Public Policy Frameworks of Li-Ion Battery Energy Storage Systems Applications

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Energy Engineering and Management

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

In the two decades from 2020 to 2040, battery energy storage systems installations are expected to grow more than 50-folds. Among these technologies, Lithium-Ion batteries are forecasted to follow a 50% price reduction in 10 years.

The present paper presents the available technologies of Li-Ion BESS, highlighting strengths and weaknesses of its alternative compositions. BESS applications are then analysed, for both Behind of the Meter operations, Microgrids and Front of the Meter operation. BESS are then compared to other Energy Storage solutions. Following this section, the Master's Thesis restricts its focus on the first renewable energy tender in continental Europe with a PV + Storage option: The 2020 Portugal Solar Auction.

The study of BESS technologies, applications and public policy frameworks is used to support the hypothesis that *a short duration LFP BESS is the favourite choice for the 2020 Portugal Solar Auction, although long duration LFP and NMC BESS will become the technologies to yield the most value in the future decades*. Moreover, it is attempted to estimate the required volume of Back-Up systems and BESS to meet the targets of the PNEC 2030. It is forecasted that *by 2030 a volume range between 5-10 GW of additional Back-Up power will have to be provided. The share of BESS will depend on public policy frameworks and it can be estimated not to surpass 1 GW*.

As the future share of BESS will be greatly impacted by public policy frameworks, a final list of public policy actions is presented.

Abstrato

Nas décadas de 2020 a 2040, espera-se que as instalações de baterías para armazenamento de energia cresçam mais de 50 vezes. Entre essas tecnologias, espera-se que as baterias de íon-lítio sigam uma redução de preço de 50% em 10 anos.

O presente trabalho apresenta as tecnologias disponíveis de Li-Ion BESS, destacando os pontos fortes e fracos de suas composições alternativas. As aplicações de BESS são então analisadas, tanto para operações de Atrás do Medidor, Microrredes quanto para operações de Frente do Medidor. O BESS é então comparado a outras soluções de armazenamento de energia. Seguindo esta seção, a Dissertação de Mestrado restringe o seu foco no primeiro concurso de energia renovável na Europa continental com uma opção de PV+armazenamento: O Leilão Solar de Portugal do 2020.

O estudo das tecnologias, aplicações e enquadramentos de políticas públicas dos BESS é utilizado para apoiar a hipótese de que uma batería LFP de curta duração é a escolha preferida para o Leilão Solar de Portugal do 2020, embora LFP de longa duração e NMC se tornem as tecnologias com maior valor no futuro. Além disso, pretende-se estimar o volume necessário de sistemas de backup e BESS para cumprir as metas do PNEC 2030. Prevê-se que em 2030 uma faixa de volume entre 5-10 GW de energia de backup adicional e um valor estimado de 1 GW de BESS terá que ser forneceu.

Como a participação futura dos BESS será afetada por políticas públicas, uma lista final de ações de políticas públicas é apresentada.

Keywords

Battery Energy Storage Systems; Li-Ion BESS; Public Policy Frameworks; Front-of-the-Meter; Behind-of-the-Meter; 2020 Portugal Solar Auction; PNEC 2030

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Table of Contents

Abstract / Abstrato	iii
Keywords	iv
Acknowledgments	v
Table of Contents	vi
List of Figures	ix
List of Tables	x
List of Acronyms	xi
Introduction	1
Methods	2
1. State-of-the-Art of Li-Ion Battery Technology	4
1.1 Components of Li-Ion battery and comparison with other battery technologies	4
1.2 Materials employed for Li-Ion battery technologies	6
1.3 Physical Structure and packaging of Li-Ion batteries	8
2. Li-Ion Battery Energy Storage Systems Applications	12
2.1 Behind of the Meter Applications (BTM)	12
2.1.1 Increase of Renewable Self-Consumption	12
2.1.2 Tariffs Optimization	13
2.1.3 Peak Shaving and Load Shifting	14
2.1.4 Backup Power	14
2.2 Microgrid Applications	15
2.3 Front of the Meter Application (FTM)	15
2.3.1 Wholesale Market	16
2.3.2 Frequency Control and Ancillary Services Market	16
2.3.3 Capacity Market	18

2.3.4 Time Arbitrage	18
2.3.5 Ramp Control	18
2.3.6 Transmission Congestion Avoidance and Grid Investment Deferral	19
3. Advantages and drawbacks of Li-Ion Battery Energy Storage Systems as opposed to other solutions for a national energy sector	20
3.1 Comparison of Li-Ion Battery Energy Storage with Pumped Hydro Storage	20
3.2 Comparison of Li-Ion Battery Energy Storage with Molten Salt	21
3.3 Comparison of Li-Ion Battery Energy Storage with Regenerative Hydrogen Fuel Cell	22
4. Public Policies Frameworks for Battery Energy Storage Systems in Europe. A Case Study: the 2020 Portugal Solar Auction	24
4.1 General context of the 2020 Portugal Solar Auction	24
4.2 Structure and Rules of the 2020 Portugal Solar Auction	24
4.3 Contribution and Remuneration Schemes of the 2020 Portugal Solar Auction	25
4.3.1 Fixed Tariff Option	25
4.3.2 Merchant Option	26
4.3.3 Merchant Option with Storage	28
4.4 Analysis of the remuneration schemes of the 2020 Portugal Solar Auction	29
4.5 Analysis of the preferred energy storage technology for the 2020 Portugal Solar Auction	30
4.6 Remarks on Policy Frameworks following the 2020 Portugal Storage Auction	31
5. Chapter 6: Analysis of Battery Energy Storage Systems required for the Portugal PNEC 2030	33
5.1 Quantification of Renewables Generation, Back-up Asset and Energy Storage capacity required for PNEC 2030	33
5.2 Cost Analysis of Battery Energy Storage Systems required for PNEC 2030	37
6. Public Policy Framework Recommendations for Battery Energy Storage Systems	39

6.1 Fund pilot projects to demonstrate business case validity	39
6.2 Resolve energy storage ownership issues for TSOs and DSOs	39
6.3 Clarify the definition of Energy Storage in order to avoid double taxation	40
6.4 Introduce a market-based remuneration for every energy provision and ancillary services	40
6.5 Harmonize grid codes of neighbouring nations and international unions	40
6.6 Include battery energy storage into national renewable targets	41
6.7 Incentivize aggregation of residential and commercial storage	41
6.8 Widen the price spread of Time of Use electricity tariffs	42
6.9 Promote Capacity Payment for the installation of Battery Storage projects	42
6.10 Abrogate feed-in tariffs for residential and commercial prosumers	42
6.11 Design tenders which promote long duration batteries for applications stacking	43
Conclusions	44
Bibliography	46

List of Figures

Figure 1: Global cumulative battery energy storage installations	1
Figure 2: Price curves of energy storage technologies. Symbols indicate technology scope and colours indicate technology. Dotted lines are linear regressions of data.	5
Figure 3: Forecast of price curves of energy storage technologies from 2015 to 2040.	6
Figure 4: Graphic comparison of the most employed Li-Ion technologies. Every characteristic is rated on a scale from 1 to 4 in relation to the other competing technologies.	8
Figure 5: Cylindrical cells stacked in battery modules. As shown, the physical cavities resulting from the stacking of cells can be optimized by laying a wavy tube for thermal cooling.	9
Figure 6: Cross-section of a cylindrical cell.	9
Figure 7: Cross-section of a button cell.	10
Figure 8: Cross-section of a prismatic cell.	10
Figure 9: Cross-section of a pouch cell.	11
Figure 10: Investment costs of CSP plants with Molten Salt energy storage.	22
Figure 11: Scheme of a regenerative hydrogen fuel cell process.	23
Figure 12: Yearly contribution scheme of Fixed Tariff option.	26
Figure 13: Remuneration scheme of the electricity producer for a Fixed Tariff option.	26
Figure 14: Yearly contribution scheme of Merchant option.	27
Figure 15: Remuneration scheme of the electricity producer for a Fixed Tariff option.	27
Figure 16: Yearly contribution scheme of Merchant option.	29
Figure 17: Portugal electricity mix from 1990-2020 divided by percentual share of energy source.	35
Figure 18: Capital costs for a fully installed usable 20MW/80MWh AC energy storage system at beginning of life.	37

List of Tables

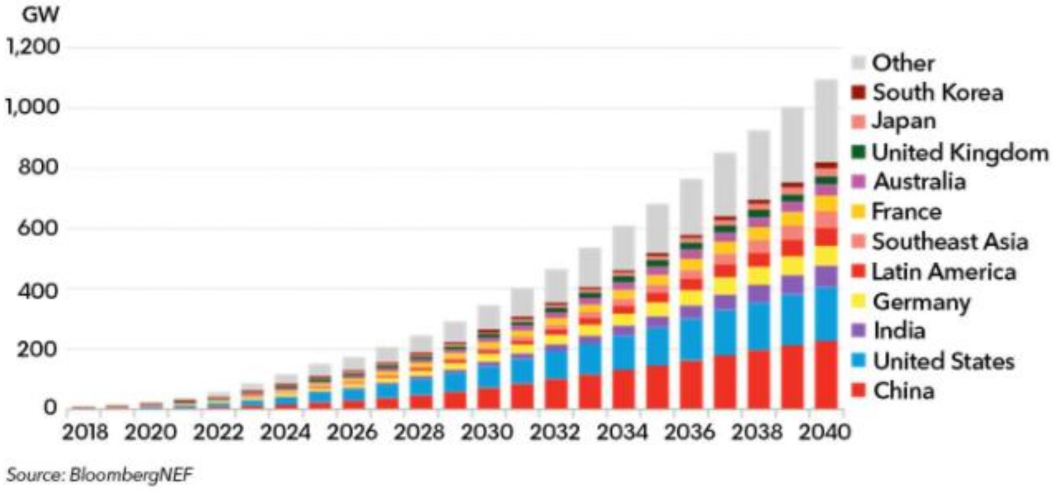
Table 1: Comparison of gravimetric and volumetric energy density limits of different rechargeable battery technologies.	4
Table 2: Summary of main targets of Plano Nacional Energia e Clima 2030 (PNEC 2030).	33
Table 3: Total installed capacity (GW) of each renewable source in Portugal for the PNEC 2030. Other Renewables accounts for Biomass, Biogas, Waste, Geothermal and Wave.	34
Table 4: Minimum indicative values of interconnectors capacity between Portugal and Spain to meet PNEC 2030's target.	36

List of Acronyms

BESS	Battery Energy Storage System
BTM	Behind of the Meter
CCGT	Combined Cycle Gas Turbine
C&I	Commercial and Industrial
DSM	Demand Side Management
DSO	Distribution System Operator
DoD	Depth of Discharge
FCAS	Frequency Control and Ancillary Services
FTM	Front of the Meter
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
Li-Ion	Lithium-Ion
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
NCA	Lithium Nickel Cobalt Aluminum Oxide
NMC	Lithium Manganese Cobalt
NPV	Net Present Value
PHS	Pumped Hydro Storage
PoI	Point of Interconnection
R&D	Research and Development
TAB	Triad Avoidance Benefit
TSO	Transmission System Operator
ToU	Time of Use
VRE	Variable Renewable Energy

Introduction

In the two decades from 2020 to 2040, battery energy storage systems installations are expected to grow more than 50-folds [1]. This exponential growth will be at the centre of a profound restructuring of the energy market. As renewables integration of wind and solar increases its share in the world electricity mix, new issues of electricity supply, frequency balance and price stability will become critical. When solar and wind reach the main share of a nation's electricity generation assets, it will not remain feasible to operate the grid without storage. From 20 GW circa of currently operative battery storage installations in the world, BloombergNEF predicts volumes around 1,095 GW by 2040, as shown in figure 1.



Source: BloombergNEF

Figure 1: Global cumulative battery energy storage installations [2]

This worldwide market expansion will require investments in the order of over $600 billion [2], redefining the way that renewable projects are financed and the degree of understanding that the world will need to gain on this technology.

In this regard, it is pivotal that a series of stakeholders involved in this market restructuring phase can understand and take advantage of the potential of energy storage. Regulating authorities will need to design public policies that are able to favour a thriving market. In this way, TSOs and DSOs will be able to use battery systems to enhance their grid resilience and flexibility. At the same time, power utilities will manage to deploy electricity with better power purchase agreements and by capturing new opportunities in the electricity trading markets.

Among all the energy storage technologies, the one that has been deployed the most in recent years, showing exponential growth, is that of Lithium-Ion battery systems [3,4]. Being the technology of choice for electric vehicles, Li-Ion represents a core solution for both the motor and the energy sector. This resulted is a particular effort in its Research and Development, which is expected to bring a 50% price reduction within the next 10 years [5]. Given these reasons, a focus on Li-Ion battery is due.

Being Li-ion battery energy storage a relatively new field with very limited track of records on all of its potential applications, it is fundamental in this moment in time to bring more clarity on the issue, so that all the stakeholders can appreciate the opportunities hidden underneath the complexity of such technology.

The purpose of this work is to present in a structured way the current state of development of Li-ion batteries (*Chapter 1*), explain the multitude of its potential applications (*Chapter 2*), compare it with the currently available alternatives (*Chapter 3*), understand how it is currently being deployed and favoured with new tailor-made policy frameworks (*Chapter 4*), estimate and analyse its future deployment considering the current targets of decarbonization (*Chapter 5)* and provide recommendations for the future on how this technology should be enhanced with proper policy frameworks (*Chapter 6*).

In order to focus on the public policies that are being designed at this moment in time (*Chapter 4*) and on the efforts that will need to be taken for future decarbonization national plans (*Chapter 5*), it was decided to use Portugal’s electricity market as case study. It is for these reasons that Chapter 4 focuses on the 2020 Portugal Solar Auction with Storage, while Chapter 5 analyses the targets of the 2030 National Energy and Climate Plan (PNEC 2030) and attempts to define an Energy Storage roadmap.

