ESSs capabilities [88].

Nowadays the power system is experimenting a change towards a new model where distributed generation, vRES technologies, and consumer empowerment shall be the main agents.This new scenario will lead to an increase of uncertainty – in terms of generation and demand forecast – hardly manageable from the classic perspective. It is here where the need of new ways to manage the grid arises, and two are the possibilities: a) increasing the control over demand and generation modules in order to keep the balance of the system, or b) decouple generation-demand and manage them separately. In the end the system will need more flexibility than ever before.

Neither of these strategies excludes the other, in fact both will have a crucial role to enhance a pacific and reliable transition between energy models. However, not so long ago, the widespread of decoupling methods/technologies between generation and demand seemed to be an unreal idea. In fact, the outcomes of the Third Energy Package do not take into account any kind of ESSs other than PHES. These outcomes are the ones guiding the actual energy legislation around Europe. For instance, the RfG NC which establishes the main requirements for the connection of generation units from a neutral-technology point of view, explicitly says that such network code shall not apply to any kind of energy storage system other than PHES, and it was published by the European Commission on 2016.

With the publication of the CEP, the role of energy storage has changed a lot. It has taken an emphasized position together with other technologies and strategies to manage and operate the distribution grid on the new scenario where DERs, such as renewable generators and electric vehicles will challenge its actual architecture and operational mode. Nevertheless, with the change already started, the first outcomes of the CEP are not expected before 2021. The reality is that, nowadays, most of the MSs are still far from a proper implementation of the outcomes of the Third Energy Package, so it will take another long period to adapt MSs legislation to the expected outcomes of the CEP.

This section of the report starts by showing the potential of BSSs for the different agents of the grid, but mainly for the grid itself; focusing on the distribution level. Secondly, it will assess the main hindrances to the widespread of BSSs through the grid found in the literature reviewed. Then, it will analyse how those MSs that are ahead in BSSs LV-legislation have approached their regulations in order to secure the equal and fair participation of these technologies into the power system. Finally, and from a flexibility perspective, an analysis and comparison of product designs and initiatives will be made. The specific definition of service requirements for energy storage assets would enhance investments and therefore promote the widespread of, from this work perspective, such an essential agent of the new distributed paradigm.

6.2 Impact of Battery Storage on the Distribution Grid

6.2.1 Applications Overview

The grid is composed, if the big picture is considered, of three principal agents: Generators, Loads, and the System itself – managed by system operators like TSOs and DSOs depending on the voltage level. This classification is an important starting point to see how ESSs, and specifically BSS, can impact the distribution grid.

One of the crucial things to address before studying how BSS impact the grid is: Why does this work focus only in battery storage technologies and leaves behind other storage technologies such as Mechanical storage or Thermal Energy storage?

As stated in [88], there are many possible technologies for energy storage. The most current and relevant characteristic among them is fast response time. Aside from that, each technology has the capabilities that make it suitable for specific applications. For instance, Pumped Hydro Storage has one of the most significant power outputs and capacities among all energy storage technologies, however, its response time is much higher than the one of a Super Magnetic Energy Storage unit.

The scope of this work is focused on the integration of Distributed Generation at MV and LV levels. From this perspective, BSSs are one of the most suitable technologies – as stated in[89] – due to their fast response time. It could be argued that they have a "short" duration of storage capacity in relative terms when compared to other technologies. However, for MV and LV applications this is usually not a concern [90]. Another interesting characteristic of BSSs is their scalability which makes the technology very versatile in terms of potential users. For instance, nowadays BSSs are being used to leverage all the potential of vRES by prosumers, who commonly have small capacity needs, and at the same time pilot projects by DSOs use them to improve the quality and reliability of grids with high share of DERs.

However, nowadays, the EU legislation is pointing towards technology-neutral definitions of the agents of the power grid. For instance, **RfG NC** *Art. 5* classifies power generation modules based on their maximum capacity no matter which their base technology is (see Section 4. Then it regulates, taking into account the differences between synchronous and asynchronous generators. However, the intention is to create a regulation that comprehends the vast majority of generation assets.
That is why, even if this report is focused on BSSs, during all this section the acronym ESSs (Energy Storage Systems) will also be used. Most of the regulations studied approach LV and MV connection of storage form a technology-neutral perspective, even if in the majority of the cases BSSs will be the technology chosen.

Once this is clarified, the next step is to study how BSSs could benefit the three mentioned above main agents of the grid. TSOs will be dismissed because the scope of this project is focused on distribution systems.

Table 16: Overview of energy storage applications in the electricity sector. Based on [91] and [92]

	Applications
Generation/ Bulk Services	Arbitrage, Electric Supply Capacity, Support to Conventional Generation, Ancillary Services RES Support, Capacity Firming, Curtailment Minimisation and Limitation of Disturbances.
Customer Energy Management	End-user Peak Shaving, Time-of-use Energy Cost Management, Partiular Requiremernts in Power Quality, Maximizing Self-production and Consumption of Electricity, Demand Charge Management, Continuity of Energy Supply, Limitation of Upstream Disturbances, Reactive Power Compensation and EV Integration.
Distribution Infrastructure	Capacity Support, Contingency Grid Support, Distribution Investment Deferral, Distribution Power Quality, Dynamic Local Voltage Control, Intentional Islanding, Limitation of Disturbances and Reactive Power Compensation.

Each agent on Table 16 could use energy storage systems applications for their benefit. It is also important to see is how the use of most of these applications will somehow affect the grid operation, so they are strongly bonded with the DSO role. In other words, most of the applications of BSSs that can use generators or end-users have its counterpart as an application that could be provided to the DSO via ESSs.
For instance, from the DSO perspective *Capacity Support* could be provided by their ESSs or the service could also be obtained via a market trade with generation assets using the *Electric Supply Capacity* of their ESSs, or even by end-users via *Peak Shaving* strategies assisted by their batteries. Another interesting example is *Limitation of Disturbances* in the distribution grid, from this perspective the DSOs could use their storage assets, or instead generators, the ones causing the disturbances, could use storage assets to help with disturbance issues via the *RES Capacity Firming* and *Limitation of Disturbances* applications of the table.
One last example that comprehends the vast majority of the applications of the table is *DSOs Investment Deferral*. This application is directly linked with the hosting capacity concept introduced in Section 3.4. In order to relief investments, distribution grid *Peak Shaving Strategies, Reactive Power Compensation, EV integration, Limitation of disturbances*, among others could be provided by end-users and generators thanks to their storage assets.

Before going any further, it is important to state that the current European legislation – **e-Regulation** *Art. 36* [15] – do not allow DSOs to own, manage or operate energy storage facilities. This requirement is based on the unbundling principle of electricity and gas networks, initially thought to avoid DSOs and TSOs possibility to stifle the emergence of competition in the supply business [10]. After several years of experience, each iteration of the Directive has gone a step forward towards the liberalization of the power sector to ensure non-discriminatory access to power networks and thus enhance competition lowering the electricity prices.

Then two are the options left, mandatory requirements for assets to behave in a "grid-friendly" manner or a market-based approach for the provision of such services. It is relevant to see that neither of the approaches needs BSSs to be developed, however, assets with BSS have more flexibility to operate no matter the scenarios.

Article [33] classifies the possible behaviour of BSS towards the grid as:

- Grid Compatible, characterized by the fulfilment of the mandatory requisites defined to have access to the grid.

- Grid Supportive, when the assets operates trying to maximize the benefit for the owner but at the same time it is keen to modify its behaviour – if possible – in order to benefit the operation of the grid.

While both approaches are interesting, the actual European legislation pivots around a market-based approach to grid services provision. That is why the *Supportive* approach do not seem a viable option unless the regulatory framework changes. Furthermore, already in section 5.2, Implicit Demand-Side Management, which would be an intermediate position close to a Grid Supportive approach, is dismissed as the best option to relief the operation of the distribution grid due to the ambiguous benefit for the customer [67].

6.2.2 Legal Barriers for Battery Storage

The regulatory framework at EU and Member State level has not evolved yet to support the cost-efficient deployment of energy storage. At the moment, even the demonstration of first-of-a-kind real-scale technologies faces regulatory barriers. Also, a fair market design is lacking for energy storage systems. The new CEP directives and regulations try to solve some of the main concerns related to energy storage legislation, and thus BSSs. From a literature review, this section will expose those regulations/lack of regulations that have been identified as important hindrances for a broad introduction of ESSs into the power system, mainly focusing on those related to market barriers. The order of the list was selected to show a serial correlation between items, that is why the first hindrance mentioned is *Demonstration projects framework*, because they can assess the needs and capabilities of new technologies, helping to develop further regulations. Then, the definition of energy storage is highlighted as a key point before the further regulatory framework is developed. Finally, the list delves into specific regulations that may hinder the energy storage deployment.

- **Demonstration projects framework**: Before even going with the market hindrances, one of the barriers identified by [91] for the proper implementation of ESSs is the lack of a clear regulatory framework to promote demonstration projects. Demonstration projects are a crucial agent of any technology development; they allow to gather valuable knowledge about market applications and commercial arrangements.

