Università degli Studi di Bergamo
Dipartimento di matematica, Statistica, Informatica
e Applicazioni

Dottorato di ricerca in Metodi computazionali per le Previsioni
e Decisioni Economiche e Finanziarie
XXII Ciclo

Tesi di Dottorato

A stochastic model for a small producer with thermal units, wind power plants and storage technologies

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Febbraio 2012

Ai miei genitori

Ringraziamenti

Giunta alla fine di questo percorso, desidero esprimere la mia gratitudine verso tutti coloro che, in modi diversi, hanno contribuito al conseguimento di questo importante obiettivo.

Ringrazio in modo particolare la mia supervisor, Prof.ssa Maria Teresa Vespucci e la coordinatrice del corso, prof.ssa Marida Bertocchi, per la fiducia concessami, per l'incoraggiamento e per il sostegno umano e lavorativo. Sono inoltre molto grata al prof. Yves Smeers e al prof. Andrés Ramos che hanno contribuito allo sviluppo di questa tesi con preziosi input e suggerimenti.

Vorrei ringraziare il personale amministrativo dell'universitá di Bergamo e i professori, i ricercatori e i dottorandi con i quali ho avuto modo di relazionarmi in questi anni: il prof. Sergio Ortobelli che é stato una costante fonte di incoraggiamento; il prof. Vittorio Moriggia e il dott. Gaetano Iaquinta che hanno sacrificato parte del loro prezioso tempo per darmi consigli e suggerimenti utili per la stesura di questa tesi; il prof. Enrico Fabrizi, che con la sua spiccata ironia é riuscito a strapparmi un sorriso anche nei momenti piú bui; i miei compagni di corso Melania e Gianfranco G. con cui ho condiviso il primo anno di dottorato; Alda, Valeria, Daniele, Michela, Francesca, Annamaria, Paolo, Angelo, Gianfranco L., Dario e Antonio, che mi hanno sempre dimostrato affetto e amicizia; Rosario, Marco e Davide con i quali ho trascorso i pochi momenti di svago nell'ultimo periodo di stesura di questo lavoro.

Ricordando con nostalgia le giornate trascorse a Louvain La Neuve, ringrazio tutti coloro che hanno reso il mio soggiorno all'estero piú sereno e piacevole, in particolare: Emanuele, Marie, Gabriele, Giacomo, Fabio, Daniela, Marco, Luca e Alessandra.

Un affettuoso grazie alle mie amiche storiche, Stefania, Ilaria, Maria Teresa e Laura, lontane fisicamente, ma sempre presenti e vicine con il cuore.

Un pensiero va a anche al Prof. Aldo Pugliese, a Josephine, a Sergio e ad Alessandro, senza i quali questo percorso non avrebbe avuto inizio.

Vorrei esprimere inoltre la mia piú sentita gratitudine verso i miei genitori, che con il loro sostegno e la loro presenza discreta e costante, hanno reso possibile il concludersi di questo lavoro. Un grazie speciale a Claudia, silenziosamente vicina, a Grazia e Jessica per i consigli di stile, e a Gianluca che, nonostante la tenera etá, ha sempre mostrato interesse e curiositá per la mia ricerca.

Infine, ringrazio di cuore Andrea a cui va tutta la mia riconoscenza e il mio affetto, non solo perché mi ha supportato e sopportato in questi anni, ma

anche per essermi stato vicino in uno dei momenti piú difficili della mia vita. A Carlotta, a cui sono legata da un sentimento di profonda stima e fraterna amicizia, vorrei esprimere la mia gratitudine, per il tempo passato insieme, per la costante presenza e per il sostegno dimostratomi in ogni istante dal momento in cui ci siamo conosciute.
Last but not least, ringrazio infinitamente Federico, per l'aiuto incondizionato, per i giusti rimproveri e gli immeritati "Brava Filo!", e perché, standomi accanto, mi rende una persona migliore.

Non esiste vento favorevole
per il marinaio che non sa dove andare.

SENECA

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Introduction

Energy resources play an important role in the world. Energy is considered a significant factor in economic development and, during the last two decades, there has been a great deal of research on renewable energy technologies. Especially wind is considered one of the most important renewable resources and is probably the fastest growing renewable energy source in the world. However, despite technological developments and economic viability for several applications, renewable energy has been exploited only to a small fraction of its potential. This is due to the existence of several types of barriers to the penetration of this kind of resources. For this reason, in recent years, is considered increasingly important the development of storage technologies, that seems to have the potential to play key role in providing energy renewable energy.

In this thesis we propose a model to evaluate the impact of using a renewable source and storage technology. The aim of the work is to provide a tool for a small producer, operating in an electricity market, that aims at satisfying a part of market demand, with both traditional energy sources and wind energy. This tool takes into account the use of some storage technology, in order to assess their impact on maximization profit.

Work is structured as follows. In the first chapter we describe the most important renewable energy sources and technologies, and identify both barriers and benefits of renewable energy penetration. The overview of renewable energies is mainly focused on wind energy. A review of recent literature, to illustrate some mechanisms used to integrate renewable sources within energy systems and make them more attractive and competitive, is presented.

In the second chapter we analyse the existing storage technologies, their main characteristics and their main applications in energy systems. The storage devices overview includes the analysis of the literature on the implications of their use in an electrical system.

In the third chapter we develop a stochastic optimization model whereby a small energy producer aims at meeting a part of the market demand, in order to maximize his own profits. In our formulation, the producer can use both traditional energy sources and wind energy, and some specific kind of storage technology. The stochastic model represents a decision support tool, on a short time horizon, that allows to evaluate the variability of both wind resource and energy prices, and the impact of using innovative storage technologies.

The fourth chapter is devoted to validate the stochastic model proposed, based on an Italian electricity market data set. Some results are shown, concerning the use of some types of storage technologies and both thermal and wind energy. We focus also on the role of spinning reserve, that is requested when the producer uses an intermittent energy source. In particular, it highlights how the model is proposed as a tool to evaluate the effectiveness of a storage technology.

Chapter 1

Integrating wind energy in power system: a literature review

1.1 Introduction

The role of renewable energy sources (hereafter RES) has grown exponentially over the last years. The fast increasing trend in energy demand, the rapid climate changes and the stochasticity of energy supply, represent the most important drivers of this growth. Therefore, RES theme has attracted an increasing interest of both energy producers and international institutions offering new opportunities in energy sources diversification.

This chapter opens with an overview of renewable energies, mainly focused on wind energy.

A review of recent literature is then presented to illustrate both the benefits and the problems related to the use and integration of renewable energies in a power system.

1.2 Renewable energy sources: opportunities and problems

There are many alternative new and renewable energy sources which can be used instead of fossil and conventional fuels. Renewable energy resources, also called alternative sources of energy, are readily available in nature. From this sources, by using renewable energy technologies, we can convert natural phenomena into useful forms of energy.

Each of renewable technologies has different characteristics and problem, that make them more or less used.

1.2.1 Classification and description

By definition renewable energies derive from natural resources (such as sunlight, wind, rain, tides, and geothermal heat) and processes which are constantly and naturally replenished.

To identify renewable energies we usually refer to the time required to regenerate theme. All energy sources are regarded as "renewable" except fossil and nuclear energy which are characterized by an extremely long regeneration time and are exhaustible in terms of availability.

In the European legislation, this heuristic distinction has been made precise by art. 2 in Directive 2001/77/EC "On the promotion of electricity produced from RES": "renewable energy sources shall mean renewable non-fossil energy sources (wind, solar, geothermal, wave, tidal, hydropower, biomass[1], landfill gas, sewage treatment plant gas and biogases)". Moreover, same article defines as "electricity produced from renewable energy sources" the "electricity produced by plants using only renewable energy sources, as well as the proportion of electricity produced from renewable energy sources in hybrid plants also using conventional

[1]"Biomass shall mean the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste" (see Directive 2001/77/EC, Art. 2).

energy sources and including renewable electricity used for filling storage systems, and excluding electricity produced as a result of storage systems".

Note that cogeneration (that is, the combined production of electrical or mechanical energy and heat), waste heat - recoverable from rivers, heating systems, electrical and industrial processes are also considered renewable energies.

Within this wide class it is worth to highlight the main types of renewable energies:

- **Hydropower**: hydropower energy is the most exploited RES; hydropower plants classification is based either on their size or on the hydrographic features of their site[2]: large plants if the installed capacity is greater than 10 MW, small power plants with installed capacity between 1 and 10 MW, mini power plants with installed capacity between 100 kW and 1 MW, and micro power plants with less capacity) (see [27]).

  The main advantage of hydropower plants is that they can respond quickly (within a few minutes) to an unexpected network demand. They are also characterized by remarkable flexibility that is the ability to accomplish the trend of load peak periods, to adjust voltage frequency and power, and to restart the network if black-outs occur.

  Despite its relevance, the role of hydropower energy as a renewable source of energy is declining, especially in developed and industrialized countries where most of the existing sites are already fully ex-

[2]It's worth distinguishing the concepts of power and energy: the former is the rate at which work is performed, and its units of measurement are watt (W), kilowatt (kW), megawatt (MW); the latter is a measure of work and its units of measurement are watt per hour (Wh), kilowatt per hour (kWh) and megawatt per hour (MWh). A wind power plant with a production capacity of 100 kW, can produce 100 kW per hour and up to 2400 kWh per day, if it works full load (nameplate capacity). However, note that, since renewable energy production is never equal to the sum of generator nameplate ratings multiplied by the total hours in a year, the capacity factor (the ratio of actual productivity in a year to this theoretical maximum) is lower than conventional generators (see [6]).

ploited and the building of new plants is limited by environmental constraints. While large power plants are expected to be promoted in developing countries, the European development programs encourage small or micro projects that have a lower environmental impact, even if they result in a higher cost of electricity.

- **Solar energy**: each country, at different levels, has obviously access to solar energy; as we can read in the papers by Bartolazzi and Menna (see [6] and [27]) the use of this resource is quite diversified :
  - direct use of sun heat through collectors for hot water (or air);
  - solar energy thermodynamics based on the solar radiations concentration, using heat in a thermodynamic cycle of energy production (through concentrating solar systems);
  - photovoltaic energy, that is direct conversion of sunlight into electricity using photovoltaic cells.
- **Wind energy**: this kind of energy is based on the exploitation of the energy contained in the wind and generated as a result of differences between pressure and temperature at different layers of the atmosphere due to solar radiation.

  Differences in irradiation determine differences in temperature; differences in pressure and density are offset against the winds; the main irradiation difference depends on both earth inclination and rotation, but more relevant effects for wind power derive by low altitude, earth friction and orography[3].
- **Biomass energy**: biomass energy is gained by conversion of organic materials (see [2], [6] and [27]). Biomass includes:
  - a wide variety of organic materials (wood, crop residues and waste wood coming from both agricultural and forestry processing or appropriate cultures) and urban wastes;

[3]Wind energy is described in more details in section 1.3.

- special crops (sunflower, rapeseed, soya) that can be used to produce biodiesel;
- waste fermentation processes from some food industry used to produce biogas.

- **Geothermal energy**: it is defined as the electricity arising from underground heat. The main use of geothermal energy is the generation of electricity from natural steam, but there is also a widespread direct use of geothermal heat (hot water used for heating).

1.2.2 Global energy issue and renewable energy development

Looking at the international energy market, we notice that nowadays we still have a production system quite focused on either fossil energy sources (oil, carbon, natural gas) or uranium (nuclear energy)[4] (see [2] and [27]).

This situation arises because, in the past, both production and consumption choices resulted from evaluations of energy sources in terms of portability, availability and transformation capacity[5].

As a consequence, the environmental impact has long been overlooked also because it is hard to evaluate it in terms of energy production costs and to include it in the decisional process.

However, in more recent years, an increasing risk in both macroeconomic stability and ecosystem balance on a global scale has led the costs of energy supply to increase, as they are heavily dependent on fossil fuels.

[4]It is worth distinguishing between primary energy, i.e. energy before processing (oil, carbon, uranium, solar, wind), and secondary energy, i.e. energy transformation (electricity and heat in the power plant).