The 2020 Portugal Solar Auction represents an unicum, being the first renewable energy bid in continental Europe in which an awarding scheme has been designed solely for a PV with Storage option. For this reason, it stands at the forefront of policy frameworks on battery energy storage systems in Europe at the moment. Similarly, the PNEC 2030 sets an ambitious plan for decarbonization which, if proven successful, will pave the way for similar roadmaps across the rest of Europe.

The hypothesis brought forward in this Master’s Thesis is that, given the various considerations of technical and economic nature made across all chapters, a short duration LFP Li-Ion technology is the favourite choice for the 2020 Portugal Solar Auction, but that both LFP and NMC Li-Ion batteries with long duration discharge time are the solutions that will yield the most value with future applications. This hypothesis is proved with an analysis of the public policy frameworks of the 2020 Portugal Solar Auction (*Chapter 4, Section 4.5 and 4.6*). In addition to it, the Master’s Thesis work attempts to define a volume range of back-up systems and BESS needed to accomplish the targets of the PNEC 2030 (*Chapter 5*) and tries to formulate specific public policy frameworks to adopt (*Chapter 6*) in order to facilitate the roadmap to achieve these targets.

Having sustained which technology of Li-Ion is the most suited one for both the immediate future and the long-time approac and having presented which policy actions should be taken in order to favour the adoption of BESS to successfully achieve the targets of the PNEC 2030, it is believed that this work can have the value of contributing to the efforts for clarity in the field of battery energy storage systems.

Methods

The three research problems investigated were to identify which Li-Ion technology is the most suited for the 2020 Portugal Solar Auction, which Li-Ion technology is the most suited for the electricity market in the next decade and what volume range of battery energy storage should be deployed to meet the PNEC 2030's decarbonization target.

In order to answer the first question, it was first attempted to systematically describe the characteristics of the different Li-Ion technologies, comparing them one another (*Chapter 1*) and with other energy storage technologies (*Chapter 1 and Chapter 3*). For this purpose, it has been necessary to perform a recollection of both quantitative and qualitative data. All information reported was secondary data that can be retrieved in the bibliography, as no primary data recollection was performed for this study. Quantitative data was recollected for indicating the gravimetric and volumetric energy density of different battery technologies [4] and the price curves of different energy storage technologies [5], Qualitative data was instead collected to rank different Li-Ion technologies in terms of safety, performance, life span, cost, capacity and specific power [6,10]. In order to understand which of these aspects are the most relevant for the electricity market, it was necessary to explore the different applications for which energy storage systems are employed (*Chapter 2*). The information collected was sourced from scientific papers and internationally accredited organizations such as IEA, IRENA and ESA. Some examples of battery storage installations were also cited from News outlets, with the attention of selecting internationally acclaimed sources such as Bloomberg NEF.

In order to understand which of these applications could be employed to participate in the 2020 Portugal Solar Auction, the rules and remuneration schemes of the auction were analysed and reported (*Chapter 4*). This information was gathered attending the online seminar of the Portugal Directorate General for Energy and Geology [50] and from the literature presented in the seminar [52,53]. Through the analysis on the requirements and remuneration schemes of the 2020 Portugal Solar Auction (*Chapter 4, Section 4.5*), with the support of the information gathered in the previous sections on the State-of-the-Art of Li-Ion BESS technology (*Chapter 1*) and BESS applications (*Chapter 2*), it was possible to assert which BESS technology constitutes the most suited solution for the 2020 Portugal Solar Auction and which technologies are likely to remain suited to the electricity market in the next decade.

In order to quantify a volume range of battery energy storage needed for the PNEC 2030, it was necessary to first gather from the PNEC 2030 the exact values of its decarbonization target and its forecasted values of total installed renewable energy capacity in 2020, 2025 and 2030. After gathering this data, in order to estimate the back-up needs it was necessary to make the assumption that for countries in which Variable Renewable Energy (VRE) penetration surpasses 40-50% it is advisable that every GW of VRE installed is balanced by 0.8 GW of back-up asset to maintain security and reliability of the grid [57]. Having obtained the value of back-up asset required for the total VRE capacity installed, it was then possible to reduce the value of the necessary back-up power by considering the improvements of the Spain-Portugal interconnection defined the PNEC 2030 [48]. Hence, it was possible to provide a range of power to be covered by a combination of Hourly Ramping of non-dismissed fossil-fuel peak plants, Demand Response programs and Energy Storage technologies. The real value of BESS installed by 2030 can be finally determined by the economic competitiveness of VRE+Storage options in the coming national public tenders. Finally, following the trends outlined by BloombergNEF [64], an optimistic scenario of covering of back-up power with BESS was indicated.

Chapter 1: State-of-the-Art of Li-Ion Battery Technology

1.1 Components of Li-ion batteries and comparison with other battery technologies

Li-Ion batteries are made of a solid anode and cathode that can both host Li-ions. The preferred material for the anode is the graphene hexagonal structure [1], which favours easy and rapid intercalation of ions, while at the cathode it is in most cases used Li_xMO_y compounds [3], which will be presented in detail in section 1.3. The reason behind the success of Li-Ion batteries is given by their high gravimetric and volumetric energy density, which allowed these batteries to be the preferable choice for portable electronic devices [4]. Table 1 shows a comparison of gravimetric and volumetric energy density achievable limits among different rechargeable battery technologies.

Table 1: Comparison of gravimetric and volumetric energy density limits of different rechargeable battery technologies [4].

Battery technology	Gravimetric energy density [Wh/kg]	Volumetric energy density [Wh/L]
Li-Ion, Li-Metal	< 250 Wh/kg	< 650 Wh/L
Ni-MH	< 150 Wh/kg	< 350 Wh/L
Ni-Cd	< 100 Wh/kg	< 250 Wh/L
Lead Acid	< 50 Wh/kg	< 150 Wh/L

As it can be noticed, Li-Metal displays similar performances to Li-Ion technology, however it presents a lower rechargeability and are more subject to safety issues such as fire hazard [4].

Constant research is being made across the world to raise these boundaries. If these were extended to 500 Wh/kg and 1000 Wh/L, battery technology could potentially enter new fields of application or establish itself in ideally every mean of transportation [5] (Aviation, Road and Sea transport).

As far as it concerns the price figures of rechargeable battery technology, as Figure 2 shows, Li-Ion is the one that in the last two decades was able to drastically increase its competitiveness, reaching in 2011 levels comparable to those of Nickel-Metal hydride and even equalling the price of Pumped Hydro Storage installations. As it can also be noticed, the size of the system is inversely proportional to the price per kWh installed, except for mature technologies employed for large storage systems such as Lead Acid batteries and Pumped Hydro Storage [5].

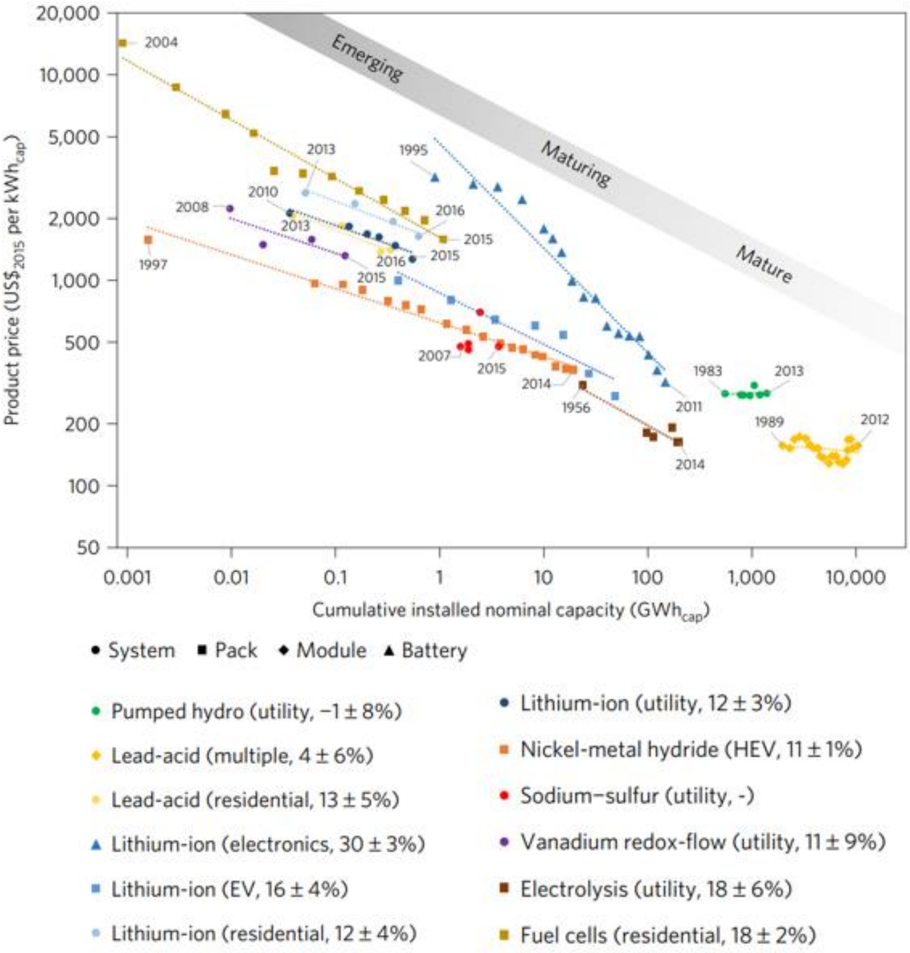


Figure 2: Price curves of energy storage technologies [5]. Symbols indicate technology scope and colours indicate technology. Dotted lines are linear regressions of data.

The study shows that the decrease in price is expected to continue with slightly slowing trends, as it can be seen in Figure 3. It is noticeable how Li-Ion is expected to continue to abate its manufacturing costs.

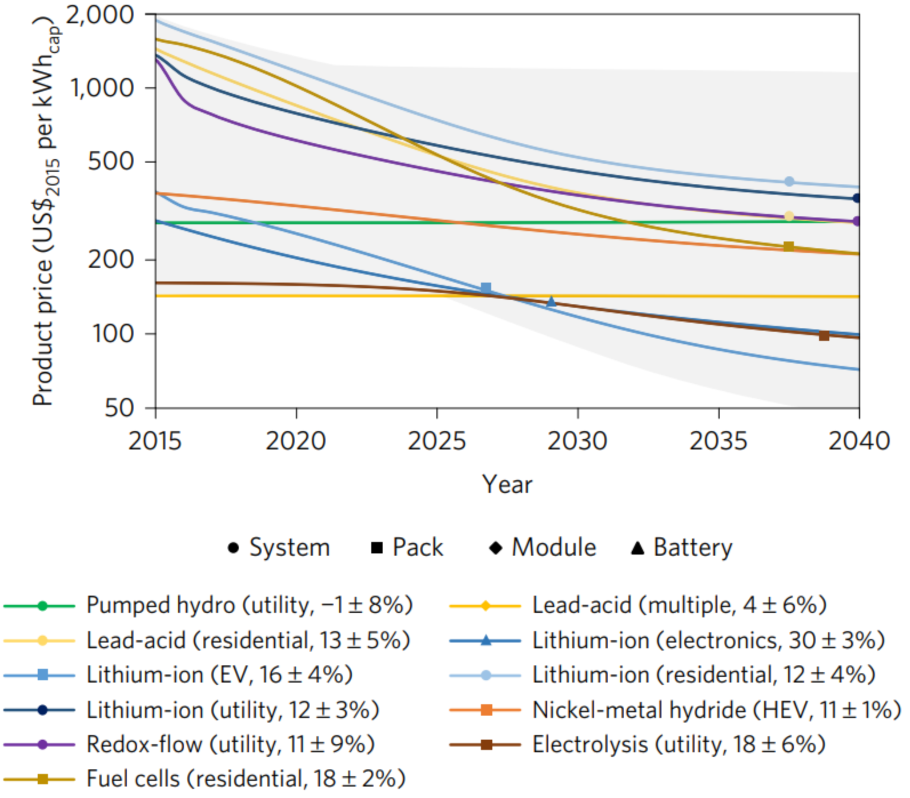


Figure 3: Forecast of price curves of energy storage technologies from 2015 to 2040 [5].

These trends constitute the backbone on which policymakers need to rely when drawing the trajectory towards which national markets will be oriented in the decades to come, ruling out mature technologies and incentivizing early investments in new promising solutions. However, being these experience curves based on empirical observations rather than analysis, they cannot be able to capture unprecedented events such as technology breakthrough, goods availability or shortage and global crisis. Since these events are hardly predictable, what can be done in order to accommodate a certain degree of uncertainty is to favour solutions that perform well in flexible environments. For instance, a modular battery storage installation with lifetime of 15 years and limited environmental impact can be considered more adaptable than a Pumped Hydro Storage solution with decades long operation, high environmental impact and difficult system size re-adaptation.

1.2 Materials employed for Li-Ion battery technologies

As previously mentioned, different technologies are available for the cathode material of Li-Ion batteries. These are all compounds that allow Li ions intercalation. The following list presents the most commonly used materials [6].

- **Lithium Manganese Oxide ($LiMn_2O_4$)** : Introduced in the 1980s, it allows for fast charging and discharging cycles at high current rating, however it suffers of low gravimetric and volumetric energy density, allowing for manufacture of batteries with only high power-to-energy ratio (C-rate). This technology is referred to as **LMO**.
- **Lithium Iron Phosphate ($LiFe_2PO_4$)** : It allows for long lifetime with both continuous cycling and high current flow levels. Moreover, it is a thermally stable technology with very limited safety issues. However, it can suffer of self-discharge issues over time [7]. This technology is commonly known as **LFP**.
- **Lithium Cobalt Oxide ($LiCoO_2$)** : introduced by Sony in 1992, it constitutes an easy to manufacture choice [8]. Its high energy density allowed wide employ in electronics field (cameras, mobile phones, laptops). However, the limited availability of cobalt hinders the competitivity of batteries and safety issues arise when employed for transportation vehicles.
- **Lithium Nickel Oxide ($LiNiO_2$)** : Nickel allows to abate the costs of Cobalt while still retaining a good gravimetric energy density. Pure $LiNiO_2$ batteries suffer however of passivation phenomena and require high cost and frequent maintenance [9], hence they are often combined in solutions with small percentages of manganese and cobalt, called **NMC** batteries (usually manganese and cobalt constitute around 20% of total volume). NMC technology allows for high density and power at competitive costs. The most common NMC battery in employed are: NMC111, NMC 622, NMC 811.
- **Lithium Nickel Cobalt Aluminum Oxide ($LiNi_xCo_yAl_zO_2$)** : Known as **NCA**, it is a substitute for NMC technology, offering similar power and energy ratings. Moreover, it also offers a long lifetime and allows to reduce the content of cobalt [8]. However, it must be supported by specific electrical control equipment to ensure safety.
- **Lithium Titanate ($Li_4Ti_5O_{12}$)** : Employed as a substitute for graphite in the anode, commonly referred to as LTO, is employed in batteries that require a particularly long lifetime, given that lithium titanate undergoes slow degradation. However, its limited conductivity hinders application at high power discharge rates.