  In the field of energy storage, they can also be useful to set the basis of new legislation. For instance, article [93] explains how the Netherlands has been redesigning the grid governance model via pilot projects, highlighting the importance of a pilot project legal framework for developing a new regulation. This experimental legislation mostly entails new temporary legislation with a limited area of application. After the pilot project, the new legislation can have its performance evaluated and based on the performance outcomes, the current regulation will be changed or will remain the same.

  In the Netherlands, the *Crown decree for Experiments with decentralised renewable electricity* generation is the base of the regulatory framework for energy projects experimentation. Another example, more closely related to the ownership of ESSs by TSOs and DSOs, appears in the report *Battery Energy Storage in the EU* [94] published by EUROBAT (the association for the European manufacturers automotive, industrial and energy storage batteries). There it is mentioned Article 36 of the Italian Decree-Law 93/11 where the Italian government allows TSOs and DSOs to own BSS in order to promote their development plan.

As it will be seen in the following section, this approach has already its outcomes in the Italian network codes where CEI-016 and CEI-021 regulate the connection of BESs into the grid.

It is also true that the EU has reinforced its compromise with electricity-related demonstration projects on the CEP **e-Regulation** *Art. (3)*. There the EU states: *"market rules shall allow for the development of demonstration projects into sustainable, secure and low-carbon energy sources, technologies or systems which are to be realised and used to the benefit of society."* This requirement has to be transposed on each MSs regulatory framework, but after that It will give a drive to demonstration projects on those countries where the regulation is still dim.

- **Energy Storage definition**: Another important concern is the lack of a clear and technology-neutral definition of Energy Storage [91, 90, 94, 95, 96] EUROBAT [94] identifies the lack of a proper definition as the biggest barrier to energy storage. Also EASE/EERA [91] points out the importance of such a definition.
  The reason why this is considered such a hindrance for ESSs is because: if no definition for energy storage is provided, in most MSs ESSs are considered a generation asset [96], which do not reflect their potential benefits, plus it tends to create a lot of market barriers and bottlenecks in the legislation due to the incomplete definition. This, therefore, could discourage investments due to regulatory uncertainties or even hindrances. As said in [90], "*the definition of energy storage as a generation asset may be adequate for large scale energy storage technologies, but it poses investment risks for BSSs and other technologies with less storage capacity since they are enclosed to provide generation services*".

  This issue is the base of all the forthcoming ones because the lack of definition makes it harder to regulate specifically for BSSs and even for ESSs. The proposed solution is, in most cases - for instance [91, 94, 96] – the establishment of a new asset type definition in the power system: Generation/Transmission/Distribution and **Energy Storage**.

- **Framework definition**: This may be the wider issue because it encompasses a broad variety of problematic. However, the need of a clear framework could be inferred from the point above. In this point some specific concerns identified by stakeholders [91, 94], researchers [96, 97] and legislative institutions [89] will be mentioned:

  - Network charging for energy storage [91, 94, 96]: This is mainly due to the lack of specific definition for energy storage. Since it is neither a generator nor a load but can behave as both, some MSs apply double taxation to energy storage assets.

  - Under-remunerated services [96, 97]: Article [96] highlights that actual balancing markets are not considering the full benefits of ESSs when offering remuneration for balancing products. EUROBAT [94] states that the recognition of the value of the services offered by storage systems is central to creating the business case for storage. For instance, when providing balancing energy through the wholesale electricity markets.

  - Market-based approach for all services [91, 94, 96]: Ancillary services could be a crucial source of revenue for energy storage [96]. Furthermore, this increase in competition, created by new agents and technologies participation to the markets, should reduce electricity costs for the consumer, being this one of the European drivers to push towards an unbundled market model. From this perspective, the opening of new flexibility-markets to provide services to DSOs, and new product designs in the existing balancing markets [96], should be a push for the economic viability of ESSs.

  - Ability to provide more than one service at once [97]: Here the problematic starts with the lack of a clear definition, since ESS is neither a generator nor a load some ESSs have the technical capability to provide more than one service at once. This should be reflected and enhanced in market designs, to provide economic viability to ESSs.

  - Ownership and operation of ESSs: The **e-Regulation** *Art. 36* states that DSOs and TSOs cannot own, develop, manage, or operate energy storage assets. Then it states that in some cases, basically when there is no third party willing to provide the same service, DSOs and TSOs could own energy storage facilities. However, this situation would need to be inspected every two years.
    As said in [90], "*this unclear ownership and operation status of ES creates uncertain investment environments, particularly for network operators*". Even in those cases where the exemption to the rule could be applied system operator may be reluctant to invest due to the uncertain horizon they will face every two years.

- **Other barriers**:

  - The Interaction of Storage with Final Consumption Levies: Over the last years new consumption levies have increased the cost of electricity to encourage the deployment of RESs. Article [90] gives some UK examples such as the Renewables Obligation (RO) levy, Feed-in Tariff (FiT) or Climate Change levy. These kinds of levies are seen in some cases as financial hindrances for those ESSs whose main objective is not to feed a final consumer of energy. For instance, article [90] states, " *It is found that the cost of RO and FiT levies account for 80% of all non-energy-related supply costs when charging a commercial grid-scale battery* ".

  - The Interaction of Storage with RESs Subsidies: Article [90] points out that public measures to enhance RESs penetration such as *Preferential Remuneration for Feeding into the Grid PV Generated Electricity* or similar initiatives with Wind-Power Plants, do not incentive RES facilities operators to store the energy generated. This is a clear hindrance to the deployment of BSSs but also provokes that REs power plants could, in some cases, become a problem for the grid by increasing its operational costs.

There is strong evidence that grid-scale storage will not reach its full potential in helping to facilitate RES integration without a complete set of tools to simultaneously address the technical (Connection Codes), economic and market (Market Codes) aspects of storage integration [97, 92].

However, with the central problematics shown it would not be fair if a reference to Section 4.3.1 is not done. As can be seen in Section 4.3.1, the publication of the **e-Directive** and **e-Regulation** has supposed an essential change of role for energy storage in the EU energetic strategy. Most of the concerns mentioned above are addressed in the e-Directive and e-Regulation, and sooner rather than later, these new guidelines shall be implemented at the national level in order to enhance the widespread of ESSs.

6.3 Member States Network Codes on Battery Storage

The introduction of battery storage systems either as physical facilities or as aggregated virtual power plants (VPPs) could have a significant impact on how the DSOs approach grid extension and reliability problems. Within the increasing penetration of DG, these are the main concerns in terms of reliability and costs. The cost-related concern is due to the significant investments needed to prepare the grid for the new DG scenario via the old fit-and-forget approach. However, the not-so-new liberalization of electricity markets in Europe opened a new horizon of possibilities for grid management where BSS can also play a prominent role. These ancillary services markets can help DSOs to increase the reliability and hosting capacity (HC) of the grid without the need for new investments in infrastructure.

The European Union has identified the development of Network Codes and Guidelines as a crucial element to enhance the creation of the internal energy market [60] (see Section 4), which inherently will give a drive to new market agents such as BSSs. In the report *The EU Electricity Network Codes (2019ed.)* [60], network codes are classified into three main groups:

- **Connection Codes**: They set the requirements for the connection of different users and technologies. In order to secure the grid and harmonize the playing field for all technologies and agents.
- **Operation Codes**: They set the minimum requirements for TSOs and DSOs concerning operational security and set rules and responsibilities for the coordination system operators at the national level and across the Internal Electricity market.
- **Market codes**: Their main objective is the creation of an ambitious new European internal energy market to reflect and enhance the changing technical features of electricity production systems [27].

The first and the most important step to integrate new technologies into the system is to clearly define their rights and duties to connect to the grid, also known as **Connection codes**. By defining a regulatory framework, the MSs give legal security to investors while at the same time defines the role towards the grid of the new technology connected. The case of BSSs is no exception, as stated in [98], "*national and international authorities are already updating their Connection Codes regarding the connection of active end-users to distribution networks, including DGs and occasionally BSSs, to counteract possible effects and maximize possible benefits of BSSs*".

Article [92], which reviews the evolution of DER interconnection standards from 2000 to 2018 in the US, focuses on the importance of interconnection standards (Network Codes guidelines) like **IEEE 1547** [99] and their constant revision in order to properly fit all new technologies into the grid. It states: "*It is important to proactively design a new set of guidelines or a standard which considers the unique characteristics of ESSs and facilitates their reliable grid integration*." Then, it points out that one effort in this direction is the **IEEE 1547.9** for interconnection of energy storage DERs with the grid. Another example in this direction is the most recent version of the European standards reporting the recommendations for connection of LV micro-generating plants in **CENELEC TS 50549-1**.

While MSs network codes regarding the connection of generation and demand are being slowly adapted to their homonymous European counterparts (**RfG NC** and **DCC**), few of them include specific sections to define the roles, duties and responsibilities of battery assets connected to the grid. We consider that this is mainly because the European Regulations do not include such sections. What is more, and has already been said during this work, **RfG NC** and **DCC** exclude their application explicitly to ESSs (*Art. 3*), and most MSs do not have an urgent need yet. In fact, it is on the **e-Regulation** (*Art.59*) where for the first time is stated the need to define specific network codes for Energy Storage.