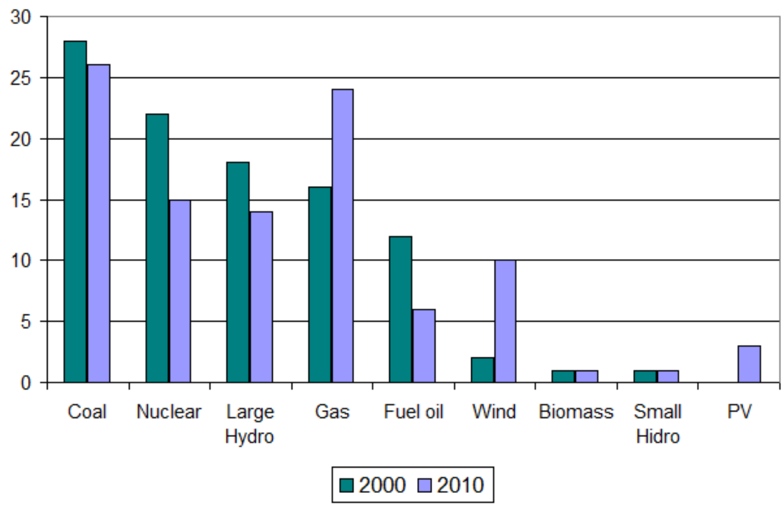
[5]Energy portability is defined as the ability to be easily transported, even to remote areas and at capillary level without losses; availability refers to the ability to use energy at any time and in any quantity; transformation capacity includes the ability to easily change the energy use for different purposes (see [6]).

Besides, rapidly increasing demand, climate changes and energy supply instability fed the debate on the existing energy models and led to assign to renewable energy (characterized by very low emissions) a key role in achieving the goals of environmental improvement, pollution emissions reduction and energy efficiency (measured in terms of energy intensity[6].

Referring to the European zone, the Figure 1.1 shows that, from 2000 to 2010, the EU power sector has moved away from fuel oil, coal and nuclear, whilst at the same time its total installed capacity has increased in order to meet increasing demand (see [45]).

Figure 1.1: EU power capacity mix 2000-2010 (MW%)

Source: author's estimated based on European wind energy association data



Historically, the issue of RES has been introduced first by the United Nations Conference on Human Environment in 1972, with the concept of "sustainable development", later revised by the World Commission on Environment and Development (WCED) that, in the Brundtland Report (1987), defined it as the "development that meets present needs without compromising the ability of future generations to meet their own needs".

[6]Energy intensity is defined as the ratio between the wealth produced in a country and its consumption of energy.

As for Europe, the promotion of renewable energy sources was taken as a priority by the European Commission first in 1986 when was outlined the new energy policy to be implemented within 10 years, and then reinforced in 1997 with the signing of the Kyoto Protocol[7].

One of the tools available to carry out the European Commission's strategy to implement the Kyoto Protocol is the European Climate Change Programme (ECCP), started in March 2000, in which a system for trading emission rights of greenhouse gases is outlined The mechanism, established by the Directive 2003/87/EC of European Parliament and Council, is called "Emission Trading Scheme" (ETS).

However, given the issues raised by this mechanism a new directive was proposed to amend the distribution system and reach the original goal "according to equity criterion and minimization cost for EU economy, taking into account the impact on international competitiveness, employment and social cohesion." The proposal, approved by the European Parliament in December 2008, has introduced a new Community Action Plan, (called "20-20-20") in the European energy policy. By 2020 three objectives are expected to be achieved:

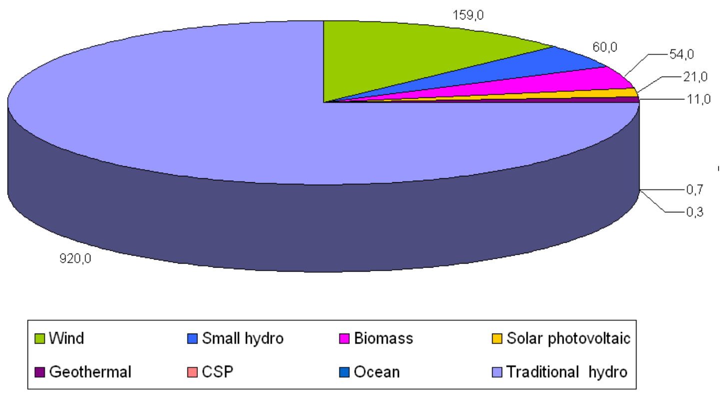
- reduction by 20% of greenhouse gases in the emissions;
- increase by 20% of energy efficiency by reducing energy consumption;
- increase of the share of energy from renewable sources up to 20% of the total energy from primary sources used in the EU. As for biofuels, at least 10% of total gasoline consumption and diesel fuel in the EU must come from renewable sources.

[7]The Kyoto Protocol represents the first attempt to reach, with the nations' consensus, an agreement to globally govern energy. By signing the Kyoto Protocol all the parties have committed themselves to reduce greenhouse gas emissions between 2008 and 2012 compared to 1990's levels.

Environmental factors and an increasing affordability reached through technological improvements, have made renewable energies more attractive; therefore, nowadays, in addition to traditional fuel sources, global energy production and consumption come from traditional renewables (biomass and hydropower) as well as new renewable sources (small hydro, modern biomass, wind, solar, geothermal, biofuels and hydrogen) that are growing at a fast rate (see Table1.1 and Figure1.2).

Figure 1.2: Renewable Electric Power Capacity, existing as of 2009

Source: author's estimated based on Renewables 2010 Global Status Report



1.2.3 Renewable energy: what are the problems?

Renewable energy sources have many advantages with respect to traditional fuel sources in terms of both production costs and reduction of pollution emissions, and they would be already competitive if the negative externalities (not easy to be quantified) determined by fossil fuels were explicitly considered.

Despite all energy sources are expensive, as time progresses, renewable energies generally get cheaper and more attractive, while fossil fuels get more expensive.

First, once a renewable infrastructure is built, the energy it produces is free: unlike carbon-based fuels, the wind, the sun and the earth itself

Renewable Electric Power Capacity, existing as of 2009 (GW)								
Technology	**Developing Countries**	**EU-27**	**China**	**United States**	**Germany**	**Spain**	**India**	**Japan**
Wind power	40	75	25.8	35.1	25.8	19.2	10.9	2.1
Small hydropower (<10 MW)	40	12	33	3	2	2	2	4
Biomass power	24	16	3.2	9	4	0.4	1.5	0.1
Solar photovoltaic-grid	0.5	16	0.4	1.2	9.8	3.4	0	2.6
Geothermal power	5	0.8	0	3.2	0	0	0	0.5
Concentrating solar thermal power (CSP)	0	0.2	0	0.5	0	0.2	0	0
Ocean power	0	0.3	0	0	0	0	0	0
Total RES capacity (small hydro)	**110**	**120**	**62**	**52**	**42**	**25**	**14**	**9**
Total hydropower (all sizes)	580	12	197	95	11	18	37	51
Total RES capacity (hydro all sizes)	**650**	**246**	**226**	**144**	**51**	**41**	**49**	**56**

Table 1.1: Renewable Electric Power Capacity, existing as of 2009
Source: Renewables 2010 Global Status Report

provide fuel over a limitless period of time, with a productive capacity limited just by the dimension of the infrastructure itself and the natural features of the site.

Second, while fossil fuel technologies are mature, RES technologies are rapidly improving. Technical innovation has determined a constant increase in their efficiency. Furthermore, the latest technological solutions allow to overcome most of the difficulties related to the use of renewable energy sources and to reduce the high incidence of fixed costs (whereby are often required some forms of incentive).

Third, once the main institutions make a clear commitment to shift towards renewable energies, the volume of production itself will sharply reduce the unit cost, while adding more incentives for additional research and development to further speed up the innovation process.

On the other hand, RES also have many problems that make difficult their use and keep high their costs. Some technological barriers remain high due to forecasting and storage difficulty. In a power system, in fact, uncertainty due to both variability and forecasting errors (made the day-ahead) implies the requirement of additional operating reserves; for example variability of the wind generation implies the requirement of another complementary flexible generation (e.g., hydro) (see [14], [38] and [42]).

Because of these reasons, both producers and system operators need a perfect forecast and control over the resources in order to manage the network efficiently and to obtain a good efficiency on renewable energy sources.

In addition, the collection and transformation of energy from renewable resources often requires much more cumbersome facilities than those used for oil and coal. In many cases this translates into profound changes to the landscape where these technologies have been installed.

Therefore the competitiveness of RES would benefit of both technological and cultural changes, because innovative solutions would make it possible to achieve higher economic returns, and a consumers' cultural change would lead to a greater market share.

1.3 Wind Energy case

Today, wind generated energy is the fastest growing source of renewable energy. This resource has numerous benefits of in terms of both costs and environmental impact. However, electricity generated from wind power can be highly variable at several different timescales: from hour to hour, daily, and seasonally. Therefore, like other electricity sources, wind energy must be scheduled, using different forecasting methods.

In the remainder we analyse we analyse the main issues related to wind resource.

1.3.1 Economic and financial feasibility of wind farms

Wind energy exploitation has experienced a remarkable development over the past decade, especially in several European countries (Germany, Denmark, Spain) where it gained a significant market share.

This was mainly due to technological progress allowing the development of offshore facilities and giving opportunities to exploit remote systems in regions characterized by network problems. This has also made possible to set up wind farms in developing countries, even though in this case special energy storage systems are required (see [27]).

The realization of wind power plants is characterized by the following key joints:

- the annual operating of a wind farm is discontinuous and related to the features of the wind site, since the production is intimately dependent on the wind speed and the size of the facility;
- initial investment costs represent the largest share of total costs and are predominant compared to the exercise costs; therefore they need to be taken into account while analysing the profitability of a wind energy initiative.

As shown in Figure 1.3, the initial investment can be divided into the following categories:

- initiative development, including the identification and qualification of a site, plant design and the authorization process (all these characteristics can vary, especially for environmental aspects) represents about 2-3% of the total investment;
- installation of wind turbines (75-80% of the total investment), as the most important expenditure. The cost of setting up the wind turbines, including purchasing, transportation, installation and start-up, is directly proportional to the rotor power and the tower height;
- ancillary products and infrastructure(16-18% of the total investment) including costs directly related to the complexity of the site, in relation to the morphology and the soil nature;
- connection to the grid (6-7% of the total investment).

Wind energy operating costs and production costs are related to:

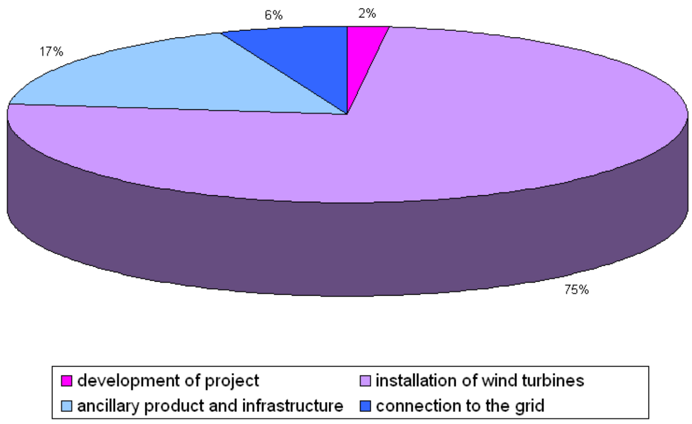
- continued operation and maintenance
- electricity production
- license fee
- dismission

As for the first two kinds of costs, it is worth mentioning that a wind farm does not have fuel costs; therefore, they include only costs referring to operative administration, license fee to local authorities for the use of the site, insurance premiums and maintenance costs (both ordinary and extraordinary).

Wind production is influenced by topography and characterized by a global trend with seasonal, daily and even hourly stochasticity. Most of wind resources are concentrated along the coastlines and in mountainous regions.

Turbines are installed and connected to the network individually or in multiple installations (wind farms), and almost all advanced countries

Figure 1.3: Wind investment costs



have now completed the sites characterization with adequate wind parameters.

Wind resources are shown in topographic maps now available for regions and countries. Of course, the amount of energy produced depends on both wind site and the size of installed devices.

