# Assessment of the contribution of storage and demand side management to power system flexibility

A thesis submitted to The University of Manchester for the degree of

***Master of Philosophy***

In the Faculty of Engineering and Physical Science

***2011***

***Ángel Rosso Mateo***

School of Electrical and Electronic Engineering

# TABLE OF CONTENTS

Final word count including footnotes and endnotes: *28996 words*

# INDEX OF FIGURES

# INDEX OF TABLES

# ABSTRACT

The increasing penetration of renewable technologies, particularly wind power, raises concerns about the levels of flexibility needed to cope with the inherent variability and uncertainties surrounding these sources of energy. Departing from the common conception of providing flexibility using fossil-fuel generators with fast ramp rates, this work proposes the use of emerging technologies and solutions.

A technique to optimize the balance between the flexibility provided by fast generation units and the flexibility achievable from demand side management (DSM) and storage of electrical energy is presented. This methodology is based on an extended unit commitment optimisation that caters for both the short- and long-term aspects, i.e., operational and investment costs. Additionally, different methods to select the patterns that model the demand and wind profiles from the date a year are presented,

The methodology is demonstrated using an adapted version of the IEEE RTS (RTS-96), using actual demand and wind profiles from central Scotland.

# DECLARATION

This thesis has been carried out as an evolution of the work performed by Juan Ma in the second year of her PhD thesis project: “Modelling the flexibility in the generation-load balance”. The work explained in the above document starts from the model developed by Juan Ma, and received some necessary modifications to accomplish this study. The necessary explanation of the base model is shown on chapter II.3.1 but no part of the text has been copied from her work.

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institution of learning.

# COPYRIGHT

# ACKNOWLEDGEMENTS


- *Dr. Luis F. Ochoa (Nando):* for all his support on the development on this thesis, for talking with me in English. You have been one of the better examples I have ever had of supervision and commitment towards work.
- *All my colleagues of the research group* for all the moments shared together sharing thoughts and analysis *specially*, *Juan Ma:* for allowing me to use your model on flexibility and helping me to understand it*,* *Ning Zhang* for his feedback on my research and *Efthymios Karangelos:* for his technical support with Xpress versions and licences.
- *Dr. Daniel S. Kirschen*: an example of a good supervisor and a responsible person. Thank you for every advice that you have shared with me.
- *Manchester University staff*: for all the information and attention provided about the administrative procedures even when i asked several times. I would like to mention specially, *Marie Davies*.
- *Gustavo Valverde and Jairo Quirós:* I will never forget all the lunch times we shared. You have made this year much easier and enjoyable.
- *Mari Paz García Alajarín*: for introducing me to Daniel S. Kirschen and providing advice about how to maximize my experience during this year.
- *My Friends and family*: for your attention and support from the distance. I would like to mention, especially *Miguel, Javi, Ana, Borja, Daniel and Alberto* for their visit(s).
- *My parents*: I ought you who i am and what i have achieved. Thank you very much for staying for me every day from the distance. This year has been tough for all of us but the time spent here has not been wasted.
- *Elena*: A few lines are not enough to say all i ought you. Regarding this thesis thank you very much feedback and the help with clustering. Thank you for every time spent on the computer to be with me from the distance. Thank you for being in my life.

# DEDICATION

*To my parents*
*Fely and Carlos*
*and to my sun,*
*Elena*

# ACRONYMS

| | |
|---|---|
| AC | Alternative Current |
| BESS | Battery Energy Storage Station |
| CAES | Compressed Energy Air Storage |
| **CAPEX** | **Capacity expenditure (Investment cost)** |
| CCGT | Combined Cycle Gas Turbine |
| DC | Direct Current |
| DG | Distributed Generation |
| **DSM** | **Demand Side Management** |
| DR | Demand Response |
| EV | Electric Vehicle. |
| GHG | Green House Gas |
| MES | Massive energy storage |
| **MILP** | **Mixed Integer Linear Programming** |
| **OPEX** | **Operational expenditure (operational costs)** |
| PHS | Pumped Hydroelectric Storage |
| SMES | Super Magnetic Energy Storage |
| SO | System Operator |
| **ST** | **Storage as a resource of flexibility** |
| **UC** | **Unit Commitment** |
| UCTE | Union for the Coordination of Transmission of Electricity (Europe) |
| V2G | Vehicle to Grid. |

***Nomenclature for scenarios***

| | |
|---|---|
| BAU | Business as usual |
| DSM | Scenario with demand side management |
| ST | Scenario with storage |
| LV | Scenario with low variable wind |
| HV | Scenario with high variable wind |

# LIST OF SYMBOLS, NOMENCLATURE

## FLEXIBILITY MODEL

### *Indexes and sets*

| | |
|---|---|
| $i, I$ | Each of the generating units of the available portfolio [-]. |
| $p, P$ | Each part of the linear approx. of the cost curve of generators [-]. |
| $t, T$ | Each of the instants evaluated for the scope of time [h]. |
| $c, C$ | Each of clusters that represent the year [weeks or days]. |
| $d, D$ | Each of the days of the weeks that represent the year [days]. |

### *System parameters*

| | |
|---|---|
| $D(t)$ | Demand of the customers of the system. [MW] |
| $D^{max}$ | Peak demand, maximum value of demand. [MW] |
| $Res_{sys}(t)$ | Total system reserve requirements. [MW] |
| $Res_{gen}(t)$ | Reserve requirements due to the possible loss of a generator. [MW] |
| $\chi_{Std}$ | Maximum fraction of standing reserve present on the system. [-] |
| $\Delta t$ | Time step of the model with a value of one hour. [h] |

### *Generator parameters*

| | |
|---|---|
| $G^{\min}(i)$ | Minimum technical power output of each generator. [MW] |
| $G^{\max}(i)$ | Maximum technical power output of each generator. [MW] |
| $G_{sg}^{max}(i, p)$ | Each of the steps on power of the piecewise linear approximation of the generation costs [MW] |
| $\Delta C\ (i, p)$ | Incremental cost of generation for each segment of the linear approximation. [$/MWh] |
| $NlC(i)$ | Cost of a generator by being committed more known as <u>no load cost</u>. |
| $SuC(i)$ | Start up cost of a generator |
| $InvC(i)$ | Investment cost of each generator. [$/MW] |
| $LifeExp(i)$ | Life expectancy of each generator. [Years] |

| | |
|---|---|
| $T_{Up}(i)$ | Minimum time that a unit has to be working after it has started. [h] |
| $T_{Down}(i)$ | Minimum time that a unit has to be cooling after it has stop. [h] |
| $R_{up}(i)$ | Maximum ramp up characteristic of each generator. [MW/h] |
| $R_{down}(i)$ | Maximum ramp down characteristic of each generator. [MW/h] |

***Wind generation parameters***

| | |
|---|---|
| $G_{wind}^{available}(t)$ | Wind available on the system [MW] |
| $G_{wind}^{\max}$ | Maximum wind generation [MW] |
| $\chi_{wind}$ | Fraction of wind in the system [-] |
| $\sigma_{wind}$ | Deviation error on wind prediction. [-] |
| $W_{ct}C$ | Price given to curtailed wind in order to ensure that wind is curtailed as minimum as possible [$] |

***Wind generation decision variables***

| | |
|---|---|
| $G_{wind}(t)$ | Wind generation present on the system. [MW] |
| $G_{wind}^{ct}(t)$ | Curtailed wind generation to ensure possible solution. [MW] |

***Cluster parameters***

| | |
|---|---|
| $\chi(c)$ | Weighting coefficient of each pattern. [-] |
| $t_0(c)$ | Initial instant of each pattern. [h] |
| $t_{end}(c)$ | Ending instant of each pattern. [h] |

***Decision variables***

| | |
|---|---|
| $e(i)$ | Indicates whether a unit has been selected or not. (Binary) [-] |
| $G_{sg}(i,t,p)$ | Power generated at each part of the piece-wise linear cost curve. [MW] |
| $G(i,t)$ | Power generated at instant t by unit i. [MW] |
| $u_c(i,t)$ | Indicates whether a unit has been committed at instant t. (Binary) [-] |

***Variables (value derived from decision variables)***

| | |
|---|---|
| $GC\ (i,t)$ | Total costs on the objective function associated to generators |
| $AIC\ (i)$ | Amortized investment cost of each generator |

***Auxiliary Parameters***

| | |
|---|---|
| $M$ | Maximum value parameter. It has a huge value and its purpose is having the possibility to add logical constraints to a MILP model. [-] |
| $m$ | Minimum value parameter. It has a huge negative value and its purpose is writing logical constraints in a MILP model. [-] |

***Auxiliary Variables***

| | |
|---|---|
| $aux_{on}(i,t)$ | Auxiliary variable that appoints if a unit has started. (Binary) [-] (used for the ramp constraints of the generators) |
| $aux_{off}(i,t)$ | Auxiliary variable that appoints if a unit has stopped. (Binary) [-](used for the ramp constraints of the generators) |

## Storage Modelling

***Storage indexes and sets***

| | |
|---|---|
| $s, S$ | Each of the available technologies to store energy. [-] |

***Storage parameters***

| | |
|---|---|
| $\eta_{ST}(s)$ | Round trip efficiency of the storage technology (s) [-] |
| $EInvC(s)$ | Capacity investment cost of each storage technology. [$/MWh] |
| $PwInvC(s)$ | Power investment cost of each storage technology. [$/MW] |
| $LiveExp_{st}(s)$ | Expected life period of the storage technology. [Years] |
| $Std(s)$ | Binary variable that indicates if a certain storage technology is only suitable for providing standing reserves (batteries). [-] |

***Storage decision variables1***

| | |
|---|---|
| $D_{st}(s,t)$ | Energy extracted from the system to store energy. [MW] |
| $G_{st}(s,t)$ | Energy put back to the system from the reservoir. [MW] |

[1] Not all the decision variables are independent; some variables are linked between them by some constraints. For example, the energy stored $E_{stored}(s,t)$ depends on the decision on when to store energy $D_{st}(s,t)$ and when return it to the system $G_{st}(s,t)$.

| | |
|---|---|
| $Res_{st}(s,t)$ | Net contribution of storage to system reserves. [MW] |
| $E_{ST}^{max}\ (s)$ | Investment in Storage capacity (Batteries). [MWh] |
| $Pw_{ST}^{\max}\ (s)$ | Investment in storage power (Power electronics). [MW] |
| $E_{stored}(s,t)$ | State of the reservoir that instant t for each technology. [MWh] |
| $SIC$ | Storage investment costs. [$] |

## DEMAND SIDE MANAGEMENT MODELLING

### *DSM Parameters*

| | |
|---|---|
| $\chi_{sh}$ | Fraction of current demand $D(t)$ that is possible to be shifted. [-] |
| $DSM_{sh}^{\max}\ (t)$ | Maximum power of demand that could be shifted. [MW] |
| $\chi_{ct}$ | Fraction of peak demand $\overline{D}$ that is possible to be curtailed. [-] |
| $AnnualE_{ct}$ | Proportion of annual energy demand that can be curtailed because of a critical price period (CPP) event. [-] |
| $DailyE_{ct}$ | Proportion of daily energy demand that can be curtailed because of a CPP event. [-] |

### *DSM decision variables*

| | |
|---|---|
| $DSM_{sh}(t)$ | Shift on demand at instant t. [MW] |
| $DSM_{ct}(t)$ | Demand that has been curtailed at instant t. [MW] |

DSM variables (value derived from decision variables)

| | |
|---|---|
| $Res_{DSM}(t)$ | Contribution to reserve by DSM |

## OTHER SYMBOLS

| | |
|---|---|
| $x(i,k)$ | Each of the observations of the daily or weekly load profile of the demand. |
| $c(k)$ | Each of the chosen patterns to model the daily or weekly load profile of the demand. |

# I. INTRODUCTION

## I.1. MOTIVATION FOR THE THESIS

Energy supply is one of the capital interests in our societies. This resource powers the economy and maintains the welfare of the countries. The consumption of energy is closely related to the economical situation and growth. Despite the improvement of the use of energy whilst maintaining sustainable levels of efficiency, consumption in national economies continues to absorb growth.

Since the industrial revolution, fossil fuels such as coal and oil have powered local and national economies and remained one of the staple elements of economic development. However, the perception on how these requirements of energy should be fulfilled is changing in our societies. In recent years, climate change has become an increasing concern. It is a fact that the $C0_2$ levels in the atmosphere have doubled since the industrial revolution. Most of the scientists believe that the increase in global temperatures is related to the increase in GHG (green house gasses) emissions. A continued increase on global average temperature can derive in melting polar ice caps and increase the sea level. This will ultimately lead to a series of consequences for the environment and life on earth.

Moreover, fossil based energies are not renewable and therefore, humanity cannot rely on them forever. As Figure 1 shows, we are near to reach a point in which the supply of oil is not going to be able to cover all the demand, this is known as peak oil. Every non renewable technology will reach its maximum capacity and ultimately will not withstand its production. As laws the economics suggest, the price is settled by the equilibrium between offer and demand. If the supply cannot cover the demand, the price is going to ascend dramatically. Furthermore, the progressive peaks in each resource will probably affect other resources by shortening the time when humanity will reach the next peak.

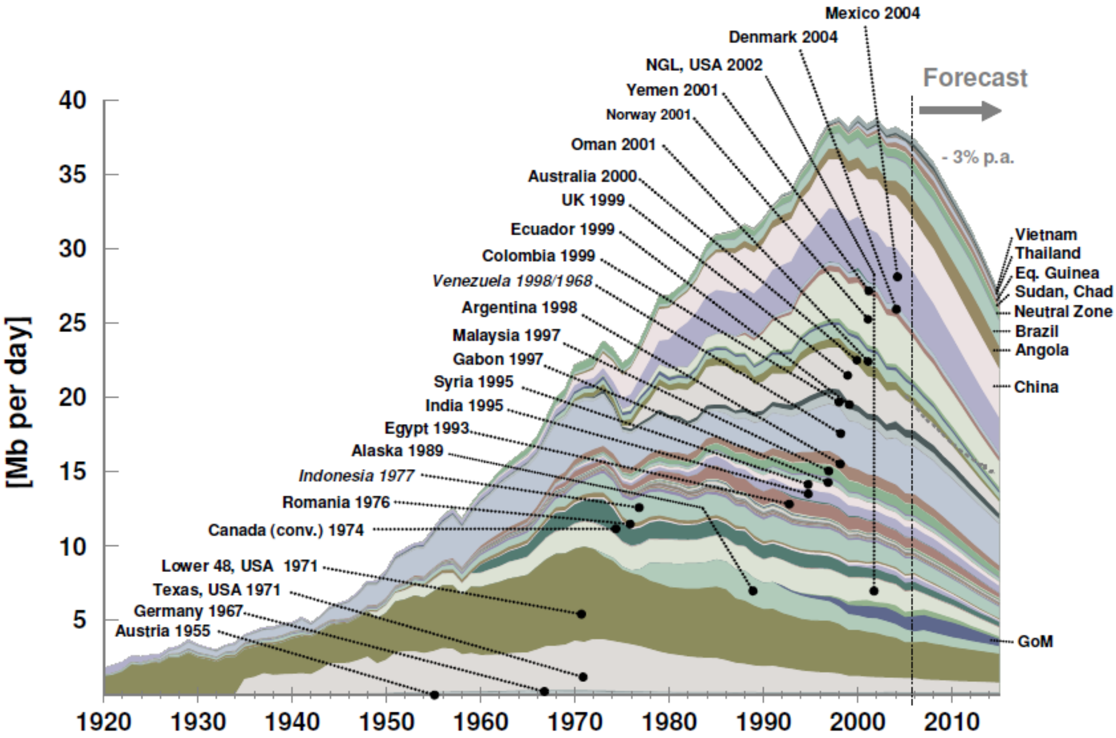



*Figure 1 Evolution of world oil production and peak in production of different countries.[49]*

Alternatively, nuclear energy has been presented as an alternative to fossil fuels. It provides a great amount of energy at a reasonable security of supply. The main concerns against this technology are the management of nuclear waste and the risk of accident. Recently, the life expectancy of nuclear facilities has been extended and some countries are investing in this possibility. However, the disaster at Fukushima´s nuclear power plant has increased the concerns and currently several countries are considering plans to stop using this technology.

Consequently, it is important that humanity moves towards other energy resources. Because of the impact on several aspects of a society, the mix of energy technologies is more a political than a technical decision. Governments usually limit investment in technologies by regulation or establishing limits on the maximum amount of capacity installed. Taking into account the necessary shift towards renewable resources, the European Union set in 2000 the 20/20/20 targets. These 2020 initiatives entail the reduction of 20% of emissions in greenhouse gases, the increase of 20% of energy efficiency in the EU and achieving 20 % of renewable generation in total energy consumption in the European Union.

All these factors have driven investment for new power plants into low-carbon and renewable technologies, with wind power being the leader among all the possibilities. These technologies have several advantages: no contribution to the emission of GHGs, an unlimited in supply in a human timeframe, and the reduction in the imports of energy from foreign sources. Therefore the energy dependence on other the countries is reduced. Because of these reasons the investment in new wind farms has followed an exponential growth over the last few years, as shown on Figure 2.

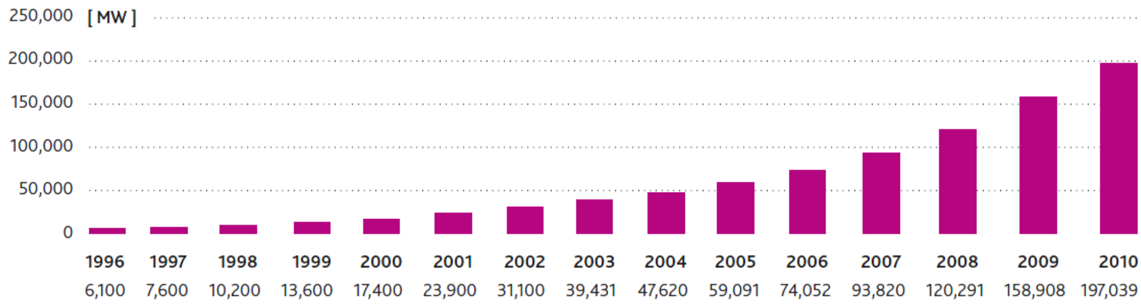



*Figure 2 Global cumulative installed wind capacity 1996-2010 [46]*

On the other hand, wind, sun, tides and waves cannot be controlled to provide energy when it is required by the system. Consequently, with the progressive introduction of these technologies more flexibility will be required to cope with their inherent variability.

Furthermore, the uncertainty on the forecast of the generation increases the reserve required to maintain security at a reasonable level. All these issues make the provision of flexibility rather expensive. Therefore, it is important to know how much flexibility is needed in a given power system.

Flexibility is usually provided by some generators that have a fast start time, high ramp-up and down rates, and low minimum up- and down-times. Interconnections with other (flexible) systems represent another conventional solution. Emerging technologies have the potential to provide these services cost-effectively. Energy storage can be used to absorb the fluctuations in wind power. By displacing (peak) consumption to low price periods, demand side management (DSM) schemes can also contribute to the flexibility of the system.

Other factors could increase the uncertainty in the provision of reserves in the future. If not handled properly, the inclusion of smart appliances that respond to the electricity market price could trigger greater fluctuations in demand when prices are around the triggering condition of the appliance to start demanding energy. The introduction of distributed generation would increase the uncertainties on the net load profile since its prediction will be more difficult to be made because of its distribution along the grid.

## I.2. AIMS OF THE RESEARCH

In this context, it is necessary to evaluate how much flexibility our systems require to handle the progressive integration of wind generation. Furthermore, it is necessary to assess among the sources of flexibility those that are the most interesting for the system and which is the best equilibrium to cope with uncertainties and allow further penetration of wind technology cost effectively.

Therefore it is important to fix some objectives for this research project:

- Evaluate how much flexibility is required with a progressive in increase in wind generation (WG) increases for a given power system. (Chapter II)
- Evaluate the contribution of storage to flexibility required by the progressive introduction of WG. Analysis of the different technologies and possibilities. (Chapter III)
- Evaluate the potential contribution of demand side management to flexibility and the contribution to WG integration. Overview of the policies to progressively introduce demand side management in power systems. (Chapter IV)
- Evaluate the overall contribution of storage and responsive demand to flexibility. Compare and optimize the amount of external resources of flexibility. (Chapter V)

This projects was carried out as a parallel development to a model created during the progress of a PhD. degree at The University of Manchester: “Modelling the flexibility in the generation-load balance” carried out by Ma Juan. An analysis tool was developed for that project to analyse the flexibility requirements in power systems. The main contribution that has been made by this project is the addition of storage technologies and demand management to the flexibility model. Furthermore some improvements were made in the management of the data and in some details of modelling of the constraints of the model.

## I.3. CONTRIBUTION MADE BY THIS WORK

The main contribution performed in this work is the assessment of the economic impact of two of the flexibility resources that can be introduced in an electrical power system: storage, and demand side management. This value depends on the amount of renewable generation, wind generation in particular. This analysis required the following developments:

- Improvement of the method developed by Juan Ma in her PhD. thesis: "Modelling the flexibility in the generation-load balance" that evaluates flexibility requirements considering operational and capacity costs. The main improvement is that the model considers the repeatability of the patterns in the constraints. Additionally the next two contributions could be applied in her thesis and are original of this.
- Development of a method to summarize the demand of a whole year by some representative patterns using clustering techniques. This method is especially useful to look for patterns that are repetitive: days and weeks.
- Elaboration of a method to choose some representative patterns of wind generation in a deterministic manner with the objective of searching for the worst-case scenario. This procedure was created for analysis when stochasticity is not employed. Furthermore, the method can select patterns with low and high variability in wind generation.
- Analysis of the contribution of storage technologies to power system flexibility. An examination of the different storage technologies and the expected contribution of storage were performed. The flexibility model was improved to analyse different storage technologies. The results showed that storage is cost effective if it participates in reserve provision and it is very suited for this service. Storage improves overall efficiency allowing further utilization of base generation especially in high wind generation scenarios.
- Analysis of the contribution of demand side management to power system flexibility. An assessment of the potential capacity and a study of different policies and tariffs were made. The flexibility model has been improved to introduce this type of schemes, modelling separately demand that will be shifted and demand that can be curtailed. The results showed the potential contribution of DSM to flexibility in power systems. Similarly to storage, the overall costs were reduced and further utilization of base generation was made possible. It also proved its contribution in high variable wind scenarios but with a
- Combined analysis of both possibilities. The introduction of these external resources in the model developed by Juan Ma was made with the objective of developing a model that could introduce both at the same time. However, the computing time required to perform this analysis made it impossible to be used to show some relevant results. Therefore, this final analysis focused on a comparison of the results

from both possibilities. From a general point of view, the results showed that storage is more suitable to provide reserves and DSM has better characteristics. However, its potential contribution is limited due to its effect on the comfort of the customers. Therefore, storage should only be part of the solution.

## I.4. OUTLINE OF THE THESIS

Based on the concepts and objectives that have been explained above, the thesis is organised in six chapters and five appendixes. The document is structured as follows:

- **Chapter II** explains the concept of flexibility, the requirements for reserves in power systems and gives a general idea of the impact of wind generation on power systems. Starting from these, the methodology to evaluate the flexibility of a generation portfolio and generate a simplified set of demand and wind profiles is presented. Finally some results that assess the performance of the model and the effect of an increase in wind generation in conventional power systems are presented.
- **Chapter III** presents the analysis that has been made for storage technologies: why storage technologies provide flexibility, which technologies are more suitable to provide this service, the methodology followed to model flexibility provided by storage and the results achieved based on the study case described in the previous chapter.
- **Chapter IV** illustrates the contribution that demand side management (DSM) could make to this problem, starting from an analysis of the different agents present in the electricity markets, the tariffs that would increase demand responsiveness and the possible contribution of DSM to power systems. Then, the improvements to model DSM in the method presented in Chapter II are discussed. Finally an analysis of the results accomplished with the flexibility model is given
- **Chapter** V presents the combined analysis of the two flexibility resources, storage and demand side management. The combined model is presented but it was not employed in the final results because of the computational burden. The chapter presents a complete overview and **comparison of the results** presented in previous chapters **about storage and demand side management**.
- **Chapter VI** presents the conclusions of the thesis and the possible improvements that could be made to the work that has been performed.

- **Appendix A**: Presents the available generation portfolio that has been used to obtain the results with the proposed methodology.
- **Appendix B**: Presents the results achieved with the clustering methodology in modelling the whole year using some representative days.
- **Appendix C**: Shows the results achieved with the clustering methodology in modelling the whole year using some representative weeks. In the final simulation, because of the computational burden, only some representative days were used. However, this chapter proves that the methodology is equally valid for weeks.
- **Appendix D:** Presents the data for wind generation and the results achieved in the wind profiles selection applying the methodology explained in chapter II.3.3.
- **Appendix E**: Presents how the piecewise linear approximation for the cost of generation is implemented in the model.

## I.5. RESOURCES REQUIRED

To accomplish the study that has been carried out for this thesis the following resources were used:

- Model developed by Juan Ma about flexibility analysis of generating units elaborated in the Mosel language. Despite starting from this model, the complete model is described in the thesis.
- The FICO Xpress-IVE optimisation suite which is based in Mosel language.
- "Zotero", an add-on for Mozilla Firefox internet browser to organise the references.
- Microsoft Excel to analyse the data and produce graphs of the results.
- Matlab 7.6 R2008a was used to draw certain graphs and for the clustering analysis.
- Microsoft Word for writing the thesis.

Every one of these resources was either open source (free) or was provided by Manchester University.

# II. FLEXIBILITY: CONCEPT AND METHODOLOGY

## II.1. INTRODUCTION

Currently the planning and operation of power systems reflects an equilibrium between security (fear) and economical efficiency (greed). This equilibrium is currently challenged by the increasing penetration of renewable generation. This integration requires an increase in the flexibility of the system to maintain the reliability of supply at an acceptable level. Our systems are already flexible because if they were not, blackouts would be a common occurence. However, more flexibility is needed to cope with this situation.

Flexibility in power systems is the capacity to maintain the balance between generation and demand over a range of operating conditions. In order to do so, it is necessary to have resources that cover fast deviations from this equilibrium and enough reserves of energy to cover unpredicted situations. However, providing flexibility is expensive. Thus, it is important to know how much flexibility is needed in a given power system.

Flexibility has usually been provided by fast generators. Their main characteristics are fast start time, high ramp-up and down rates, and low minimum up- and down-times. Interconnection with other (flexible) systems represents another conventional solution. Emerging technologies also have the potential to provide these services cost-effectively. Energy storage and demand side management (DSM) schemes can indeed contribute to the flexibility of the system. DSM and storage will be explained in the next chapters, while interconnection with other systems is out of the scope of this thesis.

Achieving an optimal flexible generation portfolio is a problem that has been studied for many years [1]. The liberalization of the electricity markets has made this issue even more complex given that it is necessary to take into account regulatory issues when analysing the flexibility provided by the different participants of the system in order to optimize the corresponding bid strategies [2]. In a context where more renewable generation is being connected, it has also been shown that when the stochastic nature of wind power is taken into account, rolling commitment strategies would lead to improved economic performance because the error on wind predictions decreases [3]. The consequence is a reduced overall utilization of expensive peaking units.

Taking into account that wind is the leading renewable technology, this thesis focuses on the increased flexibility required for the economic and reliable introduction of wind generation. However, the method could be applied to other technologies especially if stochasticity is introduced. In order to do so, it would be required to model specifically the new renewable resource.

***Outline of the chapter***

This chapter starts by analysing the impact of wind generation (WG) on power systems. Then the methodology used to analyse the impact of WG on the generation portfolio, and the procedures used to model demand and WG are presented. Finally some results are discussed.

## II.2. IMPACT OF WIND ON POWER SYSTEMS

As was mentioned in the introduction, wind generation (WG) has an impact on the required generating units to supply the demand. Furthermore, WG requires a modification of the reserve requirements in the system. These changes in turn affect the investment decisions on the generation mix. In this project, the impact of wind in a power system is mainly observed by the impact on the generation portfolio and the impact on the generation schedule, taking into account the reserve requirements of the system. A general analysis of these problems is presented separately in this section.

### II.2.1 Generation schedule and investment decisions

As a first approach, it is interesting to consider the load duration curve of a power system (Figure 3). The load duration curve shows the load data ordered from the maximum to the minimum value along the year. It is a very useful tool because it allows the observation of the investment costs and the operational costs on the same figure. The investment costs are the maximum power available for each technology. This can be seen on the vertical axes. Furthermore, the generation costs are related with the area below the curve.

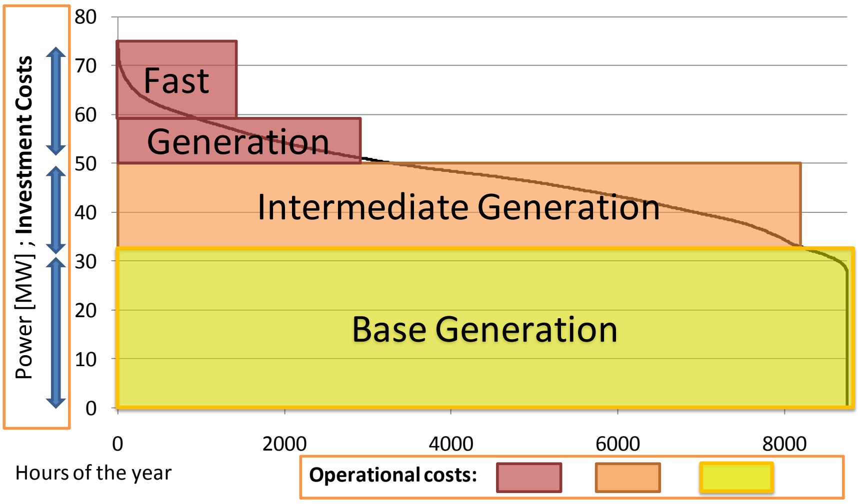



*Figure 3 Operational and investment costs on the load generation curve*

In order to recover the investment cost of the base generation, it is necessary that it is connected to the system and working for as much time as possible. This is the reason why this type of generation is committed during the whole year to supply the minimum demand. On the other hand, peak generation consists of power plants that have high flexibility, low investment costs but expensive operating costs. For these reasons, they are committed at peak times during the few hours of the year when the demand is very high. These peak situations are usually called critical price periods because they are associated with high prices in the electricity market.

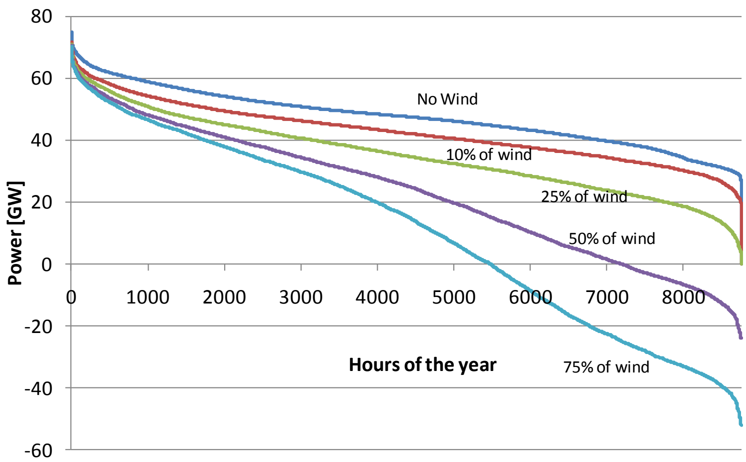



*Figure 4 Impact of wind on the net demand (load)-duration curve*

Figure 4 shows the effect of wind generation on the load duration as the proportion of energy supplied by wind generation increases. The curves show that as the ratio of

WG increases the difference between peak hours and off peak hours also increase. Therefore, as was shown on Figure 3, wind farms reduce the commitment of base generation and increase the need for fast generation to cope with the variability. Therefore, wind generation requires further investment in fast generation. Furthermore, Figure 4 shows that with high rates of wind generation (50% and 70%) part of the energy generated from the wind is wasted because the energy supplied is greater than the demand.