From the literature reviewed – this report took [45, 46, 98, 100, 101, 102, 100] as a starting point – we concluded that Austria, Denmark, Germany and Italy are, nowadays, those MSs leading when talking about network codes regarding BSSs. This selection is based on the fact that these countries have well-established connection codes, where the role of energy storage is clearly defined. Also, specific requirements for energy storage have been defined in those scenarios where energy storage systems have diverse capabilities when compared to traditional generation assets.

6.3.1 Benchmark of Connection Codes: Denmark, Germany and Italy

First of all, it seems important to us to highlight that most MSs, while adapting their new NC for Generators and Loads to their European counterparts have not developed a specific section for BSSs connected at LV. From this work we think that this is mainly due to the complete forget of ESSs in European Regulations and Directives until the recent **e-Directive** and **e-Regulation**. It is also true that other MSs are starting to promote on their network codes requirements for BSSs; for instance, the UK is currently finishing the process to include ESSs onto their Grid Code [103].

In this section, a summarized benchmark of the Danish, German and Italian network codes on BSSs will be done. The Austrian ones have not been included due to the lack of available documentation.

The following list references the name of the specific section of the Network Code referred to BSSs in the three countries studied:

- Denmark: With already high penetration of DERs by 2007 [5], among other things decided to create a specific section of their RfG NC for BSS published in 2017 and reviewed in 2019.

  - **Technical Regulation 3.3.1 for Electrical Energy Storage Facilities** [101].

- Germany: Germany experienced a large amount of DERs interconnection in their low voltage networks, which led to the development of BDEW (2009) and VDE 4105 (2012) for the medium and low voltage grids [92]. It is remarked on [29] the importance of the creation of network codes to make a safer grid. Gradually the role of BSS has also been defined in the following network codes:

  - **VDE-AR-N4100**: Technical Connection Rules for Low Voltage Grids [45].

  - **VDE-AR-N4105**: Power Generation Plants on Low Voltage Grids [46].

- Italy: Nowadays Italy is together with Germany, Austria and Denmark one of those few countries with specific network codes for low voltage connection of BSSs. The Italian connection codes are:

- **CEI 0-21**: Connection of active and passive users to the LV electrical Utilities [102].

- **CEI 0-16**: Connection of active and passive consumers to the HV and MV electrical networks of distribution Company [104].

While all the Connection Codes analyzed are influenced by the European new regulatory framework in terms of NC, each of them takes its particular approach. Related to their particular approach, and after consulting all three regulations, some perks and disadvantages of their framework have been identified.

The Italian CEI 0-21 and CEI 0-16 are specific network codes for the connection of active and passive users to the LV or MV distribution grids respectively. So, instead of the European approach of a specific network code for Generators and another for Loads, Italy has decided to approach network codes from a different perspective.
It has its advantages and drawbacks. Technically speaking a network code specific for a voltage range connection should be able to consider specific characteristics of the assets connected. However, it has to be taken into account that it is not a specific connection code only for batteries, and thus, sometimes there is a lack of clarity to understand to whom apply some requirements.

The German approach is the same as the Italian one, but in order to facilitate access to specific rules for BSSs they have published an additional document called *Connection and operation of energy storage units on the low-voltage network* [105] where the specific requirements for BSSs in VDE-AE-N4100 and VDE-AE-N4105 are summarized together with specific sections with examples, concepts definitions and suggestions for further requirements and network codes.
This approach really could help to clarify the lack of clarity found in the Italian approach.

Finally, there is the Danish regulation which is based on the European **RfG NC** model but specifically developing requirements for BSSs. Due to the broader voltage range covered, it may lack the capability to create more specific assets types in terms of power rating. However, between the legislation compared, this does not seem the case. For instance, referring to Table 17 which defines asset types in the Italian and the Danish regulations on BSSs, it is true that the Italian regulation facility Type A encompasses much smaller BSSs than the Danish one. However, already on Type B facilities, things change, and it is the Danish regulation the one able to be more specific. Furthermore, the Danish regulation also defines specific facility types for *Temporary Connected*, and *Generation facilities retrofitted with BSS*.

In terms of accessibility and ease of understanding, the Danish regulatory framework is more transparent than the Italian and German one, since it is a single document fully devoted to energy storage.

Table 17: Asset types in the Danish and Italian network codes.

Denmark		*Italy*	
Facility Type	**Rated power**	**Facility Type**	**Rated power**
A	$\leq$ 125kW	A	800W to 11,08kW
B	125kW to 3MW	B	11,08kW to 6MW
C	3MW to 25 MW	C	6MW to 10MW
D	$\geq$ 25MW	D	$\geq$ 10MW
SX	Generation facilities retrofitted with an energy storage solution	The Italian regulation is specific for LV networks while the Danish one is generic.	
T	Temporary Connected		

This benchmark is intended to showcase those points in common between existing BSSs network codes since there is not yet a European Guideline as a reference framework. Furthermore, from all the experience gained during the development of the work, we will try to find some specific characteristics that could benefit BSSs, either as design parameters or even technical requirements.

Before starting the analysis of the tables, it is essential to mention the “problematic” we have encountered with the German technical regulation. The document *Connection and operation of energy storage units on the low-voltage network* does not give detailed technical specifications and requirements; instead, it shows where the reader can find such information in the official regulation, together with some examples. On the one hand, it is useful; however, we see as a critical hindrance to the widespread of the new technology the fact that German Connection Codes have to be bought when they are a manual of basic requirements to connect to the grid.

At the moment of the development of this section, we did not have access to such codes. That is why there are a lot of N/As on the German side of the tables. However, we considered it was important to show the existence of such network codes, and, as far as we could, show which are the requirements defined on them.

Regarding to the *Tables* 18, 19, 20 and 21, and focusing on the Danish and Italian NC, it stands out that, aside from minor details there is no big difference between requirements. These similarities are the results of the standardization process Europe is trying to conduct on all its MSs network codes in order to create a stronger internal market. In fact, on Section 4.2.2 a summary of the **RfG NC** voltage and frequency requirements can be seen; the ones that apply to small generators are replicated on the Regulations studied. Moreover, when talking about Power Quality and Protection standards, there is a clear homogenization emerging from documents published by the European Committee for Electrotechnical Standardization and the International Electrotechnical Commission.

When approaching the German legislation, we have to go warily since we have not been able to study the actual LV Connection Codes. Still, some observations can be done based on the document *Connection and operation of energy storage units on the low-voltage network*.

With that said, these are the main differences observed between legislation:

- **Definition and Protection**: On the Danish legislation there is *Section 1: "Terminology, definitions and abbreviations"* and *Section 3: "The energy storage facility's storage medium"*. Section

1 defines all the concepts related to energy storage that will be used along the regulation, then Section 3 defines specific energy storage configurations or types, such as the ones in *Table* 17.

The Italian CEI 0-21, defines energy storage in *Section 3: "Definizioni"*. However, since the regulation is not specific for energy storage, in *Section 3* there is a mix of definitions for all kind of assets, loads, generators, measuring units, etc.

The German document *Connection and operation of energy storage units on the low-voltage network* where in *Section 3: "Terms and definitions"* defines the operating modes of the energy storage units, and other things related to ESSs installation, connection and operation.

In terms of Protection Requirements for energy storage systems, all three countries define their own rules. Finally, one observation has to be made; the row *System Protection Requirements* of the Table 18 is only required by the Danish regulation because it is the only one regulating assets connected to the transmission system.

Table 18: Definition of ESSs and Protection requirements in network codes.

Definition and Protections			
Country Requirement	**Denmark**	**Italy**	**Germany**
- Definition	Sect. 1.1.12 Sect. 3	Sect. 3 (68)	Document Sect. 3
- Protective Setting Requirements	General requirements Sect. 7.2 7.2.1 Assets Type A 7.2.2 Assets Type B 7.2.3 Assets Type C and D	Sect. 8.6.2.1	Not required for assets with maximum power up to 30 kVA. Assets above 30 kVA: VDE-AR N 4105, Clause 5 & 6
- System Protection	Sect. 7.2.4 Only for assets type D	No	N/A

- **Voltage Control and Support**: As can be extracted from the *Table* 19 the Danish Connection Code defines different Voltage Control methods. It also clearly states: "*A facility must not perform Q control, power factor control or automatic power factor control except by prior agreement with the electricity supply undertaking*", and finally clarifies that such methods are mutually exclusive so only one of them can be activated at a time.

  Instead, the Italian network code define capacity requirements for inverters in *Section 8.4.4.2* differentiating assets below and above 11.08 kW. Then in *Allegato E: Sect. 2*, first defines minimum mandatory requirements for voltage control $(\cos\rho = f(P))$, excluding assets below 800 W. Afterwards, on *Allegato E: Sect. 2.1*, the *CEI 0-21* defines specific requirements for assets above 11.08kW with other control methods, $(Q = f(V))$, clearly stating that the remuneration of such mandatory service will be determined by the *Autorità di Regolazione per Energia Reti e Ambiente*.

Finally, and as far as we know, the German NC establishes some required methods of Voltage support for ESSs, differentiating between ESSs operation modes. For more in-depth information see *VDE-AR N 4105: Sect. 5.7.2* for “Energy Supply mode” and *VDE-AR N 4100: Sect. 10.5.6* for “Energy Consumption mode”.

Table 19: Voltage support requirements for ESSs in network codes.