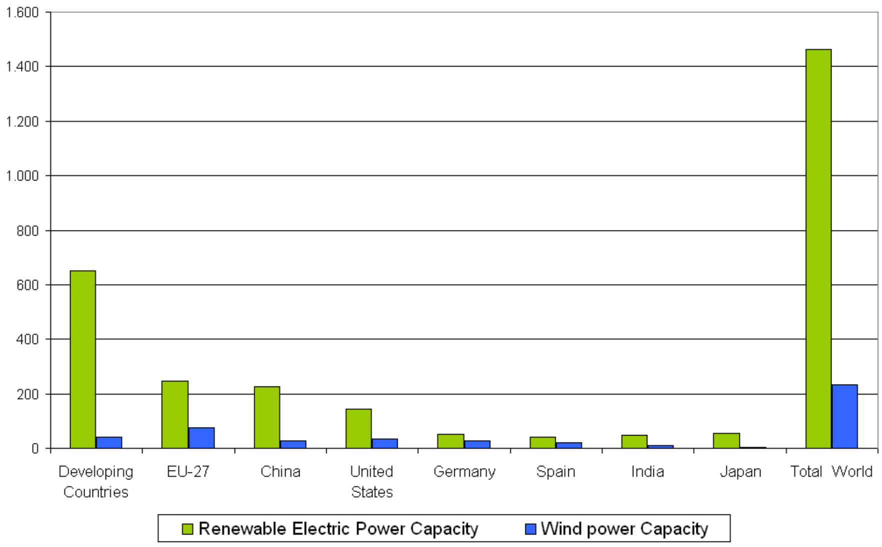
1.3.2 Wind Energy: benefits and problems of a power system integration

As shown in Figure 1.4 which compares renewable and wind power capacity in the main regions of the world and in some European countries, currently wind energy is, among the various RES, the fastest growing energy source, because wind is still (after hydroelectric) the source from which it is possible to draw the greatest amount of energy. However, the heavy penetration of electricity from wind sources, has also raised a series of problems currently being studied.

Europe is the main producer of electricity from renewable sources, when excluding large water systems. The success of wind power plants (particularly in Germany, Denmark and Spain) can be also interpreted as

Figure 1.4: Renewable and Wind power capacity in 2009

Source: author's estimated based on Renewables 2010 Global Status Report



a consequence of favourable weather conditions, and an effective incentives policy also motivated by the presence on the territory of some of the world's largest producers of devices for energy production.

In Table 1.2, we can see the wind power (cumulative) installed in Europe by end of 2010 while Figure 1.5 shows the market shares for new capacity installed during 2010[8].

This significant development also comes from some special characteristics of wind power that make it particularly attractive. First of all it has be considered a renewable source because it is inexhaustible; it is clean because it does not produce pollution emission, so providing a positive contribution to environmental protection[9].

[8]In terms of annual installations, Spain was the largest market in 2010, installing 1,516 MW, followed by Germany 1,493 MW; while France was the only other European country to install over 1 GW (1,086 MW), followed by the UK (962 MW) and Italy (948 MW). Sweden (604 MW), Romania (437 MW), Poland (382 MW), Portugal (363 MW) and Belgium (350 MW) also all performed strongly.

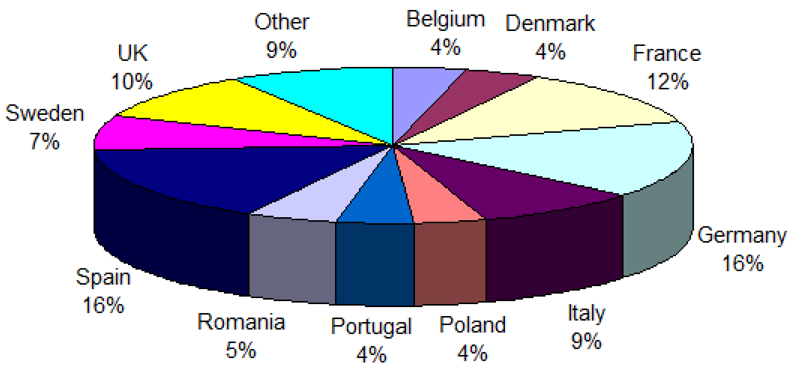
[9]However, although wind turbines have zero emissions, the environmental evaluation has to consider the system as a whole: the need to provide back-up using these

EU wind Capacity (MW)				
	Installed 2009	End 2009	Installed 2010	End 2010
Austria	0	995	16	1.011
Belgium	149	563	350	911
Bulgaria	57	177	198	375
Cyprus	0	0	82	82
Czech Republic	44	192	23	215
Denmark	334	3.465	327	3.752
Estonia	64	142	7	149
Finland	4	147	52	197
France	1.088	4.574	1.086	5,660
Germany	1.917	25.777	1.493	27.214
Greece	102	1.087	123	1.208
Hungary	74	201	94	295
Ireland	233	1.310	118	1.428
Italy	1.114	4.849	948	5.797
Latvia	2	28	2	31
Lithuania	37	91	63	154
Luxembourg	0	35	7	42
Malta	0	0	0	0
Netherlands	39	2.215	32	2.237
Poland	180	725	382	1.107
Portugal	673	3.535	363	3.898
Romania	3	14	448	462
Slovakia	0	3	0	3
Slovenia	0.02	0.03	0	0.03
Spain	2.459	19.160	1.516	20.676
Sweden	512	1.560	604	2.163
United Kingdom	1.077	4.245	962	5.204
Total	**10.486**	**75.090**	**9.295**	**84.278**

Table 1.2: Wind power installed in Europe (cumulative) 2009-2010
Source: EWEA, Wind in power 2010 European statistics

Figure 1.5: EU member state market share for wind capacity 2010

Source:EWEA, Wind in power 2010 European statistics



Moreover, similarly to other Renewable Energy Sources, the strong interest for wind power is due to the fact that energy production is available at no cost and, given the increasing cost of fossil fuel and the decreasing cost of wind power generation, it is almost competitive in cost and in the near future it will probably become even cheaper; therefore it can effectively contribute to the diversification of primary sources forming a real alternative to fossil fuels.

Finally, production facilities from renewable (and wind) sources tend to be more flexible and less dependent on scale economies than conventional systems, with better integration capabilities in the transmission and distribution system. In addition, wind can make available a variety of small and medium-sized generating plants that, especially if placed near the load, can effectively contribute to security of energy supply.

However, wind energy also presents some problems. Infaceted, wind turbines, especially if located offshore, are often installed in remote sites, away from both energy demand and existing generators. This translates into high connection costs and the need to adapt the network topology.

conventional systems run at lower efficiency translates into increased consumption and higher emissions.

As other Renewable Sources, wind power is intermittent, variable and unpredictable and these limits, in the recent past, have significantly reduced its economic attractiveness (see [19] and [21]). In general, wind power cannot be readily stored, hence system operators must balance generation with load on a real-time basis, in order to guarantee the required system reliability. Compared to other electricity-production technologies, wind resources cannot be used to maintain real-time reliability on the grid.

Wind sources fluctuate over time. Since energy is produced only when the wind is available, power output fluctuations occur when wind stops or suddenly increases. Moreover, wind is unpredictable, this means that specific short-term, minute-to-minute and hourly changes of wind power output are hard to predict. Whereas large load gradients always occur at the same time during the day and are generally easy to forecast, the unpredictability of wind farms output puts completely new requirements on the system. Operators of wind farms can do little about the minute-to-minute volatility of the wind energy, but they may be able to limit the hourly and daily differences between the actual and scheduled output by developing accurate wind forecasting systems. Finally, wind is an uncontrollable or not dispatchable energy source, since system operators have no control over the availability and quantity of this resource.

The replacement of conventional power stations, on the other hand, requires that wind turbines act as generating units capable of supporting the electrical system in voltage and frequency regulation. Therefore, wind energy penetration limits depend on several factors, such as existing utilities generation mix and their regulating capabilities, load characteristics, resource availability, and correlation between system load and resources.

In practice, a degree of uncertainty is always at work, making it harder for managers of transmission networks to ensure the seamless instantly match between generation and load. In the short-term, the characteristic of strong variability of wind power implies the need to maintain the availability of a significant share of reserves to "back up". This power, typically provided by generators with high production costs, produces supplementary poses to the system as a whole, which must then be folded on the end consumer. In addition, when a peak unexpected wind power requires action by the back-up power, the whole flow through the network has to change suddenly, making difficult a balancing act between production and load carried by Transmission System Operators (TSO)[10]

In recent years, a certain portion of the technical literature has investigated the costs and benefits related to the installation of wind turbines and their integration into the network infrastructure (see [38], [13] and [14]).

The literature has also studied the complementarity between renewable energy sources and the possible impact arising from the implementation of forecasting and storage mechanisms in order to increase predictability and reduce the fluctuations of the power fed into the grid and, consequently, the reserve power back-up provided by thermal plants.

Several studies aim to quantify the impact of this source on power system planning, by evaluating its "capacity credit", i.e. the amount of conventional sources (mainly thermal) that could be replaced by wind power without making the system less reliable. However, the evaluation of the "capacity credit" of wind source in a generation system, as the one of any other technology, is very difficult ([29], [31]).

Furthermore, it is worth mentioning that, nowadays, there are some cases of wind generation controlling its active and reactive power (e.g. in Denmark and Spain), so that the system operators starts having direct control over the availability and quantity of this resource (see [19], [28], [17], and [22]).

[10]There are two kinds of reserves associated to wind. One is due to the lack of energy that should be supplied with another technologies (e.g., CCGT=Combined Cycle Gas Turbine), while the other is the uncertainty if the forecasted generation that will be hedged with operating reserves.

1.4 Demand response and RTP versus Storage technology

In order to integrate renewable sources within energy systems it is necessary to make them more attractive and competitive by introducing some mechanisms providing the whole system with greater stability and more efficiency.

In the wind energy case, penetration limits depend upon several factors, such as existing utilities generation mix, their regulating capabilities, load characteristics, resources availability, and correlation between system load and resources.

Furthermore, some studies have shown that RES penetration limits usually have not a technical but an economic root, since their operating costs are greater than the additional value they generate. These costs and values vary from system to system, and a general conclusion on the maximum penetration limits for utility systems is very difficult to be drawn.

During the last years, several mechanisms have been designed to increase the efficiency of electricity markets in the presence of renewable energies (mainly, wind energy,) and to make these electricity sources more attractive.

Here two kinds of general strategies to mitigate the difficulties related to the use of intermittent energy sources are considered:

- development of demand-side management procedures, so that the demand can react to the available wind power;

- introduction of rapid-response generation sources, which have low costs in a regime of greater variability, such as storage technology.

Electricity demand, being elastic with respect to electricity price, plays a key role in modulating the withdrawal in response to to price signals or specific requests aimed at guaranteeing system security. The active behaviour of electricity demand when replying to price signals or to system requests is usually called Demand Response (DR).

In electricity grids, in fact, the Demand Response is similar to dynamic demand mechanisms to manage customers' consumption of electricity in response to supply conditions. This expression is generally used to refer to mechanisms used for either encouraging consumers to reduce demand, thereby reducing the peak demand for electricity, depending on the configuration of generation capacity, or to increase the demand (load) at times of high production and low demand.

Demand Response includes a wide range of contractual or service agreements based on the voluntary participation of users to specific programs and numerous and different modulation programs exist.

Today, the term Demand Response (DR) is mainly used to represent in the short-term (hours, days or weeks) the elastic behaviour of electricity demand in response to price signals generated by the Electricity Market. However, a stream of the literature (for more details see [7], [11], [12] and [41]), makes use of a classification based on the main objectives that demand actions can contribute to, and identifies two general classes of demand actions:

- **system led programs** to guarantee system reliability and to ensure supply adequacy; in this case the users accept to modify their consumption levels in order to contribute mainly to both reliability and electric system security;
- **market led programs** to maintain market efficiency, these programs exploit price signals from the electricity market (i.e. demand reacts to tariffs plans, real time prices, etc.).

There are other classifications that refer either to the timing of demand response (if it takes place in months, days, hours or minutes) or to its nature, voluntary or mandatory. Often there is some overlap between classifications.

In fact, generally the actions necessary to preserve the network security are actions required by the System Operator so they are mandatory for the agents and they must be usually taken in a very short-term (seconds, minutes or hours); On the contrary, in the case of market led actions, the user responds always voluntarily (only depending on individual sensitivity to the price level) to economic signals like real-time pricing, rates or other trading mechanisms and contractual agreements[11] and the response to market signals can be done in longer time.