From a general point of view, the generation schedule follows the pattern derived from the load duration curve: base units are committed as much as possible and fast flexible units cover the fluctuations in the demand. However, the dynamic constraints on the generators, such as minimum time cooling and working, ramp limits, hot/cold start, must be taken into account.

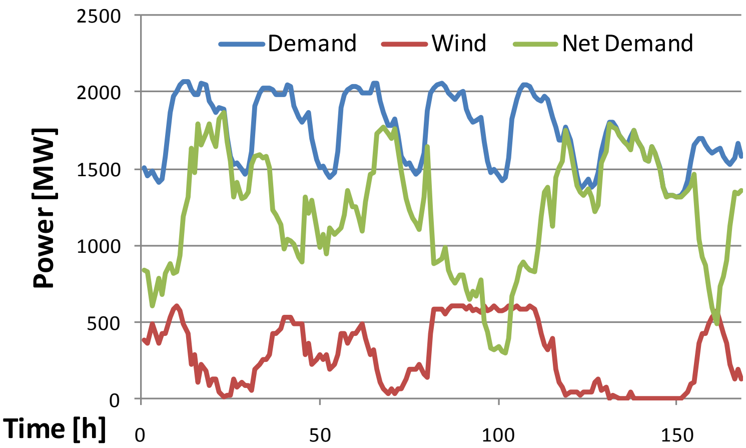



*Figure 5 Wind daily fluctuations versus demand*

Stating from these problems, Figure 5 shows why wind fluctuations are an inconvenient to the power system. Wind generation is not controllable and usually the wind production is not related to the fluctuations in demand. This increases the difference between peak and off-peak periods and therefore, the system requires the commitment of expensive units with greater dynamic capabilities. Furthermore, for the same reasons, wind generation does not ensure the reliability of supply so it requires the connection of units that can provide this service to the system.

Situations with an excess of renewable generation have already led to strange results in electricity markets. For example, Figure 6 shows how in Spain there were several days when the market reached marginal prices of 0€/MWh. The reasons for this situation were that the beginning of 2010 was a period in which wind and hydro generation were massive. This situation, combined with the presence of nuclear technology which is very expensive to be turned off, led to these results when the demand was too low to require any other generating unit which could have set the marginal price at a level above zero. Similar situations have happened in Denmark where excess of wind generation sets negative prices in the electricity market.

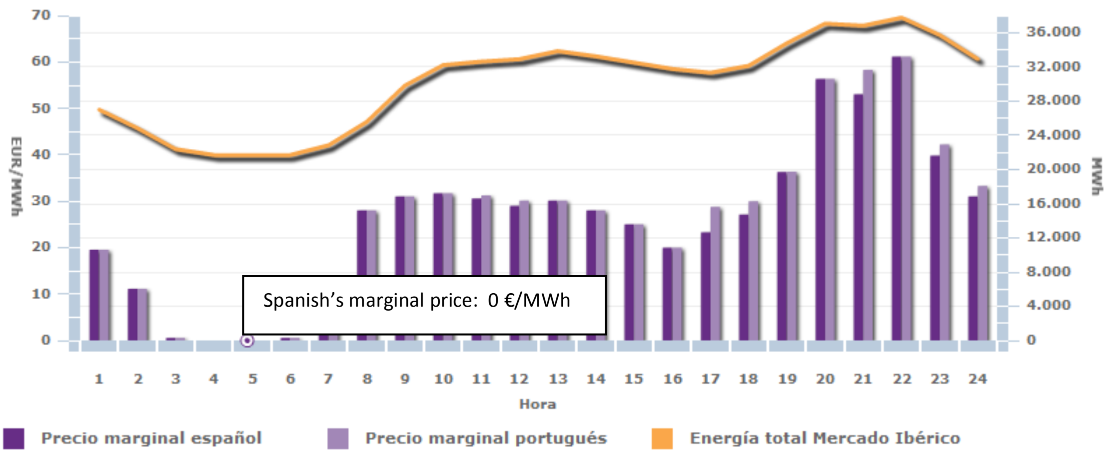



*Figure 6 Hourly price of the electricity for one day in a situation with excess of renewable generation, Iberian electricity market.[50]*

As an introduction to next chapters, both storage and demand side management are possible solution to avoid this situations in the electricity markets because both possibilities can take advantage of low cost periods.

### II.2.2 Reserve requirements

The purpose of reserves is to keep the reliability of the power systems at a reasonable level. Usually, electrical systems were supported by thermal (conventional) generation and the main function of reserves was covering the possible loss of the biggest generating unit, apart from lesser issues such as dealing with the uncertainty of demand.

The schedule of generating units is usually made on an hourly basis. Since the demand of energy fluctuates instantly, to maintain the equilibrium of the system under control it is necessary to have several “control loops” which are primary, secondary and tertiary reserves.

Primary reserve brings back the equilibrium between demand and generation but it does not return the frequency to its nominal value. The time of deployment of this reserve is between 2-20 seconds. Secondary reserve returns the frequency deviation in no more than 15 min. These first two control loops are automatic. Finally, tertiary reserve substitutes the power required by the previous reserves with an economic criterion. This analysis focuses on the optimal provision of flexibility and the impact on the generation portfolio. Therefore, the interest of this analysis is looking at the tertiary reserves.

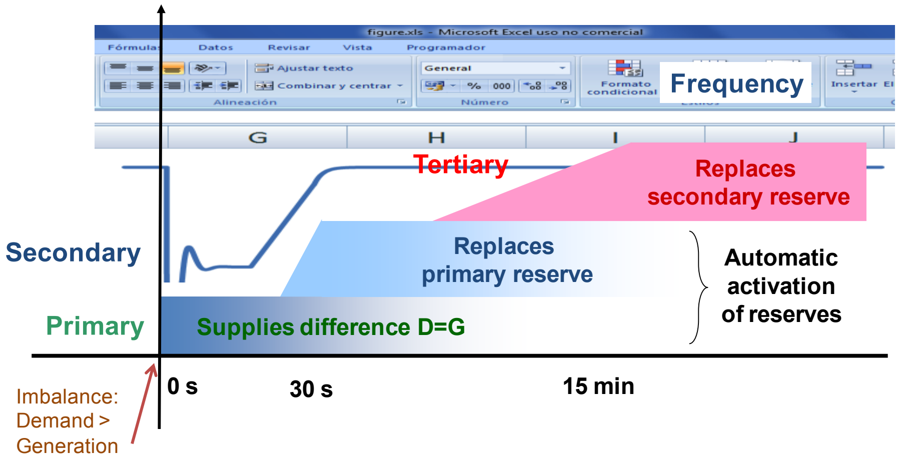



*Figure 7 Progressive reserves deployment after a disturbance.*

As has been highlighted previously, the introduction of wind generation increases flexibility requirements in power systems. The main reasons for this increase are the requirement of flexible generating units that are able to cope with the ramps in wind generation and the uncertainty on the forecast of the final wind generation (WG). The uncertainty in the wind generation requires an increase in the reserves provided by generating units in order to maintain the reliability of the system. Therefore, there are two reserve requirements that need to be considered for this project: general or system and the wind requirements.

Since the model does not allow to model big scopes of time and has been elaborated in a deterministic manner, the generation outages have not been considered

#### II.2.2.1 System reserve requirements

Reserve requirements and terminology vary between each electrical system and country [43]. Among all the possibilities, the main focus of this thesis is the reserve provided at the tertiary level, i.e. reserves that are committed on a scope of time of more than 15 minutes. This reserve needs to be scheduled and in several systems there is a specific market for the provision of reserves.

In most of the systems, the reserve requirements are determined by the SO. These needs vary between different synchronised systems. Usually, the reserves must be able to handle the worst case scenario. For example, in the complete UCTE, the reserves cover the possible loss of two nuclear power plants, about 3000MW. This looks like a very improbable event but the size of the system is enough to handle this event if the interconnections between the different countries are not constrained.

In other systems such as the United Kingdom, tertiary reserves are divided in standing reserve and spinning reserve. Spinning reserve caters for the most common variations from the schedule that happen in short times. For greater and longer variations, the system relies in standing reserve, which is provided by the units that have a fast start capability.

Some authors [4], [6], have considered the difference between standing and spinning reserves. However standing reserves are not being considered in this project for several reasons. First of all, it was proved that the inclusion of this possibility increased the simulation time to a value that was not affordable. For similar reasons, the portfolio that is considered in this project is does not have a great variety of units, so it is not reasonable to include specific units capable of providing standing reserve. On the other hand, when considering reserve provided by storage, since it is not logical that the whole system reliability relies on batteries, it is going to be considered that the maximum reserves provided by this technology will be the standing reserves.

Other sources of imbalances that would require an increase in reserve requirements would be the uncertainties on the demand side. In big systems, the forecast of demand is sufficiently accurate to avoid an impact on the results of the scheduling of generators. However, in small systems an error of few a megawatts could force the commitment of expensive units. On the other hand, the expected development of smart grids and distributed generation can increase the uncertainty of the load forecast unless some measures are taken. Since this thesis does not perform an analysed based on future scenarios this possible increase in reserve requirements is not going to be taken into account.

#### II.2.2.2 Reserve requirements due to wind generation

The comments presented in this subsection are mainly a summary of the analysis that was performed by [4]. To perform such analysis it is necessary certain data that has not available.

As it has been mentioned before, the introduction of wind generation (WG) requires more flexibility in any system. There are two factors in WG that characterise this increase: wind variability and wind forecast uncertainty. Wind variability is related to the selection of wind profiles and will be explained in chapter II.3.3 where it is explained how wind generation has been modelled. Wind uncertainty is the characteristic that modifies reserve requirements.

Wind forecast error varies with the time scale. Error on scope of seconds/minutes is low if there are enough wind farms and they are located in different regions. On a bigger time scale the forecast of meteorological conditions must be taken into account. However, these models are not very accurate. This results on bigger errors that require greater reserve requirements. Because of its importance not only for electrical generation, wind forecast is an active field of research.

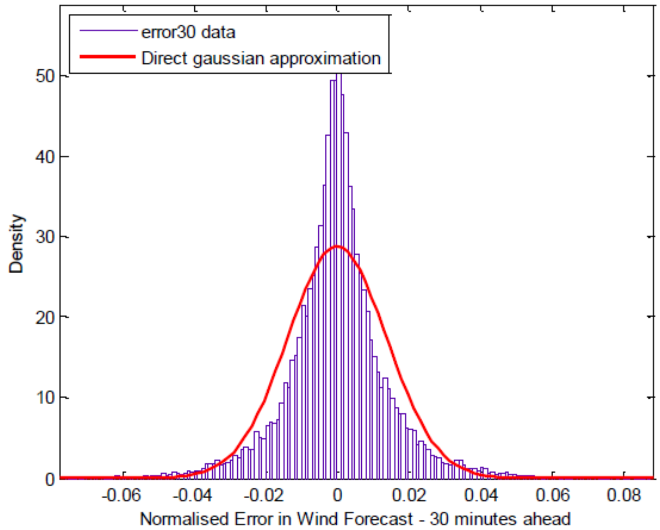



*Figure 8 Error on wind prediction 30 min ahead [4]*

Several authors have shown that the distribution has a bell shape similar to the normal distribution. However, it cannot be approximated by a normal distribution because the tails are bigger. Therefore, as in [4],[6] it will be assumed that 3.5 times the standard deviation of wind error $\sigma_{wind}$ captures approximately the 99.7% of the data and therefore, it covers the reserve requirements derived from wind uncertainty.

## II.3. METHODOLOGY ON THE ANALYSIS OF FLEXIBILITY

This section explains the different procedures that have been followed to develop the proposed analysis. More specifically, the main model that analyses the flexibility requirements of a given power systems is presented. Then the methods to provide the main data, demand load profile and wind generation profile, for this model are explained.

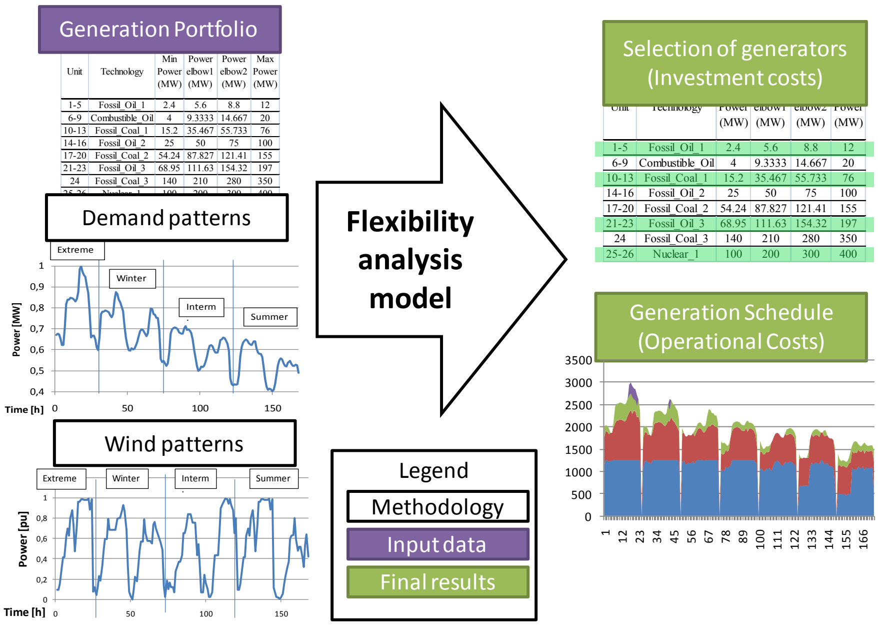



*Figure 9 General structure of the model*

Figure 9, gives an overview of the inputs for the model and the results derived from it. The flexibility model requires a portfolio of generators that are available to be invested and committed to supply the demand. Furthermore, it needs some demand profiles and some wind patterns. How the flexibility model has been implemented and how the simplification of the demand and the wind generation is explained along this chapter.

It is important to mention that this project has been performed as an evolution of the model developed by Ma Juan in her PhD thesis project: "Modelling the flexibility in the generation-load balance". However, several modifications and improvements have been made to her model. Therefore, the complete model is explained in the next chapter. However, the work performed in the selection of the demand profiles and the wind profiles is original.

### II.3.1 The flexibility analysis model

As has been mentioned before, the assessment of the flexibility requirements of a power system needs to combine the short term operational costs with the long term investment costs in order to achieve the required flexibility in the most efficient way (Figure 10 )

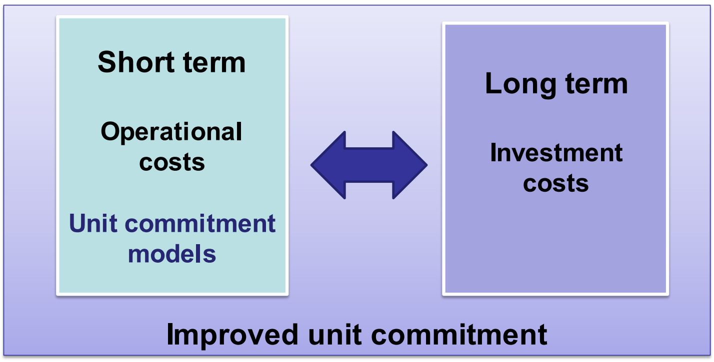



*Figure 10 Optimisation objective of the model*

The short term analysis is usually solved with unit commitment models (UC). There are three main mathematical methods to model this type of problem: Dynamic programming, Lagrangian Relaxation and Mixed Integer Linear Programming (MILP). Dynamic programming was the first method to be invented and has now been superseded. Dynamic programming does not provide a perfect solution because it considers only a subset of the feasible space. Therefore the other methods are preferable. Tao Li and M. Shahidehpour have proven that MILP is faster than Lagrangian Relaxation [5]. Therefore, as it has been made in the vast majority of studies over the last few years ([6]-[16]), the model developed has been implemented using mixed integer linear programming (MILP).

As their name indicates, in linear programming models every function must be linear. Non linear functions can be introduced using piecewise linear segments, losing precision in the final solution. If resolution is critical, the number of segments can be increased. Several methods are used to solve a model made with mixed integer linear programming model: Branch and bound (B&B), branch and cut (a mixture of B&B and the cutting-plane methods) …

To implement the MILP model, Mosel language was employed as writing language and Dash Xpress as solver. The following sections explain the mathematical formation of the model: objective function and main constraints.

#### II.3.1.1 Objective function:

$$min\left\{\sum_{c=1}^{C}\chi(c)*\sum_{t=t_{0(c)}}^{t_{end(c)}}\left(\begin{array}{c}\sum_{i=1}^{I}\big(GC\,(i,t)+AIC(i)*e(i)\big)\\ +G_{wind}^{ct}(t)*W_{ct}C\end{array}\right)\right\} \quad \text{Equation 1}$$

The objective function, Equation 1, minimizes generation costs $GC\ (i,t)$ and the amortized investment costs $AIC(i)$. All costs are multiplied by the corresponding weighting factor $\chi(c)$ of the each considered cluster. Finally, $e(i)$ is a binary variable that indicates whether a unit $i$ has been selected from the available portfolio or not. Finally, the possibility to curtail wind $G_{wind}^{ct}(t)$ is penalized by a cost $W_{ct}C$ which is greater than any of the generation cost of the other generation technologies. This allows the model to curtail wind in situations where too much wind would not permit the model to converge but at the same time avoids too much wind curtailment. This fictitious cost is not taken into account when the generation costs are analysed.

$$GC\ (i,t) = \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{i=1}^{I} G_{sg}(i,t,p) * \ \Delta C\ (i,p) + \ SuC\ (i) + NlC\ (i) \qquad \text{Equation 2}$$

$$AIC(i) = \frac{InvC(i) * \ G^{\max}(i)}{LifeExp(i)} \qquad \text{Equation 3}$$

The generation cost, Equation 2, includes the start up cost $SuC\ (i)$, the no load cost $NlC\ (i)$ and the production cost of each unit, $\Delta C\ (i,p)$ on each of the parts of the piecewise linear approximation. Equation 3 includes the amortized investment cost $AIC(i)$ of the generating units. In order to do so, the investment cost $InvC\ (i) * G^{\max}(i)$ is divided by the life expectancy of the generator $LifeExp\ (i)$.

#### II.3.1.2 System constraints:

$$D(t) = \sum_{i=1}^{I} G(i,t) + \ G_{wind}(t)\ \forall t \in 1,T \qquad \text{Equation 4}$$

The power balance between generation $G(i,t)$ and demand $D(t)$ is considered in Equation 4. Wind generation $G_{wind}(t)$ is separated from the rest of the generation to emphasize that it is not among the available generation portfolio. It could be moved to the left and be considered a “negative demand”.

$$\sum_{i=1}^{I} u_c(i,t) * \left(G^{\max}(i) - G(i,t)\right) \geq Res_{sys}(t)\ \forall t \in 1,T \qquad \text{Equation 5}$$

The reserve requirements of the system are evaluated in Equation 5. The generators’ contribution to reserve is the difference between the maximum power available $G^{\max}(i)$

and the current power output $G(i,t)$ of those units committed $u_c(i,t)$ at the considered instant *t*.

$$Res_{sys} = Res_{gen} + 3.5 * \sigma_{wind} * G_{wind}^{\max} \qquad \text{Equation 6}$$

The reserve requirements $Res_{sys}$ include the possible loss of the largest generation unit $Res_{gen}$ and a "wind factor" which accounts for the uncertainties of wind generation $3.5 * \sigma_{wind} * G_{wind}^{\max}$. The reason and value of this wind factor has been explained in II.2.2.2 .It is important to highlight the value on assessing the requirements of flexibility of this constraint since it forces the commitment of peaking units at peak times to cope with reserve requirements. The greater is the system modelled the lower is the impact of this constraint.

#### II.3.1.3 General generators constraints:

$$e(i) * M \geq \sum_{t=1}^{T} u_c(i,t) \qquad \text{Equation 7}$$

The previous equation enforces that if a unit has not been selected from the generation portfolio ($e(i) = 0$), then it cannot be committed $u_c(i,t)$ at any instant.

In this equation together with the objective function is where the main originality of the model resides. <u>The existence binary decision variable $e(i)$ is the variable that allows the model to decide between the available generators in the generation portfolio</u>.

$$u_c(i,t) * G^{\min}(i) \leq G(i,t) \leq u_c(i,t) * G^{\max}(i) \ \forall t \in 1,T \ \forall i \in 1,I \qquad \text{Equation 8}$$

If a unit has been committed at a certain instant t ($u_c(i,t) = 1$), then its power output $G(i,t)$ has to be between its boundaries $G^{\min}(i)$ , $G^{\max}(i)$. Equation 8 together with the equations described in the Appendix E, model the generation output and the costs associated to the power output at each instant t.

$$G_{wind}^{ct}(t) + G_{wind}(t) = \chi_{wind} * G_{wind}^{available}(t) \ \forall t \in 1,T \qquad \text{Equation 9}$$

As was commented in the objective function, it is necessary to allow for the possibility of curtailling wind in order to allow the model to achieve a solution in situations with high wind penetration. To model this possibility,

#### II.3.1.4 Limits on time working and cooling of the generators

$$u_c(i,t) - u_c(i,t-1) \le u_c(i,t+t1)$$
$$\forall c \in 1, C\ \forall i \in 1, I\ \forall t \in 1, T\ \forall t1 \in 1, \left(T_{Up}(i) - 1\right) \qquad \text{Equation 10}$$

Equation 10 forces that if a unit has started ($u_c(i,t) - u_c(i,t-1) = 1$), then it must be working for the instants of time t1 delimited by time $T_{Up}(i)$.

$$u_c(i,t-1) - u_c(i,t) \le \left(1 - u_c(i,t+t1)\right)$$
$$\forall c \in 1, C\ \forall i \in 1, I\ \forall t \in 1, T\ \forall t1 \in 1\,, (T_{Down}(i) - 1) \qquad \text{Equation 11}$$

Similarly, to Equation 10, Equation 11 ensures that if a unit has stopped ($u_c(i,t-1) - u_c(i,t) = 1$), then it must be cooling for the instants of time t1 delimited by time $T_{Down}(i)$.

#### II.3.1.5 Limits on the ramp rates of the generators

As it happened with the minimum time up and down constraints, the structure of the formulation for ramp up and down constraints are very similar among them.

$$1 - u_c(i,t) + u_c(i,t-1) \le M * \left(1 - aux_{on}(i,t)\right) \forall i \in 1, I, \forall t \in 1, T \qquad \text{Equation 12}$$

$$\left(G(i,t) - G(i,t-1)\right) - R_{up}(i) \le M * aux_{on}(i,t)\ \forall i \in 1, I, \forall t \in 1, T \qquad \text{Equation 13}$$

Equation 12 models that only when the unit has not started, $aux_{on}(i,t) = 1$ it has to follow the ramp up/down constraint. In that case, the output of the unit between two different instants of time t has to be below the ramp limit $R_{up}(i)$.

$$1 + u_c(i,t) - u_c(i,t-1) \le M * \left(1 - aux_{off}(i,t)\right)\ \forall i \in 1, I, \forall t \in 1, T \qquad \text{Equation 14}$$

$$\left(G(i,t-1) - G(i,t)\right) - R_{down}(i) \le M * aux_{off}(i,t)$$
$$\forall i \in 1, I, \forall t \in 1, T \qquad \text{Equation 15}$$

Similarly to the ramp up constraint, only if a unit *i* has not been turned off, $aux_{off}(i,t) = 1$ it has to follow the ramp down constraint. In that case, the output of the unit between two different instants of time t has to be below the ramp limit.

#### II.3.1.6 Simplifications introduced in the model

The next paragraphs show some constraints that could be introduced to increase the accuracy in the modelling of the generators. However, these constraints increased the simulation time making it impossible to achieve results in a reasonable amount of time.

Therefore taking into account that their impact on the final results was not critical, they were removed.

The reserve provided by generators $Res_{gen}(i,t)$ should by limited the ramp rates. This constraint could be modelled as shown in Equation 16. The contribution of each of the generators should be taken into account separately and then added in the reserves constraint. To reduce the impact on the results of the suppression of this constraint, the range between the minimum and maximum generation for base and medium units has been reduced. This modification reduces their contribution to reserves.

$$R_{up}(i) \geq Res_{gen}(i,t)\ \forall t \in 1,T$$
$$u_c(i,t) * \left(G^{\max}(i) - G(i,t)\right) \geq Res_{gen}(i,t)\ \forall t \in 1,T \qquad \text{Equation 16}$$

The possibility to differentiate between standing reserve $StdRes_{gen}(i,t)$, and spinning reserve $SpRes_{gen}(i,t)$, could be taken into account. Since the most flexible generating units (fast) have low heating and cooling times, the main impact of this constraint is on the cost account of the no load cost. The contribution of this constraint could be the optimisation of standing and spinning reserves. The standing reserve provided by a unit that has not been committed ($u_c(i,t) = 0$) would be the available power to be provided at a reasonable amount of time $StdRes(i)$ (Equation 17).The contribution of generators to spinning reserves is the reserve that has already been taken into account (Equation 18).

$$(1 - u_c(i,t)) * StdRes(i) \geq StdRes_{gen}(i,t)\ \forall t \in 1,T \qquad \text{Equation 17}$$
$$u_c(i,t) * \left(G^{\max}(i) - G(i,t)\right) \geq SpRes_{gen}(i,t)\ \forall t \in 1,T \qquad \text{Equation 18}$$

#### II.3.1.7 Modifications to the flexibility model because of the clustering simplification

As it has been commented in previous chapters and in the introduction of this chapter, in order to reduce the simulation time and allow for the possibility to model the whole year, the demand of a whole year was modelled using some representative patterns. This subchapter explains the necessary modifications to the constraints to take this into account.

The principal modification that the clustering simplification introduces is that all the constraints that affect other instants of time, instead in taking into account the next day or week, it affects the same cluster that they belong, creating repeatable patterns.

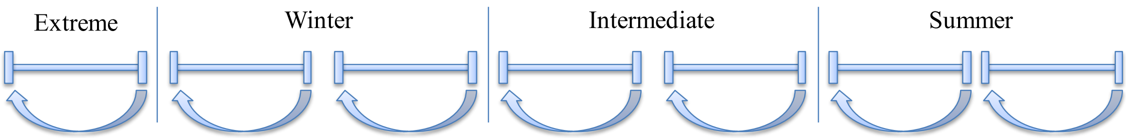



*Figure 11 Clustering approach and its effect on the constraints*

***Minimum time working and cooling of the generators***

The next groups of equations take into consideration the minimum working and cooling time of the generators. Inside of each group, the second and third equations consider that each of the clusters must be a repeatable pattern so the minimum time cooling impacts on the cluster analysed rather than the next cluster. It is easy to understand, that the shape of the groups of constraints is the same in both situations, once the constraint detects that a unit has changed its state, the periods affected are determined by the minimum time parameters.

Equation 19, Equation 20, and Equation 21, evaluate the minimum running time. In every case, if a unit has started $(u_c(i,t) - u_c(i,t-1) = 1)$, then it must be working for the required amount of time $T_{Up}(i)$. The instants of time in each equation change to account that each cluster must be a repeatable pattern.

$$u_c(i,t) - u_c(i,t-1) \le u_c(i,t+t1)\ \forall c \in 1,C\ \forall i \in 1,I \\ \forall t \in (t_0(c)+1), t_{end}(c) - \left(T_{Up}(i) - 1\right), \\ \forall t1 \in 1, \left(T_{Up}(i) - 1\right) \qquad \text{Equation 19}$$

Equation 19 focuses on every instant of time $t$ that is not affected of being close to the boundaries of each cluster $c$.

$$u_c\big(i, t_0(c)\big) - u_c\big(i, t_{end}(c)\big) \le u_c(i, t_0(c) + t1) \\ \forall c \in 1,C\ \forall i \in 1,I\ \forall t1 \in 1, \left(T_{Up}(i) - 1\right) \qquad \text{Equation 20}$$

Equation 20 evaluates the possibility that a generator starts the first time of a cluster.

$$u_c\big(i, (t_{end}(c) - tup1)\big) - u_c\big(i, (t_{end}(c) - tup1 - 1)\big) \\ \le u_c(i, t_0(c) + tup2) \\ \forall c \in 1,C\ \forall i \in 1,I\ \forall tup1 \in 1, T_{Up}(i), \forall tup2 \in 1, tup1 \qquad \text{Equation 21}$$

Equation 21 models the case that a generator starts at the end of a cluster.

In a similar way that the last three equations do, Equation 22, Equation 23, and Equation 24, evaluate the minimum time cooling. If a unit has started $(u_c(i,t-1) - u_c(i,t) = 1)$, then it must be cooling for the required amount of time $T_{Down}(i)$. As it happened before, the instants of time in each equation change to account that each cluster must be a repeatable pattern.

$$u_c(i,t-1) - u_c(i,t) \leq \left(1 - u_c(i,t+t1)\right) \forall c \in 1, C \ \forall i \in 1, I$$
$$\forall t \in (t_0(c)+1), t_{end}(c) - (T_{Down}(i) - 1), \qquad \text{Equation 22}$$
$$\forall t1 \in 1\,, (T_{Down}(i) - 1)$$

Equation 22 focuses on every instant of time $t$ that is not affected of being close to the boundaries of each cluster c.

$$u_c\left(i, t_{end}(c)\right) - u_c\left(i, t_0(c)\right) \leq \left(1 - u_c(i, t_0(c) + t1)\right)$$
$$\forall c \in 1, C \ \forall i \in 1, I \ \forall t1 \in 1, (T_{Down}(i) - 1) \qquad \text{Equation 23}$$

Equation 23 controls the possibility that a generator starts the first time of each cluster.

$$u_c\left(i, (t_{end}(c) - tdown1 - 1)\right) - u_c\left(i, (t_{end}(c) - tdown1)\right)$$
$$\leq \left(1 - u_c(i, t_0(c) + tdown2)\right) \forall c \in 1, C \ \forall i \in 1, I \qquad \text{Equation 24}$$
$$\forall tdown1 \in 1, T_{Down}(i), \forall tdown2 \in 1, tdown1$$

Equation 24 observes the possibility that a generator starting on the final stages of a cluster affects the beginning of the next cluster.

***Ramp constraints of the generators***

As it happened with the minimum time up and down constraints, the structure of the formulation for ramp up and down constraints are very similar among them. Furthermore, it is necessary again to make different equations for the limits of the cluster to take into account the requirement that every cluster must be repeatable.

$$1 - u_c(i,t) + u_c(i,t-1) \leq M * \left(1 - aux_{on}(i,t)\right)$$
$$\forall c \in 1, C \ \forall i \in 1, I, \forall t \in (t_0(c)+1), t_{end}(c) \qquad \text{Equation 25}$$

$$\left(G(i,t) - G(i,t-1)\right) - R_{up}(i) \leq M * aux_{on}(i,t)$$
$$\forall c \in 1, C \ \forall i \in 1, I, \forall t \in (t_0(w)+1), t_{end}(c) \qquad \text{Equation 26}$$

Previous equations show the ramp up constraint for periods not affected by boundaries of the clusters.

$$1 - u_c\big(i, t_0(c)\big) + u_c\big(i, t_{end}(c)\big) \leq M * \Big(1 - aux_{on}\big(i, t_0(c)\big)\Big)$$
$$\forall c \in 1, C\ \forall i \in 1, I$$
Equation 27

$$\Big(G\big(i, t_0(c)\big) - G\big(i, t_{end}(c)\ \big)\Big) - R_{up}(i) \leq M * aux_{on}\big(i, t_0(c)\big)$$
$$\forall c \in 1, C\ \forall i \in 1, I$$
Equation 28

To take into account the consideration that the pattern must be repeatable, the ending instant must be the beginning of the next pattern.

$$1 + u_c(i, t) - u_c(i, t - 1) \leq M * \Big(1 - aux_{off}(i, t)\Big)$$
$$\forall c \in 1, C\ \forall i \in 1, I, \forall t \in (t_0(c) + 1), t_{end}(c)$$
Equation 29

$$\big(G(i, t - 1) - G(i, t)\big) - R_{down}(i) \leq M * aux_{off}(i, t)$$
$$\forall c \in 1, C\ \forall i \in 1, I, \forall t \in (t_0(c) + 1), t_{end}(c)$$
Equation 30

Previous equations show the ramp down constraint for periods not affected by boundaries of the clusters.

$$1 + u_c\big(i, t_0(c)\big) - u_c\big(i, t_{end}(c)\big) \leq M * \Big(1 - aux_{off}\big(i, t_0(w)\big)\Big)$$
$$\forall c \in 1, C\ \forall i \in 1, I$$
Equation 31

$$\Big(G(i, t_{end}(c)\ ) - G\big(i, t_0(c)\big)\Big) - R_{down}(i) \leq M * aux_{off}\big(i, t_0(c)\big)$$
$$\forall c \in 1, C\ \forall i \in 1, I$$
Equation 32

Similarly to the ramp up constraint, to take into account the consideration that the pattern must be repeatable, the ending instant must be the beginning of the next pattern.

$$u_c(i, t_0(c)\ ) = \ u_c\big(i, t_{end}(c)\big)\ \forall c \in 1, C\ \forall i \in 1, I$$
Equation 33

Finally, to ensure that each cluster is a repeatable pattern, the previous constraint introduces a link between the commitment states $u_c(i, t)$ of the generators on the boundaries of each cluster ($t_0, t_{end}$).