Voltage Support			
Country Requirement	**Denmark**	**Italy**	**Germany**
- Q Control - Power Factor Control	Sect. 6.3.1 and Sect. 6.3.2	Sect. 8.4.4.2* and Allegato E: 2	"Energy Consumption" mode: VDE-AR N 4100 "Energy supply" mode: VDE-AR N 4105 Sect. 5.7.2 ***
- Voltage Control	Sect. 6.3.3	Sect. 8.4.4.2* and Allegato E: 2.1**	N/A Ënergy supply" mode: VDE-AR N 4105 Sect. 5.7.2 ***
- Additional Current Injection	Sect. 4.4.4 and Sect. 4.4.5	No	N/A

* Section 8.4.4.2 only specifies Reactive Power emision capacity. Allegato E defines how the diferent type of generators should react.

** Voltage control capacity will be remunerated according to ARERA’s defined values.

*** Access to the VDE-AR N 4105 regulation has not been obtained so it not possible to determine how the service should be provided.

- **Frequency Control and Support**: Apart from the mandatory Frequency Response requisites in cases of Limited Frequency Sensitive Mode in Overfrequency (LFSM-O) and Limited Frequency Sensitive Mode in Underfrequency (LFSM-U), the Danish Grid Code defines Frequency Control mode technical requirements for those ESSs assets that want to provide such service. It is clearly stated on **General Requirements Sect. 6.1** that: *“A facility must not perform frequency control or voltage control without prior specific agreement with the electricity supply undertaking and Energinet Elsystemansvar A/S”*.

  Instead, the Italian Grid Code only defines the mandatory Frequency Response requisites in *Section: 8.5.3.4*.

  In terms of Frequency Response, the German regulation for energy storage can be found in *VDE-AR N 4105: Sect. 5.7.4.3*. Whereas, the document does not talk about specific Frequency Control requirements for energy storage.

Table 20: Frequency support requirements for ESSs in network codes.

Frequency Support			
Country Requirement	**Denmark**	**Italy**	**Germany**
- Freq. Response	Sect.6.2.1	Sect. 8.5.3.4	VDE-AR N 4105 Sect. 5.7.4.3
- Freq. Control	Sect 6.2.2	No	N/A

- **Power Quality requirements**: As can be seen in *Table* 21, the Italian regulation only defines them as a test for new assets before connection to the grid without explicitly differentiating between generation units and ESSs assets. Also, when defining the requirements, it only states that the Italian version of the correspondent international standard (e.g.: **CEI EN 61000-3-2**) shall be fulfilled.

  Instead, the Danish section for power quality starts with the requirement of fulfilling the Danish version of the same standards. However, it then develops step by step each requirement making the legislation more accessible and legible.

  Finally, the German document does not mention any specific protection requirement for ESSs.

Table 21: Power Quality requirements for ESSs in network codes.

Power Quality			
Country Requirement	**Denmark**	**Italy**	**Germany**
- DC Content	Sect. 5.1 Asset Type: A, B and T Sect.5.2 Asset Type: C, D and T	Sect. 8.4.4.1	N/A
- Asymmetry		Sect. 8.5.1	N/A
- Flickr		Sect. 5.3.1.2 Allegato B.1	N/A
- Harmonic Distortion		Allegato B.1 (a/b)	N/A
- Interharmonic Distortion		Allegato B.1 (a/b)	N/A

Aside from the benchmark, we would like to clarify some things about the German connection codes that we have extracted from the document *Connection and operation of energy storage units on the low-voltage network*. The first one is related to the **N/A** gaps on the benchmark. While we cannot assure that they will be defined on the actual network codes, we had access to a document [106] where part of the old *VDE-AR N 4105 (2011)* was transcripted. As we would expect, most of the **N/A** requirements were there but not specified for energy storage.
Secondly, *Section: 4.10* of the document is devoted to the Energy Flow Direction sensor (**EFD** sensor), which is a device "*used to meet the technical requirements regarding financial balancing for*

energy storage systems by determining the energy flow direction". This kind of requirements, that go a step further than the connection code requirements, are also positive in terms of erasing uncertainties for investors and clear up the playing field for new technologies.

Finally, there is the UK situation. The UK Grid Code is undergoing a transformation towards the integration of ESSs via the *UK GC0096: Energy storage* [103]. It was an amendment to the Grid Code in order to define the appropriate technical requirements for Storage technologies connecting to the Transmission system and apply the associated changes to the Grid Code. Currently the consultation process has been already finished and the final report is expected to assist the Grid Code Review Panel when revising the UK Grid Code [107] at the beginning of 2020.

The main driver to develop this proposal was a policy work led by the UK Department for Business, Energy and Industrial Strategy and the Ofgem on improving market access to flexibility. Some relevant modifications that are proposed in the UK GC0096 document are:

- **Harmonization of network codes**: They proposed to include the Energy Storage modifications into the section European Connection Conditions instead of putting them on the section Connection Conditions, to create consistency between all the agents connected to the grid. This decision was taken despite the Art.3 of the **RfG NC** and the **DCC** explicitly excluding energy storage from their scope, and shows the importance of defining a clear framework for the development of ESSs in the power system.

- **Definition**: They have identified that the current definition of energy storage as a normal generation asset as a potential threat to storage, that is why they have done the following proposals:

    - *Electricity Storage* definition should be technology-neutral and setting a minimum standard noting that users can exploit their full operational flexibility through commercial services arrangements/ markets.

    - *Definition of possible electrical storage configurations* as standalone assets or co-located as part of a generation demand scheme.

- **Technical requirements**: In the majority of cases, it is expected that storage would meet the same requirements as Generation and HVDC technologies. However, some specific requirements have been identified. For instance, storage should have a requirement to cater for power output with falling frequency and power output with rising frequency.

Aside from the possible outcomes of the process, it is also interesting to study all the work-group discussions and consultation processes, since they can show some insight of the problematic from a "real-life" implementation point of view. Related to energy storage inclusion on network codes, one major conclusion from the process is: "*So far as the Grid Code is concerned, most of the changes are reflected through the Glossary and Definitions, with the rest of the code remaining more or less unchanged other than in respect of specific items relating to storage. The key point here is that by amending the definitions such that Electricity Storage is now incorporated into the definition of a Power Generating Module and Generating Unit means that the obligation on Generators will also include storage.[...] In summary, and given the intention to align storage to Power Generating Modules (as introduced under* ***RfG****), a Generator who owns an Electricity Storage Module would be classified as an EU Code User*". This conclusion shows that in order to enhance the widespread of ESSs, the

first and most crucial step should be their definition. With just this "symbolic" development, many uncertainties related to energy storage assets would be erased because they would become under the protection of network codes.
Then, further steps, like specific requirements for ESSs and even specific market products for ESSs can be developed, benefiting from the potential of ESSs and enhancing, even more, their spread.

6.3.2 Active Power Droop and Voltage Control Technical Requirements

On *section* 6.3.1, this report has approached network codes from a “high level” perspective. We have compared some of the most advanced European network codes on energy storage in order to identify those characteristics that were common among them. Also, we have tried to highlight interesting particularities and different approaches to the same requirement to provide with some ideas and guidelines for the further development of other MSs network codes.

This section objective is to go more in-depth on some of the technical requirements and capabilities that the Danish and the Italian network codes mandate to storage assets in order to provide specific services. This perspective is intended to showcase those requirements that ESSs owners and manufacturers are interested to know when planning to provide a service or designing their new product respectively. In the end, as introduced in Section 3.2.2 the energy storage system by itself cannot connect to the power grid, it has to rely on a power electronics interface (inverter) to operate appropriately and adapt its output to the grid requirement. So, these technical requirements, in most cases, will define the capabilities of the inverter needed.

Active Power Droop Requirements: LFSM-O and LFSM-U

Requirements shown on Table 22 are those for **Limited Frequency Sensitive Mode** in case of **overfrequency** and **underfrequency**.

Table 22: LFSM-O and LFSM-U technical requirements for energy storage in network codes.

Active Power droop: LFSM-O and LFSM-U		
Country Requirement	**Denmark**	**Italy**
LFSM-O Frequency band (Hz)	DK1: 50.20-51.50 DK2: 50.50-51.50	50.2-51.5
LFSM-U Frequency band (Hz)	DK1: 47.50-49.80 DK2: 47.50-49.50	49.1-49.8
Response time	0-2s	0-1s
Control function sensitivity	±10mHz	±10 mHz
Pn Variation capacity	It must be possible to set the droop for both downward and upward regulation to any value in the 2% to 12% of Pn	
Duration of the service	Up on agreement with Energinet Elsystemansvar A/S.	No time provided, instead the limits are the ESS exceeding 90% of the CUS* or going under 10% of the CUS.
Assets required	LFSM-O: A, B, C and D LFSM-U: C and D	LFSM-O: Assets over 800 W LFSM-U: Assets over 800 W

* CUS: *Capacità Utile del Sistema di accumulo*

All the information from the tables is based on, *Denmark Technical Regulation 3.3.1 section 6.2.1/ 6.2.1.1/ 6.2.1.3 and 6.2.2*, and the *Italy CEI-021 section 8.5.3.4 and Allegato F*. It is also important to mention that on both regulations there are also requirements for ESSs interacting in different manners with the grid, for instance:

- **Denmark**: Section 6.2.1.2 Power flow to energy storage facilities
- **Italy**: Section 8.5.3.4.1 which defines the behaviour of an ESS connected to the bus DC of a PV power plant, for an unidirectional and bidirectional inverter.