Several authors argue that programs exposing consumers to different prices over a short period of time (Real Time Pricing or Critical Peak Pricing) are more efficient to stimulate a rapid response than plans that change the tariff rates only every month, quarter or even year (multi-hours tariffs) (see Barbose et al. in [4], Berizzi et al. in [7] and Borenstein et al. in [8] and [9]).

When the consumer has a "Real Time Price", she/he is exposed to a price that can vary hour by hour, depending on the trend of the power exchange. Since the user reduces the energy consumption when the price is high, its elasticity should not be declared in advance.

With specific regard to the wind energy, other authors, in several recent studies investigating how to reduce the wind integrating costs, proposed the development of demand-side management procedures, where the demand reacts according to the offered wind power (see Sioshansi et al. in [35] and [37] and Madaeni at al. in [24] and [25]). They also point out that introducing a kind of demand elasticity or responsiveness in the form of real-time pricing (RTP) may allow electricity consumers to follow the actual real-time wind resource availability.

It must be emphasized, however, (as claimed in [12]) that the participation of demand in markets or in services is strongly dependent on the regulatory framework that in some cases may present many barriers inhibiting an active demand response. Other barriers also include both tech-

[11] See, for example, programs with tariff plans with variable prices and linked to the Power Exchange performance (Real-time pricing), index-price or dynamic (dynamic pricing), critical peak tariff (Critical Peak Pricing) that provide for price high only for a few days or hours of the year, multi-hours tariffs, stock market offers, Demand Side Bidding, etc.. (see [7]).

nological (i.e. devices for measurement, control and communications) and non-technological (tariffs, economics and marketing, information, culture, etc.) impediments.

It is important to stress that a permanent exposure to continuous change prices (Real Time Pricing) is not suitable for most consumers, but is only interesting for large consumers (typically large industries) which can count on resources addressed to a careful use of energy and a continuous monitoring of prices, with the aim of obtaining significant savings or even remuneration. Therefore, the fraction of users that accepts a charge "real time" is quite low, while not missing cases where the system works well[12].

Therefore, despite their many advantages, these demand mechanisms seem to be not fully efficient, first of all because they require a continuous and efficient communication system between operators and consumers and second, with specific reference to the wind resource, because generally there is not direct correlation between wind energy production and demand response.

For this reason we examine the body of the literature that suggests the use of storage technologies as support to renewable energy integration in a power system because they can produce an alternative supply source when the energy produced is not sufficient to ensure an adequate coverage of the demand. We refer in particular to the papers by [39], [23] and [40], which investigate the benefit of storage technologies in general terms, and the papers by [10], [15], [20] and [5], which analyse some storage technologies with specific reference to systems where wind energy is explicitly introduced.

Besides [36] and [16] investigated the relations between wind energy sources and the possible impact arising from the implementation of forecasting and storage internal mechanisms in order to improve predictability and reduce the fluctuations of the power into the network and, consequently, the reserve backup power provided by thermal plants[13].

[12]Norway is an example of this kind of strategy (see [7]).

[13]In this case, about the literature refers to a Virtual Power Plant (VPP) i.e. a cluster of distributed generation installations which are collectively run by a central control entity.

All these works assert that storage devices can be important tools for the integration of wind resources which, compared with traditional electricity production technologies, cannot be used to maintain real-time reliability on the grid.

The kind of energy storage most commonly used is pumped storage hydroelectric power, that is, an indirect form of storage, but there are many other new technologies that can ensure energy storage in direct form through new generation devices even if some problems related to efficiency and high storage costs still remain open[14].

1.5 Conclusion

We have considered here the main issues arising from the use of renewable energy into energy systems, with particular reference to wind resources. In the next chapter we will analyse the main types of storage technologies and their characteristics.

Then we will characterize an optimization model considering a producer who aims to use both traditional and wind energy. The model will consider a storage technology to estimate the potential benefits of using wind power and storage facilities together.

[14]See the next chapter for a description of storage devices.

Chapter 2

Energy storage technologies: state of the art

2.1 Introduction

The growth of energy demand and the increasing penetration of renewable sources in the electrical systems in recent years require a significant improvement in network management. Particularly, integration of wind power needs greater flexibility by energy system.

In this context, many studies have pointed out that the advanced electric energy storage technologies, when properly managed, can smooth out the renewable energy sources variability and may have many environmental and economic advantages (see [10], [20], [5], [39], [36], [23], [40] and [15]).

There are a variety of potential energy storage options for the electric sector, each with unique operational, performance, charge/discharge cycle and durability characteristics. Therefore, energy storage technologies have many applications and are at various stages of development and deployment. For example pumped hydro is technically and commercially mature and it is the most widespread large-scale storage technology deployed on power systems; instead, some types of batteries are still underutilized and require improvements in terms of costs and efficiency.

The implications of electrical energy storage have been extensively discussed in a number of reports and several research groups are continuing to explore this area.

In this chapter we will propose a description of current status of energy storage technology options and their main characteristics. By doing so, we will refer to several recent reports on this topic (see [33], [26], [18], [3], [34] and [32]).

2.2 Applications for the energy storage devices

Energy storage systems can provide a variety of application solutions along the entire value chain of the electrical system, from generation support to transmission and distribution support to end-customer uses.

First of all it is helpful to consider the distinction between storage technologies classified as those that are best suited for power applications and those best suited to energy applications (see [18] and [34]):

- power applications require high power output, usually for relatively short periods of time (a few seconds to a few minutes); storage used for power applications usually has capacity to store fairly modest amounts of energy per kW of rated power output[1].

- energy applications are storage technologies requiring relatively large amounts of energy, often for discharge durations of many minutes to hours. Therefore, storage used for energy applications must have a much larger energy storage reservoir than storage used for power applications[2].

It is also important to note that for all applications two key storage design criteria are essential: power rating and discharge duration of storage devices.

[1]Notable storage technologies that are especially well-suited to power applications include capacitors, SMES, and flywheels.

[2]Storage technologies that are best suited to energy applications include CAES, pumped hydro, thermal energy storage, and most battery types.

Masaud et al. (see [26]) define some applications of the storage technologies based on the system requirements that may have environmental and economic advantages. This synthetic classification of storage applications is summarized in Table 2.1.

Energy Storage Applications based on System Requirements				
	Matching Supply & Demand	Providing Backup Power	Enabling Renewable Technologies	Power Quality
Discharged Power	< 1MW - 100MW	1-200MW	20kW-10MW	1kW-20MW
Response Time	< 10min	< 10ms < 10min	< 1s	< 20ms
Energy Stored	1MWh - 1000MWh	1MWh - 1000MWh	10kWh - 200MWh	50kWh - 500kWh
Efficiency Need	High	Medium	High	Low
Life Time Need	High	High	High	Low

Table 2.1: Energy Storage Applications based on System Requirements
Source: Masaud et al. 2010

By referring to ([18] and [34]), several categories of storage technologies applications are shown in more detail in Table 2.2 and described in the next sections.

2.2.1 Electric supply

In the electric supply, the main applications of storage technologies are:

Categories of Energy Storage Applications	
Electric Supply	Electric Energy Time-shift Electric Supply Capacity
Ancillary Services	Load Following Area Regulation Electric Supply Reserve Capacity Voltage Support
Grid System	Transmission Support Transmission Congestion Relief T&D Upgrade Deferral Substation On-site Power
End User/Utility Customer	TOU Energy Cost Management Demand Charge Management Electric Service Reliability Electric Service Power Quality
Renewables Integration	Renewables Energy Time-shift Renewables Capacity Firming Wind Generation Grid Integration

Table 2.2: Categories of Energy Storage Applications
Source: Sandia Report 2010

- **Electric energy time-shift**: time-shift involves purchasing inexpensive electric energy, available during periods when price is low, to charge the storage plant so that the stored energy can be used or sold at a later time when the price is high; both storage variable operating cost and storage efficiency are especially important for this application because electric energy time-shift involves many possible transactions whose economic merit is based on the difference between the cost to purchase, store, and discharge energy (discharge cost) and the benefit derived when the energy is discharged.

- **Electric supply capacity**: in some electric supply system, energy storage could be used to defer and/or to reduce the need to buy new generation capacity.

2.2.2 Ancillary services

For the ancillary services, storage devices are used as:

- **Load following**: load following is one of the ancillary services required to operate the electricity grid; load following capacity is characterized by power output that changes (as frequently as every several minutes) in response to the changing balance between electric supply (primarily generation) and end user demand (load) within a specific region or area. Normally, generation is used for load following, however storage is more suitable to load following mainly because most types of storage can adjust very quickly (compared to most types of generation) to fluctuations in electricity demand, and also because can be used effectively for both increasing and decreasing load.

- **Area regulation**: area regulation involves managing interchange flows to match closely, moment to moment the variations in demand within the control area. Regulation is typically provided by generating units that are on-line and ready to increase or decrease power as needed, but storage may be an attractive alternative; in this case, special benefits derived from storage devices with a fast ramp rate (e.g. flywheels, capacitors, and some battery types).

- **Electric supply reserve**: any electric grid includes use of electric supply reserve capacity that can be called upon when some portion of the normal electric supply resources becomes unavailable unexpectedly[3]. When the storage devices have enough stored energy to dis-

[3]The three generic types of reserve capacity are: spinning reserve (generation capacity that is on-line and that can respond immediately (seconds or minutes) to compensate for

charge for the required amount of time (usually at least one hour), can be used as electricity supply reserve.

- **Capacity voltage support**: storage technologies can be used to maintain necessary voltage levels with the required stability for electric grid system. In case of storage devices used for voltage support, the energy stored must be available within a few seconds to serve load for a few minutes to as much as an hour.

2.2.3 Grid system

As grid system support, the storage devices are used as:

- **Transmission support**: energy storage used for transmission support improves T&D[4] system performance by compensating for electrical anomalies to improving the system performance. In order to be used for transmission support, energy storage must be capable of sub-second response, partial state-of-charge operation, many charge-discharge cycles, and cannot be used concurrently for other applications.

- **Transmission congestion relief**: storage could be used to avoid congestion related costs and charges in those areas where transmission systems are becoming congested during periods of peak demand, driving the need and cost for more transmission capacity and increased transmission access charges. In this application, energy would be stored when there is no transmission congestion, and it would be discharged (during peak demand periods) to reduce transmission capacity requirements.

generation or transmission outages); supplemental reserve (generation capacity that may be off-line but can be available within 10 minutes); backup supply (generation that can be available within one hour).

[4]Transmission and Distribution.

- **Transmission and distribution upgrade deferral**: some storage technologies can be used as alternative energy sources to meet the expected load growth. Therefore, the use of relatively small amounts of storage involves delaying (and in some cases avoiding entirely) utility investments in transmission and/or distribution system upgrades

- **Substation on-site power**: this kind of technology relates to battery storage systems at utility substations that provide power to switching components and to substation communication and control equipment when the grid is not energized.

2.2.4 End user/utility customer

The most important applications of storage technologies for end user are:

- **Time-of-use energy cost management**: Time-of-use (TOU) energy cost management involves storage used by energy end users (utility customers) to reduce their overall costs for electricity. Customers charge the storage during off-peak time periods when the electric energy price is low, then discharge the energy during times when on-peak TOU energy prices apply[5]. However, this storage design can be too difficult for many potential users, especially those with relatively small energy use.

- **Demand charge management**: energy storage could be used by utility customers to reduce the overall costs for electric service by reducing demand charges and power draw during specified periods, normally during the utility's peak demand periods.

[5]This application is similar to electric energy time-shift, although electric energy prices are based on the customer's retail tariff, whereas at any given time the price for electric energy time-shift is the prevailing wholesale price.

- **Electric service reliability**:the electric service reliability application entails using energy storage to provide highly reliable electric services. In the event of a complete power outage lasting more than a few seconds, the storage system provides enough energy to ride through outages of extended duration, to complete an orderly shutdown of processes and/or to transfer to on-site generation resources.

- **Electric service power quality**: The electric service power quality service involves the use of energy storage to protect on-site loads against short-duration events that affect the quality of power delivered to the load (variations in voltage magnitude, low power factor, interruptions in service etc.).