### II.3.2 Modelling demand

Currently, the technology of personal computers does not allow running a UC during long periods of time because of the excess of variables and constraints. Usually, this kind of problem is analysed with a scope of one or two weeks for systems with several generators. Since modelling a whole year is necessary, it is required to simplify the problem to reduce the computational burden. Clustering techniques are one of the methods used to model a group of observations by some representative patterns or clusters. Figure 12 shows an example of the results achieved with these techniques.

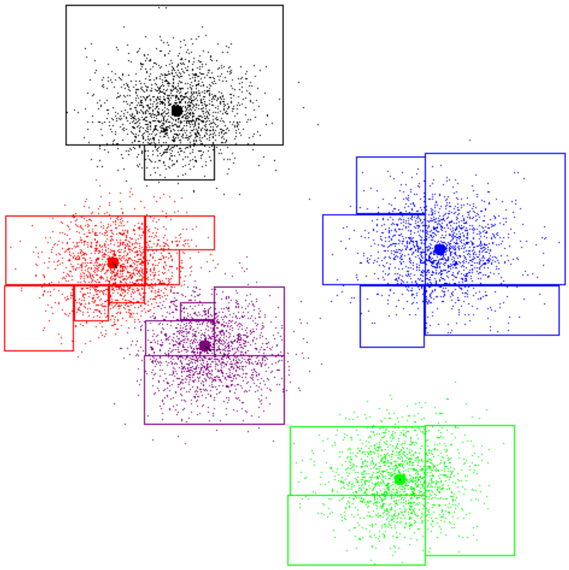


*Figure 12 Example of the results achieved with Clustering techniques [30]*

In this project, the demand of the customers of a power system is modelled with clustering techniques. There are two cyclical periods in the load profile that can be used as “observations” to model the whole year data: days and weeks. In this situation, modelling the complete year by some representative weeks is preferable because the constraints on minimum time running and cooling of the generating units have a similar order of magnitude than a day. For example, some generators have cooling times about 8-10 hours, which are enough to impact on more than one day.

In power systems, there are several clustering algorithms that are employed to model load patterns. Some of them are: K-means, Kohonen’s Self-Organized Maps (SOM), and the two-level approach, i.e. SOM applied two times. Among these, the most employed is the K-means algorithm because of its simplicity. In the comparison between this method and the other two possibilities it has been proven by other authors, that the two-level approach is the most efficient to model load in power systems. The selected patterns have more dispersion and more significance, i.e. less distance to the patterns they represent. However, this algorithm has a slight improvement from k-means [29]. On the other hand, k-means has the advantage of having a clear geometrical and statistical meaning and the disadvantage of being sensible to outliers.

Due to this reasons, in this project the k-means algorithm has been chosen to select the patterns that are going to model the whole year. Regarding the outliers issue, there are going to be chosen only a few patterns so the impact on each of the final clusters is going to be negligible if each cluster is sufficiently representative of the sample, i.e. represents several observations. Furthermore, in addition to the selected clusters, it is an extreme situation will be analysed. With this improvement, the model should guarantee that the final decision on the generation portfolio and other flexibility resources will be able to handle not only the average situations, but also the most stressful ones.

It is important to mention that there are some other possibilities to carry out this simplification such as fuzzy k-means, or Hidden Markov Models [6]. They have not being considered because they imply performing the analysis in a stochastic manner, which could be considered in further improvements, but not in the development stage of this project.

#### II.3.2.1 K-means algorithm

As was mentioned before, the objective of the clustering algorithms is modelling a group of observations by some representative patterns clusters. Generally, a good clustering algorithm provides patterns with two characteristics:

- The clusters have the maximum dispersion among them, i.e. they are as different as possible so each one models different possibilities.
- The chosen patterns must be very representative of all the data so the difference between them must be as lowest as possible.

$$min\left\{\sum_{k=1}^{K}\left(\sum_{i=1}^{I} Distance\big(x(i,k),c(k)\big)\right)\right\} \qquad \text{Equation 34}$$

Therefore, the objective on the K-means algorithm, Equation 34, is finding the requested number of clusters, $c(k)$ that minimize the sum of the distances between each observation $x(i,k)$ and the cluster $c(k)$ that it belongs. Therefore, this method focuses on the second objective mentioned above. The distance that is mentioned is the Euclidean distance. Consequently, the final cluster is the average of the observations that it represents.

More precisely, in this project the observations are each of the days of the year that is analysed, and the clusters are the days that are going to be chosen to represent the whole year. It would be preferable to use weeks but the use of weeks as observations increases exponentially the simulation time and makes it impossible to observe several cases and to perform a sensitivity analyses. However, Appendix C shows the results achieved with weeks to show that the procedure is valid and the results are interesting.

Because of its simplicity, the K-means algorithm that is embedded in the statistics toolbox of Matlab has been used. Starting from the required number of patterns as initialization, it works as follows:

First of all, some observations are chosen randomly. These are going to be the first patterns that are going to be employed through an iterative process. Then it proceeds following two iterative phases:

*"The first phase uses batch updates, where each loop consists of reassigning points to their nearest cluster centroid, all at once, followed by recalculation of cluster centroids. The batch phase is fast, but potentially only approximates a solution as a starting point for the second phase.*

*The second phase uses online updates, where points are individually reassigned if doing so will reduce the sum of distances, and cluster centroids are recomputed after each reassignment. Each loop during the second phase consists of one pass though all the points. The second phase will converge to a local minimum, although there may be other local minima with lower total sum of distances. The problem of finding the global minimum can only be solved in general by an exhaustive (or clever, or lucky) choice of starting points, but using several replicates with random starting points typically results in a solution that is a global minimum"*[2].

To summarize what the k-means algorithm of Matlab does, it finds the representative patterns starting from random patterns. Then, the selections are improved by an iterative procedure of assigning observations to the patterns and modifying the patterns using the linked data. This procedure converges to a local minimum but does not guarantee the global minimum. The model should be executed several until a good result is reached.

Figure 13 shows an example of the results achieved with this methodology. The complete results achieved by applying this procedure to the demand profile of a year with patterns of days are showed in Appendix B. Regarding that it would be better to analyse weekly profiles to observe the impact of the dynamic constraints of the generators, Appendix C shows the results applying the same method for weeks.

[2] Text extracted from Matlab help statistics chapter, [31].

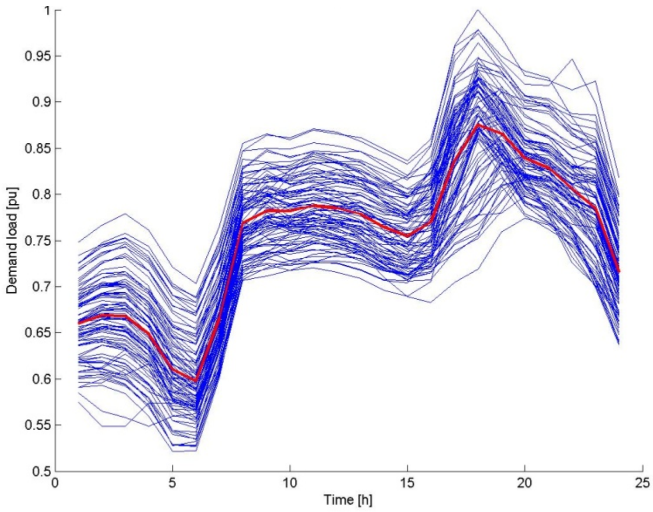



*Figure 13 Example of a daily pattern and the daily load profiles assigned to it.*

### II.3.3 Modelling wind

This chapter explains the procedure followed to select the wind profiles that model wind generation. It has been selected a wind profile for each of the demand profiles that were obtained with the method appointed in previous chapter.

As was mentioned before, one characteristic of wind generation (WG) is the hourly variability. This increases the flexibility requirements because more fast units are required to maintain the balance under control. The variability of WG is closely related with the location of the wind farms. The greater is the geographical distribution of the wind farms, the lower is this factor. Therefore, the interconnection between different power systems powered by different wind reduces WG variability and so the flexibility requirements. There are several projects in progress to interconnect different systems with HVDC (Figure 14). In the nearly future, with further penetration of renewable energies, high voltage interconnections based on HVDC will increase and probably an upper level of voltage in DC will interconnect the whole Europe.

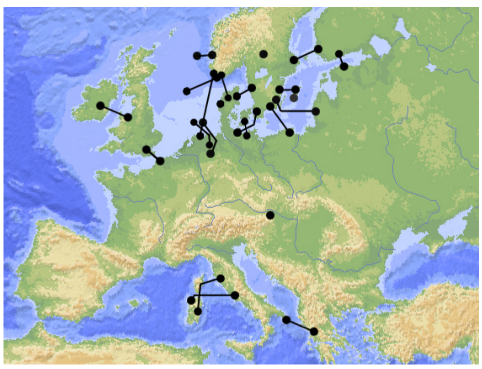


*Figure 14 HVDC projects in progress ABB.*

Regarding the tools that are available for this study, it was decided that, as a first approach, every aspect would be modelled in a deterministic approach, especially wind generation. On further evolutions of this research project, it would be interesting to account the effect of stochastic modelling of wind instead of using a constant approach on reserve requirements.

The first approximation was trying to repeat the successful modelling of the whole year by some representative patterns obtained with deterministic clustering techniques. Because wind generation is independent of workdays and weekends, the focus was finding some representative daily patterns. The results prove that this methodology is not valid (Figure 15 and Figure 16). There is not any seasonally correlation between the clusters and the assigned observations (Figure 15). Furthermore, Figure 16 shows that the relationship between the observations assigned to each pattern is almost negligible. Fuzzy clustering (stochastic) might have achieved better results but is outside the scope of this project.

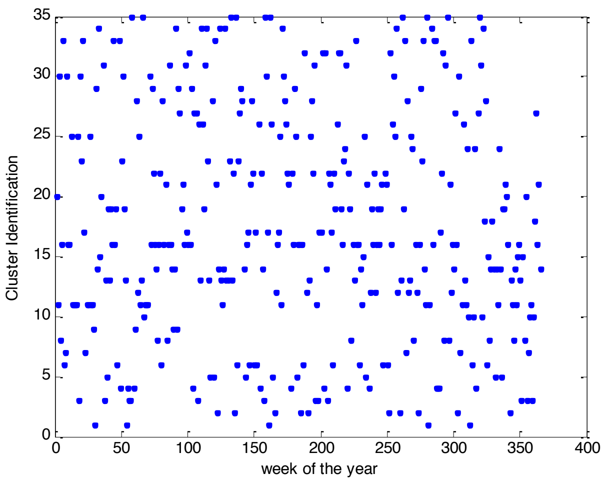



*Figure 15: Assignation of wind generation data to the clusters along the year*

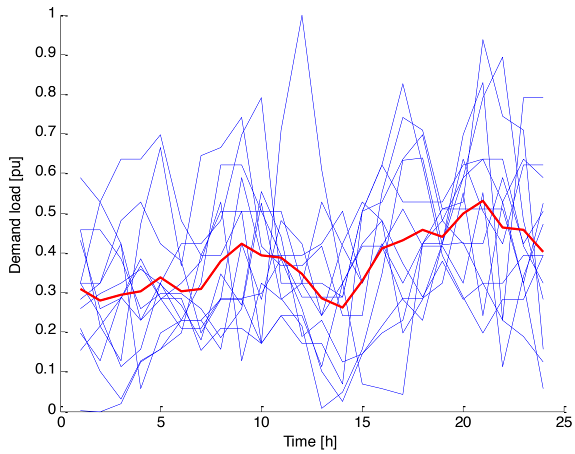



*Figure 16: Example of one cluster and the assigned observations for WG*

Regarding the fact that hard clustering techniques do not work as expected, another approach is required. Since it was impossible to give an accurate model of the year, the most reasonable approach is to look for the worst case scenario to maximize the impact of the wind on the final results.

$$\left(\sum_{t=t_0(obs)}^{t_{end}(obs)-1}\left(\Delta D(t,t-1)-\Delta w_{gen}(t,t-1)\right)^{2n}\right)^{\frac{1}{2n}} \quad n \in \boldsymbol{Z} \qquad \text{Equation 35}$$

The worst case scenario is the wind generation profiles ($obs$) that causes the biggest increase in the variability of the net demand, that is, the difference between the variability of the demand $\Delta D(t,t-1)$ minus variation in the wind generation $\Delta w_{gen}(t,t-1)$. To account the variations disregarding the sign, an even exponent, 2n, was added. The greater is this exponent, the more weight the variations that cause greater ramps have. This feature allows the possibility to choose different wind generation scenarios.

To maintain some relationship with the demand profiles and the clustering simplification, the wind profiles considered for each pattern of the demand are chosen only between the observations of the wind year that happened at the same time as each of the assigned observations of each of the clusters.

Taking into account that modelling the wind in a stochastic manner is not realistic, it has been decided to create two scenarios: a low variable wind (LW) and high variable wind (HW). The first scenario would be suitable to model situations with high wind dispersion and enough interconnection between all the branches of the system and the second scenario would be interesting to model situations with a great correlation between all the wind farms. This second scenario would be closely related to the situation that could happen in small islands with offshore wind farms. Therefore, to select the LW scenario an exponent of 2n=1 was used and to avoid outliers the wind profiles with a capacity factor greater than 70% or lower than 10% were discarded. On the other hand, the HW scenario has been selected with an exponent of 2n=8 and without removal of outliers.

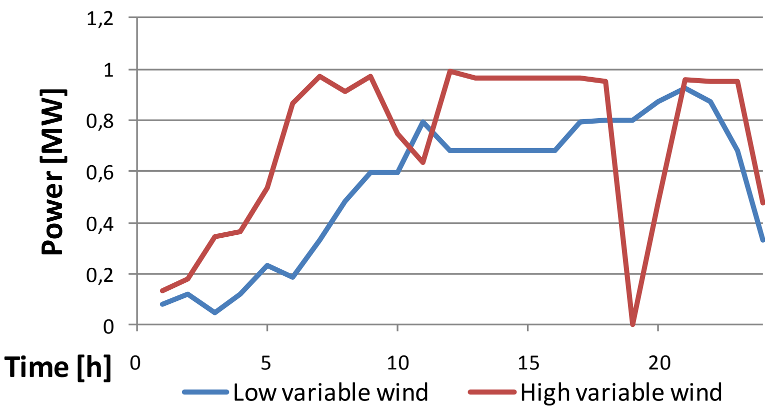



*Figure 17: Comparison of low and high variable wind scenarios, winter work day.*

Figure 17 shows an example of the wind profiles selected with the method developed. The method separates adequately scenarios with high variation and low variation.

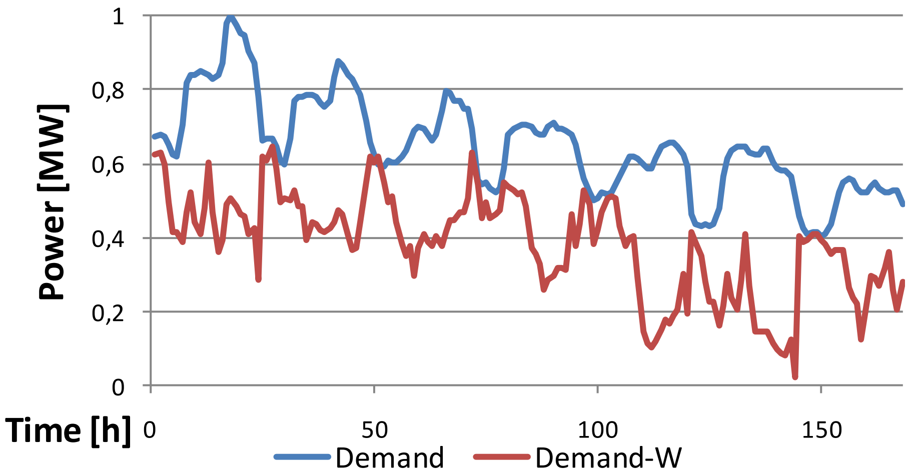



*Figure 18: Effect of the wind generation on the load profile for LW scenario.*

As Figure 18 shows, the final selected wind profiles increase the differences between peak and off peak periods of the net demand that must be supplied by the conventional generation. Taking into account the main reason to analyse the impact of the wind on flexibility requirements in the generation schedule, this “Worst Case Scenario” should provide a good observation of the effect of WG.

## II.4. Results

The analysis of the results shows the breakdown of the costs with a low wind scenario and a comparison between the low wind scenario and a high wind scenario.

### II.4.1 Low variable wind scenario

The following figures show the results derived from the model regarding the selection of the generation portfolio (CAPEX) and the generation schedule (OPEX) for a progressive integration of wind generation with low variability.

The different wind penetration degrees have been marked as W0.X where the “X” means the energy supplied by wind generation from the total energy that is required by the demand. For example, “W0.1” means 10% of the energy supplied by wind; “W0.3” means 30% and so on.

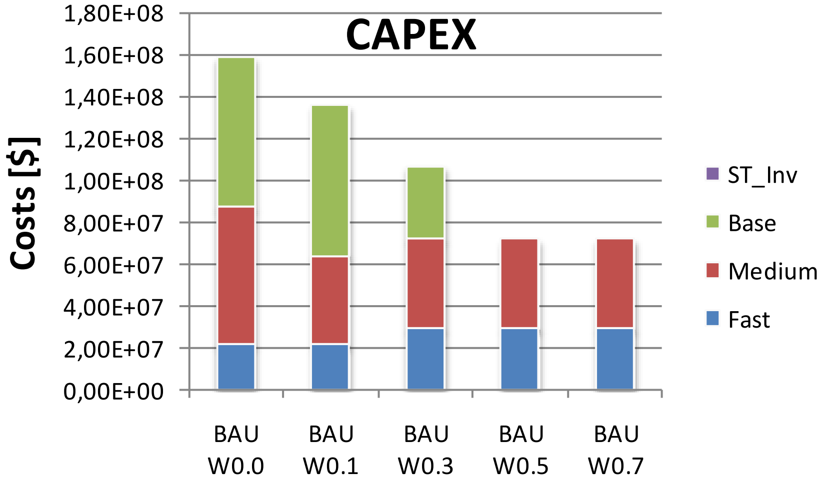



*Figure 19: Breakdown of CAPEX costs for BAU scenario, low variable wind*

As was expected, the introduction of wind generation reduces and removes base generation because of the impossibility to recover the investment costs.

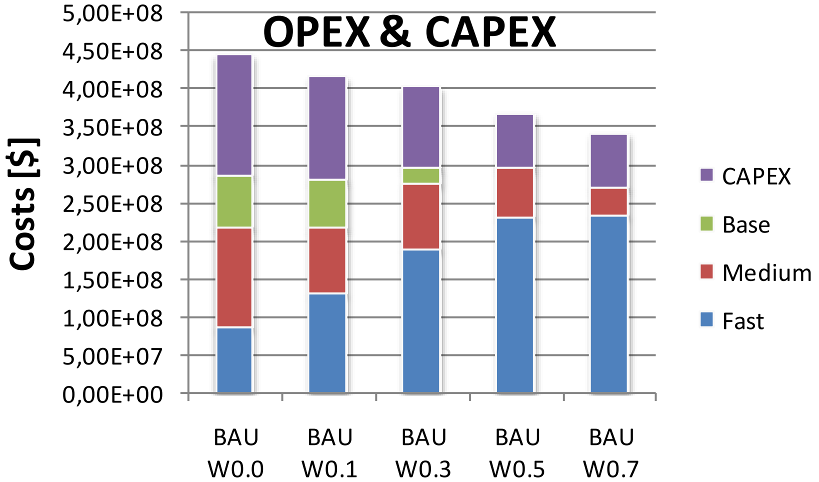



*Figure 20: Breakdown of costs OPEX costs, BAU scenario, low wind variability*

As the degree of penetration of wind generation (WG) increases, the energy produced by fast generation increases and so the operational costs. Furthermore, wind generation reduces the overall costs because less energy needs to be supplied. Probably, if wind investment costs are taken into account, the profitability wouldn`t be clear.

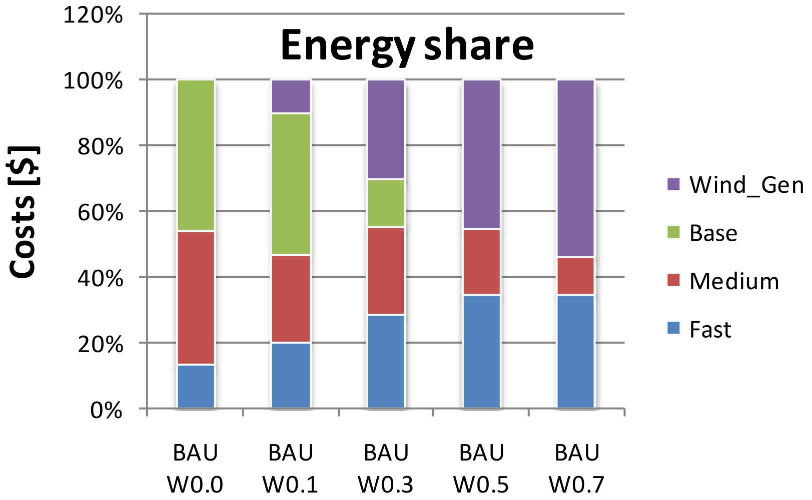



*Figure 21: Energy share, BAU scenario, low wind variability*

Additionally to the previous results, it can be seen that the wind curtailment is considerable for the scenario of 70% of wind generation. This indicates that there is a limit of wind that the system can handle without external resources.

### II.4.2 Comparison between low and high variable wind scenarios

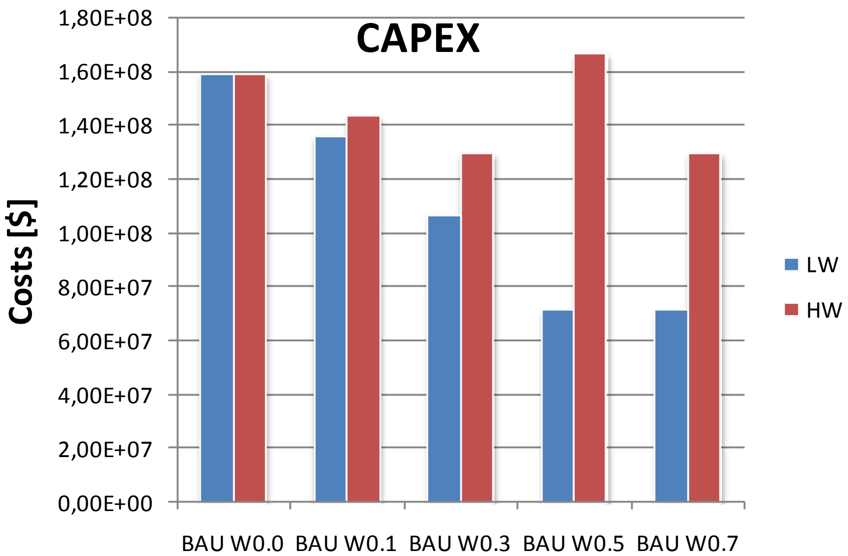



*Figure 22: Comparison of CAPEX costs, low and high variable wind. BAU scenario*

Figure 22 shows that the increase in wind variability clearly raises the investment cost. This trend increases with the energy share of the wind.

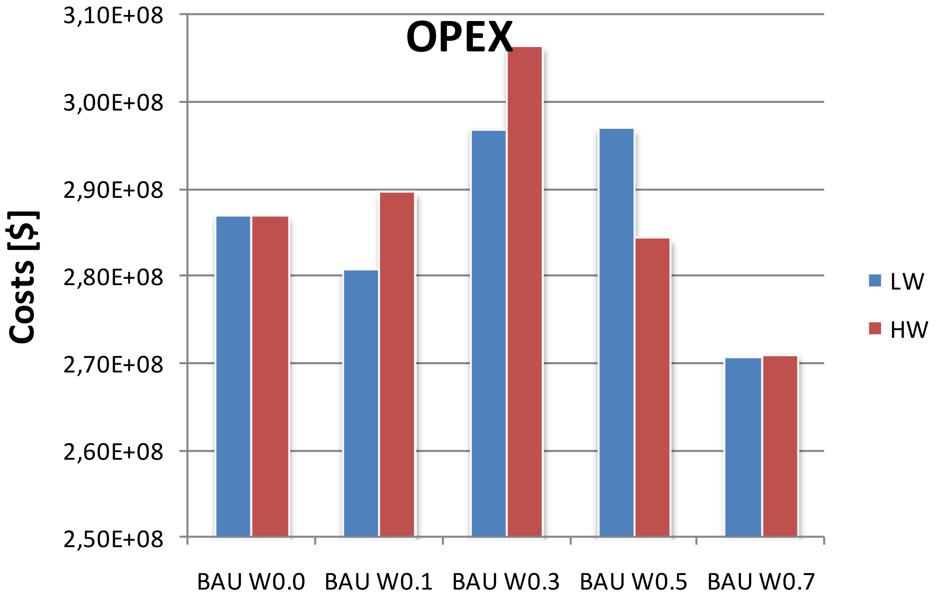



*Figure 23: Comparison of OPEX costs, low and high variable wind, BAU scenario.*

Focusing on the operational costs, there is not too much difference between the low and the high wind scenarios. It can be concluded that, once the portfolio is optimal for a certain scenario, the generation costs do not vary because of the wind variability.

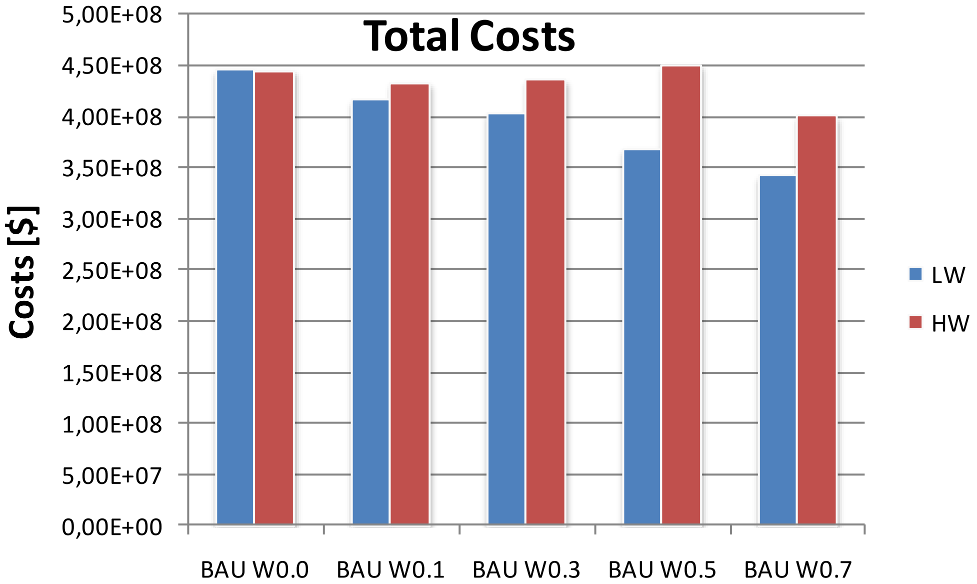



*Figure 24: Comparison of total costs, low and high variable wind, BAU scenario.*

Regarding the total costs, it is clear that an increase in the wind variability increases the overall costs, and therefore, it should be avoided using other external flexibility resources. Furthermore it is clear that with high wind variability the flexibility requirements due to high wind penetration make the system unprofitable.

## II.5. SUMMARY AND CONCLUSIONS

This chapter started analysing the impact of wind generation (WG) on power systems. From a general approach, the analysis of the investment cost and the generation schedule showed that the effect of wind generation was the reduction of base generation and an increase in fast and expensive peak generation.

A formal method to analyse more precisely the overall impact of WG has been presented. This method consists of an analysis planning tool based on an enhanced unit commitment and performed with MILP; an approach to simplify the demand profile of a whole year; and a mechanism to select the most representative wind profiles to observe the progressive impact of wind generation.

Finally, the analysis of the results confirmed that wind generation reduced and finally removed the utilization of base generation. If more wind generation is introduced in our power systems more flexibility will be needed to maintain the current level of base generation. Furthermore, this trend increases with wind variability, so a high transport capacity will be needed to maintain all the system connected and reduce this parameter.

# III. CONTRIBUTION OF STORAGE TO FLEXIBILITY IN POWER SYSTEMS

## III.1. INTRODUCTION

One of the main issues in power systems is that the energy required by the demand needs to be supplied almost instantly. This makes power systems inefficient because it is necessary to schedule generation out of its optimal spot to maintain the equilibrium between generation and demand at a reasonable security of supply. If electrical energy could be easily stored, this problem would be solved by saving energy at low load periods and returning it when necessary. However, apart from pumped hydro, storage has not been massively introduced in power systems because its profitability is not clear. The difference in the price of the generation cost (marginal cost) between high and low demand periods is not sufficient to recover the investment costs.

The introduction of wind generation (WG) in power systems has two main impacts on the generation profile that require further flexibility in power systems:

First of all, the difference between the load at peak and off peak periods that is supplied by conventional generation increases because there is proportionally more wind generation at off peak hours than at peak hours. This growth in the difference between required generation at peak and of peak periods with a further penetration of wind generation could justify from the point of view of costs the introduction of storage. Furthermore, storage could absorb the fluctuations of wind generation and reduce the requirements for fast and expensive units to cope with them.

Secondly there is an increase in the reserve requirements of the system due to the uncertainties on the forecast of WG. To cater with this problem, some generating units are operating at less than their optimal output to be ready to cover the possibility of a sudden loss of several megawatts of wind generation. However, storage technologies could provide this service to the power systems as a complement to their normal functioning because they have enough speed to response to these variations.

Because of these reasons, it is necessary to assess and clarify the possible contribution of storage of electrical energy to the flexibility in power systems from the point of view of the progressive penetration of wind mills.

***Outline of the chapter***

This chapter starts analysing the different possibilities to store electrical energy to get a decision about which ones should be considered. Then, it is presented how storage has been analysed by other authors. The improvements added to the tool that was explained in the chapter II to model storage are explained in the subchapter. Finally the results are discussed.

## III.2. STORAGE TECHNOLOGIES CHARACTERIZATION

There are several technologies capable to store electrical energy. Among all of them, only those that are capable of providing massive energy storage (MES) are interesting for this analysis. In order to affect the final generators portfolio and the schedule of generating units, it is necessary to be able to save great amounts of energy, at least enough for several hours.

Currently, as it can be seen on Figure 25, the technologies suitable for MES applications are principally: pumped hydro storage (PHS), compressed air energy storage (CAES) and battery energy storage systems (BESS). All of them are capable to store energy for about 10 hours at an important rated power (more than 10 MW). The other technologies that would allow storage, such as, fly wheels, super capacitors or superconducting magnetic coils (SMES) have interesting applications at the regulation level. However, they are not suitable for MES applications because they are not capable to save enough energy.