A graphic summary comparison of the Li-Ion technologies presented is shown in Figure 5.

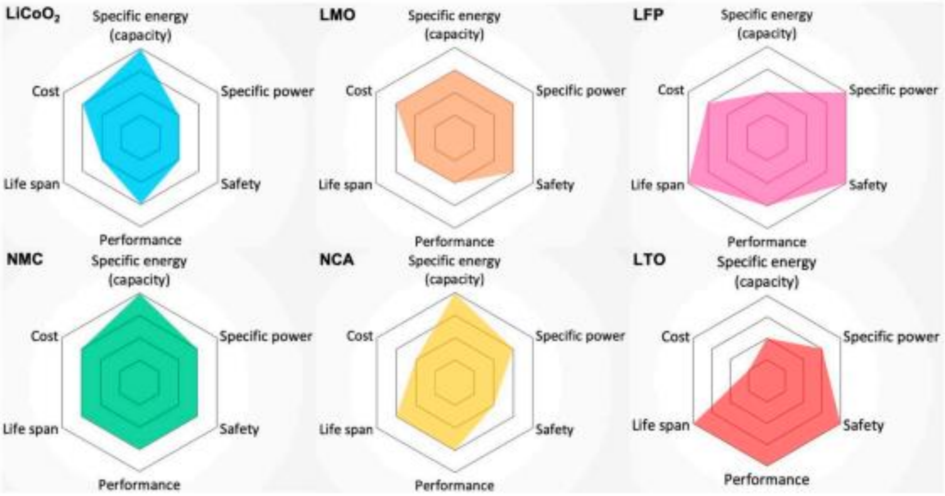


Figure 4: Graphic comparison of the most employed Li-Ion technologies. Every characteristic is rated on a scale from 1 to 4 in relation to the other competing technologies [6, 10].

1.3 Physical structure and packaging of Li-Ion batteries

Li-Ion batteries can be manufactured in different physical shapes according to their application. The most commonly employed commercially developed shapes are presented in the following list [11].

- **Cylindrical Cell**: the cylindrical shape can bear internal pressure without deforming, which results in prolonged lifetime. However, the stacking of cylindrical cells in battery modules comports structural cavities, lowering the space density of the battery system. These packaging cavities can however be employed for other uses, such as a passage for liquid cooling systems, as shown in Figure 6.

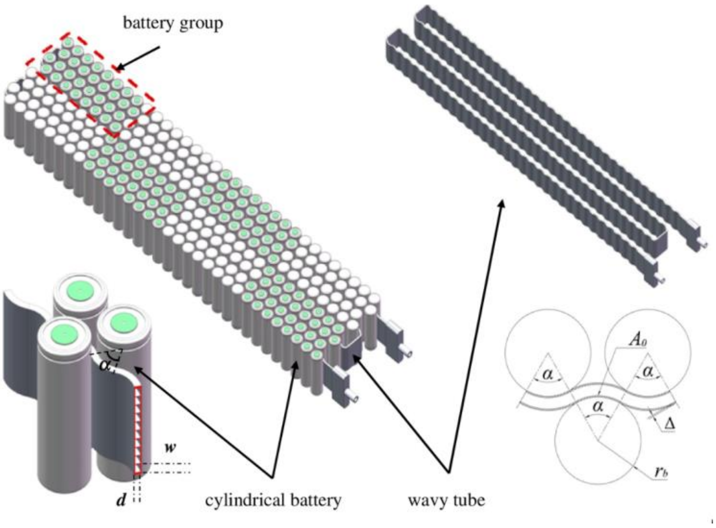


Figure 5: Cylindrical cells stacked in battery modules [12]. As shown, the physical cavities resulting from the stacking of cells can be optimized by laying a wavy tube for thermal cooling.

Figure 6: Cross-section of a cylindrical cell [13].

- **Button Cell**: This battery shape presents low manufacturing costs and can allow for extremely small and compact shapes, however it cannot withstand high power rates due to swelling phenomena that can result in safety issues. For this reason, it is mostly used in non-rechargeable cells.

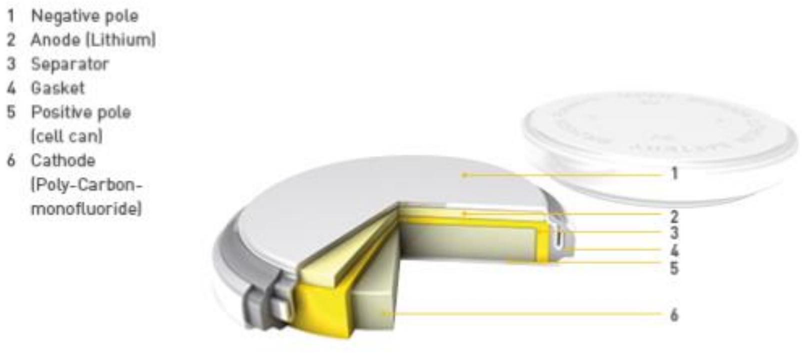


Figure 7: Cross-section of a button cell [13].

- **Prismatic Cell**: First introduced in the 1990s, this physical structure prioritize space density. The thin shape and compactness of this cell type has resulted in its widespread success in the mobile cell-phone industry. However, lifetime and thermal stability are hindered compared to cylindrical shapes.

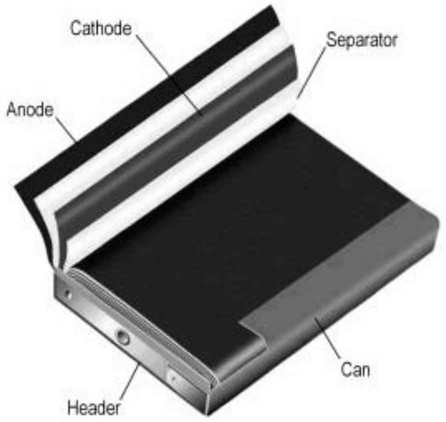
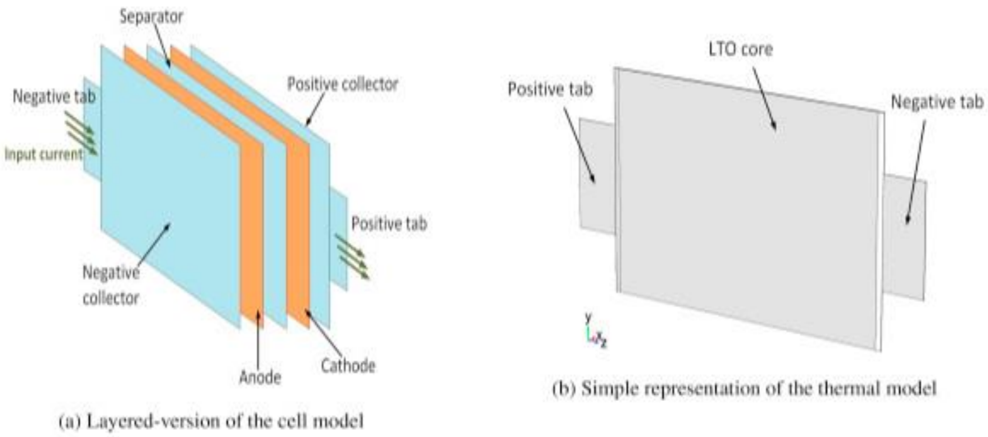


Figure 8: Cross-section of a prismatic cell [11].

- **Pouch Cell**: Also introduced in the 1990s, it consists of simple laminated layers without a metal enclosure. It is the physical shape with the highest packaging density, however its employment is limited due to swelling issues, especially when stacking of multiple battery cells is required.



(a) Layered-version of the cell model

(b) Simple representation of the thermal model

Figure 9: Cross-section of a pouch cell [14].

Chapter 2: Li-Ion Battery Energy Storage System Applications

The integration of Energy Storage systems within an electricity network has historically represented an extremely relevant milestone towards the creation of smart grids. In an infrastructure network such as that of electricity, in which demand and supply have to be constantly matched, the introduction of storage allows for a more flexible and optimized management of resources [15].

In order to present clearly and separately all the current possible applications of Battery Energy Storage System, it is useful to make a distinction between Behind of the Meter (BTM) and Front of the Meter (FTM) applications. All the applications of a Battery Storage System that do not necessarily involve interaction with the electricity network are called “Behind of the Meter”, given that all the electricity produced, stored and consumed does not transit through the distribution and transmission network. On the other hand, every application that a battery energy storage system performs towards to the grid takes the name of “Front of the Meter”.

2.1 Behind of the Meter Applications (BTM)

Every residential, commercial or industrial electricity prosumer can make use of Behind of the Meter applications in order to reduce its cost of electricity and carbon footprint. The typical battery sizes for residential sector span from a power rating of 1-20 kW and an energy rating of 5-50 kWh, with a typical standard size of around 3-5 kW and 10-15 kWh [16]. Regarding the Commercial & Industrial (C&I) sector, battery energy storage systems greatly vary according to the energy needs and can account for tens of megawatts. Generally, a battery system of multiple MW/MWh is usually employed by power utilities that sell the electricity produced to the grid, hence it is rare that a battery system over 10 MWh is only performing Behind of the Meter applications. However, in the case of large mining sites, this can be possible. A list of BTM applications is presented in the sections from 2.1.1 to 2.1.4.

2.1.1 Increase of Renewable Self-Consumption

Residential or commercial users producing their own energy can store the excess energy produced during operation to use it in times of the day when production is not possible. On a strictly economic point of view, this application results favourable only in the event that the Levelized Cost of Storage (LCOS) is lower than the electricity tariff from the grid. In the evaluation of the LCOS, any green bonuses or tax exemptions for renewable integration need to be taken into account.

Some policy actions are extremely relevant in the validation of a financial viability for this application. While Time of Use (ToU) feed-in tariffs can increase the value of energy storage in order to have complete flexibility to decide when to inject or absorb electricity in the grid [17], fixed price feed-in tariffs or credit system are in direct contrast with policy frameworks that should favour battery energy storage systems. This is due to the fact that fixed feed-in tariffs and credits allow to utilize the grid as if it were a battery, disregarding the unbalancing effects that this may cause.

Feed-in tariffs and credit systems are an effective way to create an initial rapid surge of investments in Solar PV or similar renewable energy sources, however they are rapidly displaced once renewable integration has reached a certain level in the electricity mix, because feed-in tariffs and credits are costly for system operators, tend to distort the electricity market price signal [18] and can cause disruption of the system's resiliency if Solar and Wind become the main share of the energy mix. Therefore, fixed feed-in tariffs and credit systems suffer from a short-sighted perspective on the evolution of the energy market which can give rise to heavily subsidized business sector that can become uncertain and risky in the long term. In some cases, such as in the Spanish market, feed-in tariffs had to be reverted into not only the sudden removal of the policy, but also the introduction of a "sun tax" of Solar PV generation [19].

On the other hand, markets in which prosumers are not allowed to inject any of their locally produced electricity in the grid and hence often experience curtailment can represent an extremely attractive target for BESS. The solution could be that of introducing subsidies for the installation of BESS while eliminating back feed-in tariffs program, allowing prosumers to sell their electricity at specific times of the day when this is most needed, instead of injecting it at any time they experience a surplus in production.

2.1.2 Tariffs optimization

Residential or commercial users can avoid consumption of electricity from the grid during peak time given the higher tariff rates, utilizing instead the electricity stored previously in the BESS. This application is often the most profitable among the Behind of the Meter ones, given the high price spikes of many industrialized countries [20].

Tariffs optimization is exemplified best by the case of the "Triads". In the UK electricity market, on top of a daily peak tariff, three precise thirty-minute periods are selected between the months of November and February. These three intervals are indeed called "Triads" and they represent the time slots in which the system is experiencing some of the highest demand of the year. Triads are not settled in advance and the only information known is that they tend to happen between 4pm and 6pm and that they must be distanced at least 10 days from each other. Despite only being three time slots of thirty minutes, they have an extremely relevant impact on the yearly electricity bill because tariffs for half-hourly metered electricity customers are calculated by multiplying the load consumption registered on those time slots. Therefore, triads avoidance has constituted a major business case to motivate the introduction of BESS. On top of this, in the event that an electricity prosumer were able to inject electricity into the grid during Triads time, the electricity supplier would reward the prosumer with a retribution known as “Triad Avoidance Benefit” (TAB) [20]. The Triads policy not only has fostered the spread of BESS on a granular scale, but has also pushed forward the development of advanced algorithms for battery storage software systems that could predict best the triads time.

2.1.3 Peak Shaving and Load Shifting

A relevant share of the electricity bill of residential and commercial users is given by the so-called “Demand Charge”, a tariff calculated on the maximum power requested from the grid. If that maximum level of load consumption is only reached for a limited amount of time on a daily or monthly basis, this consumption peak can be “shaved” by a BESS, which can supply the electricity needed as long as its discharge time is able to cover the entirety of the peak.