2.2.5 Renewables integration

To integrate the renewable energy in the system, the storage technologies are used in:

- **Renewables energy time-shift**: many renewable energy generation resources produce a significant portion of electric energy when demand is low (off-peak times) and energy has a low value. Energy storage used jointly with renewable energy generation could be charged using low-value energy from the renewable energy generation; so that energy may be used to offset other purchases or sold when is more valuable. Storage used for renewables energy time-shift could be located at or near the renewable energy generation site or in other parts of the grid[6]. For intermittent renewable energy generation, an important criterion is the degree to which the renewable energy generation output coincides with times when the price for electric energy is high.

[6]In case of wind generation, low-value electric energy from wind generation is stored at night and during early mornings.

- **Renewables capacity firming**: storage for capacity firming allows the use of an intermittent electric supply resource as a nearly constant power source. Renewables capacity firming applies to circumstances involving renewable energy-fuelled generation whose output is intermittent. The objective is to use storage to "fill in", so that the combined output from renewable energy generation plus storage is constant[7]. Renewables capacity firming is especially valuable when peak demand occurs and storage can have an important effect on the amount of dispatchable generation needed to meet the renewable energy generation.

- **Wind generation grid integration**: wind generation is especially attractive, given the relatively low and dropping electricity production cost from wind generation and good wind resources in many geographic regions. However, the use of this intermittent source, is likely to have a negative impact on the grid. Storage could assist with orderly integration of wind generation (wind integration) by managing or mitigating the more challenging and less desirable effects from high wind generation penetration.

2.3 Energy storage technologies overview

Storage technologies are defined as devices that allow the conversion of electrical energy from a power network into a form in which it can be stored until converted back to electrical energy.

The worldwide installed capacity of storage systems is estimated around 125GW of which more than 98% consists of hydroelectric pumping (see [34]).

The main examples of storage technologies can be included in listed as follows:

[7]The difference between renewables capacity firming, and renewables energy time-shift is that the latter involves enhancing the value of energy to increase profits and/or reduce maintenance costs.

- Mechanical: pumped hydro, compressed air energy storage (CAES), flywheels;
- Electrical: capacitors and supercapacitors, superconducting magnetic energy storage (SMES);
- Electro-chemical: batteries, flow batteries, advanced batteries.

In the next sections we will describe the main existing storage technologies by referring to some of the most recent technical reports and papers on this topic (see [18], [3], [1] [26] and [33]).

2.3.1 Pumped hydroelectric energy storage

Energy can be stored by conventional hydropower and pumped storage hydropower facilities. A pumped storage resource is a hydropower generating facility that stores water as potential energy during off-peak hours for later use when demand is higher. Conventional (reservoir) hydro electric schemes provide a significant storage capacity, based upon the potential energy contained in their reservoirs.

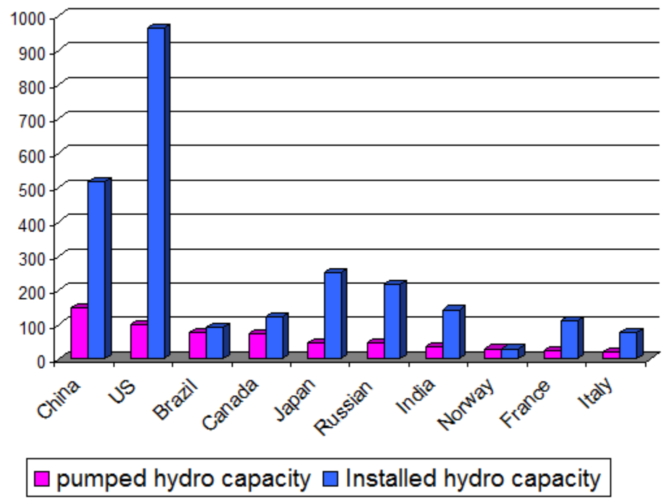
Pumped-hydro storage represents a sub-set of the overall hydro-electric capacity and is the largest and mature technology currently used at many locations around the world. Figure 2.1 shows the installed hydro capacity and pumped hydro capacity at the world level.

The key elements of a pumped hydroelectric (pumped hydro) system include turbine generator equipment, a waterway and two reservoirs at different elevations. Water is pumped by the power station from the lower reservoir to an upper reservoir where the water is stored until is needed to generate power. When the water is released, it goes through the turbine which turns the generator to produce electric power (generally when energy is more valuable).

Pumped hydro plants have very long lives on the order of 50 years and power capacity typically less than 2000MW, that operate at about 76%-85% efficiency depending on design (see [26]).

Figure 2.1: World-wide pumped-hydro and installed hydro capacity

Source: author's estimated based on Key World Energy Statistics, IEA, 2010



This technology is classified as real long-term response energy storage and generally characterised by its fast response times. Therefore, it is typically used for systems that need power to be supplied for a period between hours and days, as it enables the system to participate equally well in voltage and frequency regulation, spinning reserve, and non-spinning reserves markets, as well as energy arbitrage and system capacity support.

The value (in terms of both economics and reliability) of pumped storage resources is derived from their ability to deliver power when it is needed most. When the cost of pumping is less than the price differential between on and off-peak, pumped storage facilities can effectively arbitrage these prices by purchasing power off-peak and selling the power at peak (see [1]).

2.3.2 Compressed air energy storage (CAES)

Compressed air energy storage (CAES) is a storage technology that has much in common with pumped storage, as it has the ability to convert its stored air capacity into real power output for several hours at a time during peak hours.

These systems use excess power from the grid during off-peak hours to compress and store air in a reservoir, either an underground cavern or aboveground pipes. Therefore, compressed air energy storage involves compressing air using inexpensive energy, so that the compressed air may be used to generate electricity when the energy is worth more. When electricity is needed, the compressed air is released into a combustion turbine generator system, so as to convert the stored energy into electric energy. Typically, the compressed air is heated, expanded, and directed through a conventional turbine-generator to produce electricity.

In order to be considered viable CAES facilities need at least three basic elements. First, these facilities need a confined space that can securely store a sufficient volume of compressed air. Second, the location must have access to natural gas transmission in order to power the turbine. Finally, the site must have access to electric transmission so that the power generated can be delivered to the grid. For larger CAES plants, compressed air is stored in underground geologic formations (salt formations, aquifers, and depleted natural gas fields); for smaller CAES plants, compressed air is stored in tanks or large on-site pipes, such as those designed for high-pressure natural gas transmission.

Power Capacity of CAES system ranges between 100-300MW. This is classified as real long-term energy storage device that can supply power for days and provide backup power during long blackouts.

An emerging advanced concept still under research and development, called "adiabatic CAES" (A-CAES), would allow to consume little or no fossil fuel or external energy, by drawing instead the heat needed during expansion from thermal energy captured during compression (see [33] and [10]).

2.3.3 Flywheel

Energy stored in flywheel (flywheel storage or flywheels, known also as a kinetic energy storage system) is in the form of kinetic energy in the rotating mass of a rapidly spinning flywheel. Flywheel electric energy storage systems include a cylinder with a shaft that can spin rapidly within a robust enclosure; a magnet levitates the cylinder, thus limiting friction-related losses and wear; the shaft is connected to a motor/generator. Electric energy is converted by the motor/generator to kinetic energy and then this is stored by increasing the flywheel's rotational speed. The stored (kinetic) energy is converted back to electric energy via the motor/generator, slowing the flywheel's rotational speed. Flywheels have variable storage capacity in the range of kW to typically less than 100kW (see [26]). High efficient energy storage and relatively long life are the major advantages of flywheels. On the other hand, the high-speed rotor,the possibility of it breaking loose and releasing all of its energy in an uncontrolled manner, and the current high cost are the main disadvantages of flywheels. Moreover, flywheels are shorter energy duration systems, which makes them not attractive for large-scale grid support applications, as they require many kilowatt-hours or megawatt-hours of energy storage. Therefore, such equipments have typically been used for applications requiring short discharge time, such as stabilizing voltage and frequency.

2.3.4 Capacitors and supercapacitors

Capacitors can store electric energy as an electrostatic charge. This category includes an increasing array of larger capacity capacitors, called supercapacitors.

Supercapacitors are a relatively new technology with characteristics that make them well-suited for use as energy storage. They store significantly more electric energy than conventional capacitors. Supercapacitors have a variable storage power capacity range between 1kW-250kW , and typical energy storage less than 3MWh (see [26]).

They are classified as short-term response devices and are especially suitable to being discharged quite rapidly and to deliver a significant amount of energy over a short period of time. For these reasons, they are attractive for high-power applications that require short or very short discharge durations (i.e. for stabilizing voltage and frequency).

2.3.5 Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) systems are able to convert and store energy in a magnetic field. The storage medium in a superconducting magnetic energy storage (SMES) system consists of a coil made of superconducting material. Additional SMES system components include power conditioning equipment and a cryogenically cooled refrigeration system. Energy is stored in the magnetic field created by the flow of direct current in the coil. Once energy is stored, the current will not degrade, so energy can be stored indefinitely (as long as the refrigeration is operational).

The SMES is a short-term response energy storage device and his power capacity is suitable when the application needs a fast response time, such as, power (quality problems and improve transient stability).

The power quality conditioning by the SMES is considered to be very good. However, the SMES are very expensive, sensitive to temperature, and require a cooling system and high magnetic fields.

2.3.6 Electrochemical batteries

Electrochemical batteries consist of two or more electrochemical cells, where the electrochemical reactions occur. The cells use chemical reaction(s) to create a flow of electrons (electric current).

Primary elements of a cell include the container, two electrodes (anode and cathode), and an electrolyte material. The electrolyte is in contact with the electrodes. Current is created by the oxidation-reduction process involving chemical reactions between the cell's electrolyte and electrodes. When a battery discharges through a connected load, electrically charged ions in the electrolyte that are near one of the cell's electrodes supply electrons (oxidation) while ions near the cell's other electrode accept electrons (reduction), to complete the process. The process is reversed to charge the battery, which involves ionizing of the electrolyte. An increasing number of chemistries are used for this process (see [18] and [34]).

Batteries have the potential to span a broad range of energy storage applications due in part to their portability, ease of use and variable storage power capacity (100W-20MW). They can be classified as long-term energy storage devices and can be connected both in series and parallel to increase their power capacity for different applications. This technology is rather expensive but the advantage is that it does not need be connected to an electrical system, therefore it can be used in areas where electricity is not provided (see [26] and [34]). The current technology in batteries include:

- **Lead acid (Pb-Acid)**: is the most commercially mature rechargeable battery technology in the world, used in a variety of applications. With good battery management and a well optimised operational regime, these systems have been shown to be financially competitive. However, power output from lead-acid batteries is non-linear and their lifetime varies significantly depending on the application, discharge rate, and number of discharge cycles, which can significantly reduce life. They also have poor low temperature performance and therefore require a thermal management system. Moreover, battery price can be influenced by the cost of lead (see [3], [33] and [34]).

- **Nickel-Cadmium (Ni-Cad)**: nickel cadmium system offers significant advantages over lead acid in terms of its cycle life expectancies, its short term power rating and its low maintenance requirements. Their applications are various, including aircraft power systems, electric vehicles, power tools, portable devices and stand-by power. However, because of concerns in relation to cadmium toxicity and associated recycling issues, power utility applications to date have been limited. Safety and environmental problems represent a significant barrier to any future mass market adoption of the technology (see [3] and [34]). This technology is replaced, when possible, with nickel-metal hydride (Ni-MH) accumulator.

- **Sodium-Sulphur (Na-S)**: sodium-sulphur batteries are a commercial energy storage technology finding applications in electric utility distribution grid support, wind power integration, and high-value service applications on islands. The considerable interest and research work carried out on the sodium sulphur battery over the last 30 years derives mainly for the advantage of lower weight and smaller dimensions compared to the lead acid systems. Sodium-sulphur batteries belong to the category of high temperature batteries; they consist of liquid sulphur as the negative electrode and liquid sodium as the positive electrode, and operates at a temperature of 300^o to 350^oC. Batteries that operate at elevated temperatures exhibit improved performance compared with ambient temperature batteries, although they do require insulating to prevent rapid heat loss. Consequently, a heat source that uses the battery's own stored energy is required, thus partially reducing the battery performance. The estimated life of a sodium-sulphur battery is approximately 15 years after 4500 cycles at 90% depth of discharge (see [3], [33] and [34]).