Some observations from the table and the network codes can be done. Firstly, on both network codes is specified the information the owner of the ESSs must provide before connecting to the grid. Among other things, from these requirements, the duration of the service will be determined.

On the Italian regulation, the *Duration of the Service* is not a temporal concept; indeed, it is related to the charge situation of the energy storage asset. That is why it is based on the overall usable capacity of the ESSs (Capacità Utile del Sistema di accumulo; CUS). If the system is over 90% of its capacity or under 10% of it, the ESS can return to normal operation mode, even if the frequency deviation is not solved yet.

Instead, the Danish regulation is less clear on this requirement, stating that "*current parameter settings for activated active power control functions are determined by the electricity supply undertaking in collaboration with Energinet Elsystemansvar A/S before commissioning*." Which in some cases could be better for ESSs but, not explicitly defining requirements may leave the door open to uncertainties.

Secondly, other interesting specificities, from the Danish code, related to *Activation Time* are:

a) Regulation must be commenced no later than 2 seconds after a frequency change is detected and must be completed within 15 seconds. In this case, the regulation is laxer than the Italian one.

b) To facilitate detection of island operation in the distribution system, facilities connected in the distribution system cannot commence downward regulation of active power until 500 milliseconds have elapsed. This requirement is a good example of how 100% specific network codes for energy storage can consider a wider range of eventualities.

Voltage Droop Requirements: Voltage Control

Going one step further, there are the requirements for Voltage Control capabilities. In both the Italian and Danish regulation, this service is not mandatory for all asset types:

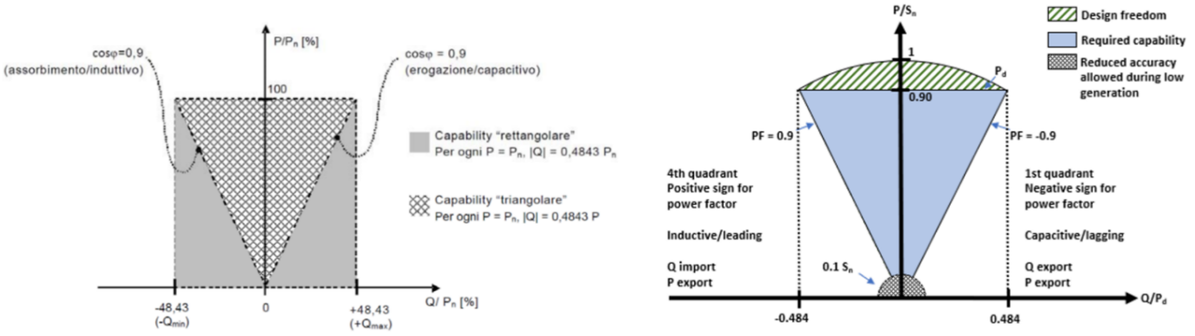
- **Italy**: only inverters above 11.08kW are required to have such capability.
- **Denmark**: only type C and D (>3MW) assets must fulfil the requirement.

However, to clarify possible misunderstandings, it has to be known that in the Danish regulation, all type of assets can provide Voltage Control services if there is a specific agreement with *Energinet Elsystemansvar A/S*. So, they have also established specific requirements for type A and B facilities connected to LV lines. This definition allows this work to carry out a fairer comparison between network codes since the Italian CEI 0-21 is limited to LV connections.

The next step is to identify those requirements that will shape the inverter needed by the BSS to provide the service. From the literature reviewed the following three requirements have been identified as the most limiting ones for a inverter:

- Inverter apparent power
- Response time
- Control curve

Starting to develop the requirements for the inverters, one important thing has to be noticed. The Italian regulation mandates inverters with a capacity above 11.08 kW to have the ability to operate with rectangular capacity curves (see Figure 14, “Capability rettangolare”). Meanwhile, the Danish regulation, for LV connection requires triangular capabilities (see Figure 14), at least for type A and B assets connected to LV. This consideration already influences the inverter needed: The one that would be required to fulfil the Italian regulation should have higher specifications, since it must deliver a constant value of reactive power no matter the active power output.



a) Italian capability requirement (*Section 8.4.4.2*)

b) Danish capability requirement (*Section 6.3.5.1*)

Figure 14: Capacity requirements for energy storage assets connected to LV grids in the Italian and the Danish regulations. Source [101, 102]

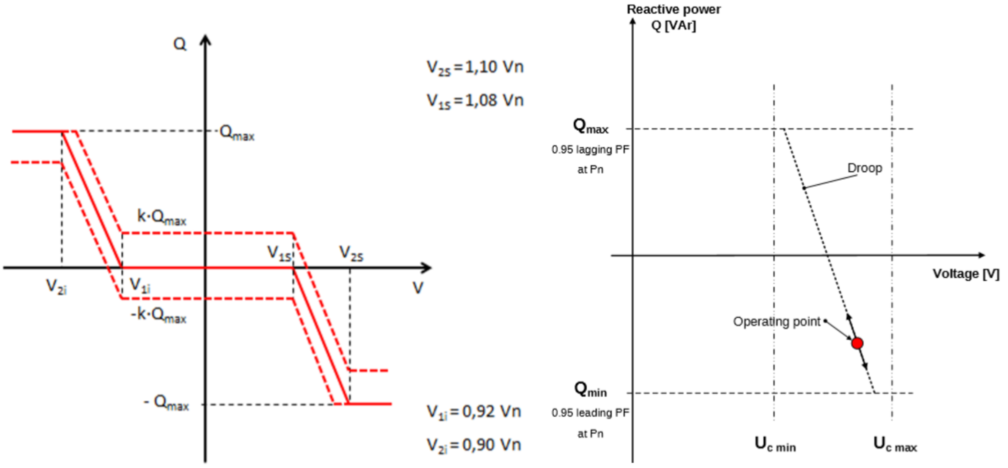
From the Figure 14 can also be extracted the apparent power capabilities required in the Italian and the Danish regulation. The most demanding point for the inverter to work on will be when the total apparent power is maximum:

- **Italy**: Active power output 100% (P/P_n) and reactive power output $\pm 48.43\%$ (Q/P_n).
- **Denmark**: Active power output 90% (P/P_n) and reactive power output $\pm 48.4\%$ (Q/P_n).

Related to the response time, or the design of the controller needed:

- **Italy**: The regulation defines a first-order filter with a configurable time constant with values ranging from 3s to 60s. It is mandatory for the inverter to reach 95% of the set point within three times the time constant selected.
- **Denmark**: The BSSs must reach the set point within 10s.

Finally, there is the curve $Q = f(V)$ needed. In this case both curves from Figure 15 are the illustration examples from the regulation documents, both of them need further definition by the system operator.



a) Italian regulation, curve *Q=f(V)*   b) Danish regulation, curve *Q=f(V)*

Figure 15: Generic curves $Q = f(V)$ for the Italian and Danish regulations. Source [101, 102]

However, before the specific definition for each particular BSSs, some differences can already be observed. In the Italian service, there is a dead band from $0.92V_\mathrm{n}$ to $1.08V_\mathrm{n}$, where there is no need to provide the service. Then voltage regulation is activated, and the maximum set point ($\pm Q_\mathrm{max}$) is reached when the deviation is equal to $\pm 10\%$ of the nominal value. Instead, the Danish regulation, from the illustrative example seems to do not have a dead band defined. Furthermore, the regulation states that *"it must be possible to set the droop for voltage control to a value in the 2-12% range. The specific droop setting must be agreed between the facility owner and the electricity supply undertaking."* The regulation also states that, before any agreement reached the standard-setting value is 4%.

6.4 Projects Using Battery Storage

This section aims to conclude the work by showing some research projects and private initiatives where BSSs are used to provide ancillary services to the grid.
On the one hand, the selection of pilot projects aims to show some potential future applications of battery storage systems together with others that are already in use. On the other hand, the private initiatives try to show the potential of BSSs for investors and the grid, if appropriate regulatory and market frameworks are defined. Together with how the definition of such frameworks could help to the widespread of BSSs via private investments.

6.4.1 Research and Development

Europe has always recognized the importance of innovation policies. However, at the beginning of the last decade, the EU identified that "*although the EU market is the largest in the world, it remains fragmented and is not sufficiently innovation-friendly*" [108]. At that moment, they decided to develop the concept of the *Innovation Union*. One of the outcomes of the *Innovation Union* is the on-going Horizon 2020 programme [109] which is the most significant EU research and innovation programme ever.

Horizon 2020 is a programme comprehended inside the *EU Framework Programme for Research and Innovation*, with a funding of nearly €80 billion and a lifespan of 7 years (2014-2020). It aims to increase Europe's global competitiveness, but also to create a simple coordinated structure where all the participants can interact and exchange knowledge and data to remove barriers to innovation. It also aims to enhance synergies between public agents, such as universities and research centres, and private sectors [108].