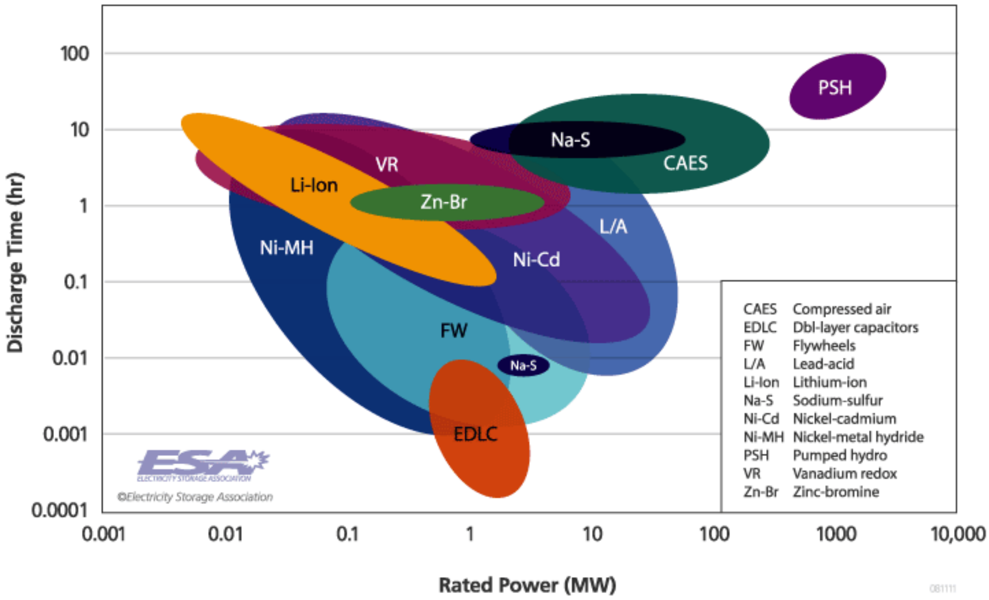



*Figure 25 Discharge time and rated power comparison of storage technologies [36]*

#### III.2.1.1 Pumped Hydroelectric Storage (PHS)

Among the massive storage technologies PHS is the most common and developed. It consists on storing energy with the shape gravitational potential energy. In order to do so, water is pumped from a low reservoir to an upper reservoir. When the energy is required, the facility generates power in the same way as hydroelectric plants do, the control valve is opened and the flow of water moves the turbines to generate electricity. In some occasions a PHS facility is a typical hydroelectric power plant that has reversible turbines which add the capability of pumping water.

To build this type of storage facility, there are several natural geological features needed. Among them it is remarkable the requirement of having adequate close land areas divided by a considerable elevation. Also it is necessary an adequate water supply. In some cases the lower reservoir is the ocean and sea water is used.

PHS is a demonstrated technology for electrical energy storage. There are about 80 GW of power installed of this technology worldwide. Furthermore, the majority of suitable locations have already been built in the developed world. Because of the difficulties of finding suitable locations, it is only expected further investment in this technology in developing countries.

Since this is a very important storage technology, the model that has been developed contemplates the possibility of analysing it. However, taking into account that the possibility to build more facilities is limited and the simulation time is a critical issue in this model, the results showed do not contemplate this technology. In future developments with an improvement on the simulation time, clearly this is one of the technologies that should participate.

#### III.2.1.2 Compressed Air Energy Storage (CAES)

These facilities store energy by compressing air and saving it in a cavern, usually located underground. To deliver back the power, compressed air is mixed with natural gas and combusted before the expansion in a turbine to generate electricity. More specifically, the compressor in the thermodynamic cycle of a combined cycle gas turbine (CCGT) is employed to store energy. The stored compressed air replaces the first compression stage of the normal cycle. The typical schematic of the configuration of a CAES facility can be addressed on Figure 26. It is very important to highlight that CAES is not a pure energy storage technology because it requires burning gas to return the energy stored.

CAES facilities improve the operation of combined cycle gas turbines (CCGT) by changing the source of energy used to compress air from the fuel (66% of the gas) to off peak electricity. To get an idea of the average operation, for every 0.72 MWh of electricity and 4.4 Mbtu of gas (1.37 MWh*)*, the plant will provide 1 MWh of electricity ([38], [39] and [40]). Furthermore, the flexibility of the facility improves as it is required less time to start working from the cool stage.

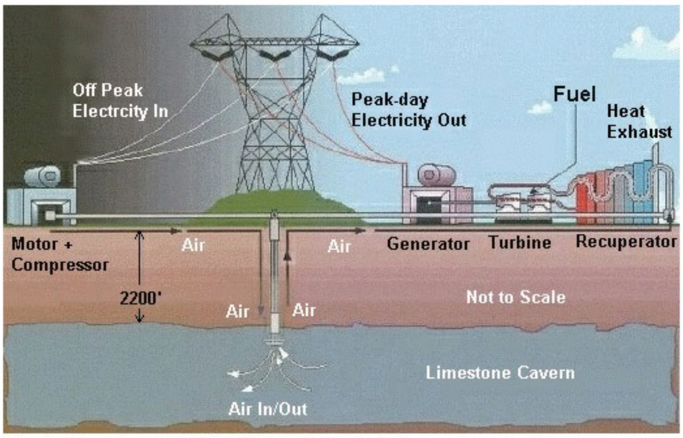



Photo Courtesy of CAES Development Company

*Figure 26 Example of the configuration of a CAES plant [36]*

There are two types of CAES, adiabatic and diabatic regarding how the heat is managed after compression process. In diabatic CAES the air is cooled before it is stored and reheated before the return to the thermodynamic process. On the other hand, in adiabatic CAES, the heat energy that was lost in the other type is saved and used to reheat the air. The second type of plants is under development and is expected to have higher efficiency and lower $CO_2$ emissions.

On the other hand, it is a technology not very developed. There are only two facilities worldwide: Germany (290MW, 1978), Alabama (110MW, 1991). There is a plant in construction in Ohio of 2700MW [36].

The importance of this technology is the association with CCGT or combined heat and power (CHP). These technologies had an important growth along the world during the last decade and are currently one of the main sources of electrical energy. However, as it happens with PHS, this type of facilities can be built only in certain locations. The position of the power plant must be suitable to build a cavern to store compressed air. This requires certain characteristics of the grounds close to the power plant. The contour of the cavern is materials that have a low permeability to air, among them, the most common is salt.

To sum up, the main characteristics of CAES which make it interesting are: I) High thermal efficiency. II) High flexibility: It can be dispatched when needed if there is compressed air left in the storage. III) It has a very quick response, so it is suitable provide ancillary services. On the other hand it has some disadvantages: I) it can only be built in specific locations. In countries with big penetration of CCGT it would be an upgrade to an existing plant. II) Despite it is an improvement to other technologies, it does not solve the problem about CO2 emissions. However, taking into account that some (flexible) thermal generation is required, currently is one of the best solutions.

For the same reasons as PHS, the model contemplates the possibility to introduce CAES but the results showed do not use this technology to reduce the simulation time. In future developments this is other technologies that should participate on the mix.

#### III.2.1.3 Battery Energy Storage Stations (BESS)

When referring to massive storage applications, the leading technology is the storage based on Sodium-Sulphur (Na-S) batteries. The main advantage of this technology is that it is manufactured from inexpensive materials. Furthermore, it has good closed cycle efficiency (about 80%) and a long life cycle. On the other hand, it operates at a high temperature (300 to 350°C) and its main materials are highly corrosive. Because of all these reasons, this technology is meant for large scale (massive), and static applications, therefore is adequate for BESS.

More specifically, Na-S battery consists of a positive electrode made of sulphur, a negative electrode made of sodium, and as conductive separation of both electrodes: Beta alumina of sodium-ion. In this type of battery the electrodes are liquid and its separation is solid.

Several demonstration projects have been carried out on this technology: There were about 55 installations of this type of technology worldwide (EPRI 2003), being the main one at Charleston (2005, 1,2MW 7,2MWh). Furthermore, American Electric Power has set the goal of having 1000MW of this type of storage in the system over the next decade [7]. The main manufacturer of Na-S batteries for BESS is NGK Insulators, Ltd.

Until the moment, this technology continues being at the demonstration stage and has not been massively adopted to store big amounts of electricity because the expected earnings are not enough to recover the investment. Perhaps, when the possibility to provide ancillary services is taken into account this technology would reach the cost-effectiveness.

On the contrary of previous possibilities, this technology has the main advantage of not being constrained by the characteristics of the location. In fact, one of the hot topics in research regarding storage in power systems is the optimisation of the location of this type of facility in the grid. On the other hand, it is more expensive than the previous ones.

#### III.2.1.4 Non massive storage technologies:

**Flywheels:** This technology consists of an inertia disc suspended in electromagnetic fields in vacuum to avoid friction. It stores energy by increasing the rotation of the disc. To return the kinetic energy, the disc is connected to an electrical generator which, through a power electronic stage, makes the transformation to electrical energy. The energy stored in a flywheel is proportional to the inertia of the rotating accumulator. The same works for the rotation speed, but with a quadratic relationship. This gives the hint of the two types of flywheels that exist: ones focused on having with big inertia, and the ones with great rotation speed. The main advantage of this technology is that it provides inertia to the frequency in the system, and therefore is suitable for spinning reserve services. Furthermore, it is not as sensible to the temperature as the other technologies. However the cost of reaching great storage capacity is not yet affordable because of the magnetic suspension and the materials required for enduring the centrifugal forces. Also, there is a risk of explosion if the flywheel is overloaded.

**Super Magnetic Energy Storage (SMES):** This technology works storing energy in electromagnetic fields. More specifically, it uses superconducting coils to store energy in the shape of direct current (DC) flowing by the coil. Therefore, it has a power electronics stage to transform AC to DC as it is done with BESS. It has a high response capacity and a very low round trip efficiency (3-5%). This makes this technology very adequate for ancillary services. However, the coil needs to be cryogenically cooled below the superconducting temperature. Furthermore, the cost of the superconducting wires makes it unprofitable.

**Super Capacitors**: It consists in capacitors whose technology has improves the energy density of an electrolytic-based capacitor by hundreds of times. The main advantages are high life cycles (about millions of times) and fast rates of charge and discharge. Therefore, this technology could be useful to store and produce energy in situations that require high power but not too much energy such as, primary regulation. The main disadvantages compared to the batteries are the requirement of a voltage control system (voltage droops during discharge) and higher self discharge ratio.

Because of its advantages on the introduction of renewable generation and the performance of the system the research in new storage technologies is a very active field. For example, it is common to hear about improvements in batteries technologies. Another example that has been lately released is the possibility to store energy in the shape of compressed air in the oceans floor. This method would be easily related with offshore wind farms.

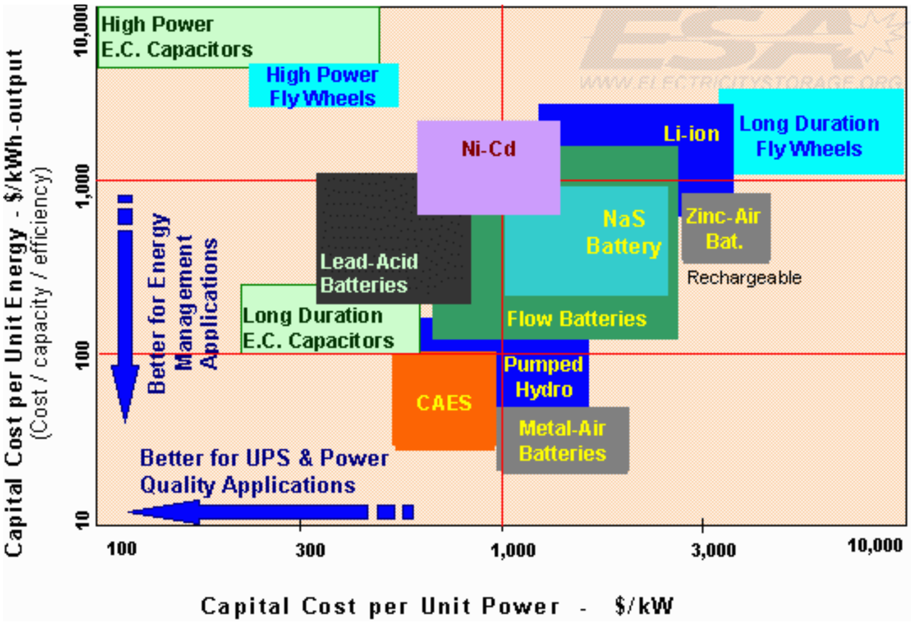



*Figure 27 Power and Energy comparison of specific costs of Storage Tech [36]*

Finally, to conclude the analysis of the storage technologies, it is important to observe the investment costs. As it can be addressed on Figure 27, among the technologies that are available and commercial, CAES and PHS would be the most interesting technologies. However, they are constrained by the conditions of their location so they cannot be deployed as it is necessary. Therefore, it is important to consider Sodium-Sulphur BESS.

## III.3. Contribution of storage to power systems

This project focuses mainly on the impact on the generation portfolio and the generation schedule of the selected generators taking into account the reserve requirements of the system.

### *Portfolio selection and schedule*

The analysis of the effect of wind on the load duration curve showed that WG reduced base generation because the amount of power that is continuously demanded during the whole year decreased and therefore, these units could not recover the investment costs. As Figure 28 shows, the introduction of storage increases the load in off peak periods so more base generation can be committed.

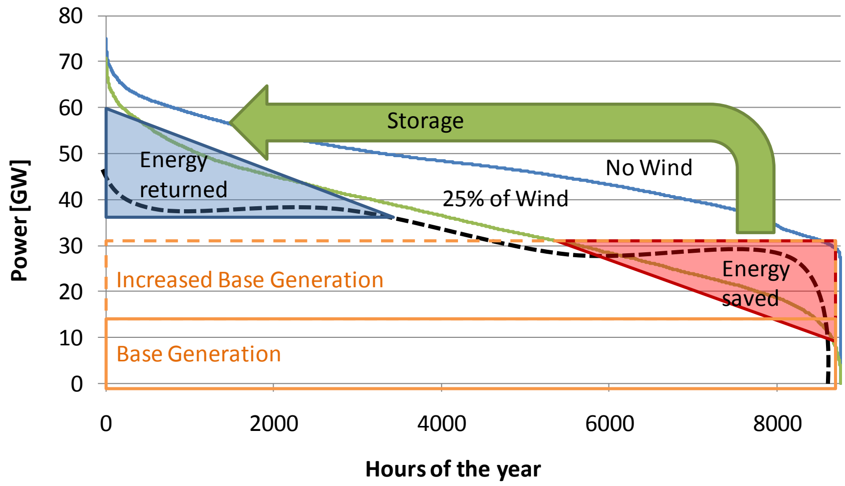



*Figure 28 Impact of storage on the load duration curve with wind*

A similar result happens regarding the schedule of storage. The energy stored must be sold at the highest price on the electricity market. Therefore it displaces the commitment of the most costly generation.

Focusing on wind generation, in high production situations, storage is a possible solution to save the energy produced, and avoid excess of generation and null prices in the electricity market. With further degrees of penetration of wind generation, a greater investment in transmission lines would be required to transport all the energy from the production centres to the location of the storage facilities.

When observed in the extreme situation in which storage would be very cheap and with a perfect efficiency, the final shape of the load profile and the generation would be perfectly flat. This is easily demonstrable by reduction to absurdity: if it not were flat it would not be the optimal solution because it would be profitable to buy energy when load is below the average and sell it when it is bigger.

### *Storage providing tertiary reserve services*

As was explained in the chapter II.2.2 from economical point of view only the tertiary reserves are considered in the schedule of the generation. In the United Kingdom and other electricity systems, tertiary reserves are divided between Spinning reserves and Standing reserves. Spinning reserves are provided by the generation that are already connected to the system and provide rotating inertia. Because of this reasons, a minimum amount of reserve must be provided by unit capable of providing spinning reserve to maintain the reliability of the system. On the other hand, standing reserve accounts for the generation that can be committed in less than 15 minutes but is not already synchronised.

Therefore, the storage technologies can be classified by the capacity to provide these services:

- Spinning reserve: **PHS, CAES**, and Flywheels.
- Standing reserve; **Batteries**. SMES and Ultra capacitors.

## III.4. LITERATURE REVIEW

Once the technologies interesting for storage on the level of generation scheduling and flexibility are clear, it is important to know what other researchers have done before explaining the models that has been elaborated.

To solve specifically the problem of wind fluctuations, some references have analysed the synergies between wind and storage. Some of them analyse the problem from a general point of view [6], other more focus on a certain technology such as PHS [10]-[14], CAES [15]-[16] or BESS [17].

When analysing storage, most of the authors have focused on pumped hydro storage (PHS). Among these studies, A. Tuohy and M. O'Malley in [14] state that when investment cost in PHS is taken into account, this technology is only price effective with large penetration of wind. E. Castronuovo and P. Lopes in [11] have focused on the interaction of wind and storage on the day a head market in order use storage as a way to cope with the uncertainties and meet the expected generation. J Garcia-Gonzalez, in [12] with the same objective as previous, makes a joint optimisation with a stochastic UC model that deals with the uncertainties of wind.

Other important storage technology is compressed air energy storage (CAES). In [15], D. Swider analyses the requirements of flexibility and the results of employing this type of storage. The main conclusion is that CAES is able to provide the required management and allows further penetration of wind. Besides, it is interesting [16], in which a security constrained unit commitment model shows that CAES would reduce the overall cost.

Furthermore, with the progressive development in batteries technology and reduction in costs, it is growing the interest in battery energy storage systems (BESS). These facilities could provide both energy storage and ancillary services. However, they not seem to be cost effective yet [17].

It is important to highlight that this work introduces a new approach to the work performed in the previous works because none of them has focused on the flexibility requirements or the impact of wind in the portfolio of generators. Furthermore the approach that has been proposed to model use a unit commitment as a planning tool is also new. On the other hand, the modelling of storage is very similar because it is based on the same procedure and there is not any improvement to be made.

## III.5. MODELLING STORAGE

### III.5.1 Modifications and additions to the flexibility model

This section explains how modelling storage impacts on the constraints explained in previous chapters (chapter II.3.1). The new factors from the base model have been highlighted in bold. Furthermore, the specific constraints to model storage are showed.

***Changes in the objective function:***

$$min\left\{\sum_{c=1}^{C}\chi(c)*\sum_{t=t_{0(c)}}^{t_{end(c)}}\left(\begin{matrix}\sum_{i=1}^{I}\big(GC\ (i,t)+AIC(i)*e(i)\big)\\ +G_{wind}^{ct}(t)*W_{ct}C\end{matrix}\right)+\ \boldsymbol{SIC}\right\} \quad \text{Equation 36}$$

The inclusion of storage requires the addition of Storage investment costs ($SIC$) to the generation cost $GC(i,t)$ and the amortised investment cost $AIC(i)$ in the objective function. The existence binary variable $e(i)$ indicates if a unit has been included or not.

$$SIC=\sum_{j=1}^{S}\frac{EInvC(s)*E_{ST}^{max}\ (s)}{LivePeriod_{st}(s)}+\sum_{j=1}^{S}\frac{PwInvC(s)*Pw_{ST}^{\max}\ (s)}{LivePeriod_{st}(s)} \quad \text{Equation 37}$$

Storage investment costs, Equation 37, consider the capacity investment cost $EInvC(s)$ for each storage technology reservoirs $E_{ST}^{max}\ (s)$, and the power investment cost $PwInvC(s)$, for the available power generation of each storage technology $Pw_{ST}^{\max}\ (s)$. Every cost is amortized by the life expectancy of each technology $LiveExp_{st}(s)$.

In the situation that CAES is considered, regarding that this technology requires burning natural gas to recover the energy, it is necessary to add the generation costs to the objective function (Equation 36). More specifically, it would be necessary to consider the no load cost, the start up cost (or energy stored) and the cost function of the facility that has been upgraded.

***Changes in system constraints:***

$$\mathrm{D(t)} + \sum_{\mathbf{s=1}}^{\mathbf{S}} \mathbf{D_{st}(s,t)} = \sum_{\mathbf{s=1}}^{\mathbf{S}} \mathbf{G_{st}(s,t)} + \sum_{\mathrm{i=1}}^{\mathrm{I}} \mathrm{G(i,t)} + \mathrm{G_{wind}(t)} \qquad \text{Equation 38}$$

The incorporation of storage to the power balance constraint, Equation 38, consists in the addition of two terms: the energy consumed by the storage to save energy $\mathrm{D_{st}(s,t)}$, and the energy return to the system from the storage $\mathrm{G_{st}(s,t)}$. As was expected, results show that when the storage is extracting energy from the grid ($\mathrm{D_{st}(s,t)} \neq 0$) it is not generating energy ($\mathrm{G_{st}(s,t)} = 0$) and vice versa.

$$\sum_{\mathrm{i=1}}^{\mathrm{I}} \mathrm{u_c(i,t)} * \left(G^{\max}(i) - \mathrm{G(i,t)}\right) + \sum_{\mathbf{s=1}}^{\mathbf{S}} \mathbf{Res_{st}(s,t)} \geq \mathrm{Res_{sys}} \ \forall \mathrm{t} \in 1, \mathrm{T} \qquad \text{Equation 39}$$

The consideration of the incorporation of storage into reserve requirements is analysed with the addition of a factor that accounts the possible reserve provided by storage, i.e. $\mathrm{Res_{st}(s,t)}$. This constraint is very important because it models part of the flexibility requirements of the system. Furthermore, it highlights one of the main contributions of storage because if this constraint is considered, the final decision in most of the cases does not include storage.

$$Res_{st}(s,t) \leq Pw_{ST}^{\max}(s) - G_{st}(s,t) \ \ \forall t \in 1,T, \forall s \in 1,S \qquad \text{Equation 40}$$

$$Res_{st}(s,t) \leq E_{stored}(s,t) \ \ \forall t \in 1,T, \forall s \in 1,S \qquad \text{Equation 41}$$

$$Res_{st}(s,t) \leq \chi_{Std} * \mathrm{Res_{sys}} * Std(s) + M * (1 - Std(s)) \qquad \text{Equation 42}$$

Reserve provided by the storage is the difference between the maximum power output $Pw_{ST}^{\max}(s)$ and the power returned to the system $G_{st}(s,t)$. This is true only if the storage facility has enough energy stored, $E_{stored}(s,t)$ in order to provide this service (Equation 42). Finally, it has been considered that certain storage technologies such as batteries cannot provide completely the reserve requirements of the system. For those technologies that only can provide standing reserve ($Std(s) = 1$, batteries), the provision of reserve is limited to a fraction $\chi_{Std}$ of the total system reserve requirements. This fraction has been considered to be a 40% of the total system reserve requirements as it were made by the author of reference [15].

***Storage constraints***

$$E_{stored}(s,t) \leq E_{ST}^{max}(s)\ \forall t \in 1,T, \forall s \in 1,S \qquad \text{Equation 43}$$

Equation 43 limits the maximum energy stored $E_{ST}^{max}(s)$ which is indicated by the decision variable $E_{stored}(s,t)$.

$$D_{st}(s,t) \leq Pw_{ST}^{\max}(s)\ \forall t \in 1,T, \forall s \in 1,S \qquad \text{Equation 44}$$

$$G_{st}(s,t) \leq Pw_{ST}^{\max}(s)\ \forall t \in 1,T, \forall s \in 1,S \qquad \text{Equation 45}$$

The maximum limit on the power, $Pw_{ST}^{\max}(s)$ used to store energy $D_{st}(s,t)$ and the energy returned from the storage $G_{st}(s,t)$ are considered in Equation 44.

$$E_{stored}(s,t) - E_{stored}(s,t-1) = (\eta_{ST}(s) * D_{st}(s,t) - G_{st}(s,t))\,\Delta\mathrm{t} \quad \forall t \in 1,T, \forall s \in 1,S \qquad \text{Equation 46}$$

Equation 46 considers the relationship between the energy stored in each stage $E_{stored}(s,t)$ , the energy saved $D_{st}(s,t)$ and the energy returned $G_{st}(s,t)$. The factor $\eta_{ST}(s)$ is the round trip efficiency of storage (0.77 for BESS). Furthermore, this equation equals energy with power which has been delivered or saved continuously for the time step Δt. This factor usually is omitted because the typical time step is one hour. It is interesting to mention that the variable $E_{stored}(s,t)$ is the final energy available for the system since the round trip efficiency $\eta_{ST}(s)$ is taken into account for the energy saved $D_{st}(s,t)$.

Some other references model the storage more accurately by considering start up cost and shut down cost, minimum generation when activated and losses. These constraints are useful when further accuracy is required. Furthermore, these constraints have more impact when PHS is considered and this is not the situation that is considered in this project.

Other constraints, such as the minimum storage level, have been omitted and in its place the net available stored energy is used. This is done by considering that the energy stored has already subtracted the minimum level required of the stored energy. Usually, it is necessary to leave a minimum energy stored (and a maximum) without being touched in order to maintain the life expectancy of the storage facility, especially with electric batteries and PHS.

### III.5.2 Clustering simplification modifications

This chapter explains the changes that have been introduced in the previous constraints that model storage in order to be coherent with the clustering simplification that was performed to model the demand (II.3.2)

$$E_{stored}\big(s, t_0(c)\big) - E_{stored}\big(s, t_{end}(c)\big) = \big(\eta_{ST}(s) * D_{st}\big(s, t_{end}(c)\big) - G_{st}\big(s, t_{end}(c)\big)\big)\,\Delta t \qquad \text{Equation 47}$$
$$\forall t \in 1, T, \forall s \in 1, S, \forall c \in 1, C$$

Equation 47 introduces a relation between the beginning and the end of a cluster to the equation that relates the energy stored at the storage facility in several stages. As was considered with the generators constraints, this makes the results coherent with the cluster approximation of a year.

There are three possible time scopes of the energy stored and its use: daily (store in night, use in at peak hours), weekly (stores energy during weekends and gives that power back in week days), monthly-seasonally (stores power from a month of lower consume to give that power back in the next month). The model that has been elaborated for this thesis assesses the possible contribution of the first two possibilities. The third scope would require very large storage facilities and long term decision tool without simplifications. Therefore it is outside the scope of this thesis.

## III.6. RESULTS: ASSESSMENT OF THE CONTRIBUTION OF STORAGE

The analysis of the results shows first the effect of the external resource (Storage) on timely evolution of the system. Then a breakdown of the costs for a low wind scenario is analysed and finally a comparison between the low wind scenario and a high wind scenario is explained.

### III.6.1 Effect of Storage on the system performance

The effect of storage on a situation without WG cannot be observed because the flexibility requirements do not to justify the investment and it is not introduced.

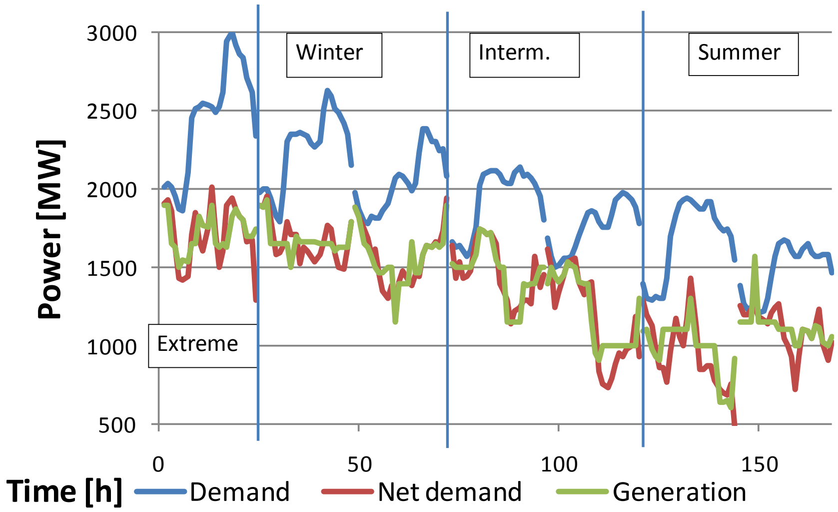



*Figure 29 Effect of storage on the net demand profile*

Figure 29 shows the effect of storage in a situation where 30% of the total demand is supplied by wind generation disregarding wind curtailment. The plots show that the net demand (Demand minus wind generation) presents a high variability that is reduced by the presence of storage. Therefore, as was expected, the main contribution of this technology is levelling the load in order to reduce flexibility requirements.

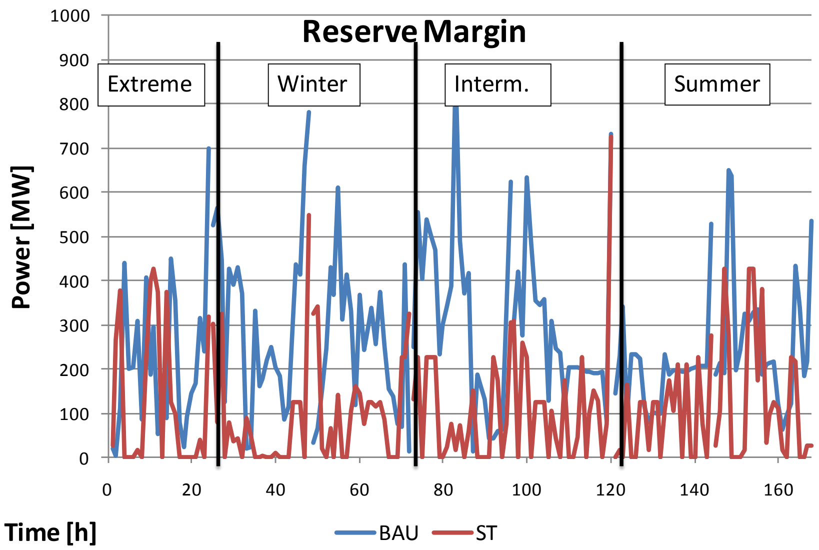



*Figure 30 Excess of reserves on the system*

Focusing on the reserves of the system, Figure 30 shows that one of the key impacts of the introduction of storage is the improvement of the reserve provided by the generating units and the storage. The excess that is present in the situation without storage gets reduced. It is important to highlight that the reserves provided by the storage are limited taking into account that storage does not provide spinning reserves.

### III.6.2 Low variable wind scenario

The following figures show the results derived from the model with the introduction of storage. A comparison with storage (**ST**) and without storage (Business as usual, **BAU**) is made regarding the selection of the generation portfolio (CAPEX) and the generation schedule (OPEX). The results are shown for a progressive integration of wind generation with low variability.

The different wind penetration degrees have been marked as W0.X where the "X" means the energy supplied by wind generation from the total energy that is required by the demand. For example, "W0.1" means 10% of the energy supplied by wind; "W0.3" means 30% and so on.

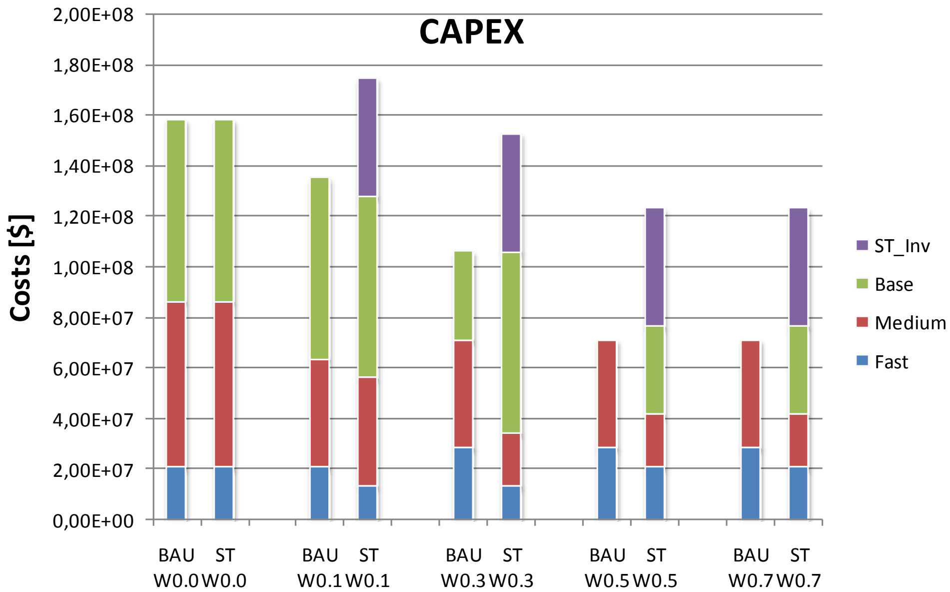



*Figure 31: Breakdown of CAPEX costs low wind scenario, BAU and storage.*

Results show that the introduction of storage increases the total investment costs (Figure 31). However, the investment in fast units reduces and the utilization of base generation increases. Furthermore, in the scenario without wind generation, storage is not cost effective. Additionally, other results showed that if storage does not participate in the system reserve requirements it is not considered in the optimal solution.