- **Sodium Nickel Chloride**: between high temperature battery technologies, we also mention sodium nickel chloride battery, better known as the ZEBRA battery[8]. ZEBRA is a high temperature system that uses nickel chloride as its positive electrode and has the ability to operate across a broad temperature range without cooling. ZEBRA's advantages compared to sodium-sulphur batteries are its ability to withstand limited overcharge and discharge, its better safety characteristics and a higher cell voltage. On the contrary, the disadvantages with respect to sodium sulphur are its lower energy and

[8] Zero Emission Battery Research Activity

power density. The principal applications for the ZEBRA battery to date has been seen in the electric vehicle and associated sectors (see [3] and [34]).

- **Lithium-ion (Li-ion)**: rechargeable lithium-ion batteries include a family of battery chemistries that employ various combinations of anode and cathode materials. They are commonly found in consumer electronic products: cameras, cell phones and computers. Compared to the long history of lead-acid batteries, Li-ion technology is relatively new. There are many different Li-ion chemistries, each with specific power versus energy characteristics. This technology is increasingly attracting interest in the electric vehicle applications sector. Moreover, the high energy density and relatively low weight of Li-ion systems make them an attractive choice for areas with space constraints. Given their attractive cycle life and compactness, in addition to high efficiency that exceeds 85%-90%, Li-ion batteries are also being seriously considered for several utility grid-support applications such as DESS (community energy storage), transportable systems for grid-support, commercial end-user energy management, home back-up energy management systems, frequency regulation, and wind and photovoltaic smoothing (see [3], [33] and [34]).

2.3.7 Flow Cells

Electrochemical flow cell systems, also known as redox flow cells, convert electrical energy into chemical potential energy by means of a reversible electrochemical reaction between two liquid electrolyte solutions. While the electrochemical batteries contain electrolyte in the same container as the cells, these battery types use electrolyte that is stored in a separate container outside of the battery cell container. Flow battery cells are said to be configured as a "stack". Therefore, the power and energy ratings are independent, with the storage capacity determined by the quantity of electrolyte used and the power rating determined by the active area of the cell stack. A key advantage of flow batteries is that the storage system's discharge duration can be increased by adding more electrolyte and it is also relatively easy to replace a flow battery's electrolyte when it degrades. Flow batteries are of particularly interest as they offer the prospect of high power ratings with a low initial cost, coupled with a low cost for additional "hours" of energy storage. These attributes make flow batteries a good theoretical choice for integration with renewables (see [18] and [3]). Vanadium redox (VRB) and Zinc-Bromine (Zn/Br) are two of the more familiar types of flow batteries:

- Vanadium redox batteries and the most mature of all flow battery systems available. This systems are unique in that they use one common electrolyte, which provides potential opportunities for increased cycle life. When electricity is needed, the electrolyte flows to a redox cell with electrodes, and current is generated. The electrochemical reaction can be reversed by applying an overpotential, as with conventional batteries, allowing the system to be repeatedly discharged and recharged. Like other flow batteries, many variations of power capacity and energy storage are possible depending on the size of the electrolyte;

- Zinc-bromine (Zn/Br) is a type of redox flow battery that uses zinc and bromine in solution to store energy as charged ions in tanks of electrolytes. As in vanadium redox systems, the Zn/Br battery is charged and discharged in a reversible process as the electrolytes are pumped through a reactor vessel. Zn/Br batteries are in an early stage of field deployment and demonstration, and are less developmentally mature than vanadium redox systems.

2.3.8 Hidrogen Fuel Cell

A fuel cell is a device (an electrochemical cell) that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent. There are many types of fuel cells, but they all consist of an anode (negative side), a cathode (positive side) and an electrolyte that allows charges to move between the two sides of the fuel cell. Electrons are drawn from the anode to the cathode through an external circuit, producing direct current electricity. As the main difference among fuel cell types is the electrolyte, fuel cells are classified by the type of electrolyte they use. Fuel cells come in a variety of sizes. Individual fuel cells produce very small amounts of electricity, so cells are "stacked", or placed in series or parallel circuits, to increase the voltage and current output to meet an application's power generation requirements. In addition to electricity, fuel cells produce water, heat and, depending on the fuel source, very small amounts of pollution emissions. Therefore, they also have applications in cogeneration systems (combined heat and power).

Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, rural locations including research stations; also there are applications for vehicles, because a fuel cell system running on hydrogen can be compact and lightweight, and has no major moving parts.

The energy efficiency of a fuel cell is generally between 40-60%, or up to 85% efficient if waste heat is captured for use. Hydrogen is the most common fuel, but hydrocarbons such as natural gas and alcohols like methanol are sometimes used. Fuel cells are different from batteries in that they require a constant source of fuel and oxygen to run, but they can produce electricity continually for as long as these inputs are supplied. Hydrogen Fuel Cell is classified as a long-term response energy storage device and has a typical power capacity less than 20MW. The advantages of this kind of storage device are, less maintenance, low emissions, and low noise. However, this technology is very expensive (see [26]).

2.3.9 Concentrated solar power (CSP)

Concentrated solar power systems use mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electrical power is produced when the concentrated light is converted to heat, which drives a heat engine connected to an electrical power generator. The plants consist of two parts: one that collects solar energy and converts it to heat (usually a steam turbine), and another that converts heat energy to electricity. Therefore, the heat energy is stored and eventually used in a conventional power plant to generate electricity.

CSP is considered a storage mechanism because, unlike solar photovoltaic (PV) technologies, the high-grade heat captured by its solar collectors can be processed immediately into electrical power, or stored as heat and converted at a later time.

CSP's power capacity ranges between 10kW for small applications to 200MW (or even higher) for grid connection applications. The thermal storage of CSP plants is classified as long-term response energy storage (several hours). The storage and backup capabilities of CSP plants offer significant benefits for electricity grids. Losses in thermal storage cycles are much less than those in other existing electricity storage technologies (including pumped hydro and batteries), making the thermal storage available in CSP plants more effective and less costly (see [30] and [26]) .

2.4 Classification and comparison of various storage devices

Storage devices applications are various and may require action times and duration of very different each other. Therefore, for each application, device size is a function of both storage capacity that must ensure and discharge duration (time) required.

In order to design a suitable energy storage system for different applications, the analysis should include:

- response time: ability to vary both delivered or withdrawn power rapidly;
- ratio between power output and energy storage to (aptitude for energy applications or power applications).

This last parameter has high value for technology characterized by "power applications", which are able to provide high power output for relatively short periods of time (es: supercapacitors and flywheels). A second class of storage systems is represented by systems with "energy applications" which are able to deliver power with few hours discharge duration; they are therefore characterized by low value of power/energy (hidro pumping, CAES and some of the electrochemical storage systems).

By combining these characteristics we obtain a classification that gives basically a measure of the amount of MWh that a storage system can provide. Energy storage technologies can be classified broadly into three categories (see [26]):

- short-term response: this category includes technologies with high power density and with ability to respond in a short-time frame. They refer to a few seconds or minutes and are usually applied to improve power quality, particularly to maintain the voltage stability during transients;
- long-term response: these technologies are used for power system applications and can usually absorb and supply electrical energy for minutes or hours. They are usually deployed to contribute to the energy management, frequency regulation and grid congestion management;
- real long-term response: it includes response energy storage technologies that are usually applied to match supply and demand over 24 hours or longer (days, weeks, or months).

The reason why so many different storage devices have been developed over the last years is that neither of them is optimal in absolute terms. However, comparing some of the key properties of these systems can contribute to determine the suitability of each one for a specific application. Some of the main storage devices characteristics are shown in Table 2.3.

In this table, devices are classified based on both power capacity (MW) and discharge duration (time); the price range for each device concerns

Device	**Power**	**MWh**	**Discharge** Duration	**Efficiency** %	**Cost** $/MWh	**Life time**
Flywheel	<100 kW	< 100kWh	Sec/Min	90	170-420	20-30
Super- capacitors	<250 kW	< 3MWh	Sec/Min	95	85-480	30-40
SMES	0.3-3 MW	< 250kWh	Sec/Min	90	240-600	40
Batteries	< 20 MW	< 200MWh	Min/Hours	70-90	85-4800	2-10
Hydrogen Fuel Cells	< 20 MW	< 200MWh	Min/Hours	70-90	—	2-10
CSP	0.1-200 MW	< 2GWh	Hours	60	3500-7000	—
CAES	100-300 MW	0.4-7GWh	Days	80	12-85	30
Pumped Hydro	< 2 GW	< 24GWh	Days	87	45-85	40

Table 2.3: Comparison of Various Energy Storage Device
Source: Masaud et al., 2010

both capacity and efficiency and the costs include the purchase cost but do not include the maintenance and installation cost.

With regard to storage devices costs a comparison can be made also in terms of LUEC (Levelized Unit Electricity Cost) (as proposed in [34]). The LUEC represents the sales price of energy generated by each storage system needed to cover construction and operation costs and obtain a certain return on investment.

2.5 Conclusion

The growth of renewable resources, open access to the grid and competitive wholesale electricity markets have attracted the attention on energy storage resource development. In this chapter has summarized the advancement of main energy storage technologies and the state of the art of their applications. It has also shown that new energy storage applications have several potential benefits (including enhancement of system reliability, dynamic stability, power quality, and transmission capacity) and represent a promising addition to the resource mix available to serve the electricity needs.

Chapter 3

The short term model: stochastic and deterministic case

3.1 Introduction

In this chapter we develop a model whereby a small energy producer aims at meeting a part of the market demand, by using both traditional energy sources and wind energy. In order to use efficiently wind energy and maximize her/his own profits, the producer takes advantage of a specific kind of storage technology.

The aim of this chapter is to create a tool that allows to evaluate how the use of innovative storage technologies in the integration of renewable sources will affect the production decisions of a small producer operating in the electricity market.

Set of power plants, wind farm, and storage technology are considered as given in our model.

For the set of thermal units, the power producer must solve a Unit Commitment problem (UC), i.e. the problem of finding the most economical times to commit and decommit all the individual generators in a control area. Therefore, he decides in which hours of the planning horizon start-up and shut-down operations have to take place, taking into account some technical constraints (see [43]). Moreover, the producer has a scheduling problem, i.e. he has to decide the production level of each committed unit (given the technical constraints) at every hour of the planning horizon, taking into account both wind resource and stored energy availability.

In our model, the small power producer must also take into account the variability of both wind resource and energy prices.

Because of the complex nature of generation cost and constraints, solving the unit commitment problem requires advanced mathematics computations.

In order to assess the impact of storage technologies in different scenarios, we develop a short-time decision support procedure based on a mixed integer LP model and consider two different cases: the first one refers to a stochastic model (considering a set of different price and scenarios), while the second one refers to deterministic model. The deterministic setting can be viewed as a special case of the stochastic set-up, since we use only one realization of values defined by the expected values of random variables of the stochastic model. Therefore, the second model represents a deterministic case.

3.2 Stochastic model

In this model a small producer aims at maximizing his own profit with $|\mathsf{K}|$ thermal plants and $|\mathsf{W}|$ wind plants over a planning horizon T with an hourly time discretization.

The power producer is assumed to be a price taker: he considers the energy prices as exogenous, i.e. independent of his own production decisions, so the optimal schedule is determined on the basis of price forecasts. Basically, considering the small producer as a price taker who ignores the market prices when making his decisions and has no control on them is equivalent to considering the market price as a random variable evolving over time according to a finite number of scenarios that, for the sake of simplicity, we assume to be equally likely.

Moreover, since the producer owns several thermal plants and a wind farm, we have to take into account the intermittency resource problem considering wind resource as an exogenous stochastic variable. Therefore both prices and wind energy production are (independent) random variables.

Finally, as regards the energy reserves required by the system operator, we model the percentage of spinning reserves actually required by the system, the actual production of spinning reserves and their price as stochastic variables.

The realization of the random variables, for every hour t, defines a scenario $s \in \mathsf{S}$. No correlation is introduced amongst the random variables within the model.