In case of long duration battery systems, this principle can be used to a wider extent to provide a quasi-constant demand profile. The loads of morning and evening time can indeed be shifted during the middle of the day, when renewable production is at its highest, by charging a Behind of the Meter BESS, the battery will then discharge when electricity needs to be consumed. Load Shifting offers a viable business case only in those markets in which solar integration has reached high levels and daily price spreads surpass 0.10 €/kWh, offering a consistent and safe revenue stream that ensures 100% certainty of payback generally within 5-10 years [20].

2.1.4 Back-up Power

Any consumer that needs to ensure reliable operation to its load can opt to install a battery system to prevent power outages during grid faults, irregular voltage variations or system blackouts. This case is particularly common for such applications in which power outages must be avoided at all costs, such as in data centres or in hospitals with life-saving equipment [21]. Moreover, battery storage systems for backup applications are also widely used in industrial sectors in which heavy machinery requires long activation times, such as furnaces in the metallurgy sector, and because of that a blackout must be avoided at all costs. Back-up function has historically been provided worldwide by fossil fuel systems such as diesel generators, however the employment of battery storage present advantages in the reaction time, since the energy transformation that takes place in a battery system (chemical to electric) takes considerably less time than the energy transformations that take place in a diesel generator (thermal to mechanical and from mechanical to electric).

2.2 Microgrid Applications

Microgrids represent one of the most widely employed applications for battery energy storage systems and one of the most rapidly growing [22]. Microgrids are systems in which electricity is locally produced, distributed, stored and consumed. Off-grid Microgrids are isolated systems not connected to any national or international grid and are usually found in remote locations such as islands, deserts, forests and any other difficult to accessible sites. Microgrids can also be grid-tied and be found in non-remote location, or even in densely populated regions. The reason for these microgrids to exist is usually to alleviate congestion to the transmission and distribution network, allow for the creation of a more flexible and resilient grid and strengthen a local community commitment to manage its own electricity.

In the case of remote locations, microgrids come as an alternative to highly expensive electrification works of national grid connection. These electrification works usually require a disproportionate amount of resources and materials, they heavily impact the local environment and a consume a considerable part of the electricity in transmission losses.

Diesel generators have so far represented an easy solution to produce electricity in remote locations [23], however this technology has high operating costs, ranging from 0.35 €/kWh to over 0.50 €/kWh. Starting from the 2010s, the sustained fall in costs of solar photovoltaics and battery storage has allowed to reach costs lower than 0.20 €/kWh, allowing for strongly profitable business cases. Moreover, the plans of decarbonization of several countries in the EU and worldwide has led to focus specifically on carbon abatement in remote locations, which being fuelled by diesel generators have always figured among the most polluting ones.

Microgrid systems powered by Wind and Solar can constitute not only the most economically viable and environmentally friendly solution, but also the safest one from the point of view of securing electricity all year long. In fact, despite diesel generators can produce electricity on site, the fuel still requires to be shipped and transported on road or by ship. Hence, the supply chain is easily disrupted in the event of supplier failure to deliver the goods, which may happen in cases of road inaccessibility, safety concerns or other situations of crisis.

2.3 Front of the Meter Applications

Any utility scale energy project developer that can actively interact with the national grid by injecting and absorbing power can make use of Front of the Meter Applications in order to increase profitability of its project and decrease its carbon footprint. The scale of battery system configurations can be upsized as much as it is needed by distribution and transmission network. The largest battery storage system installed to this day reaches a capacity of 129 MWh, however the largest project in phase of construction currently amounts for a capacity approaching 800 GWh [24].

2.3.1 Wholesale market

Power producers need to participate in the Wholesale market of electricity in order to sell the energy they produce. This market is divided in two sub-markets: Day-Ahead and Intra-Day market. While the former one takes place one day prior to power delivery, the latter is a close-to-continuous market accepting and awarding bids few minutes before the power is required, with different gate opening and closing times according to each market.

If a power producer of renewable energy sources wants to competitively participate in the Wholesale market of electricity and maximize profits with the PV or Wind capacity installed, it needs to be able to provide reliable and continuous power to the grid. Hence, by coupling a solar or wind park to a battery storage system, a power utility can not only provide firm power for a given interval of time, but can also secure availability of energy in those moments of time in which electricity is rewarded the most.

Intra-Day market offers higher price rewards and requires fast availability of power supply, for these reasons it is currently considered a more relevant revenue stream to validate the business case of battery installations. The average daily price spread range around 45 €/kWh, level that can be reached multiple times during a single day [25].

2.3.2 Frequency Control and Ancillary Services market

Among the main duties of Transmission System Operators (TSOs) there is the pivotal need of ensuring a perfect constant match of electricity supply and demand. If this balance is not maintained at all time, the frequency of the network will drop below (over-production case) or rise above (over-consumption case) the set value of 50 Hz in European markets (60 Hz in the United States electricity grid). In case of these events, power outages are likely to happen, as well as damages to loads on a national grid scale. This concern has particularly risen with the sustained growth of intermittent generation coming from renewable sources and it is expected to rise in the upcoming years [26]. To answer to this problem, TSOs have started to issue remuneration schemes for ancillary services provision. A list of the classification of ancillary services that can be provided to the grid is presented below.

Spinning Reserve: also called Fast Response or Fast Frequency Reserve, it requires an activation time of 1 second and it requires to maintain maximum nominal power contracted for a time interval of usually 30 seconds [27]. Among European markets which include a remuneration scheme for

Spinning Reserve are the Scandinavian ones (Norway, Sweden, Finland and Denmark) and United Kingdom and Ireland. This ancillary service allows for high remuneration payments, however it only requires very short activation times, hindering the economic viability of long duration batteries.

Primary Frequency Reserve: known as FCR or Firm Frequency Response, it must be provided within 30 seconds of time and maintain power for around 15 minutes [28]. Countries like the Nordics, UK and Ireland have included remuneration schemes for availability of 4 hours delivery periods for such service. This ancillary service has represented the main share of the revenue stream of battery systems performing Front of the Meter applications in Europe. The monetary value can usually be captured with a 1 hour battery, however remuneration for this service is rapidly decreasing as the market becomes congested, and installing longer duration batteries may result as a better strategy to stack up applications on top of FCR and secure revenues in the future when Primary Frequency Reserve may not constitute anymore by itself a profitable service.

Secondary Frequency Regulation: commonly abbreviated in aFRR (automatic Frequency Restoration Reserve), it requires activation times of 5-7.5 minutes with deployment time that can greatly vary from a value of 15 minutes (similar to FCR), up to 1 or 2 hours of sustained power requirements. The remuneration scheme is split in availability (€/MW/h) and activation (€/MWh). From 2021, according to the harmonization plan from ENTSO-E, it is expected that the availability component will be based on a local day-ahead auction with 4 hours deployment periods, while the activation component will be a based on a close-to-real-time auction for 15 minutes period on the Pan-European bidding platform PICASSO [29]. A short-term auction is likely to bring volatility to prices, which on top of the incentive for fast activation and upwards/downwards regulation will particularly favour BESS, allowing aFRR to possibly become the most profitable Ancillary Service in the future.

Tertiary Frequency Regulation: abbreviated in mFRR (manual Frequency Restoration Reserve), it is provided by assets with a full-power activation time of 15-30 minutes [30]. Once activated, the energy provision can be required to remain active for several hours. The operation of mFRR do not differ greatly from aFRR, if not for a slower ramp-up power. However, the occurrences of such reserve are rather sporadic, making it difficult to constitute a solid business case based solely or for the most part on such ancillary service. The remuneration scheme is split in availability (€/MW/h) and activation (€/MWh), which similarly to the aFRR it is expected to be cleared on a Pan-European bidding platform called MARI [31], with analogue gate closure times as for the secondary regulation.

2.3.3 Capacity Market

With the phase-out plans of fossil fuel and its substitution with renewable energy sources, system operators need to maintain a minimum level of energy supply on a national level. In order to meet this minimum threshold, it was necessary to create a capacity auctions that would reward power producers able to commit with long-term contracts for the availability (€/MW/year) of their power produced. This market has resulted extremely interesting for battery energy storage [32], as it allows a secure and consistent revenue stream that can be exactly quantified at the moment of the initial capital expenditure. Furthermore, the evident advantage of the capacity market is that it can be stacked up on top of other applications, since only the availability on a year-long basis is required.

2.3.4 Time Arbitrage

As in the case of Behind-the-Meter Peak Shaving and Load Shifting, a power generator of intermittent energy sources can also decide in which moments to store and to sell the electricity produced in order to yield the highest value possible from the market [33]. The ability to perform a charge/discharge operation strategy not only permits to sell more electricity in the moments of time in which this is required the most, but it also allows a solar or wind power developer in the initial phase of financing its project to secure a Power Purchase Agreement with stricter requirements and higher remunerations, since the battery storage can considerably raise the safety of supply of the generating unit. As the share of intermittent renewable energy generation in a nation’s electricity mix increases over 15%, time arbitrage of these generation assets becomes a matter not only of economic profit but also of reliability and safety of supply for the national energy grid.

2.3.5 Ramp Control and Capacity Firming

The supply curve of electricity presents wide fluctuations on a daily basis. With the deployment of large solar PV installations, this curve resulted in assuming the shape of two sudden spikes of power need at the beginning and end of the day separated by a valley of electricity overabundance lasting for the 6-9 hours of partial and full sunshine. This shape is commonly referred to as the “Duck curve” [15]. One of the main technical issues associated with it is that it created a scenario in which in few minutes of time the system operator has to ensure a sudden ramp up of several generating units that have been stayed switched off for the rest of the day. The simultaneous and improvise provision of this power needs to be perfectly coordinated in order to not destabilize the electricity grid in the moment of the day in which electricity is needed the most. In this regard, a solution that can regulate precisely the amount of power supplied comes at great benefit for the grid operator. Battery storage systems are the most suited technology to carry out such task, due to their ability to both inject and absorb power in the timeframe of milliseconds. On top of this, batteries can constantly firm the power output of one or several renewable generating units pooled together, allowing for constant injection levels of PV and Wind power, which contribute to a more resilient and manageable electricity grid. As requirements for ramp control and capacity firming become stricter, battery assets will need to grow in volume in order to maintain a reliable network operation.

2.3.6 Transmission Congestion Avoidance and Grid Investment Deferral

Renewable energy generation units are often needed to be installed in distant locations and not in the extreme proximity of a large basin of users. While a Nuclear or a CCGT power plant can be constructed in the outskirts of each city that needs to be supplied with such power, in the case of large wind parks or hydroelectric power plants it is the natural conditions that dictate the exact site location. This and other factors have resulted in several countries having a clear imbalance of power generating and power consuming regions. One evident case is that of Germany, in which most of the on-shore and off-shore wind power generation happens in the rural North of the country, while a consistent share of energy consumption is required by the wealthy and industrial South [34]. The transmission grid can only handle a limited level of power, resulting in bottlenecks along the main country electricity connectors. Not only this results in the failure of the delivery of the desired amount of power, but it can also create serious damages to the power grid and spark the incurrence of power outages. Battery energy storage can hence be employed as an infrastructure service, releasing pressure from the electricity grid and avoiding or deferring the expensive and time-consuming investment in grid restructuring and modernization [35]. This application allows to create a flexible grid that does not require oversized transmission lines and substations that would only be fully utilized during peak hours but would considerably impact on the initial capital expenditure investment of the electricity network.

Chapter 3: Advantages and Drawbacks of Li-Ion Battery Systems as Opposed to Other Energy Storage Solutions.

Most of the Front of the Meter applications previously presented in Chapter 2, namely energy arbitrage, renewable integration and frequency control and ancillary services have historically been provided by disparate energy sources present in national electricity mixes. The energy storage technology that has been employed the most for such tasks in the last decades has been Pumped Hydro Storage. Nowadays, albeit several new energy storage technologies are under development and show promising results (such as Hydrogen, CAES and Molten Salt), the most relevant share of energy storage resources is still being played by Pumped Hydro and large scale batteries. This section aims at comparing battery storage systems with other prominent energy storage technologies, highlighting differences and points of strengths of each solution.

3.1 Comparison of Li-Ion Battery Energy Storage with Pumped Hydro Storage

Both large scale batteries and pumped hydro can efficiently provide ancillary services to balance the electricity grid [36]. However, the extremely fast response time of batteries, superior to that of Pumped Hydro, can allow to provide power support more promptly to those services that require an instantaneous activation time [37, 38], such as Spinning Reserve and Primary Frequency Reserve. Moreover, these services do not require a very prolonged operation time, which means that batteries with discharge time within 15 min – 1 hour can accomplish to this role. On the other hand, for what concerns ancillary services with longer activation time of over 5 minutes, such as Secondary and Tertiary Frequency Regulation, Pumped Hydro can efficiently be employed [39]. Given that Frequency Control does not follow a complete cycle discharge operation profile, since its activation time lasts only minutes (presumably less than the total duration of a storage system), the charge/discharge profile of the energy storage are likely to assume disparate aspects, from various micro-cycling within a day to constant single full-cycle discharges. While in the past complete cycling at 100% depth of discharge had represented an issue in battery storage [40], fostering degradation of the chemical components, this is not an issue anymore with modern Li-Ion Batteries, which can withstand every type of cycling profile without altering the energy retention.

The substantial difference between these two technologies is the extremely long discharge duration achievable with Pumped Hydro, which cannot be obtained with large battery storage due both to its high cost €/kWh and to its self-discharging phenomena. For these reasons, Pumped Hydro becomes a much preferable choice for purposes of bridging long periods of low sun and wind or inter-seasonal energy balancing.