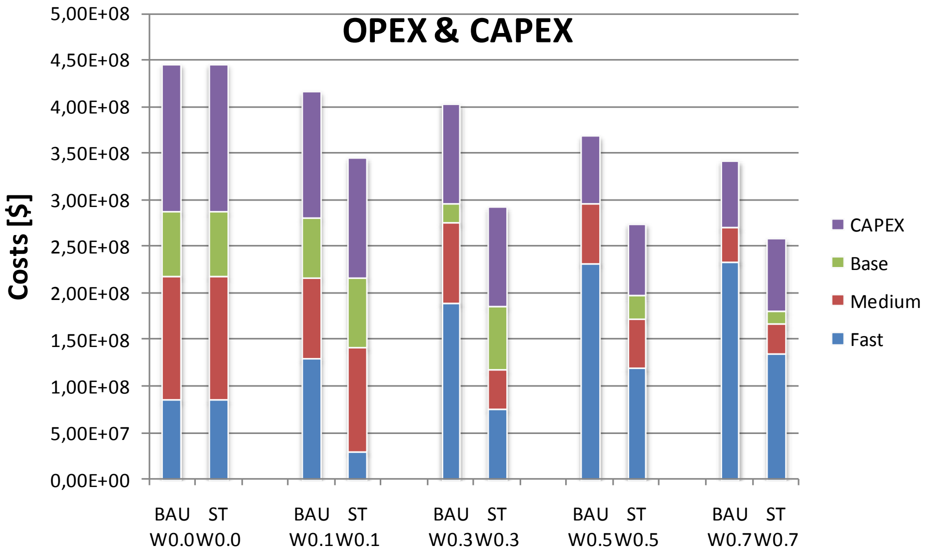



*Figure 32: Breakdown of TOTAL costs, low variable wind, BAU and storage*

Figure 32 shows the total costs with a breakdown of the operational costs. Regarding the operational expenditure, the main contribution of storage is the reduction on the costs of fast generation and the reintroduction of base generation in scenarios with high wind (50% and 70%). Furthermore, the total costs addressed in the previous figure show that storage always improves the operational costs of the system.

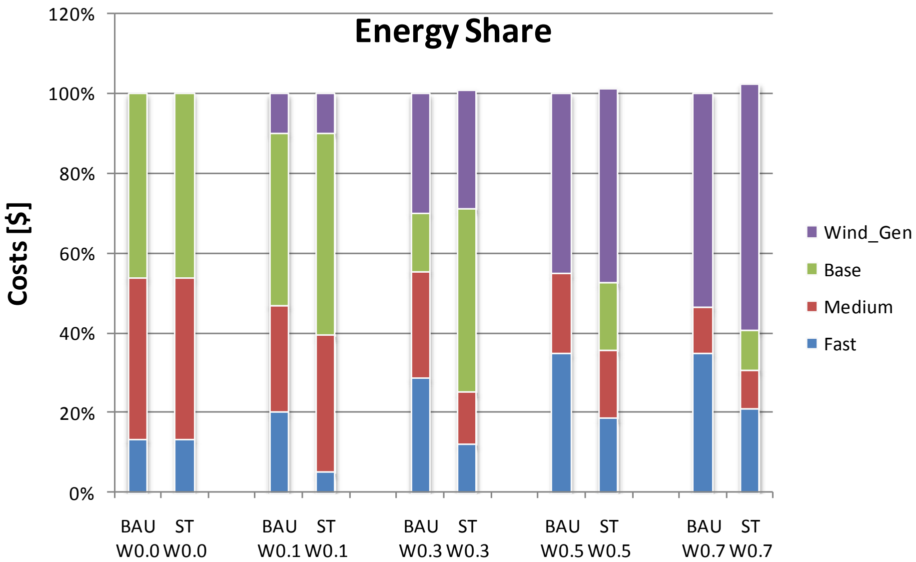



*Figure 33: Energy share low variable wind generation, ST and BAU*

Apart from the results addressed in the previous figure, Figure 33 shows wind curtailment in high wind scenarios is reduced but does not disappear completely with the utilization of storage.

### III.6.3 Comparison between low and high variable wind scenarios

The next figures show the comparison of CAPEX, OPEX and total expenditure with scenarios of low and a high variable wind generation for the possibilities considered previously.

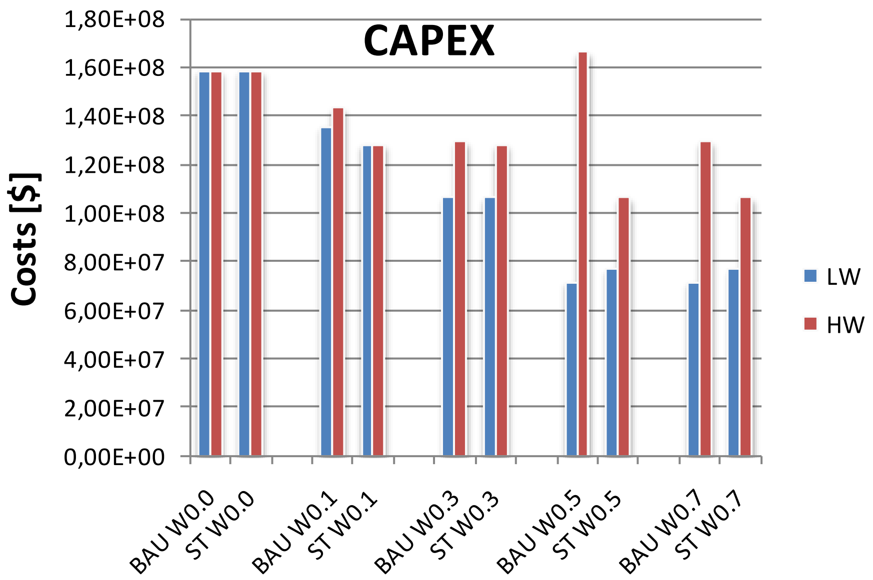



*Figure 34: Comparison of CAPEX costs low and high wind variability, ST and BAU*

Focusing on the capital expenditure, Figure 34 shows the increase in the investment induced by wind variability reduces due to the introduction of storage.

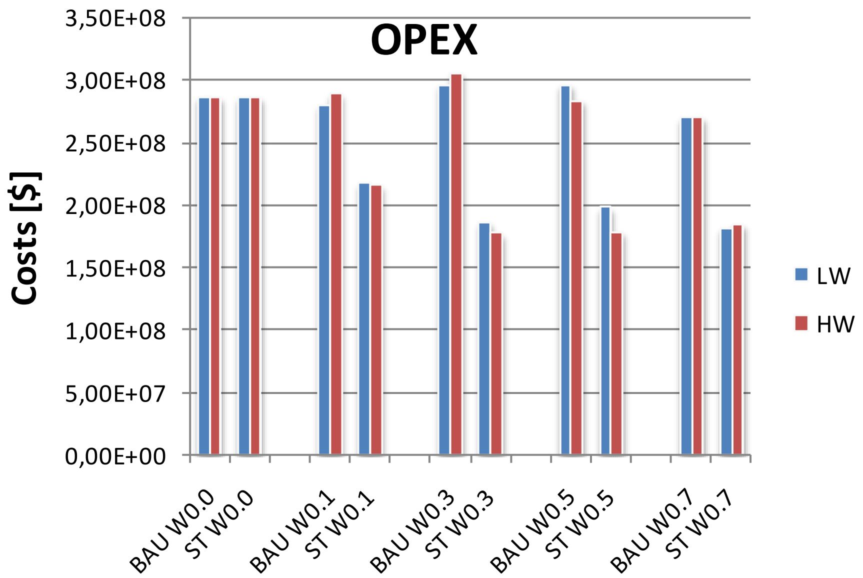



*Figure 35: Comparison of OPEX costs, low and high variable wind, ST and BAU.*

As happened in the business as usual case, the operational costs do not vary excessively with wind variability disregarding the degree of wind penetration. Once a portfolio is optimized for a certain situation, the operational costs do not vary excessively due to the variability present in wind generation.

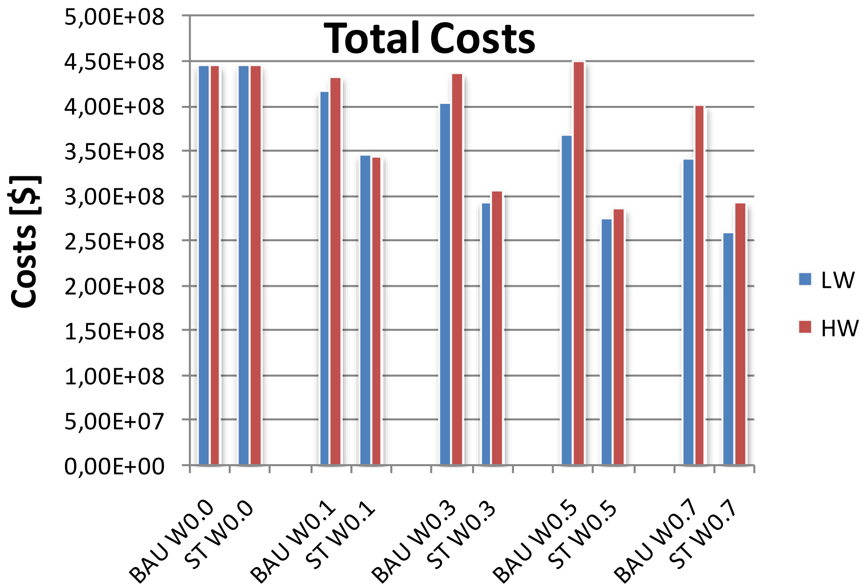



*Figure 36: Comparison of total costs, low and high variable wind, storage and BAU.*

Finally focusing on the overall performance, the final increase due to wind variability is highly reduced thanks to the introduction of storage. The increase generated by high wind variability is always lower than in the BAU situation.

## III.7. SUMMARY AND CONCLUSIONS

This chapter started by analysing the different storage technologies and the possible contribution of storage to power systems with increasing wind generation. A general approach showed that the main contribution of storage was levelling the load so the energy supplied by the generators constituted a less variable profile. This flattening results in an increase in the utilization of base generation. Then, the improvements to the flexibility model developed in the chapter II.3.1 to model storage were explained. The modifications involved some additions to the main constraints and specific constraints for the storage facilities.

The analysis of the results showed that storage increases the flexibility and the capability of a system to introduce wind generation maintaining base generation. More specifically, the performance of the system was improved by reducing the operational costs and the reserves present in the system. If higher wind variability was considered, storage reduced the increase on the overall costs. This result is particularly interesting in systems where reliability is an important issue and high wind variability could create contingencies such as islands or small islanded systems.

On the other hand, in systems with low flexibility requirements because of the lack of renewable resource, results showed that storage was not cost effective. Some test on the model showed that, storage is profitable only if it contributes to the reserve requirements.

Due to its high investment costs, and the losses when storing energy, storage states as part of the solution to integrate WG, especially in scenarios with high capacity. In order to solve this problem in a cost effective manner, other solutions such as demand side management or interconnections with other systems should be considered.

# IV. Contribution of Demand side management to flexibility

## IV.1. Introduction

Regarding the interactions between demand and generation, there are several approaches to define demand side contribution. Some authors refer to it as demand response (DR) because they expect an interaction between the customer and the market price. The U.S. Department of Energy (DOE) defined DR in its February 2006 report to Congress, as:

*"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized".*

In this project, the contribution to flexibility provided by demand has been analysed from the point of view of the overall system. Furthermore, this service has the objective to improve the system performance. Because of these reasons, it has been considered that the terminology Demand Side Management (DSM) is more accurate.

More specifically, DSM refers to loads that can be controlled by an external agent that participates in electricity markets. Therefore, this analysis assumes the presence of a framework that would allow remote control. This is a reasonable assumption because the developments in telecommunications over the last few years have triggered research of smart appliances and smart grids. Some demonstration projects on these topics are already being carried.

Additionally to the possibility to control domestic loads, during the next years, the introduction of electric vehicles is expected to have a significant impact. These new loads are connected to the system most of the time, have large charging times and occasionally could provide energy to the grid (V2G). With an adequate managing infrastructure, this loads fits perfectly the concept of DSM.

Because of these reasons it is clear that DSM is a resource that will be available progressively in future networks. It is therefore necessary to assess the possible contribution of DSM schemes to power system flexibility and more specifically to the progressive integration of renewable energies such as wind.

***Outline of the chapter***

This chapter starts analysing the different possibilities agents that participate in electricity market and the consequences of the introduction of DSM. Next section explains the impact on power system planning that DSM potentially has. Then, it is presented how DSM has been analysed by other authors. The improvements added to the tool that was explained in the chapter II to model DSM are explained in the subchapter. Results are discussed in the section. Finally starting from the results achieved with the model, an analysis of the procedures and policies will be made.

### IV.1.1 Electricity markets and DSM

The aim of this section is analyse and clarify the impact of demand side management schemes on the different agents that participate in electricity markets.

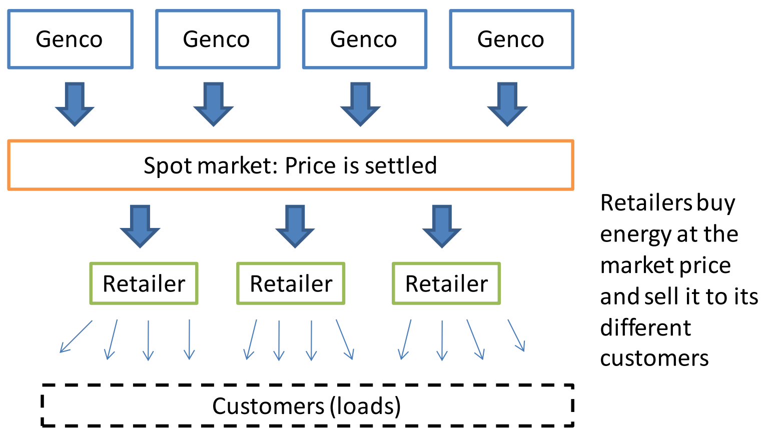



*Figure 37 Schematic of the different agents in the liberalized electricity markets*

One of the inconsistencies that characterize our current power systems is the lack of interaction between what is happening at the generation level, the hourly result of the spot market, and the hourly price that a customer pays for the energy consumed. The final price at each hour reflects the situation in the system, hours with peak prices correspond to situations in which more expensive (flexible) units are required to be committed to ensure the security of supply [19].

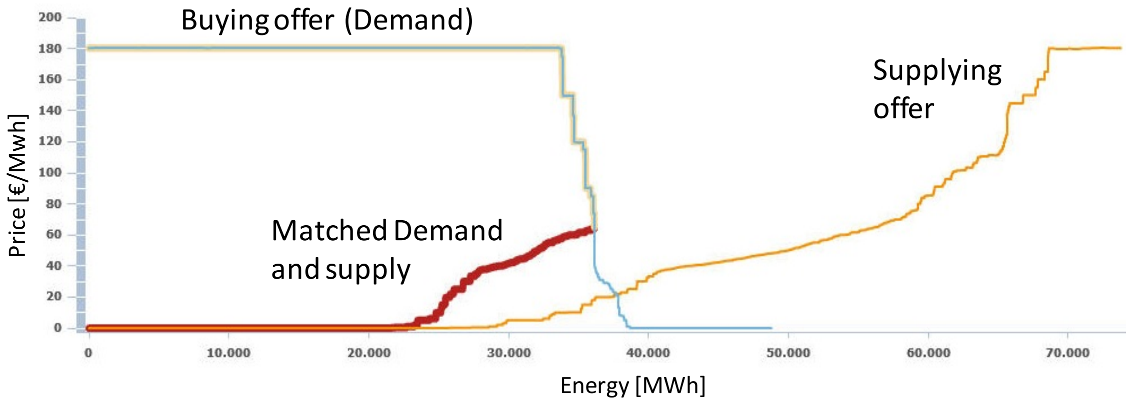



*Figure 38 Supply demand curve in the Iberian power system [50]*

As Figure 38 shows, the elasticity of the demand to the supply curve is very low. The main reason for this result is that the different retailers buy energy in the market and sell it to the customers at tariffs that usually do not have any hourly variation, i.e. at a fixed price rate. From the point of view of the retailers it increases the risk when buying energy. On the other hand, there is no incentive for the customers to change their behaviour while the energy is sold at a fixed rate.

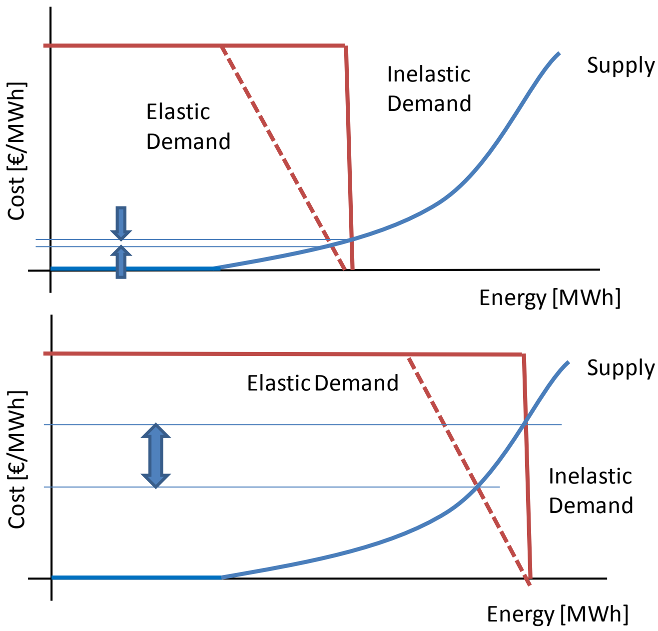



*Figure 39 Effect of enhanced elasticity on demand side*

The effect of enhancing elasticity of demand side reduces flexibility requirements because the situations with high price are related with the necessary commitment of fast units with a high marginal cost.

On the other hand, it is not expected that the customers will be constantly aware of the situation of the market on the moment of requiring electricity. Therefore, if demand is going to response to the market spot price some automation on how and customers consume electrical energy is required, especially if demand is going to participates in the bids of the spot and the reserve markets. Due to this reasons, it is expected that the retailers will become aggregators of manageable demand and use this resource to participate in the markets. This scenario will reduce the risk and the purchasing price of the energy for the retailer and consequently will increase the profits.

Moreover, DSM could participate in reserves markets. The concept of aggregation of customers gets complete sense when this possibility is considered. In order to fulfil the minimum requirements for this type of service it is necessary to have minimum capacity on power availability and time of response. Only when customers are grouped the availability and the reliability of this resource can be ensured.

Focusing on the demand side, it looks reasonable that some of this profitability of the retailer-aggregator should be shared so the customer will allow the control of loads that could be reduced (heating appliances) but also loads that could be delayed (smart appliances).

On the other hand, an improvement in the elasticity of the demand is not interesting from the point of view of the generating companies (gencos.) because it reduces the profits by reducing the final electricity price in the market. Therefore, the introduction DSM will need to be promoted by policies created by governments [19]. Other disadvantage of this new framework is that it is not clear if the information infrastructure required will justify the savings.

### IV.1.2 Mechanisms to introduce demand responsiveness

A perfect demand management by the retailers (aggregators) is not likely to come to our power networks during the next few years. Therefore, it is interesting to analyse which are the policies or tariffs in the contracts between retailers and customers that have been considered or applied in demonstration projects to increase demand side contribution and response.

The electricity price set by the retailers is made of two components: the electricity cost and the insurance. The last one covers the uncertainty and variability of the prices of the electricity. This price is high due to the lack of interaction between the customer and the electricity market. There are two types of contracts that increase the demand elasticity: time varying tariffs and incentive-based reduction. The final objectives of these possibilities are the reduction of the load at peak times and consequently an increase at low stressed situations.

***Time varying tariffs***

These tariffs try to increase the response of the customers to the electricity market result and share the risk. This risk is shared between the retailer and the customer.

- **Time of use (TOU):** The price of electricity is based on the estimation of the cost of electricity during groups of hours. The prices offered to the customers are usually divided in two to four groups of hours. The values are known in advance and usually vary through the seasons.
- **RTP Real time pricing (RTP):** The prices offered to the customers are related to the market result. The values are known by the customers an hour or a day in advance.
- **Critical time pricing (CPP):** Usually is a mixture between the previous possibilities. Customers are on a TOU but sometimes a critical price event is called, and cost rises several times. The number of times and hours that these events are committed is limited (An example of this values is showed in Table 3 in the next chapter).

***Incentive-based reduction***

This possibility gives the customers incentives to reduce their load additionally to the agreed price.

- **Direct load control (DLC):** Traditionally DLC has been used to curtail loads by the SO when contingencies threaten the security of the system. If the customer agrees, DLC could be used by the retailer to avoid high price situations. This approach is close to the approach to model demand management that has been assumed, especially regarding demand curtailment.

- **Demand buyback program:** This possibility consists of bids of the customers of how much load would they be willing to curtail at the price offered by the retailer. Then the retailer decides which reductions will be committed usually based in their performance.

## IV.2. DEMAND CHARACTERIZATION

The step before modelling the demand is the analysis of how the demand is constituted. There are two types of contribution that have been considered:

- **Shifted demand**: Customers that will allow changing the moment in which draw energy from the grid. This constitutes the main contribution given by the demand and it that has been addressed by several authors ([21] [23] [24] [26]).
- **Curtailed demand:** Customers that will contribute in critical situations by reducing or removing their load ([22] [25] [26]).

An analysis of the different types of customers in the power systems is necessary to give an estimation of the possible amount of these different types of demand side management. There are three different types that are easily distinguished: Domestic, Industrial and Commercial demand. Each has its own characteristics and will participate in demand side mechanisms in a different way.

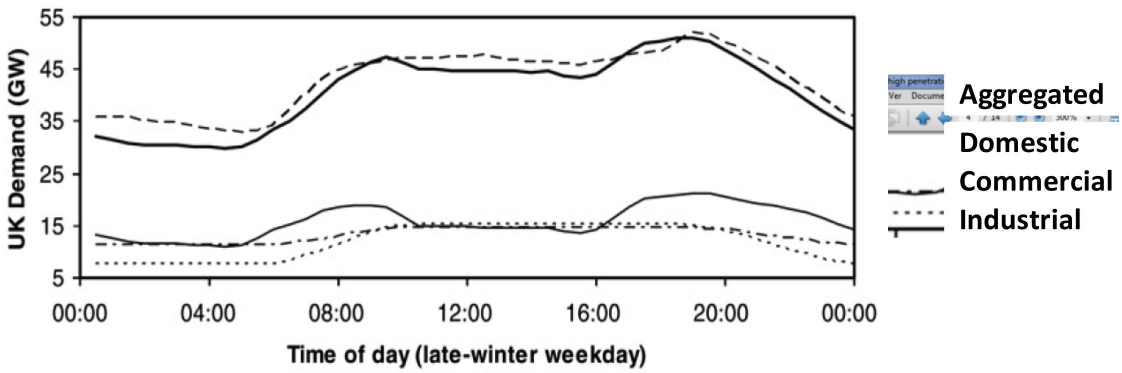



*Figure 40 Domestic load profile UK [41]*

Observing Figure 40 it can be easily seen that the load profile of industrial customers is almost flat. On the other hand, the variation in the total load is principally created by the domestic loads. For these reasons, it has been assumed that domestic loads will constitute the main contribution for load shifting. Opposite to them, industrial customers, more concerned of their expenditure in electricity, probably will be more interested than domestic loads to contribute to critical price situations (usually called critical price periods, CPP) by reducing their demand. Finally, it is not likely that commercial customers will participate too much in any of these possibilities since their demand is directly connected to their profits.

| Type | Average UK demand (GW) for 25 million households | Ratio |
|---|---|---|
| domestic | 13.8 | 37% |
| commercial | 11.1 | 30% |
| Industrial | 12.7 | 34% |
| **Total** | **37.6** | 100% |

*Table 1 Energy share of the different types of customers [41].*

Table 1 shows the energy share of each different customer for the UK and allows to provide and estimation of the amount of each resource. It is interesting to highlight that the three different possibilities have the same order of magnitude.

| Type | Ratio |
|---|---|
| electric lights | 15% |
| **fridges, freezers** | **14%** |
| electric hobs and ovens | 8% |
| consumer electronics | 22% |
| washing machines, driers, dishwashers | 11% |
| **electric space heating** | **19%** |
| **electric water heating** | **11%** |

*Table 2: Energy share of the main types of domestic loads [41].[3]*

Focusing on the domestic demand, Table 2 shows the main loads that constitute this type of customers. Among these, it has been assumed that the main contribution to load shift will be constituted by thermal loads. The main reason for this assumption is that thermal systems have enough inertia to be curtailed for some hours. If managed properly, the comfort of the customers should not be affected by the shift of the load to other periods.

Additionally, washing machines, driers or dishwashers could be part of this scheme. They could be shifted by waiting to start their program until an external controller gives the order. For example, the user would just give a finishing time and the system would manage it. In this situation, energy would be stored as “dirty clothes”.

---

[3] The ratios of this table have been elaborated using the data from reference [41][42]

$$\chi_{sh} = 50\% * Domestic_{share} * heat_{share} = 50\% * 37\% * 34\% = 6\%$$ Equation 48

Therefore, as Equation 48 shows, the available ratio of the demand that could be managed has been assumed to be a 6%. The initial 50% is just an index to show that not all the customers will participate in these programs and to make a conservative approach. Other references set this value between 4-20% so the current value is enough conservative.

This ratio will be used in the analysis to model the available shifted demand. To take into account that the variations in the total load profile are mainly caused by the domestic demand, this ratio has been assumed to be part of the demand connected at every instant.

Focusing on industrial loads, it is necessary to set the maximum power capacity that can be curtailed. This ratio has been set from the values from the same reference as the domestic loads analysis [41]

$$\chi_{ct} = 12.5\%\, Industrial\ Demand = 12.5\% * 34\% = 5\%$$ Equation 49

From all the industrial demand, it has been assumed that only a 12.5% will be available to be curtailed. This ratio that is lower than the previous domestic load value, models that only a few industrial customers will be willing to stop manufacturing. Furthermore, opposite to the demand ratio, the complete 6% is a ratio from the total **peak** demand since industrial demand has been considered to be low variable. If greater degrees are considered an excessive curtailment is introduced in the system.

Additionally to the power that could be curtailed from the total demand, it is necessary to know how much energy will be possible to be curtailed. The estimation of the maximum annual energy, $AnnualE_{ct}$ and the maximum daily energy, $DailyE_{ct}$ that is available is based on the parameters of a demonstration project made in California [42] that tried to implement this type of mechanisms. The energy proportion has been directly estimated by the maximum number of hours that was agreed in that experiment (Table 3).

| CPP characteristics |
|---|
| 125 h/year |
| 25 periods/year |
| 5 h/period |
| 2 periods/day |

*Table 3 Critical price periods (CPP) parameters [42]*

$$AnnualE_{ct} = \frac{\frac{125h}{year}}{\frac{8760h}{year}} = 1.15\% \qquad \text{Equation 50}$$

$$DailyE_{ct} = \frac{\frac{10h}{day}}{\frac{24h}{day}} = 21\% \qquad \text{Equation 51}$$

## IV.3. Contribution of demand side management to power systems

As was commented in chapter II.2, in this project the impact of WG in a power system is mainly observed by the impact on the generation portfolio (CAPEX) and the impact on the generation schedule (OPEX) of the selected generators taking into account the reserve requirements of the system.

### *Contribution of DSM to the portfolio selection and schedule*

As it has been observed in previous chapters, the introduction of wind in power system increases the differences between peak and off peak periods in the load profile. This increases the operational system cost because of the reduction of the total base load committed.

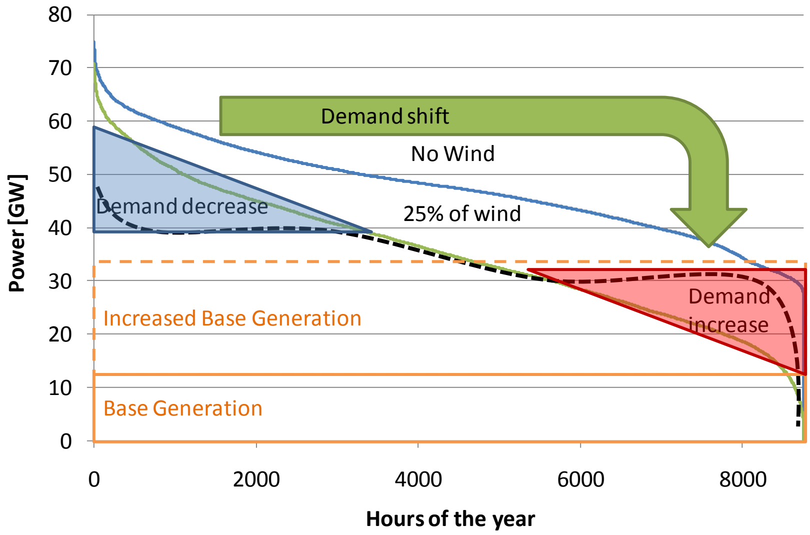



*Figure 41 Impact of DSM on the load generation curve with wind*

The final effect of DSM schemes, especially shifted demand, is very similar to the contribution of storage: the final profile flattens. Shifted demand behaves as a storage facility. The energy is “stored” in the shape of tasks that are needed to be done such as clothes to be cleaned or food to be cooled. Demand curtailment reduces the load when the situation is critical and leads to very high prices. Its impact is difficult to be addressed observing the load duration curve because the final energy curtailed should be very low. It just avoids the commitment of peaking units at critical moments.

Focusing on wind generation, the main expected contribution of demand side management is reducing stress on the system by adapting the load to the current generation. Therefore, the necessary contribution of generators to flexibility should be reduced.

***Contribution to reserves***

The possibility to control demand also opens the option to increase the reserves present in a system and reduce the contribution of the generators to reserve requirements at a given power system.

In order to provide reserves, any resource must be reliable, have enough response time and a certain amount of energy/power to be provided to the system. These technical requirements are achievable by managed demand if this resource is controlled by aggregators of customers.

Focusing on the potential contribution of DSM, the results of [27] have shown that the participation of demand side management in the provision of reserves improves the system performance reducing the use of fast units and increasing required connection time for the units committed to provide reserves.

National Grid already contemplates the possibility that demand management contributes to the provision of reserves in contingency time scales. More specifically, National grid encourages the participation of demand management in the provision of reserves via aggregators or agents [44].

## IV.4. LITERATURE REVIEW

Currently, it is common for certain types of large consumers (e.g., refrigeration industry, air conditioning systems of commercial buildings) to be offered special arrangements/contracts where –paid or not– part or the whole load is disconnected (due to energy prices or network constraints). The period and frequency of disconnection will depend on the technical and economic impact on the industrial/commercial customer.

This type of DSM, although beneficial to the system, is limited due to the number and volume (i.e., capacity) of these loads. For this very reason, it is believed that the largest contribution from DSM schemes will come from residential customers. The advanced (market) integration of real-time monitoring and control of smart appliances, part of the concept behind Smart Grids, will potentially enable DSM schemes resulting in an aggregated effect that will significantly contribute to power system flexibility [19], [20].