The importance of pilot projects in order to assess the potential and needs of new technologies has been already stated in Section 6.2.2. There, the lack of a *demonstration project framework* is indicated as an important hindrance to energy storage deployment.
A high number of demonstration/research projects in Table 23 are part of the Horizon 2020 programme. However, it is also important to mention that a lot of MSs, such as Italy and the UK, within their energy transition plan have included initiatives and funds to enhance demonstration projects in the energy sector. For instance, UK is promoting demonstration projects inside their *National Energy and Climate Plan* [110], Denmark has its demonstration project framework, the *Energy Technology Development and Demonstration Program* [111]. In Italy, since 2010 the *Autorità per l'Energia Elettrica* gives beneficial remuneration schemes to the selected DSO Smart Grid projects in order to promote them (see Section 6.2.2 for more information).

The following list contains all the projects in Table 23 with a description of their overall objective and the role of battery storage inside the project.

a) **INVADE**: The *Integrated electric vehicles and batteries to empower distributed and centralised storage in distribution grids* project [112] is a project encompassed inside the Horizon2020 programme that is focused on overcoming the challenges the grid face related to high RES penetration. In order to increase system resilience and flexibility INVADE opts for better use of existing infrastructures together with new technologies.
The core of the project is a cloud-based flexibility management system integrated with electric vehicles and BSSs. It tries to show the full potential of energy storage assets in a smart grid interconnected environment with an appropriate regulatory and market framework. As the INVADE project web-page states, "*Combining physical batteries with state of the art data technology will open new marketplaces to trade energy and energy services, which in turn will provide the end-users with better services. The electric grid manager will also benefit from this by better being able to manage their resources, and discover patterns in the power consumption, all made possible by the latest technology within big data analytic.*"
Due to the holistic perspective of the project, energy storage systems are used with multiple objectives depending on the pilot location. From DSOs investment grid deferral via an ancillary service market, to enhance self-consumption or study how electric vehicle storage can impact the grid.

b) **InterGRIDy**: InterGRIDy project [113] is also a project encompassed inside the Horizon2020 programme. It aims to facilitate the optimal and dynamic operation of the distribution grid through the connection of energy networks and stakeholders via the transformation of the grid into a Smart Grid. It also aims to develop the appropriate framework to interconnect them.
From the BSSs perspective the project aims to foster the stability and coordination of distributed energy resources, enabling collaborative storage schemes in grids with a high share of vRES, with a specific goal of reducing grid congestion and avoid RES curtailment. Finally, they do also approach battery storage potentialities from the prosumer viewpoint.

In this case, it is used to promote and maximize self-consumption strategies.

c) **Tilos**: *Technology Innovation for the Local Scale Optimum Integration of Battery Energy Storage* (Tilos) [114] is another project comprehended inside the Horizon 2020 programme. In this case, the project is 100% focused on the development and operation of a BSS to provide services to a local microgrid. The scope of the project is pointed towards island regions, specifically those whose power systems are isolated from the main grid. In these situations, the reliability and stability of the grid are even more crucial than in non-insular energy systems.
Insular energy systems are a clear example of how battery storage systems can be highly beneficial for the power grid. For instance, BSSs providing capacity firming to RESs power plants is an option to avoid the higher costs of activation of fuel-powered PGMs, which in isolated power systems tend to be very expensive.

The main services provided by the BSS durig the project are:

- Micro grid energy management
- Grid Stability
- Maximization of RESs penetration

d) **Isernia Project**: The Isernia project [115] is a demonstration project that was initially funded by the incentives to specific Smart Grid projects awarded by the Italian regulator in 2010. The pilot site has also participated in iGREENgrid, a Horizon 2020 funded project.
ENEL developed the demonstration project in 2011 to study the possibilities of the Smart Grid framework to cope with the higher penetration of DG in the Italian power grid, focusing on distribution grid active management. Then with the inclusion of the pilot site in the iGREENgrid, the project kept its initial purpose but inside a much broader approach to Smart Grids.
The primary role of battery storage in the pilot is to increase the integration of a PV power-plant in a MV feeder via capacity firming strategies, avoid curtailing of the PV generation and when possible provide services to the grid such as voltage regulation.

e) **POI-PAN**: The POI project (2007-2014) [55], later on, known as *Puglia Active Network* (PAN) project (2014-2024) [116] is a project also comprehended inside the incentives programme started by the Italian regulator in 2010. It also benefits from the *Decree Law 93/11* (See Section 6.2.2) that allows DSOs and TSOs to own ESSs.

This project may be the wider one of all of the projects in Table 23 because it comprehends the active management of networks across the entire region of Puglia. The PAN project aims at two objectives. The first one is to create a region-wide smart grid to optimize the operation of Puglia's distribution grids which have a high penetration of RES. The second one is to enhance end-user empowerment trough a constant availability of consumption and grid data [116].
The project is divided into specific sub-projects that have their pilot site associated. Battery storage capabilities are tested in the POI-P3 sub-project which is focused on increasing the hosting capacity and controlling voltage variations of a MV feeder with DG connected.

f) **CLNR**: The *Customer-Led Network Revolution* project [117] is a project funded by the Ofgem *Low Carbon Network Fund* which is comprehended inside the *UK National Energy and Climate Plan* [110].
The goal of the project is to develop and try solutions to cope with the forthcoming revolution in the power grid, or how they define it on their web-page: "*UK electricity networks will need to be ready to support the widespread uptake by customers of new sources of generation and electricity-intensive low carbon technologies like electric vehicles and heat pumps.*"
The role of battery storage inside the CLNR project is centred on demand-side management – from the prosumer side –, and peak shaving strategies together with the enhancement of network efficiency and helping with RESs integration – from the DSO side.

g) **NINES**: *Northern Isles New Energy Solutions* (NINES) [118] is a project aimed to deliver a secure, affordable and reliable energy system for the Shetland Islands, which have an isolated power system supported by an ageing power generation plant. The NINES project is thus funded via special electricity distribution licence conditions determined by the Ofgem and under the umbrella of the UK's *National Energy and Climate Plan*.
The BSS in this project has the main objectives of grid stabilization and investment deferral via:

  - Operation improvement of the old 67 MW diesel-fired station.
  - Management of current network constraints.
  - Grid reinforcement for further RESs connections.

h) **Virtual Power Lines**: Virtual Power Lines (VPLs) [119] stand out from the Projects table for many reasons. Firstly, it is not a project, it is a new implementation of energy storage capacities, and secondly it is – together with Enhanced Frequency Response and the Ruien Energy Storage NV – the only case where the point of connection of the BSS is at HV.
However, from this work perspective we consider that it is also relevant to show those "BSS-based" projects that are capable of exploiting the specific capabilities of battery storage systems in innovative ways, even if they are not intended for distribution grids.

The VPL concept consists of connecting two equal BSSs in both ends of a transmission line. During normal operation phase the storage system could help the TSO to balance the system, but at those moments when the line is expected surpass its capacity due to the amount of demand, for instance, the BSS on the PGMs side should absorb the excess energy while the one closer to the loads is releasing the power, with the effect of not achieving the congestion of the line, but at the same time, being able to provide all the expected demand through the line.
Figure 16 is a graphic example, provided by RTE, of how the concept would work.

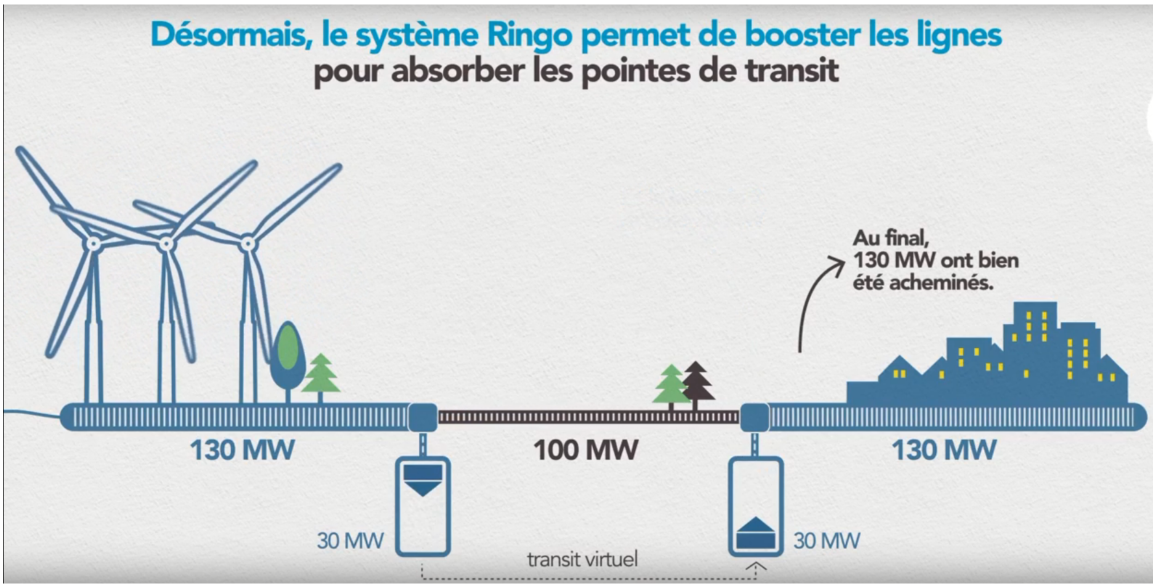


Figure 16: Virtual Power Line operation. Source [120].