Overall, it appears that Li-Ion can cover less applications than Pumped Hydro, with the only advantage of faster reaction time but the great disadvantage of shorter discharge periods. However, some relevant remarks need to be added. Pumped Hydro is a technology that requires a large amount of space. While the energy density of Pumped Hydro can span from 0.2 to 2 Wh/L, that of Li-Ion Battery ranges from 200 to 400 Wh/L [37]. For many countries or regions of the Earth, space is a constraint that cannot be overcome. On top of this, topography also plays a relevant role. While for some nations with vast water resources on mountain ridges it may appear easier to construct water basins at different altitude levels, nations with poor water resources and a flat land may need greater construction works, which translates into higher costs. Moreover, great infrastructure such as dams and river basin create a huge impact on the surrounding biosphere, raising additional issues of environmental concerns. Furthermore, given that these construction works require several years to be completed, solutions with faster completion timeline are usually preferred. On top of this, obtaining small land permissions for the 15-year period of a battery lifetime can usually be a much easier process than that of obtaining the permission to build an infrastructure expected to last no less than 30 – 50 years and possibly more than double this time span. Finally, Pumped Hydro constitutes a less flexible solution given the fact that it does not address the issues of transmission and distribution grid congestion. Pumped Hydro sites are indeed likely to be found in remote locations far away from urban centres, meaning that in order to supply electricity to most users, electricity would still need to be transmitted for hundreds of kilometres of distance. Contrarily, battery energy storage systems can be located right within cities, relieving bottlenecks from the electricity national network and fostering the adoption and performance of distributed generation.

3.2 Comparison of Li-Ion Battery Energy Storage with Molten Salt

Molten salt is the most common storage carrier for large volumes of high-temperature thermal energy. CSP plants currently employ Molten Salt tanks in order to exercise energy arbitrage and abate back-up diesel genset use. CSP with Molten Salt storage tanks can technically provide the same electricity services of Solar PV or Wind Parks coupled with Battery Storage. On the other hand, the sizing configurations for such storage systems tend to differ. While Li-Ion Batteries rarely surpass discharge times over 4-6 hours, due to the self-discharge issues that very large capacity may lead to, Molten Salt tanks for CSP Parabolic Trough usually range around 7-9 hours of discharge time [41]. Moreover, these numbers are found to increase in newer CSP technologies such as Power Towers, which are usually coupled with 10-12 hours of storage in Molten Salt tanks. Hence, Molten Salt thermal storage usually does not enter direct competition with battery storage, but is rather an energy storage asset usable for dispatching energy for longer time intervals, similarly to Pumped Hydro Storage. As for PHS, Molten Storage presents a lower energy density than Li-Ion Battery, ranging 70-210 Wh/L [42], requiring more available space for construction works in remote locations far away from the main hubs of electricity consumptions. The cost of installing CSP remains much higher than that of installing PV, ranging 4,000-6,000 USD/kW, as it can be seen in Figure 11 [43], therefore still far above the 500-1,500 USD/kW range of Solar PV farms. Conversely, once the installations cost for the respective power plants are carried out, Molten Salt energy storage only accounts for a cost around 30 USD/kWh, an impressively low value compared to the 250-500 USD/kWh range of Li-Ion Battery Storage.

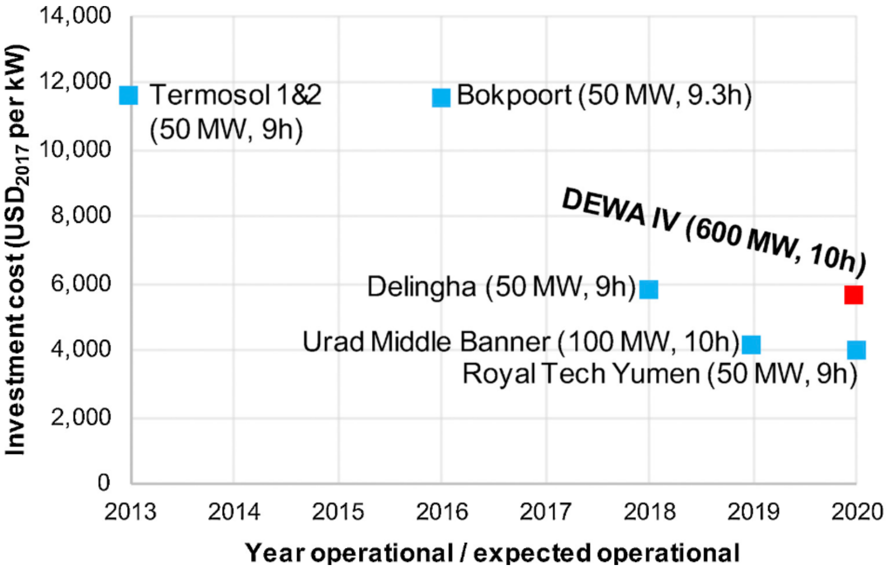


Figure 10: Investment costs of CSP plants with Molten Salt energy storage [31]

Molten Salt tanks energy storage constitutes hence an extremely valuable asset for a national electricity network. However this technology is greatly limited by geography, having shown a profitable track of records only in region with large yearly solar irradiation, such as Spain, Middle East, South Africa or South-West United States.

3.3 Comparison of Li-Ion Battery Energy Storage with Regenerative Hydrogen Fuel Cell

A third promising energy storage solution is that of regenerative hydrogen fuel cell. With this technology, energy can be stored in the form of hydrogen gas. The process starts by providing electricity to a water electrolyser, which splitting $H_2 0$ in $\frac{1}{2} O_2$ and H_2 can hence extract hydrogen and store it in a compressed tank. The hydrogen is then used in a fuel cell to produce electricity at the desired time. A simplified scheme of the process is displayed at Figure 12.

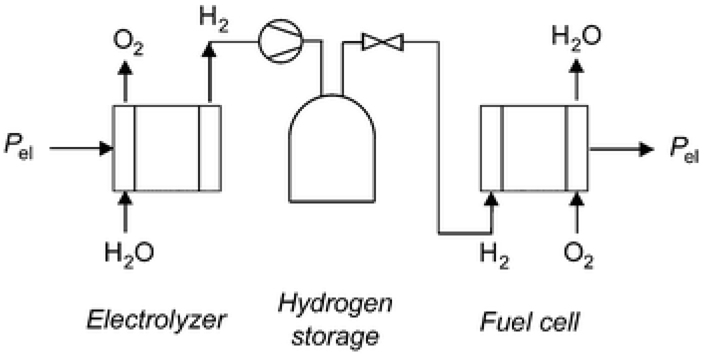


Figure 11: Scheme of a regenerative hydrogen fuel cell process.

Hydrogen storage presents a similar flexibility of Li-Ion Batteries, not being restricted to any specific geographies and not needing large space requirements, due to its high energy density [44]. Moreover, hydrogen shows very low levels of self-discharge, allowing for the possibility of longer duration storage. The cost of hydrogen storage ranges around 600 USD/kWh [45], making its economics comparable to that of Li-Ion battery storage.

Overall, it appears that given the same quantity of manufacturing energy input, hydrogen is able to provide more kWh of energy stored over its lifetime than Li-Ion Batteries, however much of it will be consumed in transformation losses. Indeed, while commercially available Li-Ion cells can reach up to 90% of AC round-trip efficiency, hydrogen storage efficiency only accounts for 30% round-trip efficiency [46]. In terms of applications, hydrogen can be used for fast discharge operations similarly to Li-Ion Batteries. The technical competitive edge of hydrogen technology over battery energy storage lies in the extremely rapid times of recharge that a regenerative fuel cell can have, consisting only in the injection in the storage tank of previously produced hydrogen, while battery storage needs to undergo longer recharge times due to limitations in power input and output. If production costs and transformation losses are improved over the course of the next decade, the technical advantage of hydrogen will allow for a rapid commercialization of the technology not only for stationary storage, but also for the motor sector of road, rail and sea transportation.

Chapter 4: Public Policy Frameworks for Battery Energy Storage Systems in Europe. A Case Study: the 2020 Portugal Solar Auction

4.1 General context of the 2020 Portugal Solar Auction

In 2019, Portugal set the record for the world lowest bid ever received on a solar auction. The public tender under which these results were recorded was deemed an unprecedented success and brought to the award of 1 GW of solar PV under fixed tariff option, while 288 MW were awarded under a merchant option with variable tariffs [47].

The 2020 solar auction is part of a larger pipeline of projects and tenders of the Energy and Climate National Plan 2030 (PNEC 2030), which envisions the installation on 6.9 GW of additional solar generation in order to meet the target of 47% of renewables in gross energy consumption by the end of the decade [48]. The accomplishment of the PNEC 2030 is a fundamental milestone for the roadmap to complete decarbonization of the country in 2050. The total capacity auctioned for the 2020 is 700 MW, to be installed in selected locations in the Alentejo and Algarve region of Central and Southern Portugal [49].

The 2020 tender is aiming at improving the successes of the 2019 tender, this time not only by repeating the two remuneration schemes of 2019 but also by adding a third option which includes energy storage systems coupled with solar generation.

4.2 Structure and Rules of the 2020 Portugal Solar Auction

The auction is designed to receive bids for the three revenue schemes mentioned in the previous section, namely the “fixed tariff option”, the “merchant option” and finally the “merchant option with storage”. The storage option is technology neutral, hence it may include not only battery technologies but also thermal storage for CSP or Fuel Cells [50].

Every injection point can have a capacity within 10 MW and 100 MW, setting a floor and a roof for the photovoltaic system sizing. The auction will award bidders with a Pay-as-bid system. With this bidding strategy, bidders must consider a trade-off in order to establish the highest possible bid that can still allow victory. Moreover, this scheme avoids the risk of underbidding, which can result in the impossibility to respect the contract at the price of the bid [51].

In order to ensure market diversification, a single company or corporate group cannot surpass a threshold of 50% of the total bids capacity on the auction.

The auction is set to follow an “ascending clock” process. With the use of this method, the bidding phase includes a multiple non-fixed number of rounds. At every round, all the received bids are gathered and the regulator calculates the Net Present Value that every bid would yield. In case that the total volume bidded in a batch is higher than the total volume available for that batch, then the round is run again requiring higher NPVs. This process is repeated until the bidded volume is lower than the volume available [52].

The government is expected to award bidders whose offer is able to yield the highest possible Net Present Value for the government. The revenue streams of the three schemes is presented below. Note that the yearly cash flows to calculate the NPV are in EUR/MW, assuming a standard estimate of generation hours per injection point within a year [53].

4.3 Contribution and Remuneration Schemes of the 2020 Portugal Solar Auction

4.3.1 Fixed Tariff Option

According to the tender rules, a reference tariff is selected for each auction batch. This reference tariff is considered the price ceiling from which every bidder has to offer the greatest discount possible, which constitutes the effective tariff the bidder is able to accept. The effective tariff represents indeed the price in €/MWh of the PPA contracted by the electricity seller with the system operator. In order to compare it with the other two options, the contribution in €/MWh/year is converted to €/MW/year by estimating the generation hours per injection point, as it was already mentioned in the previous section.

The regulatory authority forecasts with a capture curve the price of PV in the next 15 years (the duration of the awarded contracts). The NPV is calculated as the discounted sum of every year's difference between the capture curve and the effective tariff. As it can be noted, As long as the capture curve remains above the effective tariff, the regulator will receive a revenue equal to the difference of the two curves, however if the capture curve falls below the effective tariff, the difference of the two curves will translate in a payment of the regulator towards the bidder in order to match the payment of the contracted fixed tariff [53].

This solution is a very safe one from the bidder's perspective, which allows a secure revenue stream over a very long horizon of time, even if the fixed tariff is set at a very low level. On the other hand, the revenue streams to calculate the NPV from the government's point of view are not easily predictable and greatly vary year by year. A scheme of the government's NPV calculation is presented in Figure 13, while a graph of the electricity producer remuneration is shown on Figure 14.

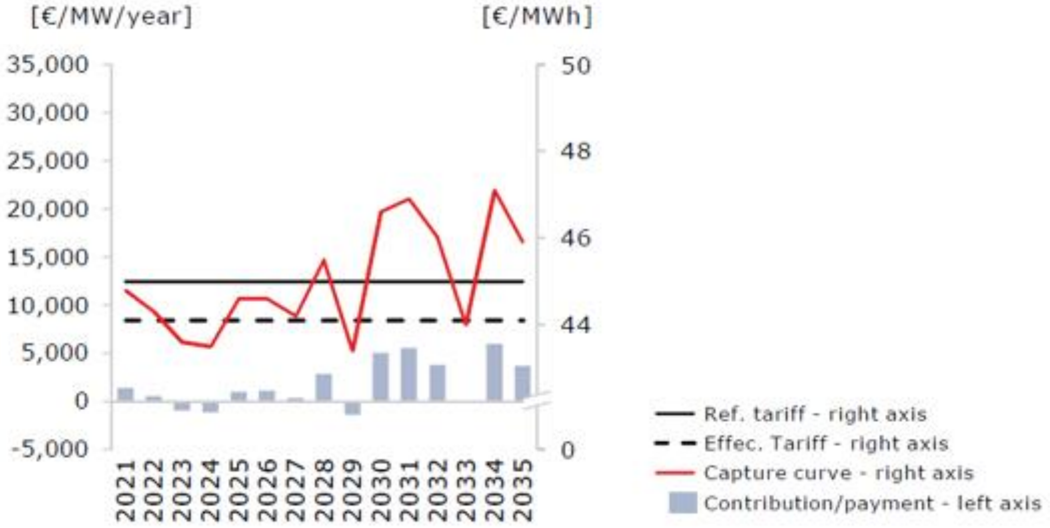


Figure 12: Yearly contribution scheme of Fixed Tariff option [53].

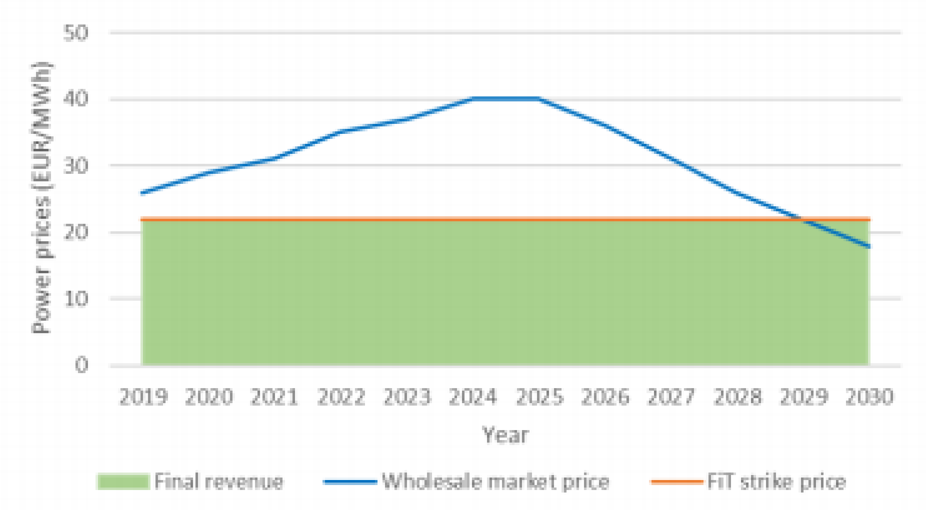


Figure 13: Remuneration scheme of the electricity producer for a Fixed Tariff option [54].