Enhancing the ability of demand to respond to price signals can help markets operate more efficiently resulting in less onerous flexibility requirements [21]. The optimal scheduling of DSM during critical price periods, particularly thermal loads, was explored in [22], resulting in a significant reduction of flexible generation units. Using a security-constrained unit commitment approach, [23] showed that introducing DSM would reduce both load curtailment (and the corresponding loss of profit) and investment in grid reinforcements.

The interaction between DSM and renewable technologies has also being investigated in the literature. In [24], two particular ways of managing under floor heating (from electrically operated heat pumps) are evaluated: for peak shaving and for charging/discharging following high/low wind periods, respectively. In this case, DSM reduces the start of peaking units and wind curtailment specially when there is an interaction with wind production. However, this approach does not optimize overall generation or the generation portfolio. Other strategies such as real time pricing (RTP) have proved to reduce reserve requirements and load curtailment events so the cost of wind uncertainty is reduced [25].

More recently, [26] has analysed the impact on power systems with wind penetration of the different possibilities of DSM i.e. load shifting, and load clipping. Furthermore, it has been considered a framework in which the different customers have been aggregated in the shape of virtual power plants that interact with the system.

Despite the fact that increasing amounts of renewable generation capacity requires more flexible power systems, not enough work has been done to provide reliable estimates of the amount of flexibility needed. Furthermore, it is also important to assess the contribution that DSM might have in future, so it is possible to establish the benefits and profitability (from the energy suppliers' perspective) of this resource.

## IV.5. DEMAND SIDE CONTRIBUTION MODELLING

### IV.5.1 Modifications to the flexibility model

This section explains how modelling DSM impacts on the constraints described in previous chapters (chapter II.3.1). The new factors from the base model have been highlighted in bold. Furthermore, the specific constraints to model DSM are showed.

***Objective function:***

It has not been considered any cost in the introduction of DSM hence, it is not necessary to add a term in the overall costs related to DSM. Therefore, the objective function remains as was explained in previous chapters (II.3.1.1)

***System constraints:***

$$D(t) - \boldsymbol{DSM_{ct}(t)} - \boldsymbol{DSM_{sh}(t)} = \sum_{i=1}^{I} G(i,t) + \mathrm{G_{wind}}(\mathrm{t})\ \forall t \in 1,T \qquad \text{Equation 52}$$

Power balance between generation $G(i,t)$, demand $D(t)$, and the committed aggregated capacity of demand side management (DSM) schemes is considered in Equation 53. The contribution of DSM is separated in demand that is available to be curtailed $DSM_{ct}(t)$ and demand that is available to be modified by shifting it $DSM_{sh}(t)$. It is important to clarify that $DSM_{sh}(t)$ is positive when demand has been removed and negative when it returns to the system.

$$\sum_{i=1}^{I} u_c(i,t) * \left(G^{\max}(i) - G(i,t)\right) + \boldsymbol{Res_{DSM}(t)} \geq Res_{sys}\ \forall t \in 1,T \qquad \text{Equation 53}$$

$$Res_{DSM}(t) = DSM_{sh}^{\max}(t) - DSM_{\mathrm{sh}}(t) \qquad \text{Equation 54}$$

Reserve requirements of the system are evaluated in Equation 53. The generators' contribution to reserve is the difference between the maximum power available $G^{\max}(i)$ and the actual power output $G(i,t)$ of those units committed $u_c(i,t)$ at instant *t*. The reserve-related contribution of DSM schemes $Res_{DSM}(t)$, is similar to the generation contribution: it is the DSM capacity still available, i.e., $DSM_{sh}^{\max}(t) - DSM(t)$ where $DSM_{sh}^{\max}(t)$ is the maximum DSM capacity that can be used at instant *t*. Demand curtailment has not been considered in reserve provision because it is a resource to be called only at critical price periods (CPP) and should not be used to ensure the reliability in the normal evolution of the system but to help when the security is in risk.

***Constraints for shifted demand***

$$-DSM_{sh}^{\max}(t) \leq DSM_{sh}(t) \leq DSM_{sh}^{\max}(t) \; \forall t \in 1, T$$
$$DSM_{sh}^{\max}(t) = \chi_{sh} * D(t) \; \forall t \in 1, T \qquad \text{Equation 55}$$

$$\sum_{t=t_{0(d)}}^{t_{end(d)}} DSM_{sh}(t) = 0 \; \forall d \in 1, D \qquad \text{Equation 56}$$

As mentioned above, there is a maximum DSM capacity at every instant *t*. This limit is modelled as a fraction, $\chi_{sh}$ of the actual demand $D(t)$, during that period (Equation 55). Additionally, Equation 56 corresponds to the constraint that ensures that committed DSM capacity is being put back to the demand during the same day.

***Constraints for curtailed demand***

$$DSM_{ct}(t) \leq \chi_{ct} * D^{max} \; \forall t \in 1, T \qquad \text{Equation 57}$$

The maximum limit of available demand that could be curtailed is considered in Equation 57. It has been assumed that this resource should be modelled as a fraction $\chi_{ct}$ of the peak demand $D^{max}$ instead of a fraction of the current demand $D(t)$ as was made with demand shift. As was explained in chapter IV.2, it has been assumed that mainly industrial demand will participate in CPP events and these loads are more similar to a constant demand.

$$\sum_{t=1}^{T} DSM_{ct}(t) \leq T * (\chi_{ct} * D^{\max}) * AnnualE_{ct} \qquad \text{Equation 58}$$

The energy curtailed during the whole time horizon T must be below an annual limit $AnnualE_{ct}$. This fraction is considered from the total maximum amount of energy that could be curtailed, i.e. the maximum power available to be curtailed ($\chi_{ct} * D^{\max}$) at each instant of time multiplied by the scope of time T.

$$\sum_{t=(24*(d-1)+1)}^{24*d} DSM_{ct}(t) \leq 24 * \chi_{ct} * D^{max} * DailyE_{ct} \forall d \in 1, D \qquad \text{Equation 59}$$

In a similar way that previous equation did, Equation 59 evaluates the maximum energy that can be curtailed during a day $DailyE_{ct}$.

### IV.5.2 Clustering simplification modifications

This chapter explains the changes that have been introduced in the previous constraints that model DSM in order to be coherent with the clustering simplification that was performed to model the demand (II.3.2). Spain's victory in The changes impact only on curtailed demand because the only constraint on shifted demand that affects several instants of time is for each day, the minimum size that has been considered to generate the clusters.

***Constraints for curtailed demand***

$$\sum_{c=1}^{C}\left(\chi(c) * \sum_{t=t_{0(c)}}^{t_{end(c)}} DSM_{ct}(t)\right) \leq \sum_{c=1}^{C} \chi(c) * \left(t_{end}(c) - t_0(c)\right) * (\chi_{ct} * D^{\max}) * AnnualE_{ct} \quad \text{Equation 60}$$

The total energy curtailed during must be below an annual limit $AnnualE_{ct}$. This fraction is considered from the total maximum amount of energy that could be curtailed, i.e. the maximum power available to be curtailed $(\chi_{ct} * D^{\max})$ at each instant of time multiplied by the duration of each cluster $\left(t_{end}(c) - t_0(c)\right)$. Furthermore, the weighting coefficients of each pattern $\chi(c)$ have been considered for the energy curtailed to take into account the cluster simplification (Equation 60).

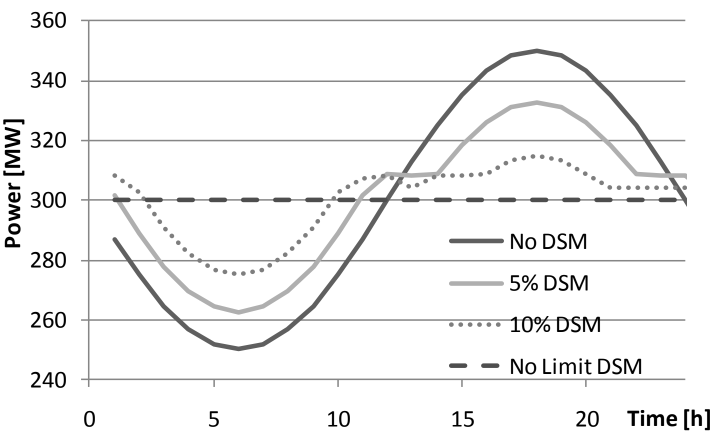
### IV.5.3 Test case 24-hours

In order to evaluate the performance of the model and understand the impact of shifted DSM on the demand-supply balance, this subsection presents a simple case study for 24 hours. The demand is modelled in a sinusoidal way to provide some sort of variation, i.e., $D(t) = 250 - 50 * sin((t) * \pi/12)$ [MW]. This very well known shape makes it easier to visualize the impact of different DSM penetrations on the generation profile. The available DSM capacity is taken as a fraction of the scheduled demand of the corresponding hour. In addition, the committed DSM capacity has to be 'put back' to the demand during the same day in order to mimic the behaviour of energy price-sensitive smart appliances. In other words, committed DSM capacity is shifted from a given period to another during the same day. As for the generation portfolio, it consists of only two units: Unit A as base unit, with cheap generation cost and slow ramp rates, and Unit B with opposite characteristics. This 24-hour problem was implemented using the Xpress Optimisation Suite.

| Unit | A | B |
|---|---|---|
| Min Power (MW) | 60 | 60 |
| Power elbow1 (MW) | 236 | 150 |
| Power elbow2 (MW) | 240 | 240 |
| Power elbow3 (MW) | 244 | 360 |
| Max Power (MW) | 400 | 600 |
| Variable Cost 1 ($/MW) | 8 | 25 |
| Variable Cost 2 ($/MW) | 8.4 | 25.5 |
| Variable Cost 3 ($/MW) | 8.8 | 26 |
| Variable Cost 4 ($/MW) | 10 | 26.5 |
| No Load Cost ($) | 200 | 25 |
| Investment Cost (M$) | 20 | 10 |
| Ramp Up/Down (MW/h) | 50/200 | 50/60 |
| Min time Up /Down (h) | 8/5 | 1/1 |

*Table 4 Generators Characteristics – Test case*

Figure 42 clearly shows that with higher penetrations of DSM, the final energy profile flattens. It is important to mention that the piece wise approximation of generation costs has an impact on the final shape of the profiles. Since the cost function is a linear approximation, any load point between two elbows of the piecewise linear curve has the same final value in the objective function. Since, this is a demonstration case, the location of the elbows of the piece wise linear approximation was selected so the final profile with no limit on DSM would give a result of a flat profile.



Contribution of Demand side management to flexibilityContribution of Demand side management to flexibilityContribution of storage to flexibility

*Figure 42 Progressive impact of DSM on the generation profile of DSM.*

Since Unit A is cheaper than Unit B, this unit should be committed at its maximum capacity, and before any other. However, in order to cope with the reserve requirements of the system, Unit B is needed to be online at its technical minimum. DSM could improve the performance of the system reducing the necessity of keeping peaking units online to provide spinning reserves. In systems with a wider portfolio, some of the peaking units would not be committed.

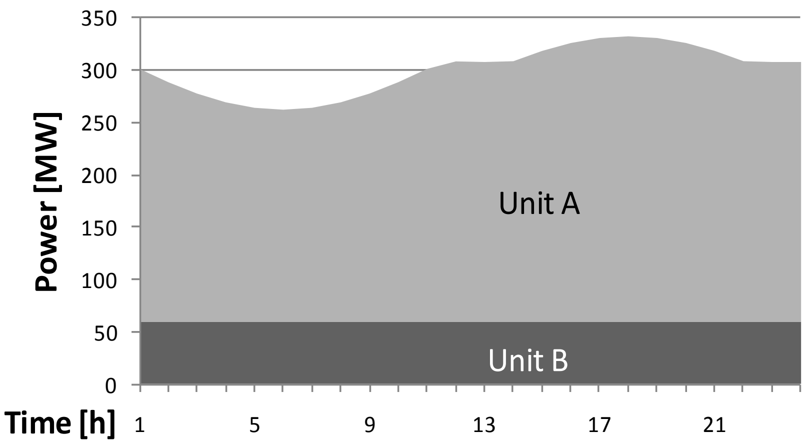



*Figure 43 Energy coverage diagram.*

## IV.6. ASSESSMENT OF THE CONTRIBUTION OF DSM

The analysis of the results shows first the effect of the external resource (DSM) on the evolution of the system. Then a breakdown of the costs in a low wind scenario is analysed and finally a comparison between the low wind scenario and a high wind scenario is explained.

### IV.6.1 Effect of DSM on the system performance

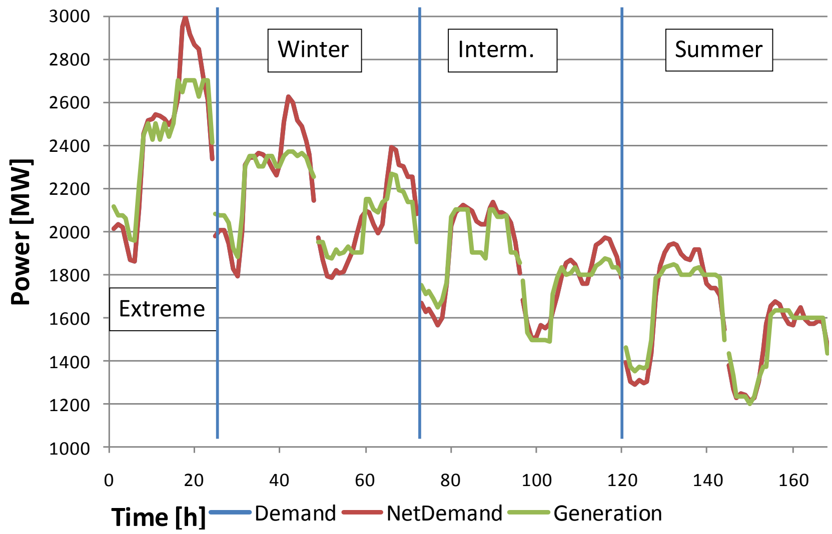



*Figure 44: Effect of DSM on the load profile without wind generation*

When demand side management is utilized in the situation without wind generation, as the test case showed, the main contribution of DSM is levelling the load by shifting load from peak to off-peak periods. The current tariffs that encourage this behaviour explained in chapter IV.1.2 should be enough to achieve this result in the practice.

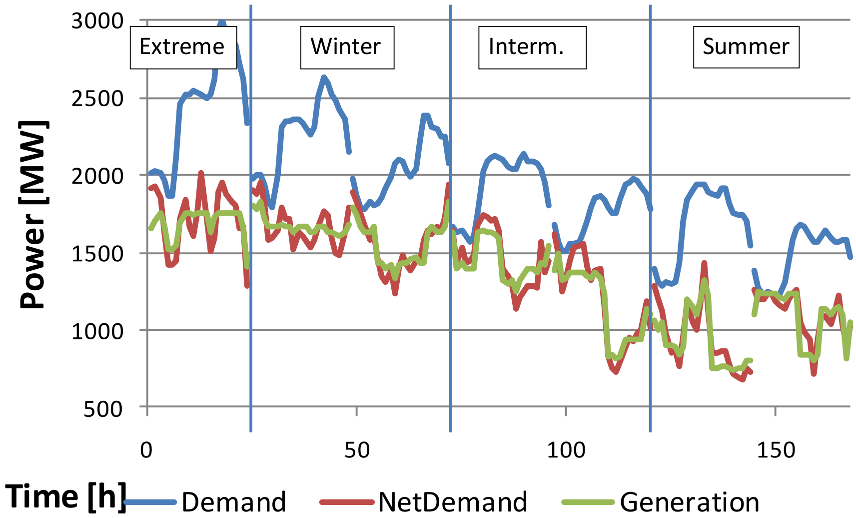



*Figure 45 Effect of DSM on the load profile with high wind generation*

If a high degree of wind generation is considered, the main contribution of DSM is levelling the load and reducing the wind variability. Therefore, since a deterministic behaviour of the demand would not be enough to achieve this result in a practical application, external control techniques would be necessary.

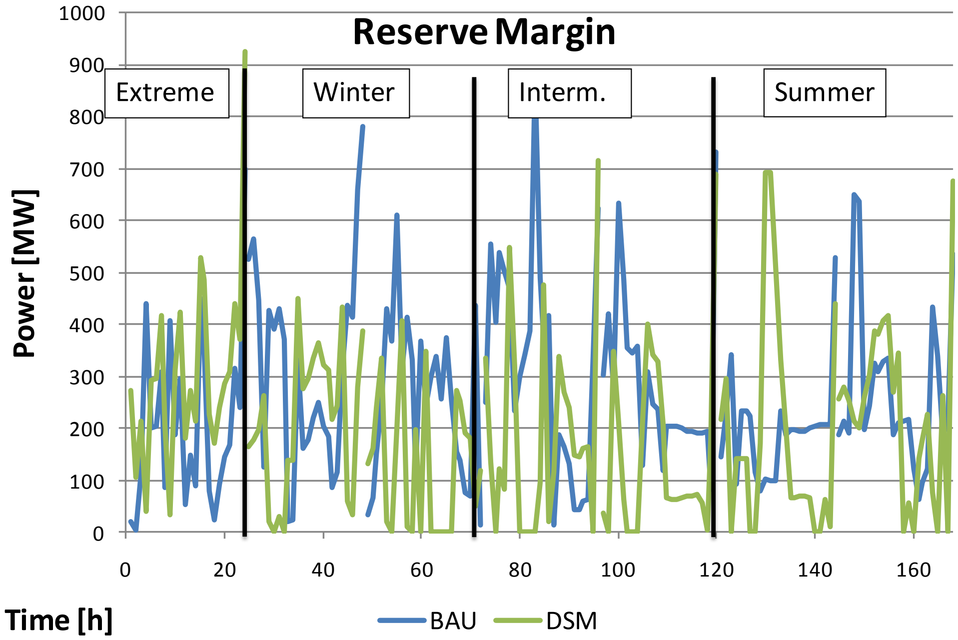



*Figure 46 Excess of reserves in the system*

Focusing on the reserves of the system, Figure 46 shows that one of the key impacts of the introduction of DSM is the minor improvement of the reserve provided by the generating units and DSM. However the contribution is not very high and sometimes the excess is increased. This reduced contribution could be a result of the limited capacity considered for DSM schemes.

### IV.6.2 Low variable wind scenario

The following figures show the results derived from the model with the introduction of demand side management (DSM). A comparison with **DSM** and without DSM (Business as usual, **BAU**) is made showing the results regarding the selection of the generation portfolio (CAPEX) and the generation schedule (OPEX) for a progressive integration of wind generation with low variability.

The different wind penetration degrees have been marked as W0.X where the "X" means the energy supplied by wind generation from the total energy that is required by the demand.

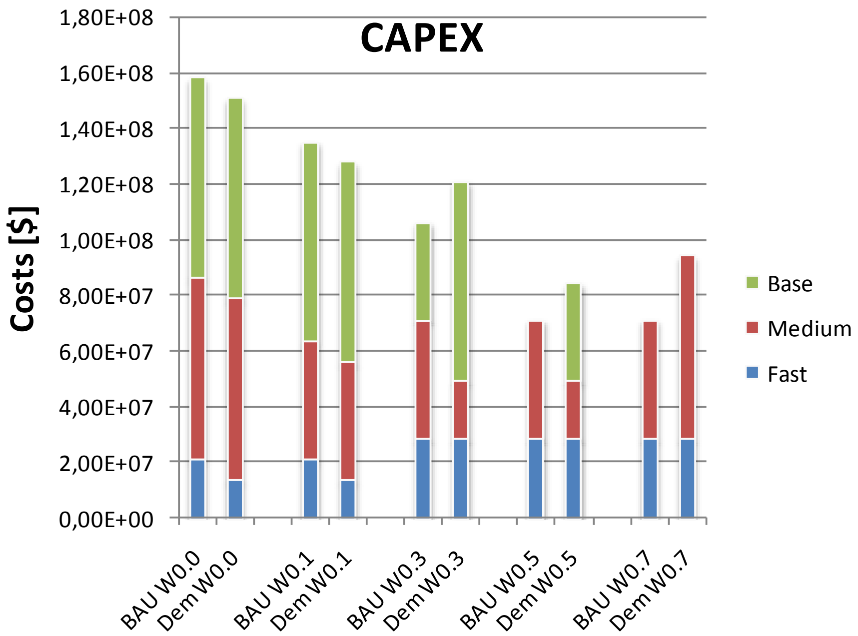



*Figure 47: Breakdown of CAPEX costs, low variable wind, DSM and BAU.*

Regarding the selection of the generation mix, the results show that the introduction of DSM reduces the utilization of more flexible units (red and blue). Conversely, the presence of wind power increases it. In scenarios with low WG, DSM reduces the expenditure because less fast units are required. In high wind scenarios, the cost increases from the BAU case because DSM allows the utilization of base generation.

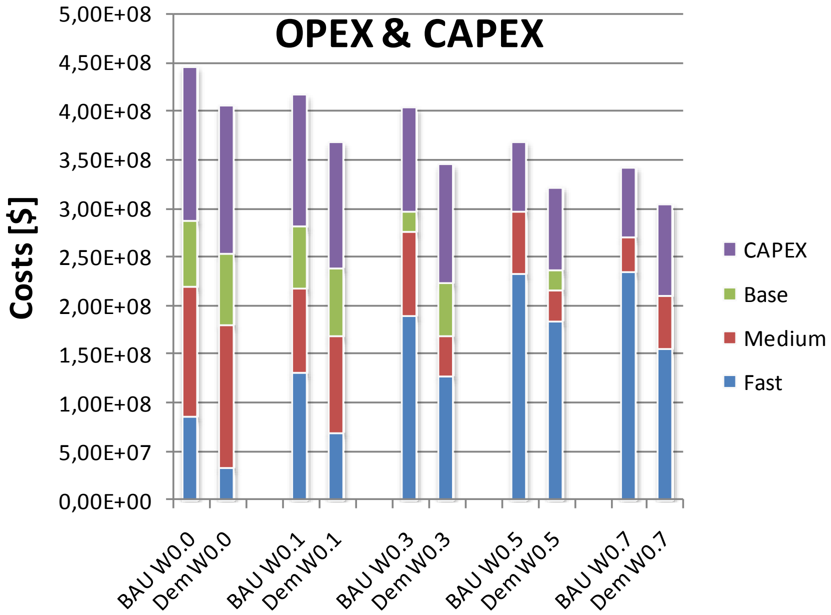



*Figure 48: Breakdown of TOTAL costs, low variable wind, DSM and BAU.*

Figure 48 shows the total costs with a breakdown of the operational costs. The main contribution of DSM is the reduction of fast generation cost. DSM has been considered to be limited so in scenarios with very high wind generation the capability of this resource should be greater in order to introduce such a great amount of WG.

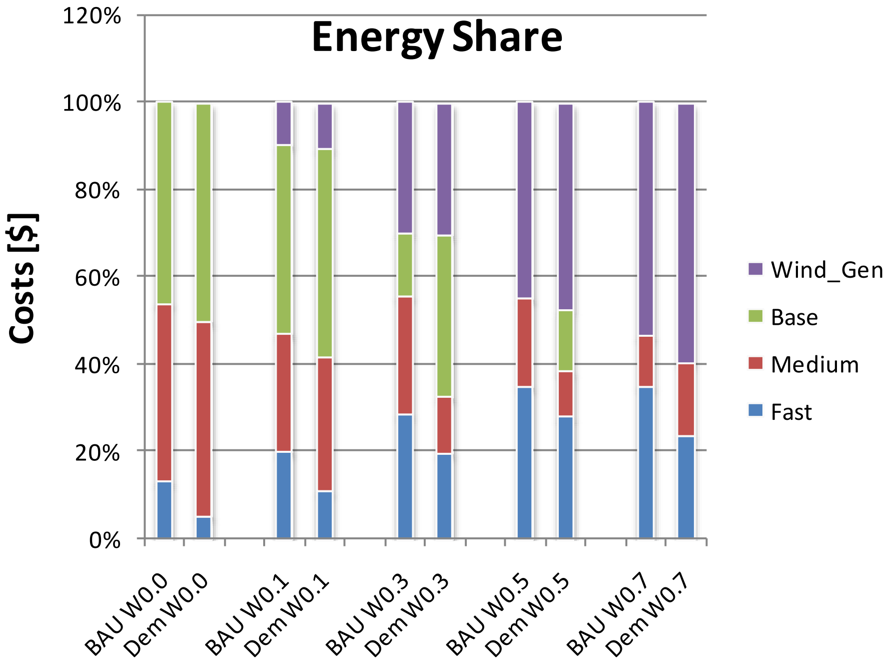



*Figure 49: Energy share, low variable wind, DSM and BAU*

Figure 49 shows that DSM reduces wind curtailment in very high wind scenarios and increases dramatically the utilization of base generation.

### IV.6.3 Comparison between low and high variable wind scenarios

The next figures show the comparison of CAPEX, OPEX and total expenditure with low and a high variable wind generation for the possibilities considered previously.

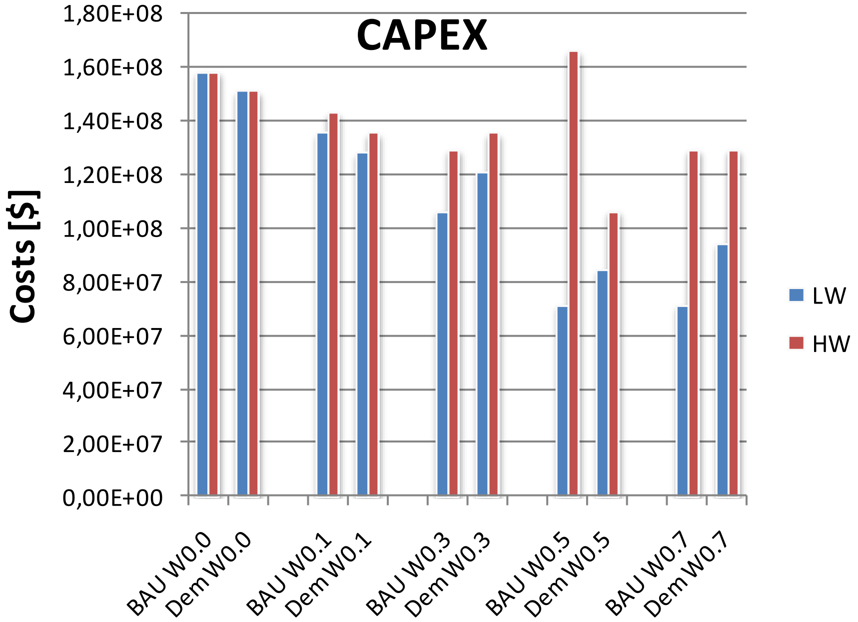



*Figure 50: Comparison of costs low and high variable wind, BAU and DSM.*

Despite of its low capability, the utilization of DSM clearly reduces the increase in the investment costs caused by wind variability.

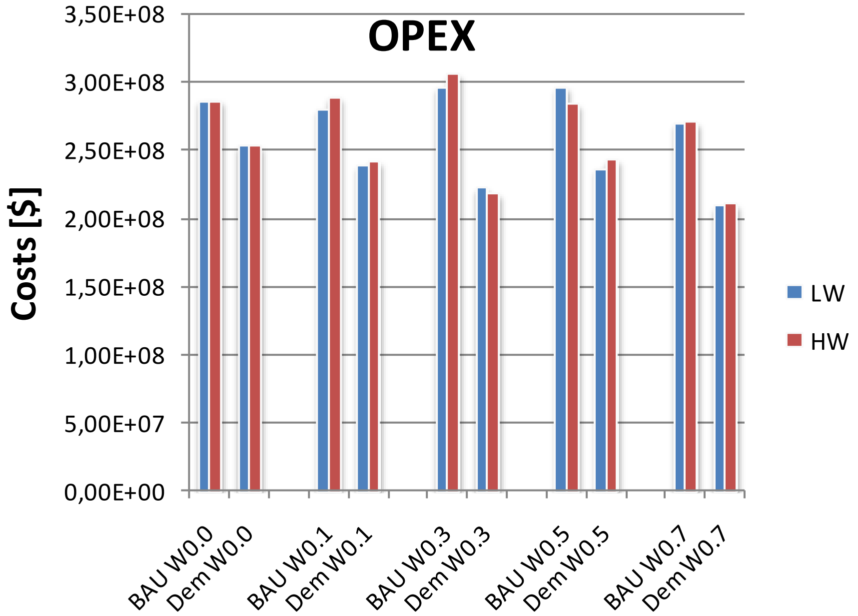



*Figure 51 Comparison of OPEX costs low and high variable wind, BAU, DSM*

As it happened with previous results in BAU, and ST scenarios, the operational costs do not vary between low and high wind scenarios. Once a portfolio is optimized for a certain situation, the operational costs do not vary excessively due to the variability present in wind generation.

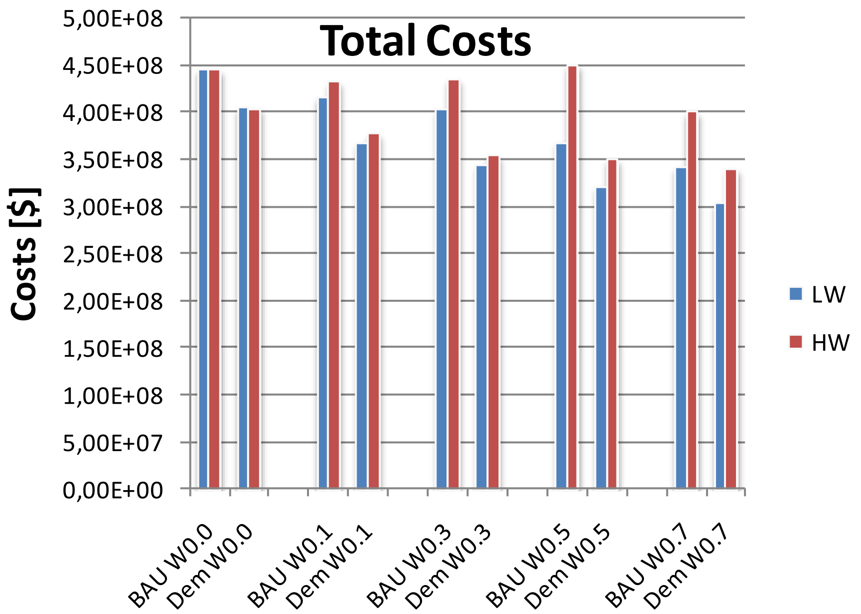



*Figure 52: Comparison of total costs, low and high variable wind, DSM and BAU.*

Finally, the total costs show that DSM reduces the impact of wind variability in the system, especially for low wind generation scenarios. The increase generated by high wind variability is always lower than in the BAU situation.

## IV.7. SUMMARY AND CONCLUSIONS

This chapter illustrates the contribution that demand side management (DSM) could make to the integration of wind generation (WG). The chapter started by analysing the different agents present in the electricity markets, the tariffs that encourage demand responsiveness and the expected contribution of DSM to power systems. This general approach showed that the main contribution of DSM was reducing the load in critical, peak situation and increasing it on off peak situation where there is an excess of capacity in the system.

Then, the improvements to model DSM in the method presented in the Chapter II were presented. The modification involved some additions to the main constraint and specific constraints for the DSM schemes.

The results derived from the model proved that DSM is a powerful resource not only to improve the performance of the system but also to increase the flexibility and allow further penetration of renewable generation maintaining the levels of base generation if enough capacity is considered.

DSM also proved its value in the integration of high variable wind generation, especially interesting in islanded systems where the reliability of the system is critical.

The analysis of the load profiles showed that in scenarios of low utilization of WG, the effect of DSM is levelling the load. In those cases, tariffs that encourage a shift of the load to off peak periods should be enough. Greater WG will require load control by the retailers. Customers should be grouped to reduce the uncertainty of this resource.

On the contrary, DSM is not likely to constitute solely the solution to integrate great amount of WG because of its limited capacity and reliability due to its impact on the comfort of the customers. Therefore, other external resources such as storage or international connections should be considered.