It is an innovative concept that is on its firsts stages of development. Some TSOs, such as *Réseau de Transport d'Électricité* (RTE) from France, TERNA in Italy and TransEnergie (MurrayLink 2.0 project) in Australia, are currently undertaking demonstration projects. However, there is little information about the projects available, and even some of them like the RTE Ringo project seems to have vanished.

6.4.2 Products

While Demonstration projects are developed before the maturity of a technology and with the willingness to investigate and enhance its potential benefits, develop adequate regulatory frameworks, demonstrate real life applications, explore possible business models, etc. The appearance on the market of products using that technology proves that the overall framework for it is sufficiently stable to erase investors doubts and uncertainties.

The part of the Table 23 devoted to private initiatives not only aims to show the new potential business cases in the power grid that BSSs can create, but also to show how with the adequate regulatory framework and support to BSSs initiatives, the private investments will be enhanced and thus the energy model transition towards a cleaner power system.

The private projects from the Table 23 can be classified in three groups:

- Projects where the BSS is focused on providing services to the grid. In these cases a proper regulatory framework for energy storage connection to the grid together with well defined market products should be enough to give equal footing for energy storage to the service provision. This approach is the one taken in the Ruien Energy Storage NV and M5BAT. Respectively located in Belgium and Germany.

- Virtual Power Plants are innovative projects taking advantage of the technical capabilities of battery assets together with a proper communication interface. These projects are not completely focused on grid ancillary services provision, instead they leverage the poten-

tial of virtual clustering of individual assets to provide ancillary services while at the same time each asset is used by its owner. In this category Crowdnett and Sonnen Community are included.
In these kind of products the need for a regulatory framework for battery storage connection may not be enough. It is important to develop regulations and markets that take into account aggregation services specificities and needs.

- Specific market designs for energy storage systems. This is the case of the UK's Enhanced Frequency Response. It exploits the unique capabilities of energy storage assets to provide almost instantaneous response to create a new balancing product aimed to provide an improved grid stability, going one step further from the already fast Frequency Containment Reserve.
  This group of projects is on the Table 23 to show how specific products and markets designs for energy storage will promote the investment on such technologies and can create an overall more stable and better power system.

The following list presents the projects on Table 23, giving a better idea of the aim, capacities and objectives of each project.

a) **Crowdnett**: The Eneco Crowdnett [34] is a product created by the Dutch provider and supplier Eneco. It consists on the creation of a battery storage virtual power plant to provide ancillary services to the grid.
First ENECO builds its VPP the following way: Eneco sells at half the retail price to the end-user, a battery, *LG Chem RESU 7H/10H* or *Tesla Powerwall 2*, together with a four or five years long agreement between Eneco and the owner of the battery asset. During the lenght of the agreement Eneco will pay from 400€/year to 500€/year to have control over part of the BSS capacity.
Once the VPP has reached a capacity over the minimum bid required to enter balancing markets, Eneco uses the aggregated capacity of the assets to participates in the ancillary service market operated by TenneT.

b) **SonnenComunity**: Sonnen GmbH [121] is the leader German producer of home energy storage systems. In 2016 Sonnen GmbH launched the *SonnenCommunity* which is a community integrated by photovoltaic system operators (at prosumer level), that with the help of BSSs have created the first decentralized local energy community.
Within the Sonnen community the BSSs are first and foremost an instrument to enhance self consumption and Peer-to-peer – decentralized – trading between community members, then with the overall exceeding energy, *SonnenCommunity* uses the potential of its VPP to also participate in Frequency Control strategies in the TenneT grid.

c) **Ruien Energy Storage NV and M5BAT**: Both *Ruien Energy Storage NV* [122] and *M5BAT* [123] are BSSs installations aimed to make revenue via services provision or energy trading, benefiting from the technical capacities of BSSs.
On the one hand, the *Ruien* project participates in the FCR market while at the same time provide services, such as black start capabilities to a former 800 MW coal-fired power plant.
Meanwhile, *M5BAT* also participates in the FCR market and aims to participate to the wholesale market via the exploitation of price arbitrage strategies.

d) **Enhanced Frequency Response**: Enhanced Frequency Response is a balancing market product developed by National Grid the UK's TSO. It is aimed to provide super-fast reserve capacity to stabilize grid frequency during the start of a frequency deviation event. The service first tender period (Phase I) [124] took place in 2016, and the winners were awarded with a 4 years long contract to provide the service. Now, reaching the end of the first period, Phase II (Auction trial) [125] is starting. During this second phase the service will start to tender on a weekly basis on the UK's balancing market.

The product was firstly designed to fully benefit from energy storage fast response capabilities. However, technical information available from Phase I is scarce (only one source avaliable form NationalGrid: [124]) , and the one found seems to indicate the service definition has slightly changed on Phase II.
Now, on the new auctions, Enhanced Frequency Response has been divided into two products:

- **Low Frequency Static (LFS)**: This is a static service that is triggered at 49.6Hz. Minimum requirement is 1MW and must be able to deliver full output in 1 second.

- **Dynamic Low High (DLH)**: This is a dynamic service that delivers equal volumes of Primary, Secondary and High frequency response

Over all, and thanks to the inherent need of fast response capabilities of the assets providing this service, it continues to have its main market providers among BSSs.

Table 23: Grid-related EU demonstration projects and private initiatives using battery storage systems.

	Objective	ESS owner	Country	Regulatory framework	Operator	Market Based	Line level	Year	Funding entity
INVADE	Integration of DER, such as BSSs, in distribution grids to provide flexibility, via congestion management, peak shaving strategies, etc.	Prosumers and DSOs. Depending on the pilot.	Different pilot locations: Norway, The Netherlands, Spain, Bulgaria and Germany.	Depends of the country.	DSOs	No	LV	2017-2019	H2020 Work Programme (European Comission)
InteGRIDy	Utilize storage technologies and their capabilities to relieve the DG and enable significant avoidance of Renewable Energy Sources (RES) curtailment, enhancing self-consumption and net metering.	Prosumers and DSOs. Depending on the pilot.	Different pilot locations: Spain, Portugal, Greece, France, UK, Italy, Cyprus and Romania.	Depends of the country.	DSOs and end-users	No	LV	2017-2020	H2020 Work Programme (European Comission)
TILOS	a) Micro grid energy management b) Maximization of RES penetration c) grid stability provision d) Ancillary services to the System	DSO	Main pilot: Greece	N/A	DSO	No	LV	2015-2019	H2020 Work Programme (European Comission)
Isernia Project	Voltage Regulation; RES Integration	DSO; Enel Distribuzione	Italy	Yes*	Enel Distribuzione	No	MV	2011-2015	Eneco (but with the incentive of ARG/elt 39/10, which provided with an extra 2% of WACC to the selected SG investments)
POI & PAN project	Increase of hosting capacity of MV feeders. POI-P3 subsection is aimed at the mitigation of vRES intermitency, via the control energy exchange profiles between the HV/MV substations. (Control reverse power flows)	DSO; Enel Distribuzione	Italy	No * (**)	Enel Distribuzione	No	MV	2007-2024	Italian Government
Virtual Power Line: **a) Ringo Project** **b) Terna's VPL** **c) MurrayLink 2.0**	Transmission grid congestion management, and grid investment deferral.	TSO	Ringo - France Terna - Italy MurrayLink 2.0 - Australia	Depends of the country	RTE; Terna; ElectraNet	No	HV	N/A	RTE; Terna; ElectraNet
Customer-Led Network Revolution Project	DSO: Enhance grid efficiency and RES integration Prosumer: Demand side management strategies.	DSO	United Kingdom	No**	Northern Powergrid	No	MV-LV	2010-2016	OFGEM, LCNF and Northern Powergrid
NINES Project	Management of disitribution network constraints. Increase the RES hosting capacity of the distribution grid. Operation optimization of a power station	DSO	United Kingdom	No**	Scottish Hydro Electric Power Distribution (SHEPD)	No	MV-LV	2011-2016	SHEPD, Ofgem, DECC and Hjaltland Housing Association
Service provision: Enhanced Frequency Response (first 4 years tender)	(Fast) Frequency Control.	Third Party: a) EDF ER b)Vattenfall c) Low Carbon d) E.ON UK e) Element Power f) RES g) Belectric	United Kingdom	Yes	Facilities owners Under National Grid activation signal	Yes	HV	2016-2020	Private investors
Crowdnett	Reserve Capacity provision.	Prosumers	Netherlands	N/A	Aggregator: Eneco	Yes	LV	2016 (ongoing)	Private investors
Sonnen Community	Peer-to-peer trading and Ancillary services provision (FCR).	Prosumers	Germany	Yes	Aggregator: Sonnen	Yes	LV	2016 (ongoing)	Private investors
Ruien Energy Storage NV	Ancillary services provision (FCR), and energy service offerings at the site of the former 80 MW coal fired power plant	Third Party	Belgium	N/A	Third Party	Yes	HV	Early 2020	Private investors
M5BAT	Ancillary services provision (FCR) and wholesale market participation.	Third Party	Germany	Yes	Third Party	Yes	MV	2016 (ongoing)	Private investors

∗ In Italy there is an exemption for TSOs and DSOs to own and manage energy storage facilities since 2011. [Decree Law 93/11, see Section 6.2.2]

∗∗ Only as demonstration project.