The model sets are defined as follows:

- $\mathsf{T} := \{1, ..., t, ..., T\}$ set of planning horizon, indexed by t
- $\mathsf{K} := \{1, ..., k, ..., K\}$ set of thermal units, indexed by k
- $\mathsf{W} := \{1, ..., w, ..., W\}$ set of wind farms, indexed by w
- $\mathsf{I} := \{1, ..., i, ..., I\}$ set of storage devices, indexed by i
- $\mathsf{S} := \{1, ..., s, ..., S\}$ set of equally likely scenarios, indexed by s

where the model parameters are:

- $\overline{q}_k$: maximum quantity produced by thermal unit k
- $\underline{q}_k$: minimum quantity produced by thermal unit k
- δ^u_k: ramp-up limit of thermal unit k
- δ^d_k: ramp-down limit of thermal unit k
- t^u_k: minimum up-time of thermal unit k
- t^d_k: minimum down-time of thermal unit k

- $\gamma_{0,k}$: initial state of thermal unit k
- $\overline{c}_k^{su}$: maximum start-up cost of thermal unit k
- c_k^v: variable cost of thermal unit k
- $\overline{r}_k$: maximum spinning reserve of thermal unit k
- $\overline{z}_i$: maximum capacity of storage device i
- $\overline{z}_i^u$: ramp-up limit of storage device i

The stochastic parameters[1] are:

- $g_{w,t,s}$: energy provided by wind farm w at hour t, in scenario s
- $p_{t,s}$: electricity price at hour t, in scenario s
- $u_{t,s}$: percentage of spinning required at hour t, in scenario s
- $\theta_{t,s}$: request for spinning reserve at hour t, in scenario s
- $p_{t,s}^r$: spinning reserve price at hour t, in scenario s

The decision variables are:

- $q_{k,t,s}$ energy provided by thermal unit k, at hour t, in scenario s
- $r_{k,t,s}^{av}$ spinning reserve made available by thermal unit k, at hour t, in scenario s
- $r_{k,t,s}$ spinning reserve actually produced by thermal unit k, at hour t, in scenario s
- $z_{i,t,s}^+$ the amount of energy added in the storage device i at hour t, in scenario s
- $z_{i,t,s}^-$ the amount of energy withdrawn from the storage device i at hour t, in scenario s

[1]We define stochastic parameters the realization of random variables.

- $z_{i,t,s}^{cum}$ the actual amount of energy stored by device i at hour t, in scenario s

Finally, the power producer decisions are represented by the following binary variables:

- $\alpha_{k,t,s}$ binary variable indicating if thermal unit k is started up at hour t, in scenario s:

$$\alpha_{k,t,s} = \begin{cases} 1 & \text{if a start-up operation of thermal plant } k \text{ takes place} \\ & \text{at hour } t \text{ in scenario } s; \\ 0 & \text{otherwise} \end{cases}$$

- $\beta_{k,t,s}$ binary variable indicating if thermal unit k is shut down at hour t, in scenario s:

$$\beta_{k,t,s} = \begin{cases} 1 & \text{if shut-down operation of thermal plant } k \text{ takes} \\ & \text{place at hour } t \text{ in scenario } s; \\ 0 & \text{otherwise} \end{cases}$$

- $\gamma_{k,t,s}$ binary variable referring to the state of the thermal plant k at hour t, in scenario s:

$$\gamma_{k,t,s} = \begin{cases} 1 & \text{if thermal plant } k \text{ is ``on'' at hour } t \text{ in scenario } s \\ 0 & \text{if thermal plant } k \text{ is ``off'' at hour } t \text{ in scenario } s \end{cases}$$

3.2.1 Model constraints

Our stochastic model is characterized by the following constraints:

- Thermal generator minimum generation bound:

$$q_{k,t,s} \geq \underline{q}_k \cdot \gamma_{k,t,s} \tag{3.1}$$

  At every hour t, for $\forall k \in K$ and in every scenario s, if generator k is "on", then the production must be greater or equal to the minimum output by thermal unit k.

- Thermal generator maximum generation bound:

$$q_{k,t,s} + r^{av}_{k,t,s} \leq \overline{q}_k \cdot \gamma_{k,t,s} \tag{3.2}$$

At every hour t, in every scenario s and for $\forall k \in K$, if generator k is "on",then the sum of production $q_{k,t,s}$ and available spinning reserves must be equal or lower than the maximum output by thermal unit k[2].

- Thermal generator ramping limits describe the maximum increase or decrease in actual production in an hour ($\forall k \in K$, $\forall t \in T$), in every scenario s. As regards the case of decreasing production we consider the following constraint:

$$q_{k,t-1,s} + r_{k,t-1,s} - (q_{k,t,s} + r_{k,t,s}) \leq \delta^d_k \tag{3.3}$$

otherwise the constraint reads:

$$q_{k,t,s} + r_{k,t,s} - (q_{k,t-1,s} + r_{k,t-1,s}) \leq \delta^u_k \tag{3.4}$$

- Thermal generator minimum up-times constraint:

$$\sum_{\tau=max(t-t^u_k,1)}^{t} \alpha_{k,\tau} \leq \gamma_{k,t,s} \tag{3.5}$$

Defining t^u_k as the minimum number of hours "on" after a start-up operation, $\forall k \in K$ and $\forall t \in T$, if generator k is "off" in t, ($\gamma_{k,t} = 0$), it cannot have been turned on in any of the t^u_k previous hours; it follows that if generator k is "on" in t, ($\gamma_{k,t} = 1$), then it may have been turned on in any of the t^u_k previous hours (or it was already "on").

[2]Given constraints 3.2 and 3.10 we also have $q_{k,t,s} + r_{k,t,s} \leq \overline{q}_k \cdot \gamma_{k,t,s}$.

- Thermal generator minimum down-times constraint:

$$\sum_{\tau=max(t-t_k^d,1)}^{t} \beta_{k,\tau} \leq 1 - \gamma_{k,t,s} \tag{3.6}$$

Defining t_k^d as the minimum number of hours "off" after a shut-down operation, $\forall k \in K$ and $\forall t \in T$), if generator k is "on" at hour t, ($\gamma_{k,t} = 1$), then it cannot be turned off in any of the t_k^d previous hours; hours. On the contrary, if generator k is "off" at hour t, ($\gamma_{k,t} = 0$), then it may have been turned off in any of the t_k^d previous hours (or it was already "off" in the previous hours).

- Thermal generator start-up and shut-down state transition, $\forall k \in K$, at every hour t, in scenario s:

$$\gamma_{k,t,s} = \gamma_{k,t-1,s} + \alpha_{k,t,s} - \beta_{k,t,s} \tag{3.7}$$

In this equation $\gamma_{k,0}$ stands for a binary data representing the status of thermal unit k ($0 =$ OFF, $1 =$ ON).

Table 3.1 shows a representation of constraint 3.7 and the corresponding values of the binary variables $\alpha_{k,t,s}$, $\gamma_{k,t,s}$, $\gamma_{k,t-1,s}$ and $\beta_{k,t,s}$. Note that some cases are relevant: in fact we can see that the constraint 3.7 is satisfied in the cases "***". The constraint is also satisfied in the cases "**" where both start-up and shut-down operations at hour t in scenario s are associated to a thermal unit k which is "on" (or "off") both in $(t-1, s)$ and (t, s). However these solutions are sub optimal and will never appear in the set of optimal solutions (see [43]), since the operations would result in a cost without changing the state of the thermal unit. Finally the cases "*" are infeasible, as shown in the Table 3.2.

- The total spinning reserve constraint reads:

$$\sum_{k \in K} r_{k,t,s}^{av} = u_{t,s} \sum_{k \in K} \overline{q}_k \tag{3.8}$$

$\gamma_{k,t-1}$	α_t	γ_t	β_t	case
0	0	0	0	***
0	1	0	1	**
1	0	1	0	***
1	1	1	1	**
0	1	1	0	***
1	0	0	1	***

Table 3.1: Feasible transition cases

We assume that the total amount of spinning reserves available at every hour t and in every scenario s must be equal to the amount potentially required by the market. Spinning reserves available by thermal units as a whole become a random variable themselves being equal to the product of a random variable and a constant. This constraint thus defines the amount of spinning reserves, which, if required (depending on the value of the binary variable $\theta_{t,s}$) will become generated energy at every point in time and in every scenario[3].

- The second spinning reserve constraint relates to the spinning reserve available $\forall k \in K$, at every hour t, in scenario s:

$$r^{av}_{k,t,s} \leq \overline{r}_k \cdot \gamma_{k,t,s} \tag{3.9}$$

[3] A more sophisticated formulation introduces a lower bound on spinning reserves fixed by law:

$$\sum_{k \in K} r^{av}_{k,t,s} \geq \underline{u}_{t,s} \sum_{k \in K} \overline{q}_k$$

i.e. at every hour t and in every scenario s the amount of spinning reserve must be equal or larger than a given amount. Then $r^{av}_{k,t,s}$ are real decision variables so the producer decides whether increasing the spinning reserves over the minimum or not, giving both $u_{t,s}$ and $\theta_{t,s}$ each with a probability distribution depending on both t and s and given the spinning price $p^r_{t,s}$.

$\gamma_{k,t-1}$	α_t	γ_t	β_t	case
0	0	0	1	*
0	0	1	0	*
0	1	0	0	*
1	0	0	0	*
0	0	1	1	*
1	1	0	0	*
0	1	1	1	*
1	1	1	0	*
1	0	1	1	*
1	1	0	1	*

Table 3.2: Infeasible transition cases

where the maximum spinning produced $\forall k \in K$ and in every hour t, in every scenario s is:

$$\overline{r}_k = \overline{q}_k - \underline{q}_k$$

- The third spinning reserve constraint refers to the spinning reserve actually produced by $\forall k \in K$, at every hour t, in every scenario s:

$$r_{k,t,s} \leq r^{av}_{k,t,s} \tag{3.10}$$

- The first storage constraint defines a maximum quantity of storage for $\forall i \in I$, at every hour t, and in every scenario s:

$$z^{cum}_{i,t,s} \leq \overline{z}_i \tag{3.11}$$

- The second storage constraint imposes a maximum hourly increase on the stored quantity:

$$z^{+}_{i,t,s} \leq \overline{z}^{u}_i \tag{3.12}$$

3.2.2 Spinning reserves formulation

Spinning reserves refer to a part of the productive capacity that is not actually exploited by the producer, although can be made available, on demand, to the system at short time. Since the actual production of energy spinning reserves is not decided by the producer but the regulator (based on grid balancing), spinning reserves could remain a potentially unsold quantity. On the other hand, if actually required by the regulator, the energy produced exploiting the spinning reserves will be sold at a price usually remarkably higher than the current market price.

In order to describe the spinning formulation within the model, we start defining the total amount of energy produced by both thermal units, indexed by k, and the wind farm w (without considering the spinning reserves) at time t in scenario s as:

$$A_{t,s} = Q_{t,s} + G_{t,s} \tag{3.13}$$

where

$$Q_{t,s} = \sum_{k \in K} q_{k,t,s}$$

is the total thermal production, and

$$G_{t,s} = \sum_{w \in W} g_{w,t,s}$$

is the total wind energy produced in scenario s.

Taking into account the availability of spinning reserves, the available total quantity of energy becomes:

$$Q^{av}_{t,s} = A_{t,s} + R^{av}_{t,s} \tag{3.14}$$

where $R^{av}_{t,s}$ is the total amount of available spinning reserves:

$$R^{av}_{t,s} = \sum_{k \in K} r^{av}_{k,t,s}$$

As already pointed out spinning reserves could remain a potentially unsold quantity. Hence, it is necessary to distinguish between available reserves and reserves actually required by the market operator. Therefore we introduce the following variables:

- $u \in [0, 1]$: random variable with a uniform probability distribution (that is, identical at each time t and in every scenario s) representing a non negative percentage of the maximum thermal capacity, required by the system operator; $u_{t,s} \in [0, 1]$ is the realization of the random variable at time t in scenario s.

- $\theta = \{0, 1\}$: binary random variable with Bernoulli distribution (which takes value 1 with success probability p and value 0 with failure probability $q = 1 - p$ indicating whether the system has required a positive amount of available spinning reserves; $\theta_{t,s} = \{0, 1\}$ is the realization of the random variable at time t in scenario s.