# V. COMBINED ANALYSIS: STORAGE AND DEMAND SIDE MANAGEMENT

Once the effect of each possibility has been cleared, it is interesting to analyse the synergies and influence that both possibilities have between them. The main contribution of this chapter is the overall comparison of the results showed in the previous chapters focusing on the differences between storage and demand side management. Furthermore, the model for both ST and DSM is explained but it has not been used for the final results because it cannot be run at a reasonable time.

## V.1. COMPARISON OF STORAGE AND DEMAND SIDE MANAGEMENT

As it has been addressed in previous chapters, both external technologies, storage and demand side management, have similar results when applied to a power system: both level the load, increase flexibility requirements and therefore, they increase the flexibility of the system. However there are some advantages and disadvantages of each one when compared to the other.

The main advantage of the storage is the flexibility of its operation and reliability of availability. On the other hand, the efficiency losses reduce its profitability and the availability of the resource to interact with the system and provide reserves depends on the amount of the energy stored.

On the other hand, the main advantages of Demand Side Management are that there are not efficiency losses in its utilization and it is a resource that would require just a change in the policies to be used. However, for further utilization an investment in the infrastructure will be need. Other disadvantages are its lower flexibility in its utilization, lower reliability and uncertainty in the amount of the available capacity.

## V.2. STORAGE AND DEMAND SIDE MANAGEMENT MODELLING

All the previous work was made with the objective to elaborate a **final model** that evaluates **at the same time storage and demand side management**. The model has been elaborated and it works but the **simulation times make it impossible to be used**. One simulation with a very simple case takes more than 5 days to be run. However, taking into account that it has been part of this project, it is going to be explained.

This subchapter explains together all the changes that have been explained in previous chapters that belong to the addition of Storage, and demand side management to the base model. Since it is a linear programming model, the combined analysis just requires all the factors that were added previously for each possibility. This means that if the reader has understood properly the mathematical formulation of previous chapters a quick review of the following equations should be enough to understand the whole model. To facilitate the comprehension of the comprehension an explanation is made again. The new factors in the system constraints of the base model have been highlighted in bold.

#### V.2.1.1 Objective function:

$$min\left\{\sum_{c=1}^{C}\chi(c) * \sum_{t=t_{0(c)}}^{t_{end(c)}}\left(\begin{matrix}\sum_{i=1}^{I}\big(GC\ (i,t) + AIC(i) * e(i)\big) \\ +G_{wind}^{ct}(t) * W_{ct}C\end{matrix}\right) + \boldsymbol{SIC}\right\} \qquad \text{Equation 61}$$

As it has been explained, the objective function takes into account the generation cost $GC(i,t)$ and the amortised investment cost $AIC(i)$ in the objective function. The existence binary variable $e(i)$ indicates if a unit has been included or not. The inclusion of storage requires the addition of Storage investment costs ($SIC$). Storage investment costs $SIC$, consider the amortized investment costs of the power output and the capacity of the reservoirs. On the other hand, it has been assumed that the introduction of DSM does not introduce further costs in the objective function. Finally, the possibility to curtail wind $G_{wind}^{ct}(t)$ is penalized by a cost $W_{ct}C$ which is greater than any of the generation cost of the other generation technologies. This feature allows the model to curtail wind when the excess of it avoids achieving a feasible solution (generation greater that demand) but at the same time wind curtailment is avoided. This fictitious cost is not taken into account when the generation costs are analysed.

#### V.2.1.2 System constraints:

$$D(t) + \sum_{s=1}^{S} \mathrm{D_{st}}(\mathrm{s,t}) - \boldsymbol{DSM_{sh}(t)} - \boldsymbol{DSM_{ct}(t)} = \sum_{i=1}^{I} G(i,t) + \sum_{\mathbf{s=1}}^{\mathbf{S}} \mathbf{G_{st}(s,t)} + \mathrm{G_{wind}}(\mathrm{t})\ \forall t \in 1,T \qquad \text{Equation 62}$$

The incorporation of storage to the power balance constraint consists only in the addition of the energy consumed by the storage to save energy $\mathrm{D_{st}}(\mathrm{s,t})$ , and the energy return to the system from the storage $\mathrm{G_{st}}(\mathrm{s,t})$. As was expected, results show that when the storage is extracting energy from the grid ($\mathrm{D_{st}}(\mathrm{s,t}) \neq 0$) it is not generating energy ($\mathrm{G_{st}}(\mathrm{s,t}) = 0$) and vice versa. The contribution of DSM is separated in demand that is available to be curtailed $DSM_{ct}(t)$ and demand that is available to be shifted $DSM_{sh}(t)$. It is important to clarify that $DSM_{sh}(t)$ is positive when demand has been removed and negative when it returns to the system.

$$\sum_{\mathrm{i=1}}^{\mathrm{I}} \mathrm{u_c}(\mathrm{i,t}) * \left(G^{\max}(i) - \mathrm{G}(\mathrm{i,t})\right) + \sum_{\mathbf{s=1}}^{\mathbf{S}} \mathbf{Res_{st}(s,t)} + \boldsymbol{Res_{DSM}}(\mathbf{t}) \geq Res_{sys}\ \forall \mathrm{t} \in 1,\mathrm{T} \qquad \text{Equation 63}$$

The consideration of the incorporation of storage into reserve requirements is analysed with the addition of a factor that accounts the possible reserve provided by storage, i.e. $\mathrm{Res_{st}}(\mathrm{s,t})$. This constraint is very important because it models part of the flexibility requirements of the system. Furthermore, if reserve requirements are not considered, in scenarios of low wind penetration the final decision usually does not include storage.

Reserve provided by the storage is the difference between the maximum power output of the $Pw_{ST}^{\max}(s)$ minus de power returned to the system $G_{st}(s,t)$. This is possible only if the storage facility has enough energy stored, $E_{stored}(s,t)$ in order to provide this service. Finally, it has been considered that certain storage technologies such as batteries cannot provide completely the reserve requirements of the system. For those technologies that only can provide standing reserve ($Std(s) = 1$, batteries), the provision of reserve is limited to a fraction $\chi_{Std}$ of the total system reserve requirements. This fraction has been considered to be a 40% of the total system reserve requirements as was made by the author of reference [15].

$$Res_{st}(s,t) \leq Pw_{ST}^{\max}(s) - G_{st}(s,t)\ \forall t \in 1,T, \forall s \in 1,S$$
$$Res_{st}(s,t) \leq E_{stored}(s,t)\ \forall t \in 1,T, \forall s \in 1,S$$
$$Res_{st}(s,t) \leq \chi_{Std} * \mathrm{Res_{sys}} * Std(s) + M * \left(1 - Std(s)\right)$$

Equation 64

The reserve-related contribution of DSM schemes $Res_{DSM}(t)$, is similar to the generation contribution: it is the DSM capacity still available, i.e., $DSM_{sh}^{\max}(t) - DSM(t)$ where $DSM_{sh}^{\max}(t)$ is the maximum DSM capacity that can be used at instant *t*. Demand curtailment has not been considered in reserve provision.

To the previous constraints, it would be necessary to add the specific constraints that affect only to generators (II.3.1.3), storage (III.5.1) and demand side management (IV.5.1). These constraints have been properly explained in previous chapters and do not change because of the simultaneous analysis of storage and DSM so they are not going to be reproduced again.

## V.3. RESULTS ANALYSIS AND OVERALL COMPARISON

In this chapter, the analysis of the results focuses on the comparison of all the possibilities at the same time. First of all, a comparison of the effect of the external resource on the timely evolution of the system is showed. Then, as it has been made in the previous chapter, a breakdown of the costs in a low wind scenario is analysed and finally a comparison between the low wind scenario and a high wind scenario is explained.

### V.3.1 Comparison of the effect on the System performance

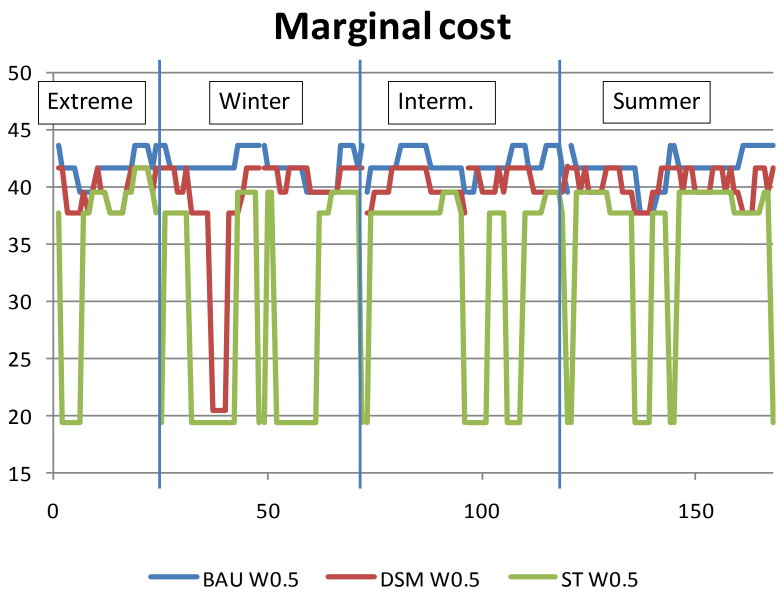



*Figure 53 Example of the time evolution of the Marginal cost.*

Figure 53 shows a representative example of the evolution of the marginal price in the system. Both storage and demand side management improve the performance of the system reducing the marginal price being storage who shows the greater improvement. This could be a result of its grater power capacity (500 MW) but also a consequence the limited capacity available for DSM. However, there will be always a limit on the penetration of demand side management. The limit of the storage is only the investment.

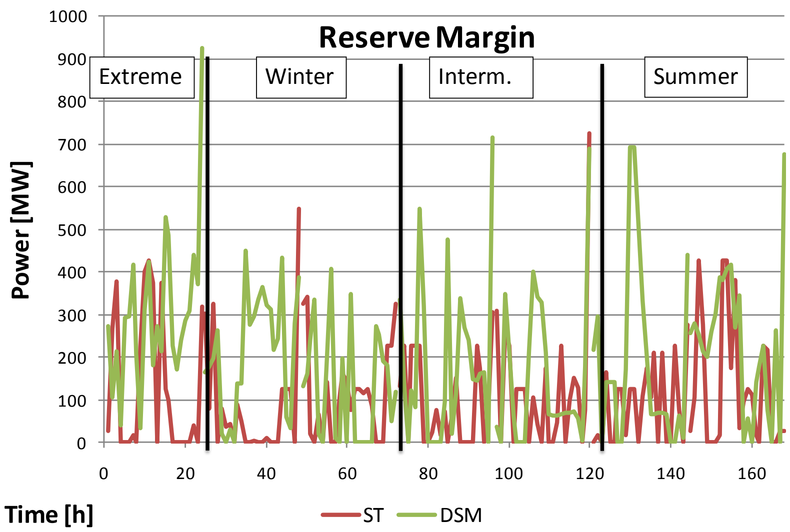



*Figure 54 Reserve requirements*

Similarly to the previous figure, the time evolution of the reserve requirements shows that storage is the external resource that produces the greatest reduction of the excess of reserves in the system. As it has been commented this difference is probably a result of the limited power capacity of DSM. In previous chapters it has been showed that both possibilities have an improvement compared to the BAU situation.

### V.3.2 Low variable wind scenario

It is important to highlight that the objective of this chapter is the comparison of the results of storage and DSM. A separate analysis has been made in previous chapters.

The following figures show the results derived from the model with the introduction of storage or demand side management. A comparison between scenarios with storage (**ST**), **DSM** and without both of them, business as usual, **(BAU)** is made. The situation with both resources at the same time has not been made because of the impossibility to run the complete model with a reasonable amount of time. The results regarding the selection of the generation portfolio (CAPEX) and the generation schedule (OPEX) are showed for a progressive integration of wind generation with low variability.

The different wind penetration degrees have been marked as W0.X where the "X" means the energy supplied by wind generation from the total energy that is required by the demand. For example, "W0.1" means 10% of the energy supplied by wind; "W0.3" means 30% and so on.

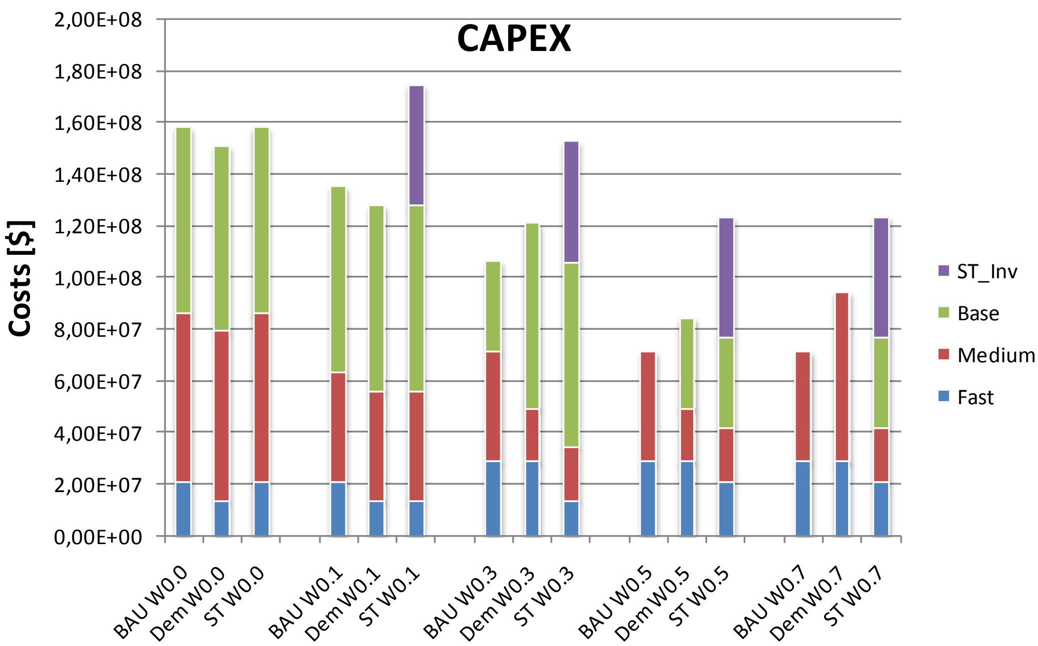



*Figure 55: Breakdown of CAPEX costs, low variable wind scenario*

Regarding the selection of the generation units, Figure 55 shows that the introduction of external flexibility resources reduces the requirements of peaking units (blue and red). Conversely, the presence of wind power increases it. The progressive increase in wind generation decreases the total amount of units required. It is interesting that storage is not cost effective until some wind is considered in the system.

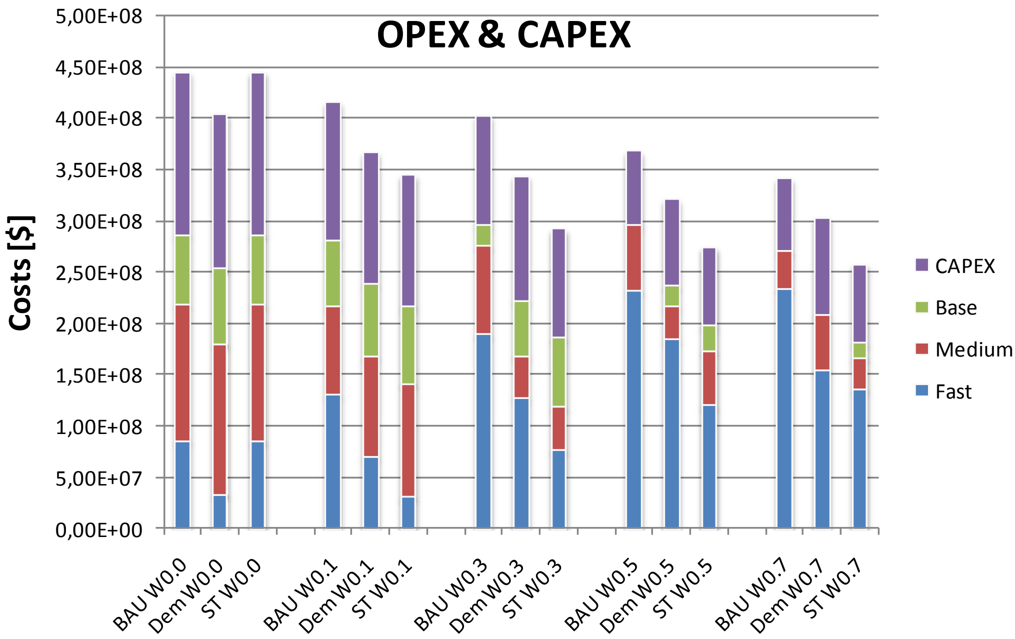



*Figure 56: Breakdown of OPEX costs, low variable wind scenario*

Figure 56 presents the breakdown of costs for all the studied cases. As expected, due to the incorporation of DSM or Storage, costs were reduced. Interestingly, DSM does not improve overall costs as much as it does when wind power is considered. For greater degrees of wind penetration, again the contribution of DSM reduces probably because its limited capacity considered. However, for the cases with and without wind generation, the introduction of DSM reduces significantly the requirements of peaking units. Storage clearly increases the capacity investment costs but at the same time reduces the necessity of fast an intermediate units. Thus, it can be said that storage and DSM make the system more flexible.

As was expected wind generation, not part of the generation portfolio, reduces the demand, and it results in a reduction of generation costs. However, **investment related to wind power is not considered in the problem formulation** as the focus is the search of the generation portfolio that will make the system flexible and introduce as much wind as possible.

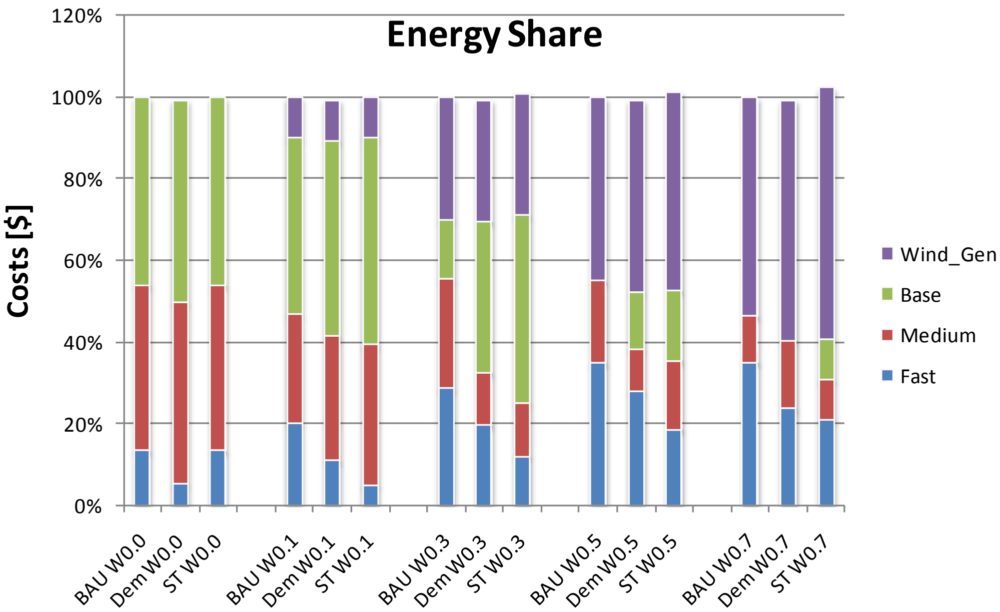



*Figure 57 Energy share, low variable wind scenario*

The trend observed in the operational costs is clearer in the energy share of technologies Figure 57. The increase in wind generation requires an increase in fast generation technologies and reduces the commitment of base generation.

### V.3.3 High variable wind scenario

Finally, next figures show an overall comparison of the results with wind profiles with low (previous charts) and high variability.

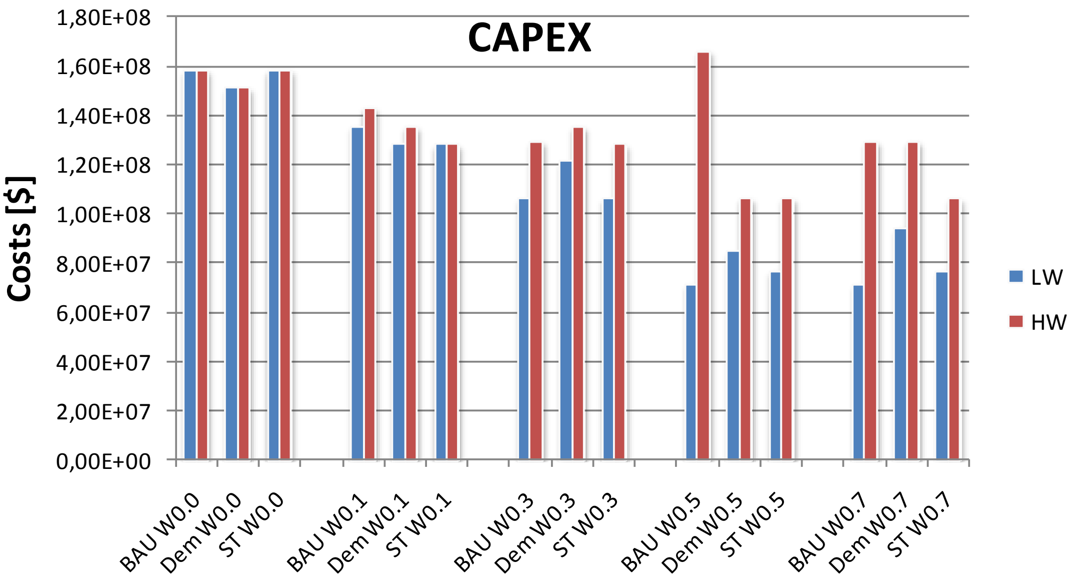



*Figure 58: Comparison CAPEX costs, low and high variable wind*

Figure 58 shows that once the generation mix is optimized for a certain wind situation, the operational cost does not vary. However, this could be a result of the selected wind profiles. Furthermore, the final energy to be delivered is the same so it is not very estrange that the final cost does not vary too much. On the other hand, the variability of wind generation increases notably the operational costs and this trend increases with the degree of wind penetration.

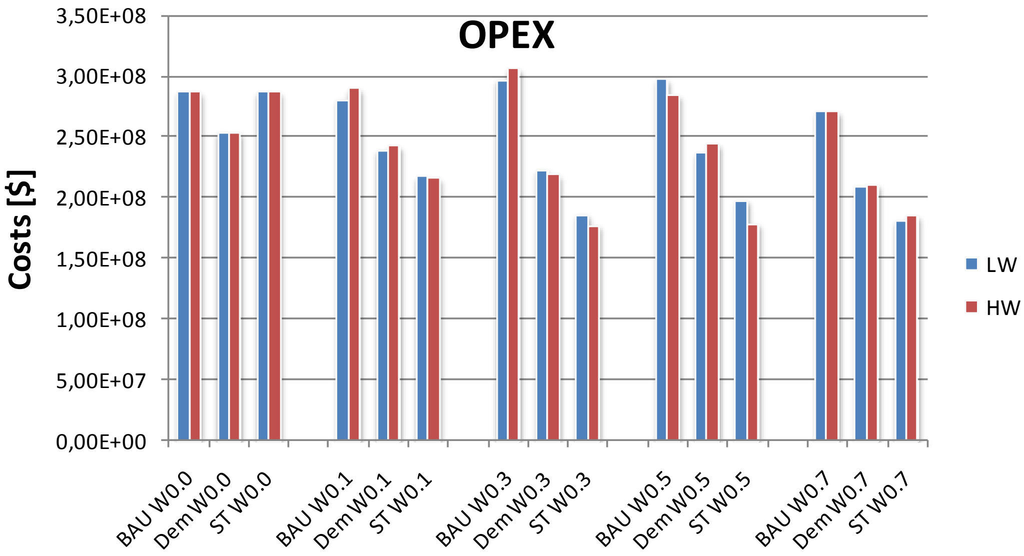



*Figure 59 : Comparison OPEX costs, low and high variable wind*

As it has been observed previously, wind variability does not have a great impact on the operational cost of the system. This could mean that once the generation portfolio is ready to handle difficult situations the effect on the final costs is not very high. On the other hand, this could be a result of the method employed to select the wind profiles.


*Figure 60: Comparison Total costs, low and high variable wind*

Finally, the overall comparison of costs shows that wind variability increases the total expenditure and this effect is clearer while the degree of penetration of wind generation increases. Therefore, the more wind is present of a system the variability of this wind needs to be reduced so the overall cost does not increase.

## V.4. SUMMARY AND CONCLUSIONS

During this chapter a comparison of the external flexibility resources (storage and demand side management) has been made. Moreover, the improvements to introduce both possibilities in the model have been explained. The complete model cannot be run at a reasonable duration so the final results have not contemplated this possibility. Finally, an overall comparison of the results showed in the previous chapters has been made focusing on the differences between storage and demand side management.

The analysis of the evolution of the state of the system (marginal price and reserves) showed that both DSM and storage improve the performance of the system reducing the cost and the reserve provided by conventional generation. Storage showed a better performance than DSM but this result is conditioned to the lower energy that is possible to be shifted by DSM.

The study of the overall costs showed that both storage and DSM increase the share of base generation and reduces the requirements of peaking units and the cost associated to the energy provided by them. Similarly, storage showed a greater reduction of the costs despite of the introduction of the storage investment cost. However, DSM has been considered a limited resource and therefore, the comparison is not completely fair.

Finally, the comparison of the costs associated to the variability of the wind showed that the main impact of this parameter was an increase of the investment cost (CAPEX). The operational costs were not affected by the wind variability probably because the increase in the energy given by fast units is not very high.

# VI. CONCLUSIONS AND RECOMMENDATIONS

## VI.1. CONCLUSIONS ANALYSIS

This work has proposed a methodology based on an enhanced unit commitment, able not only to consider short-term but also long-term operational and planning aspects. This technique has proven to be a powerful tool to analyse the requirements of flexibility in power systems. Results from its application to the simplified RTS system show that as wind is introduced in the generation mix, more flexibility is required. This translates in the displacement of base generation by fast and expensive generation in order to handle wind variability and maintain the reliability of the system. To reduce this effect other external flexibility resources are required.

Provided the corresponding real-time monitoring and control, demand side management (DSM) schemes, such as the aggregation of smart appliances, have demonstrated their ability to not only improve the performance of the system, but also allow greater degrees of renewable resources penetration, especially wind. During the first stages of deployment of renewable energies tariffs that encourage the displacement of load from peak to off peak periods would get a reasonable approach to an optimal solution. For greater degrees of renewable generation, more interaction between the demand and the generation will be needed. Since demand is not going to be constantly aware of the system situation, aggregators of customers will handle demand response and guarantee its reliability. Furthermore, if not managed properly, DSM threatens the comfort of the customers so there should be a compensation for the provision of this type of services. Furthermore, this means that the maximum demand that could be controlled is limited

Starting from the disadvantages of DSM, storage has proven that has the capabilities to be part of the solution in a cost effective manner. The main contribution of this resource is the reduction of the cost to maintain the reliability of the system and saving wind energy when there is an excess of it.

More specifically, storage has proven its profitability in high wind penetration scenarios and situations with a high wind variability, especially if reserve requirements are considered. This result is particularly important in islanded systems where reliability is a mayor issue. Furthermore, storage does not have the uncertainties on its availability so it is more suited to provide reserves if enough energy is stored. On the other hand, demand side management does not have efficiency losses so it a preferable resource to be used than storage.

## VI.2. SUGGESTIONS FOR FUTURE WORK

The recommendations to improve the analysis that has been presented in this thesis are the following:

***Improvements in the method:***

- **Interconnections with other systems**: to have a complete modelling of the possibilities of flexibility it could be interesting to add international connections to the model already developed [22]. This would increase the precision on the analysis of the effect of wind variability on the system performance.
- **Stochastic modelling**: other authors in [3], [6] and [26] have shown that employing stochastic approaches reduces the overall cost when Unit Commitment models are used.
- **Fuzzy Clustering:** Combined to the previous stochastic modelling, it would be more precise to model the input profiles (demand and wind) with fuzzy clustering instead of using hard clustering (k-means). This approach is especially interesting with wind generation due to its uncertainty.
- **Imperfect competition**: It could be interesting, especially in the analysis of the contribution of DSM to observe the impact of imperfect competition on the results.

***Other possible additions:***

- **Future scenarios and incremental situations:** With real data of a certain power system, it would be interesting to observe the results with an incremental situation: start from a current portfolio of a system, elaborate a future scenario of wind generation and decide the required evolution of the current generation portfolio.
- Improvement of demand side modelling to include other loads, such as other appliances, and electric vehicles (which could constitute a combination of DSM and storage if vehicle to grid schemes are considered).
- It the computational time of the model is improved it would be interesting to perform **a sensitivity analysis of the price of the storage**.
- Introduce the investment cost of wind generation and DSM inside the model so the complete investment costs are analysed.

# VII. REFERENCES

## GENERAL AND FLEXIBILITY REFERENCES

[1] F. P. Sener, "System planning using existing flexibility," IEEE Trans. on Power Systems, vol. 11, no. 4, pp. 1874-1878, Nov. 1996.

[2] G. Xu, C. Kang, G. Yang, and Z. Wang, "A novel flexibility evaluating approach for power system planning under deregulated environment," in Proc. 2006 International Conference on Power System Technology (PowerCon), pp. 1-6

[3] A. Tuohy, P. Meibom, E. Denny, and M. O'Malley, "Unit Commitment for Systems With Significant Wind Penetration," Power Systems, IEEE Transactions on, vol. 24, 2009, pp. 592-601.

[4] V. Silva, "Value of flexibility in systems with large wind penetration" thesis submitted to University of London for the degree of Doctor of Philosophy.

[5] Tao Li and M. Shahidehpour, "Price-based unit commitment: a case of Lagrangian relaxation versus mixed integer programming," Power Systems, IEEE Transactions on, vol. 20, no. 4, pp. 2015-2025, 2005.

## STORAGE REFERENCES

[6] Mary Black and Goran Strbac, "Value of Bulk Energy Storage for Managing Wind Power Fluctuations," *Energy Conversion, IEEE Transactions on*, vol. 22, no. 1, pp. 197-205, 2007.

[7] DOE/NETL-2008/1330, "Market Analysis for emerging electric energy storage systems", July 31, 2008.

[8] M. Kandil, S. Farghal, and N. Hasanin, "Economic assessment of energy storage options in generation expansion planning," Generation, Transmission and Distribution, IEE Proceedings C, vol. 137, 1990, pp. 298-306

[9] S. Schoenung and C. Burns, "Utility energy storage applications studies," Energy Conversion, IEEE Transactions on, vol. 11, 1996, pp. 658-665.

[10] J. Garcia-Gonzalez, R. de la Muela, L. Santos, and A. Gonzalez, "Stochastic Joint Optimisation of Wind Generation and Pumped-Storage Units in an Electricity Market," Power Systems, IEEE Transactions on, vol. 23, 2008, pp. 460-468.

[11] E. Castronuovo and J. Lopes, "On the optimisation of the daily operation of a wind-hydro power plant," Power Systems, IEEE Transactions on, vol. 19, 2004, pp. 1599-1606.

[12] P. Brown, J. Peas Lopes, and M. Matos, “Optimisation of Pumped Storage Capacity in an Isolated Power System With Large Renewable Penetration,” Power Systems, IEEE Transactions on, vol. 23, 2008, pp. 523-531.

[13] O. Nilsson and D. Sjelvgren, “Hydro unit start-up costs and their impact on the short term scheduling strategies of Swedish power producers,” Power Systems, IEEE Transactions on, vol. 12, 1997, pp. 38-44.

[14] A. Tuohy and M. O'Malley, “Impact of pumped storage on power systems with increasing wind penetration,” *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, 2009, pp. 1-8

[15] Derk J. Swider, “Compressed Air Energy Storage in an Electricity System With Significant Wind Power Generation,” Energy Conversion, IEEE Transactions on, vol. 22, 2007, pp. 95-102.