4.3.2 Merchant Option

Electricity producers opting for a merchant option accept to pay a yearly set contribution to the regulator in order to be able to participate in the wholesale market of electricity. From the government point of view, the NPV of such bids is easy to calculate, being a set contribution that does not alter throughout the years and thus needs no forecasting.

On the other hand, from a bidder's point of view, this option is much more uncertain. Indeed, the revenue streams are highly dependent on market price fluctuations, with even the possibility of wholesale electricity prices falling below the value of the set yearly contribution of the bidder to the regulator, which would result in bidder's losses. However, price fluctuations can also follow the exact opposite trend by spiking upwards and resulting in far greater financial gains than those that could be yielded by a fixed price scheme [53]. A scheme of the government's NPV calculation is presented in Figure 15, while a graph of the electricity producer remuneration is shown on Figure 16.

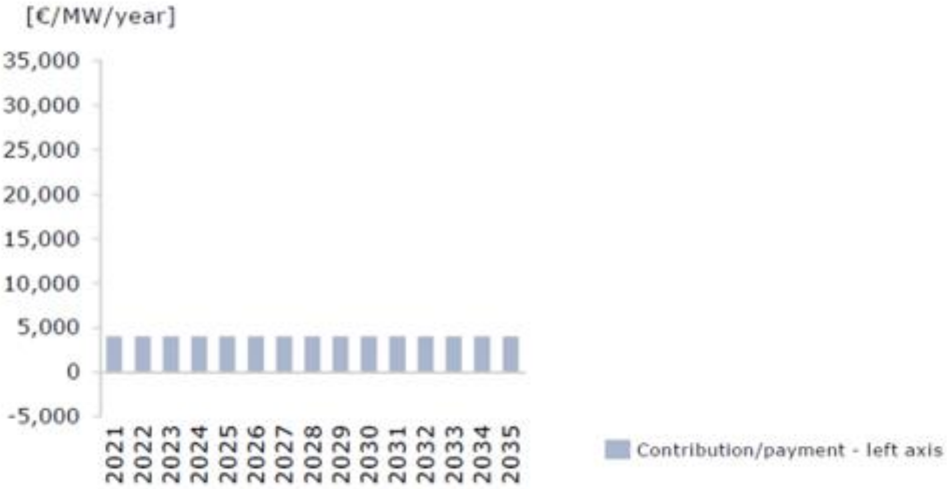


Figure 14: Yearly contribution scheme of Merchant option [53].

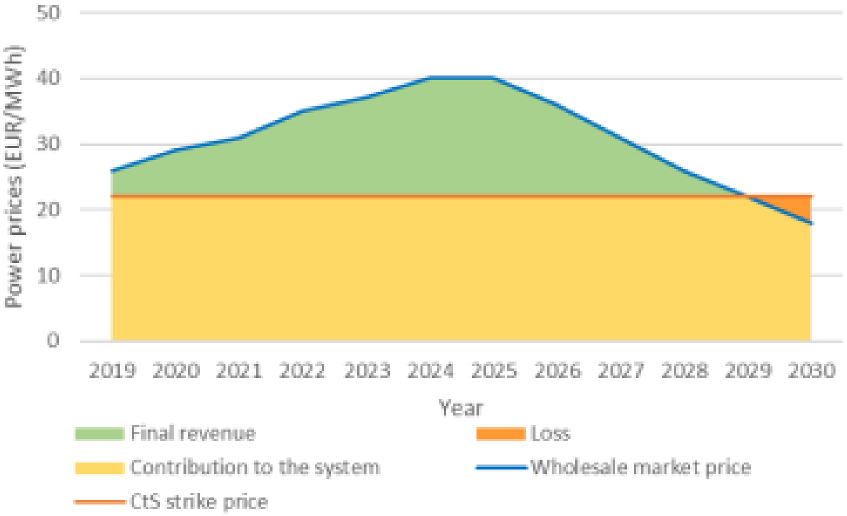


Figure 15: Remuneration scheme of the electricity producer for a Fixed Tariff option [54].

4.3.3 Merchant Option with Storage

This third option allows bidders to receive a fixed payment (effective tariff) for the capacity installed (remuneration in €/MW/year).

This effective tariff is compared against the curve of the forecasted benefit from option activation (the capture curve). When the effective tariff curve lies below the forecasted benefit curve, the system operator receives a contribution equal to the difference of the two curves, while in the opposite case it would be the system operator to pay the energy producer in order to make its remuneration equal to the agreed fixed tariff.

The electricity producers that are awarded bids with this option can participate in the wholesale market of electricity and in the frequency control and ancillary services market. Hence, the difference with the Merchant option without storage is that through the possibility of doing energy arbitrage and ancillary services, the revenue streams of the energy producers can increase and diversify. Moreover, the capacity payment adds a fixed revenue stream that partly reduces the yearly contribution that the supplier owes to the system operator (as in the merchant without storage option) [53]. Furthermore, the storage system can add benefits in terms of reducing the transmission congestion, compensating the energy generation forecast errors and stabilizing output power through ramp rate control. The possibility of ensuring a fixed power output avoids the payment of imbalance prices on market position deviation. Finally, many power utilities interested in deploying storage systems in the future may want to grasp the opportunity to include the storage option this year and utilize just one point of interconnection, abating future costs for requiring a second PoI in the future.

The requirements of the energy storage are of 20% of the grid capacity (2 MVA – 22 MVA changing by location) and a minimum battery duration of 1 hour at End of Life. (15 years). A scheme of the government's NPV calculation is presented in Figure 17.

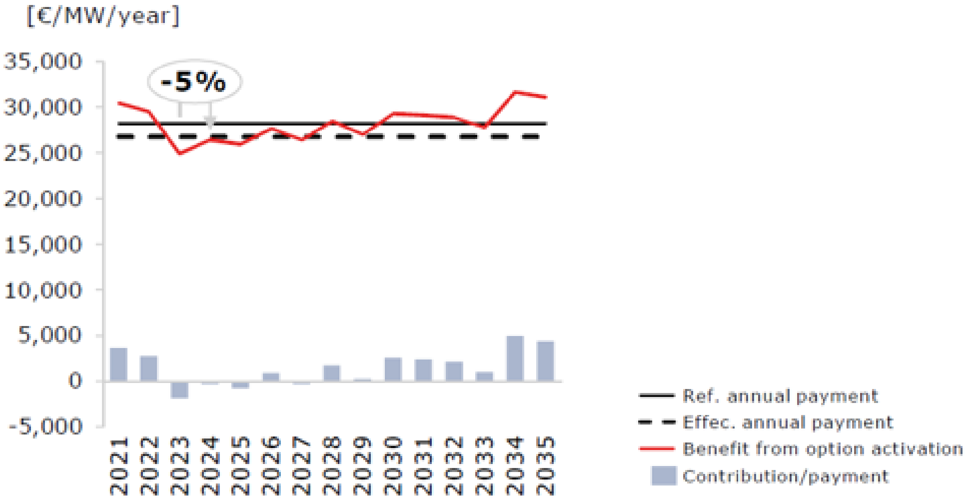


Figure 16: Yearly contribution scheme of Merchant option [53].

4.4 Analysis of the remuneration schemes of the 2020 Portugal Solar Auction

The 2020 Portugal Solar Auction appears overall as a very balanced tender. All the three options offer the possibility to generate consistent revenues and no option greatly surpasses the other two in terms of economic attractiveness. From the electricity producer’s point of view, the Fixed Tariff option appears as the most economically safe but at the same time as the one that would generate very low revenues, the merchant option appears as more risky and uncertain but with much more potential for large revenue streams, while the merchant option with storage is offsetting the uncertainty of the simple merchant option by optimizing the use of energy while increasing and diversifying more revenue streams, but its initial CAPEX is far greater.

From the system operator’s point of view, the Net Present Value of the three options also appear similar. One remark that needs to be made is that for both the Fixed Tariff and the Merchant with Storage Option one fundamental value to calculate the NPV is that of the capture curve forecasted by the regulator. The real price curve could differ from the capture curve, revealing more opportunities in case of this being higher than expected, or lowering them in the event of the real curve being lower than its forecast.

4.5 Analysis of the preferred energy storage technology for the 2020 Portugal Solar Auction

Focusing on the Merchant with Storage option, it is important to analyse which energy storage technology can provide the best NPV and hence maximise the chances of a bid being awarded. Although the choice of Li-ion battery is currently the preferred one given the techno-economic advantages described in Chapter 2, it is more debatable and uncertain which specific technology within those of Li-ion will offer the best solution. The two technologies that have been employed the most in battery energy storage systems are LFP and NMC, whose characteristics have been presented in section 2.3.

The rules of the auction have set a minimum discharge time required from the battery system of 1 hour (C-rate = 1) at End of Life. This value can be considered as a trade-off between the very fast discharge battery systems usable for frequency regulation, which can go down to 15-30 minutes discharge, and long duration batteries used for load shifting applications, commonly lasting 4 hours or longer. The choice of the discharge time to offer is hence a decision of the bidder, given that this is equal or longer than 1 hour End of Life.

Given a set value of the rated power (MW) of the battery storage system, each bidder for the Storage Option will need to choose how much energy capacity (MWh) to provide the system with. Clearly, the more capacity is added to the system, the higher the initial capital expenditure. The reason that would justify the installation of long energy duration batteries is the existence of a business case for energy arbitrage, in which consistent revenues can be made through peak shaving and load shifting. To validate such business case, one must look at the daily price spread of electricity tariffs during on-peak and off-peak times. If this time spread is higher than 30 €/MWh (as explained in Chapter 3), the installation of BESS can be motivated. In case that this time spread is maintained daily over long periods of time (tariff peaks of several hours), then the battery storage system should be ideally sized with as much capacity needed to shave the entirety of the peak. However, the portuguese wholesale electricity market does not experience price spreads higher than the indicative value of 30 €/MWh and therefore energy arbitrage alone is not a sufficient application to motivate the investment. For this reason, bidders do not wish to rise their development costs in order to increase capacity, therefore they align on offering batteries of 1 hour discharge EoL, the lowest accepted by the auction. For 1 hour systems, technologies with high specific power result more technically interesting than technologies with high specific energy. In this case, LFP li-ion solutions are considered to perform best than NMC li-ion, which would have instead been the favourite choice in the event of long durations required for an energy arbitrage business case. Another major point to consider is that of the battery life span. Due to high cycling, degradation of the BESS can cause a considerable loss of energy capacity over the 15 years of operation required by the tender. The way to prevent the battery to reach a capacity below 1 hour discharge before the End of Life (set at 15 years) is either oversizing the system, adding a capacity Beginning of Life superior than 1 hour, or substituting on a yearly basis some modules of the battery which are not functioning at 100% of their rated capacity. In both cases, it is desirable to opt for a technology that maximises the battery lifetime. In this case as well, LFP seems to have reached better performances than NMC [6,10]. Finally, being Cobalt an element that particularly increases the cost of batteries, NMC li-ion systems are usually more expensive and can hardly compete with LFP batteries when specifications are for a C-rate equal to 1. For the reasons presented, it is believed that LFP li-ion battery storage solutions are able to provide the best NPV to the 2020 Portugal Solar Auction.

4.6 Remarks on Policy Frameworks following the 2020 Portugal Storage Auction

With the current market remunerations for wholesale electricity and frequency regulation, the business case that motivates the installation of BESS is mainly constituted by the revenue streams coming from secondary and tertiary frequency regulation, as explained in Chapter 3. This situation is however expected to vary in the future. As it happened in the past years with a more mature and structured market for frequency regulation such as the United Kingdom, the progressive installation of more BESS from different competitors brought the market to a fast saturation and saw remunerations to drop drastically. Developers that decide to install extremely high specific power batteries (with duration between 15 minutes to 1 hour of discharge), usable only for frequency control and other ancillary services, can face unexpected profit reductions and in some cases be forced to file for bankruptcy [55]. On the other hand, those developers that install systems with more energy capacity can prove to be more resilient and are able to draw revenues by stacking different applications. Another expected trend, with the scheduled future increase of solar energy share in the electricity mix, is the increase of the daily price spread [32]. The increase in the daily price spread will unlock the business case of energy arbitrage, making it profitable to add energy capacity able to provide power for the entirety of the peak. Considering these two trends, long duration batteries (discharge time over 2 hours), both of LFP and NMC composition, will become a more interesting option than short duration batteries (discharge time below 1 hour) over the next decade. In order to provide the electricity network with farsighted energy storage systems, policy frameworks should incentivize high energy capacity batteries. In this way, the share of solar energy production in the national electricity mix could be ramped up easily without the risk of experiencing curtailment and wholesale prices of electricity would become more predictable. On top of this, the saturation of the frequency control regulation would happen at a slower pace since the market would not be overflooded with many cheap fast discharge batteries. Finally, longer duration batteries will not only allow for more PV to be installed but would also increase the level of renewable integration of the existing systems, allowing Portugal to get much closer to its targets of gradual decarbonization. Therefore, the most advisable recommendation for policy frameworks following the 2020 Portugal Solar Auction is that of incentivizing energy shifting with long duration battery, which can be achieved by introducing a premium payment for the provision of electricity during the daily peak. If this regulation is introduced, the national grid can anticipate its forecasted trend and promptly enhance the flexibility of the electricity network.