7 Budget

The budget of this project encompasses the time and personnel devoted to the project, the equipment used and the literature resources needed.

Personnel Costs

In this section of the budget the personnel cost breakdown is developed accounting for the time devoted by the student to the thesis, and the time during which the external help from consultants has been used. All the other people that have participated in the development of the project – apart from the student – are considered external consultants, from the thesis Director and Codirector to the researchers who have been consulted.

The devoted time to the project is assumed as the expected time to develop a bachelor thesis in the Escola Tècnica Superior d'Enginyeria Industrial de Barcelona, this means around 300 hours. This calculation is based on the number of ETCS of the Final Project Subject, 12 ECTS, together with the assumed hours per ECTS, which are 25 h/ECTS.

Inside the personnel cost the student developing the project will be considered as a technical engineer with a wage of 30€/h, while the external consultants will be considered superior engineers with an average wage of 45€/h.

Table 24 shows the breakdown of the personnel cost of the project.

Table 24: Cost breakdown of personnel of the project

Concept	**Dedication (h)**	**Hourly wage (€/h)**	**Total Cost (€)**
Technical Engineer (Student)	300	30.00	9000.00
External Consultant (Director and Codirector)	20	45.00	900.00
External Consultant (Others)	10	45.00	450.00
Total	-	-	10350.00

Equipment and Cloud Services Cost

To develop this project, the equipment used have been one laptop and one Ipad Pro. To calculate the cost of the owned devices usage during the project, the *Amortized Cost* method has been applied, considering seven months the duration of the project, and a period of amortization of the devices of five years.

Table 25 shows the breakdown of the equipment amortized cost during the project.

Table 25: Cost breakdown of the equipment used during the project

Concept	Unit price (€)	Units	Amortized Cost (€)
Laptop (Dell Vostro 5391)	1031.60	1	120.35
Tablet (Ipad Pro 2018)	1247.65	1	145.56
Total	-	-	265.91

When talking about cloud services the cost breakdown includes the internet connection plan, which is crucial in order to access all the literature sources, the Dropbox cloud sharing service used to carry on with the project out of the workplace if needed, and the Grammarly cloud service to improve the overall final document quality.
The Grammarly cloud service has only been used during the final stages of the project, to be more precise during the last two months. Meanwhile, the internet plan and the Dropbox Subscription are necessary during all the project duration.

Table 26 shows the breakdown of the cloud services and internet connection costs of the project.

Table 26: Cost breakdown of cloud services and internet connection

Concept	Monthly price (€/month)	Number of months	Total Cost (€)
Internet plan (Movistar Conecta)	38.00	7	266.00
Cloud Service (Dropbox Subscription)	10.00	7	70.00
Cloud Service (Grammarly Subscription)	30.00	2	60.00
Total	-	-	396.00

Literature Resources Cost

To develop the literature research of the project, some books and legal documents needed to be bought.
The book *Análisis y operación de sistemas de energía* was provided by the thesis Director. At the current date it has been discontinued and it is not possible to know the market value of it. However, it has been considered important to take account of it in the budget section since similar academic books have prices that cannot be neglected.

Table 27 shows the breakdown of the literature resources and legal documents costs of the project.

Table 27: Cost breakdown of the literature resources

Concept	Unit price (€)	Units	Total Costs (€)
Book **(Análisis y operación de sistemas de energía)**	Discontinued	1	-
Book **(Integration of Distributed Generation in the Power System)**	123.59	1	123.59
Book **(Micro and Local Power Markets)**	123.93	1	123.93
Legal Document **(Connection and operation of energy storage units on the low-voltage networs)**	59.00	1	59.00
Total	-	-	306.51

Total Cost

Table 28 shows the total budget of the project.

Table 28: Total cost of the project

Concept	Total Costs (€)
Personnel Budget	10350.00
Equipment Budget	265.91
Cloud Services and Internet Budget	396.00
Literature Resources Budget	306.51
Subtotal	11318.42
VAT (21%)	2376.87
Total	13695.29

Date: 18 of April 2020

Signature: Pau Plana Ollé

Conclusions

This bachelor thesis aimed to study and analyse the state of the art of measures to promote the integration of renewable energy sources in the distribution grid. Based on the literature reviewed and the recently published European legislation, it can be concluded that nowadays the direction of the measures to allow a higher share of renewable energy sources in distribution grids point towards a market-based approach. Inside this new framework, new agents and technologies will play a crucial role.

The thesis started with a summary of how the power system works and the challenges it has been facing during recent years. The increased share of DERs, such as RESs, is a challenging opportunity for grid operators in terms of grid management and safety. From this perspective, two conclusions can be drawn: First and foremost, the new issues arising from a higher share of RESs will be mainly local and will only be solvable locally. Secondly, to face such a challenging outlook, DSOs will need to change from a passive to an active grid management strategy.
Within the scope of this section, this thesis has identified hosting capacity indexes as an interesting and promising field to develop further research on. Adequate hosting capacity indexes and evaluation mechanisms could be very helpful to integrate more RESs to distribution grids.

From the regulatory perspective, after the homogenization process started with the Third Energy Package, the recently published CEP has gone a step further. Regarding to RESs integration, the CEP is focused on enhancing DERs participation in flexibility markets to secure the operation and management of the grid. From the CEP e-Directive and e-Regulation, this thesis would like to highlight the enhanced role of aggregation and energy storage technologies as crucial agents to increase the flexibility available, together with the stated need to develop network codes for non-frequency ancillary services. Because the new issues of the DER-based power system are locational, this thesis finds the definition of non-frequency ancillary services for DSOs, one of the crucial outcomes of the CEP to increase the share of RESs without compromising the operation of the grid.
The new European regulation opens a vast field of interesting topics to do research on. Some possible fields to develop are: product design for non-frequency ancillary services markets, the creation of an appropriate balancing responsibilities framework, and how to appropriately remunerate system operators in a grid with less investment in passive management – investment on physical assets – and more in active management – real-time operation of the grid via market trading.

Once flexibility markets have been identified as the main drivers to promote a higher share of RESs, the thesis has focused its sight on how market designs could enhance participation. Starting with the theoretical discussion about which is the best approach to new flexibility markets, this thesis concluded that a decentralised approach to non-frequency ancillary service markets is the best option to manage a higher share of DERs in the distribution grid. This statement is based on the locational character of the new problems that will face distribution grids, together with the fact that local markets can shape better their products to the assets and needs of each DSO. Overall, this thesis considers that decentralized local markets will enhance participation and will be more effective in fulfilling DSOs needs.
Then from this theoretical discussion, the thesis passed to study existing flexibility markets that are following the European guideline and promote higher participation of DERs. This thesis concluded that *Pooled Asset pre-qualification* is the fundamental market design barrier to DERs participation, and is particularly harmful for those ones that need from aggregation to enter the

market. One step below a *Low Minimum Bid* requirement is also important to ease participation. Finally, in the field of product requirements, this thesis ascertained the importance of *Specific Product Design* to enhance participation. This last point is highly linked to the thesis positioning for a decentralised approach to flexibility markets.
The new power system scenario, decentralized or not, will have more agents than ever before. This increase in the number of agents will increase the complexity of management of the power system. From this viewpoint, this thesis suggests the study of the possible increment of grid operational costs related to this new scenario. Besides, it would be interesting to investigate if it is possible to simplify the expected market framework in order to ease and optimize the grid management.

Related to energy storage, this thesis identified the lack of proper regulatory definition to fit in the power system as the core problem of it. This lack of definition leads them to have applied requirements for generators and loads at the same time, which is a significant hindrance. So, as a conclusion, there is an urgent need to define European connection codes to clarify energy storage assets rights and duties towards the grid. This will also erase uncertainties and hindrances for investors.
The lack of definition has just been solved with the entry into force of the e-Directive. Furthermore, the specific network code is expected to be an outcome of the CEP. However, before that happens this thesis suggest each member state to start developing their own energy-storage focused connection codes, based on the RfG NC and other already existing specific connection codes for energy storage.
From the connection codes centered on energy storage, the thesis would like to highlight the evident influence in all of them of the European harmonization process.
To promote the spread of energy storage, the creation of specific market products has been identified as the necessary next step after defining the connection codes. Specific Product Designs will allow taking advantage of ESSs capabilities, such as super-fast response times, which can be highly beneficial in terms of RESs integration at the distribution level.

Finally, in the field of energy storage, this thesis would like to question the benefits of the application of the unbundling principle to energy storage ownership by DSOs, at least during the transition phase towards a DER centred power system. For further research this thesis suggests studying the technological, legal and economic impact of a temporary moratorium of Article 36 of the e-Regulation.

So, while this thesis has started with the aim to study measures to promote a higher share of RESs in distribution grids, the recent publication of the CEP has reoriented the scope of the thesis towards flexibility market participation enhancement and the specific role of energy storage in distribution grids. Nowadays, this is a very incipient field in most of the European countries. Hence, the conclusions aim to give first guidelines about how the future of the power system will be shaped and which are the first steps needed to promote a safe and reliable transition towards a DERs predominant power system.

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Annex A

Publications