[16] A. Daneshi, M. Khederzadeh, N. Sadrmomtazi, and J. Olamaei, “Integration of wind power and energy storage in SCUC problem,” World Non-Grid-Connected Wind Power and Energy Conference (WNWEC), 2010, 2010, pp. 1-8.

[17] N. Miller, D. Manz, J. Roedel, P. Marken, and E. Kronbeck, “Utility scale Battery Energy Storage Systems,” *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1-7.

[18] K. Aoki, M. Itoh, T. Satoh, K. Nara, and M. Kanezashi, “Optimal long-term unit commitment in large scale systems including fuel constrained thermal and pumped-storage hydro,” Power Systems, IEEE Transactions on, vol. 4, 1989, pp. 1065-1073.

### DEMAND SIDE MANAGEMENT REFERENCES

[19] D. Kirschen, "Demand-side view of electricity markets," IEEE Trans. on Power Systems, vol. 18, no. 2, pp. 520-527, May 2003.

[20] G. Strbac, "Demand side management Benefits and challenges," Energy Policy, vol. 36, no. 12, pp. 4419-4426, Dec. 2008.

[21] C.-L. Su and D. Kirschen, "Quantifying the effect of demand response on electricity markets," *IEEE Trans. on Power Systems*, vol. 24, no. 3, pp. 1199-1207, Aug. 2009.

[22] R. Tyagi, J. Black, and J. Petersen, “Scheduling demand response events with constraints on total number of events per year,” *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, 2010, pp. 1501-1504.

[23] A. Kowli and G. Gross, "Quantifying the variable effects of systems with demand response resources," *in Proc. 2010 Bulk Power System Dynamics and Control Symposium (iREP)*.

[24] M. Akmal, D. Flynn, J. Kennedy, and B. Fox, "Flexible heat load for managing wind variability in the Irish power system," *in Proc. 2009 International Universities Power Engineering Conference (UPEC)*.

[25] R. Sioshansi, "Evaluating the impacts of real-time pricing on the cost and value of wind generation," *IEEE Trans. on Power Systems*, vol. 25, no. 2, pp. 741-748, May 2010.

[26] A. Keane, A. Tuohy, P. Meibom, E. Denny, D. Flynn, A. Mullane, and M. O'Malley, “Demand side resource operation on the Irish power system with high wind power penetration,” *Energy Policy*, vol. In Press, Corrected Proof.

[27] Yun Tiam Tan, Daniel S. Kirschen, “Co-optimisation of Energy and Reserve in Electricity Markets with Demand-side Participation in Reserve Services” in *Power Systems Conference and Exposition, 2006. PSCE ’06. 2006 IEEE PES*, 2006, pp. 1182-1189.

[28] M. Parvania and M. Fotuhi-Firuzabad, “Demand Response Scheduling by Stochastic SCUC,” *Smart Grid, IEEE Transactions on*, vol. 1, no. 1, pp. 89-98, M2010.

CLUSTERING

[29] F. Rodrigues, J. Duarte, V. Figueiredo, Z. Vale, and M. Cordeiro, “A Comparative Analysis of Clustering Algorithms Applied to Load Profiling,” *Machine Learning and Data Mining in Pattern Recognition*, Springer Berlin / Heidelberg, 2003, pp. 73-85-85.

[30] Data mining tutorials, K-means and Hierarchical Clustering, Andrew Moore, http://www.autonlab.org/tutorials/

[31] Help browser, Matlab 7.6.0, Statistics toolbox k-means.

REFERENCES OF DATA EMPLOYED TO ELABORATE ANALYSIS CASE

[32] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, "The IEEE Reliability Test System-1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee," IEEE Trans. on Power Systems, vol. 14, no. 3, pp. 1010-1020, Aug. 1999.

[33] ETSAP Energy Technologies Systems Analysis Program, Energy technology data source series. Available at: http://www.etsap.org/E-techDS/

[34] System Operator for Northern Ireland, “Minimum Function Specification for centrally dispatched Closed Cycle Gas Turbines (CCGT)”, April 2010.

[35] T. Boehme, J. Taylor, A. R. Wallace, and J. W. Bialek, "Matching renewable electricity generation with demand," Scottish Executive, Edinburgh, Feb. 2006.

[36] http://www.electricitystorage.org/ESA/

[37] ALChe MES white paper “Massive electricity storage”. Available online at http //www.aiche.org/

[38] Patrick Sullivan, Walter Short, and Nate Blair, “Modelling the Benefits of Storage Technologies to Wind Power”, Presented at the American Wind Energy Association (AWEA) WindPower 2008 Conference , June 1–4, 2008

[39] Holst, Kent. “Iowa Stored Energy Plant, Status Report,” California Energy Commission. February 2005.

[40] Greenblatt J. B., Succar S., Denkenberger D. C., Williams R. H., 2004, “Toward Optimisation of a Wind/Compressed Air Energy Storage (CAES) Power System”, Proc. of ASME Power 04 Conference, Baltimore, MD, 30 March – 1 April 2004.

[41] A. J. Roscoe and G. Ault, “Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response,” *Renewable Power Generation, IET*, vol. 4, no. 4, pp. 369-382, 2010.

[42] Virginia Electric and Power Company Schedule, “RESIDENTIAL CRITICAL PEAK PRICING (EXPERIMENTAL)”, November 2009. Downloadable at: http://mvproject.com/downloads/Virginia%20Electric%20and%20Power%20Company_1-CPP%20Rates%20%28Experimental%29.pdf

RESERVE REQUIREMENTS:

[43] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, “A Survey of Frequency and Voltage Control Ancillary Services—Part I: Technical Features,” Power Systems, IEEE Transactions on, vol. 22, no. 1, pp. 350-357, 2007.

[44] National grid documents about balancing services, http://www.nationalgrid.com/uk/Electricity/Balancing/services/

WIND:

[45] Global Wind Energy Council, “Global wind energy outlook 2010,” Available http://www.gwec.net.

[46] Global Wind Energy Council, “Annual market update 2010,” Available http://www.gwec.net.

[47] www.windpower.org.

[48] I. E.-. Europe, "Wind Energy - The Facts (WindFacts)," 2009.

OTHER REFERENCES

[49] Dipl.-Kfm. Jörg Schindler, Dr. Werner Zittel “Crude Oil – The supply Outlook”, Energy Watch Group / Ludwig-Boelkow-Foundation, February 2008

[50] Spanish electricity and gas market operator website: www.omel.es

"Dash Xpress MP - Optimisation Software", Dash-Associates. Available from: http://www.dashoptimisation.com.

# Appendix A. GENERATORS PORTFOLIO. IEEE RTS

In this section, the proposed generation portfolio used to test is applied using a simplified and updated version of the IEEE Reliability Test System (RTS-96) [32]. It is important to highlight that is theoretical portfolio to compare fast, medium and base generation. However, each possibility represents generally some of the main generation technologies: fuel or carbon, CCGT and nuclear generation.

| Unit ID | Unit | Investment cost | life expectancy | Min. Power | Step 1 | Step 2 | Max. Power | No load cost | Start up cost | Marginal cost 1st segment | Marginal cost 2nd segment | Marginal cost 3rdt segment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | Name | [$/MW] | [year] | [MW] | [MW] | [MW] | [MW] | [$/h] | [$] | [$/MWh] | [$/MWh] | [$/MWh] |
| 1-4 | Fast | 400000 | 30 | 200 | 300 | 400 | 500 | 117.31 | 5 | 37.711 | 37.839 | 37.967 |
| 5-8 | Medium | 1250000 | 30 | 300 | 350 | 425 | 500 | 170 | 50 | 18.467 | 18.779 | 19.09 |
| 9-10 | Base | 2100000 | 45 | 400 | 433 | 466 | 500 | 271.2 | 0 | 8.0741 | 8.4621 | 8.8501 |

*Table 5 Cost characteristics of the generators portfolio*

| Unit ID | Unit | Investment cost | life expectancy | Min. Power | Max. Power | Min. Time up | Min. Time down | Ramp up down limit |
|---|---|---|---|---|---|---|---|---|
| Number | Name | [$/MW] | [year] | [MW] | [MW] | [h] | [h] | [MW/h] |
| 1-4 | Fast | 400000 | 30 | 200 | 500 | 4 | 4 | 300 |
| 5-8 | Medium | 1250000 | 30 | 300 | 500 | 6 | 4 | 150 |
| 9-10 | Base | 2100000 | 45 | 400 | 500 | 8 | 8 | 50 |

*Table 6 Dynamic characteristics of the generators portfolio*

The costs have been actualized taking into account the analysis performed by [33]. Base generation is characterized by high investment cost and low generation cost. On the other hand, fast generation is characterized by a high generation cost and a low investment cost (Table 5). Similarly to how the costs have been modelled, the dynamic characteristics are based on the generators capacities from [32] for fast and base and from [34] for medium generation (Table 6).

In the decision of the final number of available generators that constituted the portfolio, was made to balancing the required computing time of the model and the precision of the final results. The required time increases exponentially with the number of days analysed and the number of generators available. Since the number of clusters shouldn't be reduced more, the final decision was on the number of generators.

# Appendix B. RESULTS DAY SIMPLIFICATION OF THE YEAR

As demand data, it has been used the demand profile of Scotland of the year 2006 [33]. The tests performed, showed that a reasonable equilibrium between simulation time and resolution was using six days to model the year, three work days and three weekends, and an additional day to model extreme situations. Using this quantity as initialization parameter of the clustering algorithm, the results are the following:

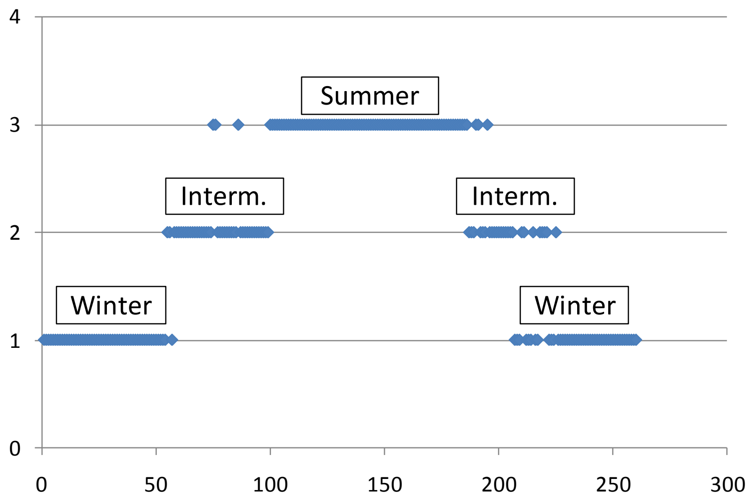



*Figure 61 Assignation of clusters along the year for work days*

To simplify ensure that the selection of the clusters did not mixed work days and weekends, the selection was made separately. Figure 61 shows the assignation of the clusters through all the days of the year. Looking it without too much detail, the seasons of the year can be clearly distinguished. For some observations the results get mixed a little bit but the shape is clear. To make it more friendly, the clusters are going to be identified by the name of the season that they correspond.

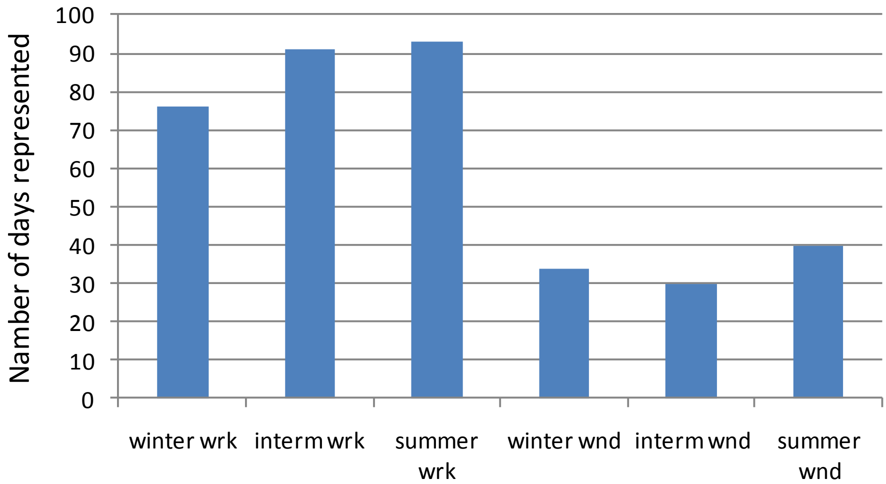



*Figure 62 Clustering assignation result*

Figure 62, shows how many observations have been assigned to each of the clusters that have been created. It is important to highlight that all the clusters are representative of the sample. The coefficients for the objective function of each pattern are directly the number of days that each pattern represents.

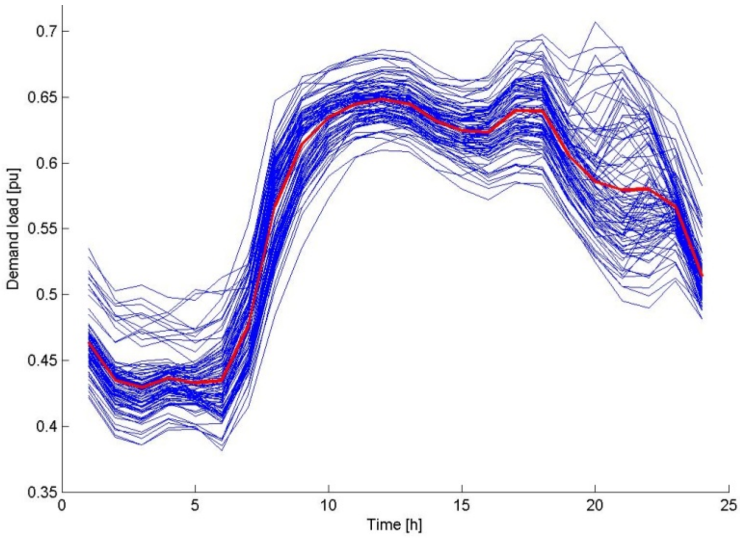



*Figure 63 Example of a Cluster and the assigned observations*

An example of a cluster and the day loads assigned to it is showed on Figure 63. The results show that the majority of the observations are close to the pattern as the previous results showed. The few that are different do not have a critical impact on the shape of the pattern.

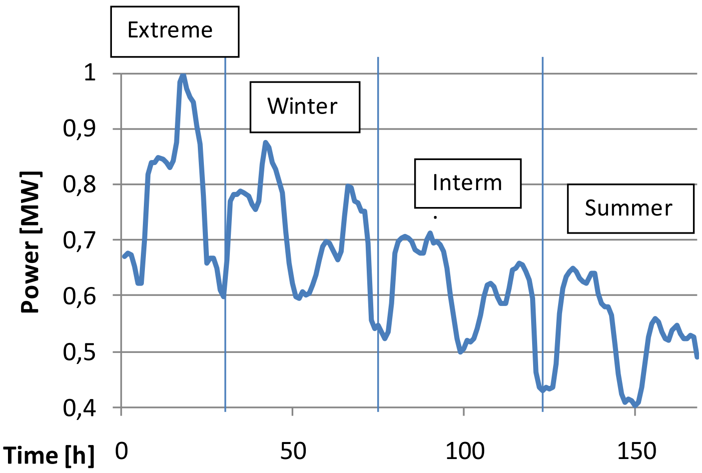



*Figure 64 Different profiles clusters and the extreme week profile.*

| | | Weighting coeficient | Standard deviation | Average load (pu) | Maximum load (pu) | Part of the year |
|---|---|---|---|---|---|---|
| Work days | | 76 | 2.6% | 0.78 | 0.88 | winter |
| | | 91 | 4.2% | 0.64 | 0.71 | interm. |
| | | 93 | 3.4% | 0.56 | 0.65 | summer |
| Weekend days | | 34 | 2.8% | 0.68 | 0.80 | winter |
| | | 30 | 3.7% | 0.59 | 0.66 | interm. |
| | | 40 | 4.1% | 0.49 | 0.56 | summer |
| Extreme week | | 1 | - | 0.82 | 1.00 | - |

*Table 7 Characteristics of each cluster*

As it has been mentioned, to ensure that the final solution would be able to handle every possible situation, it has been added an extreme day that has a small impact on the objective function, but ensures that the dynamic constraints are going to be respected during hard times. Together, Figure 64 and Table 7 show the main characteristics of the final patterns selected. As was expected, the winter week is over all the cluster profiles and close to the extreme situation. Furthermore, as was observed on Figure 63, the standard deviation between the clusters and the assigned observations is reasonable, so the method is reasonable.

To sum up, some patterns to model the whole year have been achieved using the methodology explained in the chapter II.3.2. The method has proven to be useful since the results show that the clusters are representative of the sample. Furthermore, an extreme situation has been added to ensure that the final generation portfolio will be able to handle not only normal situation but also extreme conditions.

# Appendix C. RESULTS WEEK SIMPLIFICATION OF THE YEAR

This annex shows the results achieved on modelling the year with weeks. They were **not used on the final analysis** because it was too much **burden for the computer**. However, they are showed here because the year model was accurate and could be interesting for other models.

As demand data, it has been used the demand profile of Scotland of the year 2006 [33]. To have enough resolution to model the year, it was considered that four weeks would be enough, one for each season of the year. Using this quantity as initialization parameter of the clustering algorithm, the results are the following:

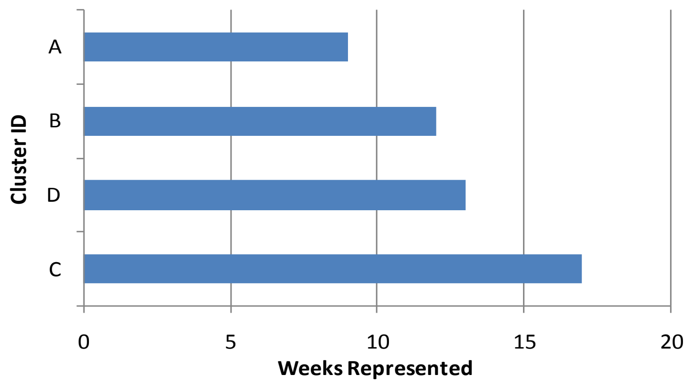



*Figure 65 Clustering assignation result. Week clusters*

| Cluster ID | Weeks Represented |
|---|---|
| A | 9 |
| B | 12 |
| C | 17 |
| D | 13 |

*Table 8. Weighted coefficients of each pattern. Week clusters.*

Figure 65, shows how many observations have been assigned to each of the clusters that have been created. It shows that all the clusters are representative of the sample. The coefficients for the objective function of each pattern showed in Table 7 are directly the number of weeks that each pattern represents.

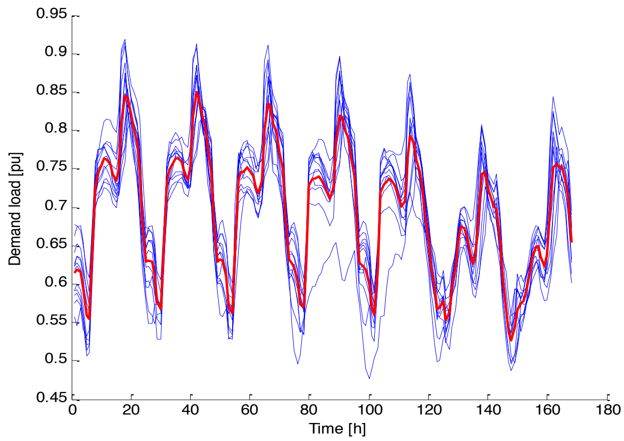


*Figure 66 Example of a Cluster (B) and the assigned profiles*

An example of a cluster and the weeks assigned to it is showed on Figure 66. The results show that the majority of the observations are similar to the pattern. The few that are different do not have a critical impact on the shape of the pattern.

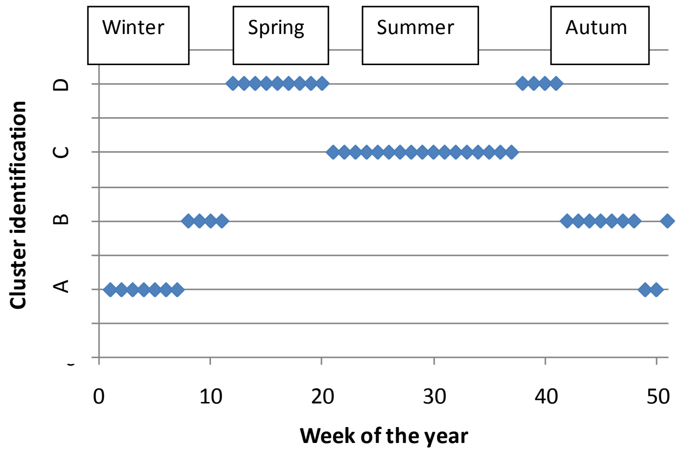



*Figure 67 Assignation of clusters along the year.*

Figure 67 shows the assignation of the clusters through all the weeks of the year. Looking it without too much detail, the four seasons of the year can be distinguished. To make it more friendly, the clusters are going to be identified by the name of the season that they correspond.

Despite this profiles are enough to model the average load of the year with reasonable resolution, they do not guarantee that the final selection would be able to handle the whole year. To avoid this problem, it has been added an “extreme winter” week that has a small impact on the objective function, but ensures that the constraints are going to be fulfilled during hard times.

| Cluster ID | Weighted coefficient OF |
|---|---|
| Winter | 9 |
| Autum | 12 |
| Summer | 17 |
| Spring | 13 |
| Ext. Winter | 1 |

*Table 9 Final coefficients on the objective function*

In order to have complete weeks starting from Monday some days were removed. Because of that a complete week was missing. Therefore, the addition of the extreme winter week does not change the weighting coefficients of the rest of the weeks. The final year has 52 weeks as it should have.

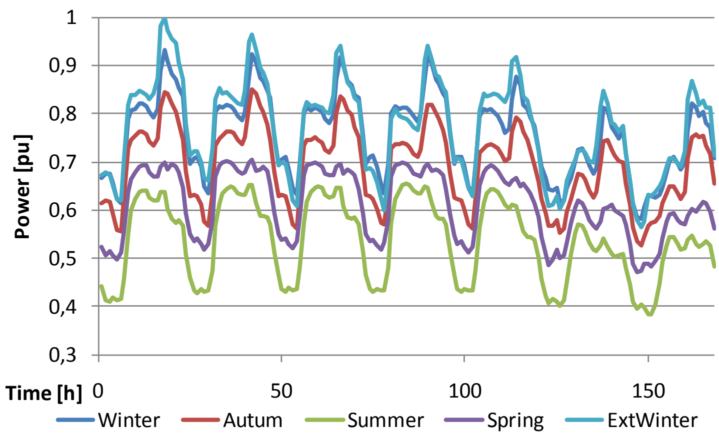



*Figure 68 Different profiles clusters and the extreme week profile.*

Finally, Figure 68 shows a comparison between the different weeks that have been chosen. As was expected, the winter week is over all the cluster profiles and very close to the extreme situation. It is interesting to see that spring and summer have flatter shapes so probably they will not suppose a big challenge on flexibility requirements.

To sum up, some patterns to model the whole year have been achieved using the methodology explained in the chapter II.3.2. The method has proven to be useful since the results show that the clusters are representative of the sample. Furthermore, an extreme situation has been added to ensure that the final generation portfolio will be able to handle not only normal situation but also extreme conditions.

# Appendix D. WIND DATA, SELECTION OF THE DAILY PROFILES

This subchapter explains the results that have been achieved from the methodology explained on II.3.3. First of all, the general characteristics and some explanations of the wind data are presented. Finally, the wind profiles that have been chosen for each of the patterns are presented below. As wind input for the model it has been used some wind profiles from Scotland [35]. The final wind profile is the average of some wind profiles. This average provides a wind which is not very highly location sensible and gives a general idea of the wind generation output of a certain area.

On a first sight, the distribution of the date of the wind output of the generation, Figure 69, could give the sensation of being excessive because of having too much hours of maximum output. However, taking into account the wind distribution Figure 70 and the relation between wind and power output, Figure 71, it is reasonable for location where the average wind speed is high.

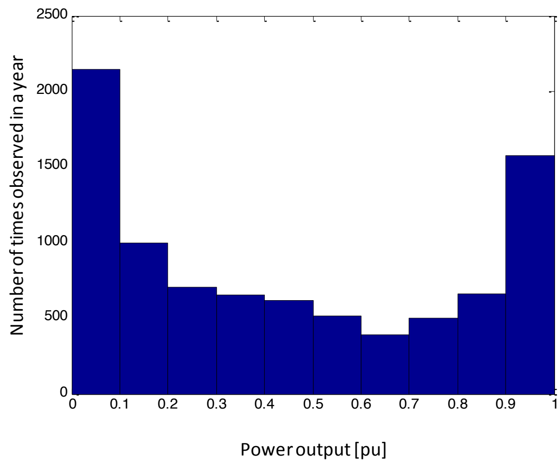



*Figure 69: Probability distribution of wind input data*

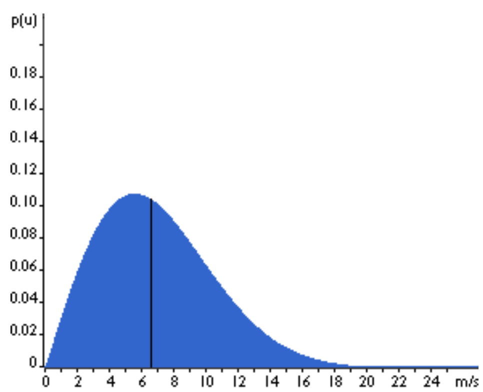



*Figure 70 Wind speed distribution*

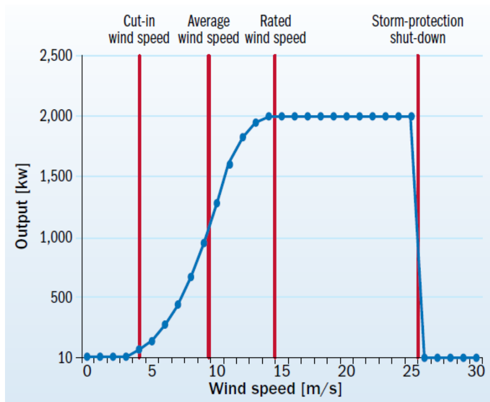



*Figure 71 Wind turbine power curve*

Starting from this wind as input data, as it has been explained on chapter II.3.3 some wind profiles have been chosen with the idea of representing a low (not very high) variable wind scenario, Figure 72, and a high variable wind scenario, Figure 73. As was observed in the trial of modelling the wind with clustering the results do not present any seasonal pattern.

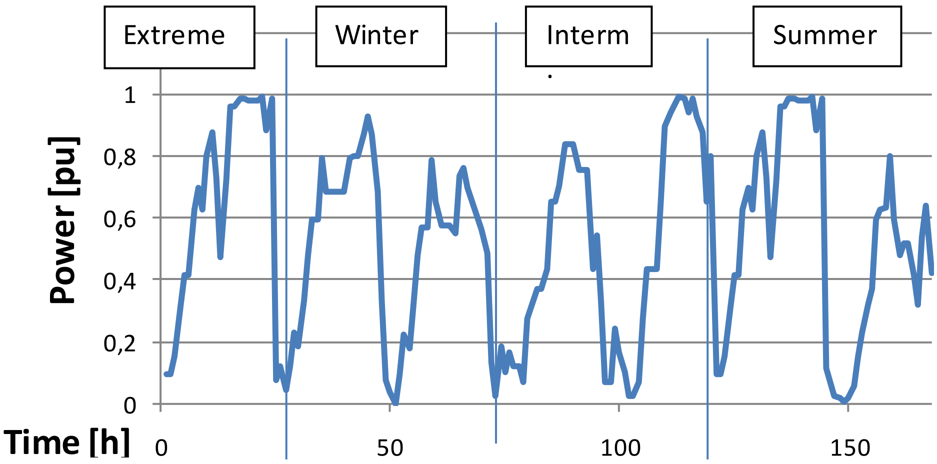



*Figure 72 Selection of wind profiles. Low wind scenario*

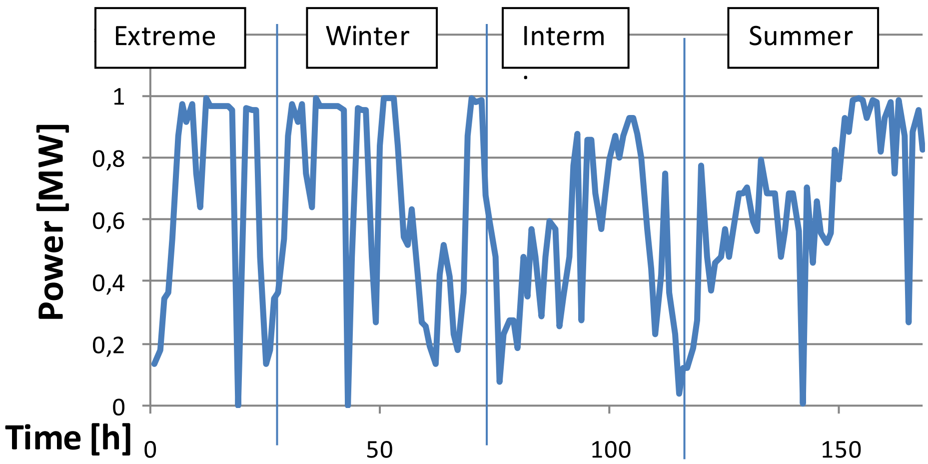



*Figure 73 Selection of wind profiles. Low wind scenario*

# Appendix E. PIECEWISE LINEAR APPROXIMATION OF THE GENERATION COST FUNCTION

Regarding that the developed model is based on mixed integer linear programming (MILP), it is necessary to simplify on a linear the cost curve of the generators. Usually, this is made by modelling the curve with linear segments as it is showed on Figure 74. When more simplicity is needed, an approximation without segments is adopted.

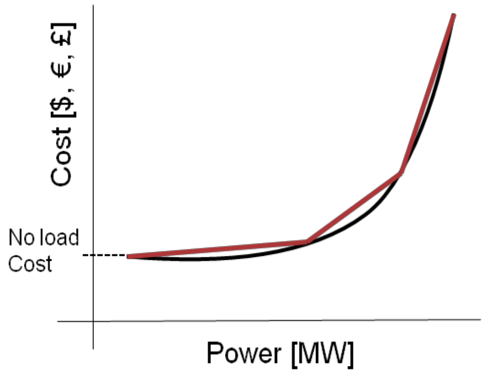


*Figure 74 Piecewise linear approximation of the curve of generation costs*

$$GC\big(P(i)\big) = a(i) + b(i) * P(i) + c(i) * \big(P(i)\big)^2 \qquad \text{Equation 65}$$

Equation 65 shows the typical quadratic approach of the curve of generation costs. Next equations show how this approach is modelled on a mathematical manner:

$$\sum_{p=1}^{P} G_{sg}(i,t,1) = G(i,t) \qquad \text{Equation 66}$$

$$G_{sg}(i,t,p) \geq 0.0 \ \forall t \in 1,T \ \forall i \in 1,I \ \forall p \in 1,P \qquad \text{Equation 67}$$

$$G_{sg}(i,t,1) \leq u_c(i,t) * G_{sg}^{max}(i,1) \ \forall t \in 1,T \ \forall i \in 1,I \qquad \text{Equation 68}$$

$$G_{sg}(i,t,p) \leq u_c(i,t) * \Big(G_{sg}^{max}(i,p) - G_{sg}^{max}(i,p-1)\Big) \qquad \text{Equation 69}$$
$$\forall t \in 1,T \ \forall i \in 1,I \ \forall p \in 2,P$$

Equation 66 shows that the total Generation $G(i,t)$ must be equal to the sum of the generation at each segment of the curve $G_{sg}(i,t,1)$. The group of equations Equation 67 to Equation 69 set the limits of each segment of the generation output $G_{sg}(i,t,p)$. Each segment must be over 0, Equation 67, and below the difference between its limit and the previous one, Equation 68 and Equation 69.