Chapter 5: Analysis of Battery Energy Storage Systems required for the Portugal PNEC 2030

5.1 Quantification of Renewables Generation, Back-up Asset and Energy Storage capacity required for PNEC 2030

As Portugal moves forward in its path to carbon neutrality by 2050, a first ambitious milestone has been proposed and approved by the government [56] with the Plano Nacional Energia e Clima 2030 (PNEC 2030). The goal of the PNEC 2030 is to target decarbonization of the economy on each sector, prioritizing as a first necessary step that of increasing energy efficiency. Moreover, a roadmap to decreasing energy dependence and diversifying energy production by increasing the share of renewable energy has been drawn in detail [48]. A summary of the main energy and climate indicators set as target for the PNEC 2030 is reported in Table 2.

Table 2: Summary of main targets of Plano Nacional Energia e Clima 2030 (PNEC 2030) [48].

Target of PNEC 2030	**Value**
Renewable Energy share of national energy consumption	47%
Renewable Energy share of electricity production	80%
Renewable Energy share of transportation (non-conventional fuel vehicles)	20%
Reduction of primary energy consumption (energy efficiency)	35%
Reduction of GHG emissions	45-55%
Energy dependence	65%
Additional Renewable Energy capacity in the electricity production sector	15GW
Electricity share transportable by Interconnectors	15%

As the table shows, objectives such as 80% of renewables share in the electricity mix and 15GW of additional installed capacity will bring relevant changes and technical challenges in the energy sector. In order to avoid disruption, it is suggested that the electricity network can highly improve its flexibility by strengthening domestic distributed generation, demand side management (DSM) and energy storage [48]. The three energy storage technologies that the PNEC 2030 highlights as fundamental to employ are Pumped Hydro Storage, BESS and Hydrogen [48]. To understand the need for these storage technologies by 2030, it is first necessary to analyse the generation capacity to be installed. In 2020, the total installed capacity of RES accounts for 14.7 GW. In order to meet the target of 80% renewables share in the national electricity mix by 2030, it is estimated that renewable capacity will have to surpass the following threshold displayed in Table 3.

Table 3: Total installed capacity (GW) of each renewable source in Portugal for the PNEC 2030. Other Renewables accounts for Biomass, Biogas, Waste, Geothermal and *Wave [48].*

	2020	**2025**	**2030**	**2020-2030 difference**
Hydro	7.0	8.2	9.0	2.0
Wind	5.4	6.6	8.8	3.4
Solar	1.9	5.5	8.1	6.2
Other RES	0.5	0.5	0.7	0.2
TOTAL	14.7	20.8	26.6	11.9

For countries in which Variable Renewable Energy (VRE) penetration surpasses 40-50%, it is advisable that every GW of VRE installed is balanced by 0.8 GW of back-up asset to maintain security and reliability of the grid [57]. This is due to the fact that the electricity network can usually rely on existing coal and gas back-up to meet demand peaks and counterbalance VRE intermittence, however back-up assets start becoming insufficient over the 40-50% VRE threshold [57].

Among the RES reported in Table 3, only Wind and Solar figure as VRE. According to the International Energy Agency, as displayed in Figure 18 [58], the 5.4 GW of installed Wind assets currently account for 26% of the national electricity mix, while the 1.9 GW of installed Solar only account for 2%. Therefore, the total VRE share in the 2020 electricity mix is 28%. This value is still apparently far from the 40-50% threshold in which Energy Storage is considered a useful back-up asset to avoid disruption of the network [57].

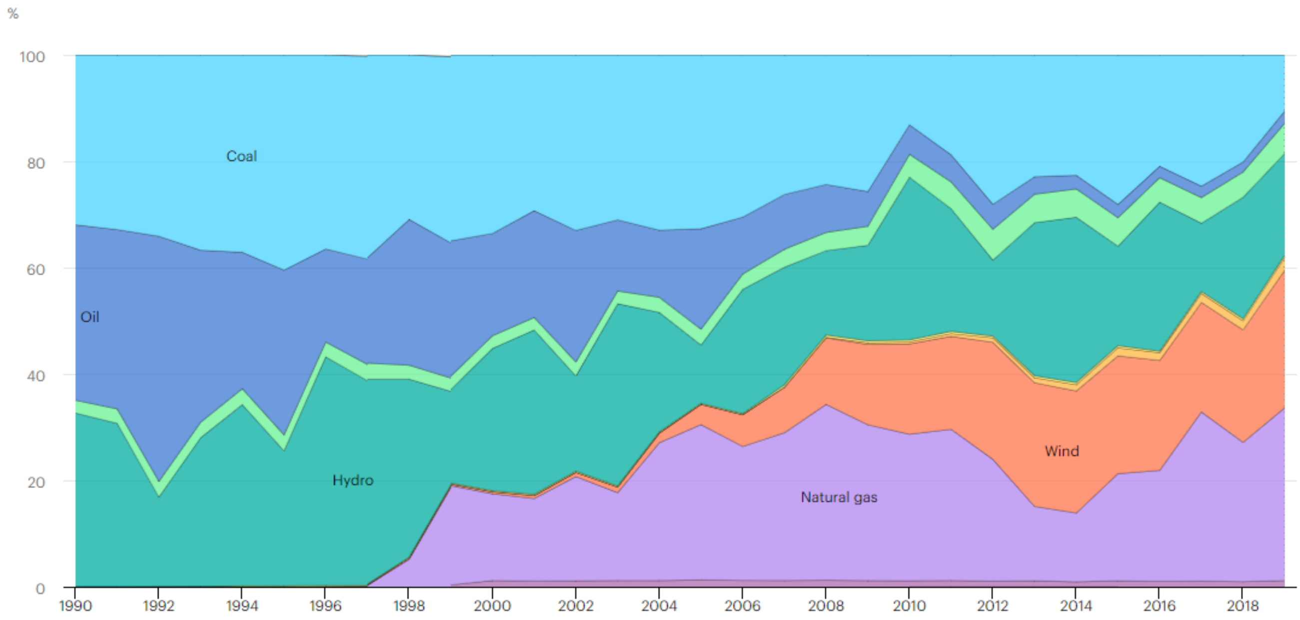


Figure 17: Portugal electricity mix from 1990-2020 divided by percentual share of energy source [58].

However, this situation is expected to rapidly change. As the last 10 years of electricity production shows [59], it can be assumed that electricity generation from 2020 to 2030 will maintain similar total volumes, due to the fact that the installation of new RES will be counterbalanced by fossil fuel decommissioning and energy efficiency measures. With this assumption of constant electricity production over the 2020-2030 decade, in order to meet the PNEC 2030's target displayed in Table 3, Wind will need to account for 31.8% of the electricity mix in 2025 and 42.4% in 2030, while Solar will need to account for 5.8% in 2025 and 8.5% in 2030. This means that the share of VRE will reach 37.6% in 2025 and 50.9% in 2030.

Therefore, despite the fact that the current share of 28% of VRE may not appear as an existential threat to the grid, by 2030 this share will have fully surpassed the 40-50% threshold under which 0.8 GW of back-up asset is advisable for each GW of VRE [57]. Given that the operating nominal power of VRE will account for about 16.9 GW [48], this will require a back-up asset of 13.52 GW.

Some large-scale projects that will greatly benefit grid stability have already been started, such as the 1.158 GW Tamega Pumped Hydro Storage plant currently in construction by Iberdrola in the north of Portugal [60]. This installation is a strategic step in order to obtain full decommissioning of the 1.256 GW Sines Coal Plant, the last coal-relying power plant in Portugal and accounting for 13.5% of the country's GHG emissions [61]. Moreover, it will constitute the largest employment of Pumped Hydro Storage in Portugal to this date and it will add to the already existing 2.820 GW of PHS national installed capacity [62].

It needs to be noted that the figure of 13.52 GW back-up advised for 16.9 GW VRE would only apply to completely isolated markets that can solely rely on their national electricity grids, such as in the case of Australia [57]. For highly interconnected markets, the possibility of relying on international electricity pools can considerably lower the need of back-ups. This is indeed the case for countries such as Denmark, in which VRE shares have surpassed 45% in 2020 and will approach 70% by 2022. However its capability to buy and sell electricity on the Nordic Pool market has permitted to balance and maintain reliance of the grid [63]. By connecting with a larger pool of energy resources, a national grid can effectively offset its risk of VRE intermittence, using interconnectors as if they were a back-up source. The current values of interconnection between Portugal and Spain are reported on Table 4, alongside the value required by 2030 to meet the PNEC 2030's target of 15% of interconnected electricity share [48].

Table 4: Minimum indicative values of interconnectors capacity between Portugal and Spain to meet PNEC 2030's target [48].

	Portugal → Spain	**Spain → Portugal**
2020	2.6 GW	2.0 GW
2025	3.2 GW	3.6 GW
2030	3.5 GW	4.2 GW

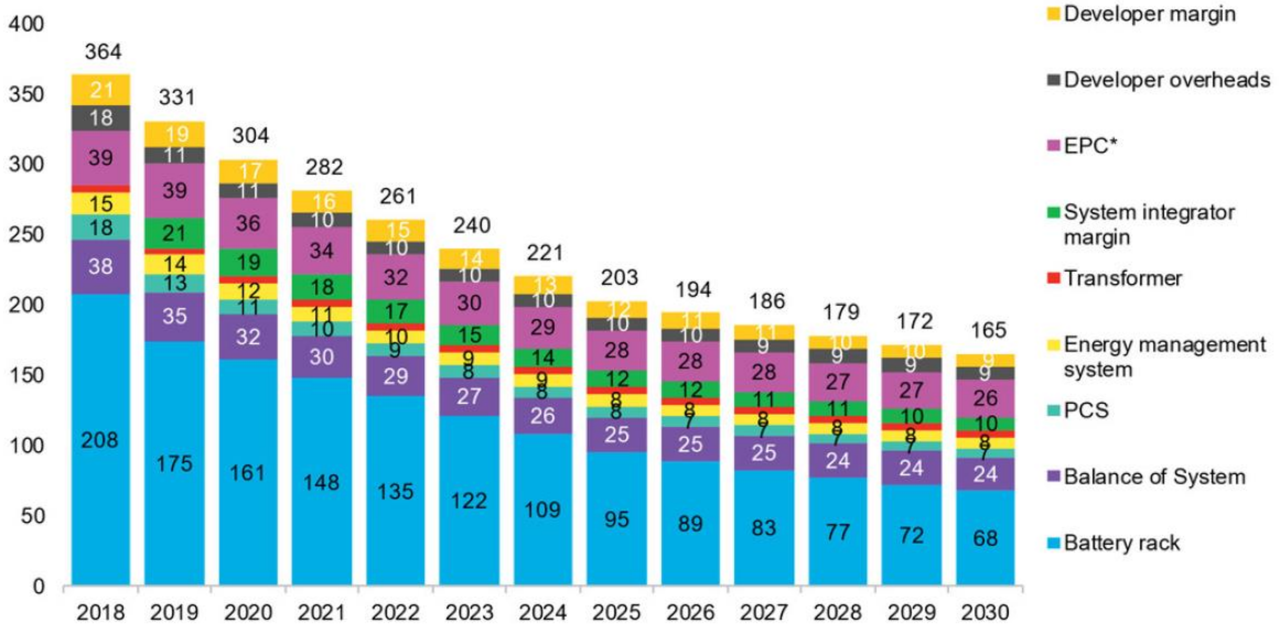
Given the 4.2 GW of interconnection power from Spain to Portugal and the 4.1 GW of PHS available by 2030, the national back-up power needed by 2030 can be considerably lowered to a range of 5-10 GW. This value will have to be covered with a combination of Hourly Ramping of non-dismissed fossil-fuel peak plants, Demand Response programs and Energy Storage technologies such as BESS and hydrogen.

Both BESS and Hydrogen Storage, as previously explained in Chapter 3.3, are suitable technologies for the purpose of stabilizing the grid. Of the back-up power needed, it is likely that the majority of it will be constituted by hourly ramping of fossil-fuel peak power plants in decommissioning phase, which will still constitute 20% of the electricity mix by 2030. However, in the event of rising tariffs on carbon footprint and incentives for Energy Storage, BESS would be considered as a valid alternative and some cases as a more economically viable one. The real value of GW of BESS installed by 2030 will indeed be finally determined by the economic competitiveness of VRE+Storage options in the coming national public tenders. Following the trends outlined by BloombergNEF [64], an optimistic scenario would be that of covering 1 GW of back-up power with Battery Energy Storage Systems.

As previously mentioned in Chapter 5, the ideal duration for BESS in order to cost effectively balance the grid and carry out load shifting, peak shaving, frequency control and ancillary services is around 4 hours with 100% Depth of Discharge. Therefore, the capacity suggested for a 1 GW BESS is 4 GWh.

5.2 Cost Analysis of Battery Energy Storage Systems required for PNEC 2030

An estimate of the evolution of costs of BESS from 2020 to 2030 is provided by BloombergNEF and is reported in Figure 19.



Source: BloombergNEF. Note: Excludes warranty costs, which are often paid annually rather than as part of the initial capital expenditure. These costs do not explicitly include any taxes, although due to a lack of transparency in the market, some may be unknowingly included. This is for a brownfield development so excludes grid connection costs. Includes a 5% EPC margin. Does not include salvage costs or project augmentation. 2018 figures adjusted for inflation to convert to real 2019 $. 2018 battery rack figures may include submissions for nameplate, rather than usable capacity figures due to participant approach in the 2018 survey.

Figure 18: Capital costs for a fully-installed usable 20MW/80MWh AC energy storage system at beginning of life [65].

As it can be seen, prices are expected to drop consistently in the coming years. It cannot be forecasted precisely in which precise years the BESS installations will take place, however it can be pointed out that for a framework of BESS projects totalling 1 GW / 4 GWh it results that an investment between 0.55 and 1.025 billion EUR is to be considered. Given that, as previously explained in section 6.1, VRE share in the electricity mix will reach the 40-50% threshold after 2025, it can be expected that the full potential and need for energy storage will only be recognized in the second part of the decade. However, this will allow BESS to be available at lower capital expenditure than what they would cost in the next 5 years. Given that, as explained in section 5.1, the real value of GW of BESS installed will highly depend on its economic viability, specific policy frameworks should be designed in order to foster competitivity of BESS over fossil fuel back-up sources. The following chapter attempts to provide the main public policy framework recommendations that would enhance the development of BESS in the coming years, allowing for a sustained transition towards decarbonization.

Chapter 6: Public Policy Frameworks Recommendations for Battery Energy Storage Systems

The 2020 Portugal Solar Auction represents a clear case of policy making tailored to include battery storage in large renewable energy developments. The concept of coupling a new and from a financing point of view less secure technology such as battery storage with a business that has been for more than a decade on a constant rising trend such as solar photovoltaics is a strategy that may reveal to be extremely beneficial to support constant innovation. The creation of proper policy requisites is at the pillar of this innovative modus operandi. An extensive list of policy recommendations is provided in the following section. These frameworks do not only apply to the specific case of the Portugal electricity sector, but can be valid for every market that has committed to full or partial decarbonization goal within the next 20-50 years.

6.1 Fund pilot projects to demonstrate business case validity

As largely explained in Chapter 2, Battery Storage Systems do not rely on a single revenue stream, hence have a rather complex business case. Moreover, most of its revenue streams, such as frequency regulation, voltage control, day-ahead and intra-day trading, are all strongly related to market fluctuations which can hardly be predicted years in advance and require forecasting softwares, most of them based on machine learning, that need to be trained with years of data. Financing such projects only by looking at simulation analysis can be not only unreliable, but also risky on a financial standpoint [66]. Large investment funds tend to shy away from technologies without a proven track of successful record, hence many battery storage projects cannot turn out to be profitable due to a high cost of capital. The concerns are not limited to the untrustworthiness of partially trained bidding softwares, which may fail to grasp the desired revenue in the electricity trading markets, but also to the hardware itself. In fact, financing limitations can arise due to doubts on fire safety of battery racks, or on the reliability of the warrantied energy degradation throughout a 15-20 year lifetime of a technologies only manufactured few years ago for the first time. Public entities or System Operators should stance funding for small scale state-of-the-art battery energy storage systems that may serve as demonstrative proof of validity of the technology, disclosing information to funding institutions in order to lead towards lower costs of capital [67].

6.2 Resolve energy storage ownership issues for TSOs and DSOs

Regulated entities such as Transmission System Operators and Distribution System Operators face limitations in owning or operating energy storage systems since this technology is commonly used for market services such as energy arbitrage. However, in a context in which Energy Storage is being employed for infrastructure services, such as alleviation of grid congestion or as an alternative to the installation of oversized transformers in substations, TSOs and DNOs should be fairly allowed to employ battery storage [66]. Hence, ownership of battery systems for regulated entities is not an issue that can be ruled out regardless from the application that it is used for. Hence an impartial decision maker such as the National Regulatory Authority should be held responsible for the removal of regulating barriers and for the approval of case specific projects.

6.3 Clarify the definition of Energy Storage in order to avoid double taxation

Being able to both absorb and inject electricity, batteries can mistakenly be identified both as load and generators. In this regard, grid charges may be applied from both standpoints. This is detrimental to the commercialization of energy storage, and particularly unfair given that it constitutes an asset that greatly alleviates grid congestion, and should be offered tax waives instead of double charges [68].

Furthermore, considering battery storage systems as either a load or an electricity generator poses serious concerns to the accountability of the electricity grid data recollection. In fact, a single unit of power produced, stored and then consumed would risk being registered from a fiscal point of view as produced and consumed twice.

6.4 Introduce a market-based remuneration for every energy provision and ancillary services

Every country can regulate its own energy and ancillary services national markets. However, in some countries, certain services that have historically not been procured on an open market are still subject to unfair regulation. For instance, only certain technologies can provide certain services, even if at a higher cost, and the remuneration can be either set at very low levels or it can just be non-existent, making the specific service provision a requisite for that generating asset. One evident case is that of the Italian market for Frequency Containment Reserve (primary regulation), which is currently required and not remunerated by Terna, the Italian Transmission System Operator [69]. In order to foster the transition to a more competitive market, national grid codes should be updated to include new technologies and market-based remuneration schemes.

6.5 Harmonize grid codes of neighbouring nations and international unions

Most of the above policies often require the renewal of network codes and regulations that can result in a time consuming and expensive process. Moreover, nations may not see the interest in actualizing a grid code in order to expand a certain electricity service market, if that market is too small. On the other hand, if instead of a national based grid code update, a new regulation had to be developed on an international scale, the efforts and costs of actualization would be centralized. In this way, rather than updating each system, there would only be the need to harmonize every country on a unique set of rules.

In this regard, considerable efforts have already been carried out by the European Network of Transmission System Operator for Electricity (ENTSO-E), which has developed pan-European bidding platforms for secondary and tertiary control, respectively named PICASSO and MARI [70, 71], which are expected to provide favourable conditions for market participation of battery systems, especially for those able to place bids in an effective way by employing AI powered control software.

6.6 Include battery energy storage into national renewable targets

The introduction of standards, roadmaps and goals of required storage provision represents not only the certainty of future battery developments, but it also gives a strong signal to the market for incentivizing new independent projects [72]. The inclusion of energy storage targets have proved to be successful in different parts of the United States, even if those targets have been set indicative or non-binding.

As previously mentioned, battery storage is a technology that can currently offer a considerable spike in revenues only by allowing financing costs. This means that battery energy storage systems do not necessarily need a new breakthrough in technological development, but rather a reliable track of records and clear market signal and public policies that recognize their usefulness in the electricity network [73].

6.7 Incentivize aggregation of residential and commercial storage

In several countries, the development of battery storage systems at residential scale has been able to develop way earlier and with much wider volumes than large-scale battery systems. The reasons are mainly the following:

- The easier policies formulation of tax incentives to homeowners compared to system operators
- The thrust provided by the private electric vehicles market
- The low initial investment required for a residential battery, which can be tolerated easily by a homeowner despite the uncertainty on the ROI. On the contrary, large-scale battery programs require detailed analysis from investors to validate multi-million budgets.
- The possibility for battery manufacturers to rely on an established and large network of installers of home equipment which can promote the products on a regional level.

Hence, residential and commercial have an established footprint in different nations and have been proved to operate efficiently in Behind of the Meter applications such as load shifting, peak shaving and renewable integration of locally produced electricity. A multitude of smaller systems can however provide the same services of a large-scale battery once a proper aggregation software is employed. This can allow small battery units to pool together to provide Front of the Meter services to the grid [74]. In this way, most of the barriers of large-scale systems ownership and financing can be overrun, while at the same time fostering a solution which maximizes system flexibility and distributed generation.

6.8 Widen the price spread of Time of Use electricity tariffs

Most of the residential and commercial Behind of the Meter applications worldwide has spread in markets that have introduced Time of Use rates and have made the daily price spread large enough to motivate energy shifting [75]. Higher tariffs during peak hours have proved to effectively incentivize customers to reduce their energy usage. These customers are expected to keep lowering their consumptions even more once in possess of a software platform to control the energy balance of their PV + Storage system in real time. On the other hand, using a flat tariff for every hour of the day proves to make irrelevant the benefits of a Behind of the Meter grid-tied battery storage system for residential or commercial users. Furthermore, flat tariffs disincentivize consumer to raise their awareness on peak-time consumptions, hence they should be preferably changed in favour of more energy efficient ToU rates.

6.9 Promote Capacity Payment for the installation of Battery Storage projects

In order to obtain a business model for energy storage that may look more solid and safe to investors, the revenue streams with fixed remuneration over time should not be overlooked compared to those coming from merchant operation. As described in Chapter 4, while operating a merchant system in an open trading market may often allow considerable revenues for BESS, these revenue streams are hard to predict with certainty. On the other hand, a capacity payment in the form of €/MW/year of power installed allows to clearly define with a maximum certain payback time, which can then be reduced if the merchant operation in the electricity and ancillary services markets is proved to be fruitful.

6.10 Abrogate feed-in tariffs for residential and commercial prosumers

More than a decade ago, as distributed generation of solar photovoltaics was starting to appear in large volumes, feed-in tariffs were introduced to allow households or businesses to inject the solar power produced but not consumed, obtaining in return a remuneration or a credit for the later use of electricity. This system allowed thousands of prosumers to utilize the national grid as if it were a battery. On small volumes, this approach is sustainable, as the uncontrolled injection of electricity from different users does not constitute an unbalancing factor. However, this is not the case if the target for renewable integration of a country's electricity mix are set to a path to partial or full decarbonization. In these scenarios, the required distributed generation needs to ramp up considerably, and no uncontrolled electricity injection can be sustained. Battery storage can result extremely helpful in this regard, given its modularity and possibility to be deployed in small and distributed scale, however the remaining feed-in tariffs constitute a competitor that not only is slowing down new technology adoption [76], is actively contributing in destabilizing the grid, but is also mostly seen as superfluous at a moment in time in which solar photovoltaics has been able to consistently decrease its costs and prove its profitability.

6.11 Design tenders which promote long duration batteries for stacking up applications

As previously discussed in Chapter 4, longer duration batteries allow for the participation in multiple markets and for the possibility of stacking up applications of different revenue streams. This allows for a more diversified business case that can prove its resiliency in the event that one of the several revenue streams may drain out. This can happen with market saturation [55], which would drive down remuneration rates and consequently erode margins. As many battery storage tenders tend to be designed to solely employ BESS for frequency regulation or peak shaving, there is often a high tendency in favouring batteries with short duration [77], (usually below 1 hour discharge) compared to batteries with longer discharge times (above 2 hours). This tendency is likely to rise the risk of flooding the market with cheap short-duration batteries and send the wrong signal to battery developers, which will focus more resources on short-duration batteries instead than on BESS with larger capacity [76]. These batteries not only tend to saturate their market quickly, potentially causing more economic downfalls than benefits, but are also the least environmentally sustainable option for battery energy storage systems, given that they have a limited lifetime and require repeated restack, revealing to be rather carbon intensive solutions due to their production and disposal footprint [78].

Conclusions

As the market of Battery Energy Storage Systems is expected to grow exponentially in the next decades, as such, public policy frameworks will need to be accurately tailored in order to better address the many issues related to the incorporation of such a disruptive technology in the status quo of the electricity sector.

The present paper first presented the currently available technology of Li-Ion BESS, qualitatively ranking strengths and weaknesses of its the main alternative compositions such as $\mathrm{LiCoO_2}$, LMO, LFP, NMC, NCA and LTO (*Chapter 1*). Then, a description and analysis of the BESS applications was presented (*Chapter 2*), for both Behind of the Meter operations (Renewable Self-Consumption, Tariffs Optimization, Peak Shaving, Load Shifting and Back-Up) and Front of the Meter operation (Wholesale Market participation, Frequency Control, Ancillary Services, Capacity Market, Time Arbitrage, Ramp Control, Transmission Congestion Avoidance and Grid Investment Deferral). A separate distinction was made for BESS employed in Microgrids.

BESS solutions were then compared to other commercially available and most widespread Energy Storage technologies (*Chapter 3*), namely: Pumped Hydro Storage, Molten Salt and Regenerative Hydrogen Fuel Cell. This section analysed which precise use and application was best suited for each technology, how BESS can complement with other types of Energy Storage and how can competition between technologies drive further innovation. Following these first three chapters, the Master's Thesis restricted its focus on the first renewable energy tender in continental Europe in which a PV with Storage option has been designed: The 2020 Portugal Solar Auction (*Chapter 4*). The analysis of the tender was used to understand at which level of deployment and refinement are public policies currently used to drive the employment of BESS in national electricity networks.

The study of BESS technologies, applications and public policy frameworks was used to support the hypothesis that *a short duration LFP BESS is the favourite choice for the 2020 Portugal Solar Auction, although long duration LFP and NMC BESS will become the technologies to yield the most value in the future decades*. Furthermore, in order to define the needs of BESS in the next decades, it was attempted to estimate the required volume of Back-Up systems and BESS to meet the targets of the PNEC 2030, the Portugal National Energy and Climate Plan for 2030 (*Chapter 5*). It was estimated that *by 2030 a volume range between 5-10 GW of national Back-Up power will have to be provided by Hourly Ramping fossil-fuel peak plants, Demand Response programs and Energy Storage technologies excluding PHS. The share of BESS will highly depend on future public policy frameworks and it can be estimated not to surpass 1 GW of installed power*.

Using the notions of optimal BESS sizing explained in Chapter 4, it is estimated that the 1 GW of installed power should allow for 4 GWh of energy capacity. The cost of deploying such an amount over the course of the next decade is estimated to be in the range between 0.55 and 1.025 billion EUR.

Finally, as this Master Thesis's hypothesis states that the future share of BESS will be greatly impacted by future public policy frameworks, a list of public policy actions is presented as means to facilitate the deployment of BESS. These include funding pilot projects, resolve ownership issues for TSOs and DSOs, avoid double-taxation, incentivize remuneration of ancillary services, harmonize grid codes among neighbouring nations, define national targets for energy storage deployment, promote aggregation of residential and commercial users and design Time-of-Use tariff structures.

As a follow-up to this work one should analyse the operation, revenue schemes and degradation over the lifetime of a short duration LFP BESS so as to quantitatively compare it with long duration LFP and NMC. Another suggested research topic would be to evaluate the competitivity of BESS over Hourly Ramping fossil-fuel peak plants in order to establish which price point can increase the share of BESS and help define with more granularity the volume of BESS needed to be deployed for the PNEC 2030 to be achieved. Finally, it would be interesting to analyse and quantify the effects of each proposed public policy in order to compare each one and suggest an order of priority specific to the Portugal electricity market. With this thesis and the suggested future studies, it is envisaged that a relevant contribution to understanding the use of BESS can be achieved. The hope is to see the implementation of public policies that not only focus on incentivizing new energy production, but also strive to store energy efficiently, championing the use of flexible low-impact technologies that will contribute to a rapid transition to carbon neutrality.

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