Then we define the total reserves potentially required by the operator as a percentage of the maximum thermal plants capacity:

$$R^{pot}_{t,s} = \sum_{k \in K} \overline{q}_k \cdot u_{t,s} \tag{3.15}$$

and the total amount of the available spinning reserve actually required by the system:

$$R_{t,s} = \theta_{t,s} \cdot R^{pot}_{t,s} = \sum_{k \in K} r_{k,t,s} \tag{3.16}$$

In our formulation we consider a market constraint on reserves, thus there is a global amount of reserves required by the system operator. The producer can meet this request with any combination of his thermal plants. Finally, depending on specific market conditions, the system operator might require any part of the spinning reserves to be actually produced.

Therefore, only the reserves actually required by the system operator become produced energy and only these are included in the objective function. It should be noted that the price of the spinning reserves is usually greater than the market energy price; then, in our model we consider a spinning reserve price at hour t in scenario s defined by

$$p^r_{t,s} = (1+h) \cdot p_{t,s} \qquad p^r_{t,s} \geq p_{t,s}$$

where $p_{t,s}$ is the electricity price at hour t in scenario s and h is the price spinning coefficient that multiplied by $p_{t,s}$ defines the price of spinning reserve.

3.2.3 Storage formulation

We suppose that the producer can store both kinds of energy resources: thermal production and wind production. Therefore:

$$Z^+_{t,s} = \sum_{i \in I} z^+_{i,t,s}$$

is the total amount of energy added to the storage devices at hour t in scenario s, and

$$Z^-_{t,s} = \sum_{i \in I} z^-_{i,t,s}$$

is the total amount withdrawn from the storage devices at hour t in scenario s.

Since we are considering a small producer, we assume that the whole quantity produced can be sold on the market, and we define the sold quantity as:

$$Q^{sold}_{t,s} = A^{sold}_{t,s} + R_{t,s} \tag{3.17}$$

where $A^{sold}_{t,s}$ is given by:

$$A^{sold}_{t,s} = A_{t,s} - \left(Z^+_{t,s} - Z^-_{t,s}\right) \tag{3.18}$$

Equation (3.18) means that the quantity sold must be considered as the difference between the quantity actually produced and the total storage amount. Given the introduction of a storage technology in the model, the stochasticity of the supply due wind energy can be smoothed. We define the total amount of stored energy at the end of hour t in scenario s, as:

$$Z_{t,s}^{cum} = \sum_{i \in I} z_{i,t,s}^{cum} \tag{3.19}$$

with

$$z_{i,t,s}^{cum} = (1 - \epsilon) \cdot z_{i,t-1,s}^{cum} + z_{i,t,s}^{+} - z_{i,t,s}^{-} \tag{3.20}$$

In this formulation we consider $\epsilon \in [0, 1]$ as the decay factor per hour of the stored energy, which indicates how much energy gets lost after being stored. In addition, we define c_i^z as the unitary cost of storage that, for the sake of simplicity, is set independent of both time and scenario, although is different for each storage devices in I.

Therefore, in the model the storage technology is identified by two parameters exogenously set: the decay factor and the unit cost.

3.2.4 Thermal production costs

In the whole model we consider only thermal costs and storage costs, because we assume that the marginal wind cost is equal to zero and we do not consider investment costs because we focus on a short-term analysis. Therefore, we consider an existing set of thermal plants, a wind farm and storage devices.

In this section we introduce two different kind of costs related to thermal units: "generation costs" related to energy production and "costs" associated to each start-up or shut-down operations.

Generation costs $C_{k,t,s}^{v}$ are modelled as a linear increasing function of the energy actually produced. Then:

$$C_{k,t,s}^{v} = c^{v} \cdot (q_{k,t,s} + r_{k,t,s}) \tag{3.21}$$

where c^v is unitary cost of produced energy.

Referring to start-up costs we consider the following stochastic variable and parameters[4]:

- $c_{k,t,s}^{su}$ start-up operation cost of thermal unit k, at time t, in scenario s
- $\tilde{c}_{k,t,s}^{su}$ linearised start-up cost operation cost of thermal unit k, at time t, in scenario s
- $c_{k,t,s}^{sd}$ shut-down operation cost of thermal unit k, at time t, in scenario s

We consider the start-up cost $c_{k,t,s}^{su}$ $\forall k \in K$, at time t, in scenario s as an exponential cost depending on how much time has passed since the last shut down operation on thermal unit took place. The start-up cost equation as function of time t (numbers of hours) is given by:

$$c_{k,t}^{su} = \overline{c}_k^{su} \cdot (1 - e^{-\frac{t}{b_k}}) \tag{3.22}$$

where $\overline{c}_k^{su}$ is the maximum start-up cost and b_k is an arbitrary parameter. The final equation is obtained iteratively. We write the equation 3.22 at time $t-1$ as:

$$c_{k,t-1}^{su} = \overline{c}_k^{su} \cdot (1 - e^{-\frac{t-1}{b_k}}) = \overline{c}_k^{su} - \overline{c}_k^{su} \cdot e^{-\frac{t-1}{b_k}} \tag{3.23}$$

Combining equation 3.22 and 3.23 we obtain:

$$\begin{aligned} c_{k,t}^{su} &= \overline{c}_k^{su}(1 - e^{-\frac{-(t-1+1)}{b_k}}) = \overline{c}_k^{su}(1 - e^{-\frac{t-1}{b_k}} e^{-\frac{1}{b_k}}) = \\ &= \overline{c}_k^{su} - \overline{c}_k^{su} e^{-\frac{t-1}{b_k}} e^{-\frac{1}{b_k}} + \overline{c}_k^{su} e^{-\frac{1}{b_k}} - \overline{c}_k^{su} e^{-\frac{1}{b_k}} = \\ &= \overline{c}_k^{su} - \overline{c}_k^{su} e^{-\frac{1}{b_k}} + \overline{c}_k^{su} e^{-\frac{1}{b_k}} (1 - e^{-\frac{t-1}{b_k}}) = \\ &= \overline{c}_k^{su}(1 - e^{-\frac{1}{b_k}}) + e^{-\frac{1}{b_k}} c_{k,t-1}^{su} \end{aligned} \tag{3.24}$$

and starting by 3.24 we derive the start-up costs linear equation for every scenario s and every hour t with $t \geq 1$[5]:

[4]For start-up costs formulation and their linearisation we referred to Prof. Ramos' work and his private communication.

[5]For the case $t = 0$ we obviously consider equation 3.22. Therefore $c_{k,0}^{su} = 0$

$$c_{k,t,s}^{su} \geq e^{-\frac{1}{b_k}} \cdot c_{k,t-1,s}^{su} + (1 - \gamma_{k,t-1,s})\overline{c}_k^{su} \cdot (1 - e^{-\frac{1}{b_k}}) - \alpha_{k,t-1,s} \cdot \overline{c}_k^{su} \quad (3.25)$$

with

$$c_{k,t,s}^{su} \geq 0$$

where $\overline{c}_k^{su}$ is the maximum start-up cost, $\gamma_{k,t-1,s}$ and $\alpha_{k,t-1,s}$ are the binary variables that indicate, respectively, the state of the thermal unit and the switching-on operation at time $(t-1)$ and b_k is an arbitrary parameter.

This formulation of the start-up costs reflects the fact that thermal power is contained in the boiler. If we allow the boiler to decreases, then we need more energy for the next start-up operation; on the other hand, if the unit shuts down for a few hours, then we do not need to use too much energy for the next start-up.

Equation 3.25 means that, when the thermal unit is shut down (i.e. $\gamma_{k,t,s} = 0$), the start-up costs increase up to a maximum of $\overline{c}_k^{su}$. When a start-up operation takes place (i.e. $\alpha_{k,t,s} = 1$), the start-up cost will be downloaded into the objective function and the costs computation will restart from zero.

These costs are the start-up costs that should be consider at hour t if there was a start-up operation. Therefore they will be considered in the objective function only when a thermal plant is actually started-up. To get this, we should multiply the start-up costs by $\alpha_{k,t,s}$ representing the start-up operation at time t:

$$c_{k,t,s}^{su} \cdot \alpha_{k,t,s} \quad (3.26)$$

To avoid the non linearity of this formulation, we redefine start-up costs as follows:

$$\tilde{c}_{k,t,s}^{su} = c_{k,t,s}^{su} - \overline{c}_k^{su} \cdot (1 - \alpha_{k,t,s}) \quad (3.27)$$

with

$$\tilde{c}_{k,t,s}^{su} \geq 0$$

Given this reformulation, when a start-up operation does not occur at time t (i.e. $\alpha_{k,t,s} = 0$), he right hand side of equation 3.27 becomes negative. Therefore start-up costs are equal to 0 in the objective function by non negativity of costs. On the other hand, when a start-up operation occurs at time t (i.e. $\alpha_{k,t,s} = 1$) we have $\tilde{c}^{su}_{k,t} = c^{su}_{k,t}$ [6].

3.2.5 Objective function

To define the objective function we consider the following price variables:

- $p_{t,s}$ the stochastic electricity price at hour t, in scenario s
- $p^r_{t,s}$ the spinning reserve price at hour t, in scenario s with $p^r_{t,s} = (1+h)\, p_{t,s}$ where h is a non negative parameter.

Defining π_s as the probability of scenario $s \in S$, for the objective function we have two cases.

In the first case we do not consider the storage technology, the objective function then is:

$$\max \sum_{t\in T} \Big\{ \sum_{s\in S} \pi_s \Big[\Big(p_{t,s} \cdot \Big(\sum_{k\in K} q_{k,t,s} + \sum_{w\in W} g_{w,t,s} \Big) \Big) + \Big(p^r_{t,s} \cdot \sum_{k\in K} r_{k,t,s} \Big) - \sum_{k\in K} \left(C^v_{k,t,s} + \tilde{c}^{su}_{k,t,s} + c^{sd}_{k,t,s} \beta_{k,t,s} \right) \Big] \Big\} \tag{3.28}$$

In the second case we do consider the storage technology and again here the small producer tries to maximize his profits by means of production scheduling, therefore the objective function becomes:

[6] Note that when t increases start-up costs rapidly increase and converge to $\bar{c}^{su}_k$ for every k. Once a thermal unit has been shut down at some time $\bar{t}$ it must remain inactive for, at least, t^d_k periods. Therefore, when it can be reactivated, start-up costs are greater or equal to $c^{su}_{k,\bar{t}+t^d_k} = \bar{c}^{su}_k \cdot (1 - e^{-\frac{(\bar{t}+t^d_k)}{b_k}})$. If t^d_k are sufficiently high, given an appropriate choice of parameters b_k, start-up costs could be considered constant and equal to their maximum.

$$\max \sum_{t \in T} \Big\{ \sum_{s \in S} \pi_s \Big[\Big(p_{t,s} \cdot \Big(\sum_{k \in K} q_{k,t,s} + \sum_{w \in W} g_{w,t,s} + \sum_{i \in I} z^-_{i,t,s} \Big) \Big) + \Big(p^r_{t,s} \cdot \sum_{k \in K} r_{k,t,s} \Big) - \sum_{k \in K} \Big(C^v_{k,t,s} + \tilde{c}^{su}_{k,t,s} + c^{sd}_{k,t,s} \beta_{k,t,s} + c^z_i \cdot z^+_{i,t,s} \Big) \Big] \Big\} \tag{3.29}$$

where c^z_i is the unitary cost of storage that, for the sake of simplicity, is independent of both time and scenario, although it is different for each storage devices in I and indicates how much energy is lost when stored.

Even here, as in the previous formulation, there is stochasticity on both sides, supply and prices, but in this case the producer can decide the quantity of thermal power to be produced by exploiting some storage technology.

3.3 Deterministic model

We have also considered the deterministic version of the previous model where a small producer owns several thermal plants, a wind farm and a storage device. We consider the same sets and parameters as introduced before. The decision variables are defined only at time t as follows:

- $q_{k,t}$ energy provided by thermal unit k, at hour t
- $r_{k,t}$ spinning reserve available by thermal unit k, at hour t
- $\tilde{r}_{k,t}$ spinning reserve actually produced by thermal unit k, at hour t
- $z^+_{i,t}$ the quantity of energy added in the storage device i at hour t
- $z^-_{i,t}$ the quantity of energy withdrawn from the storage device i at hour t
- $z^{cum}_{i,t}$ the actual quantity of energy stored by device i at hour t

- $\alpha_{k,t}$ the binary variable indicating if thermal unit k is started-up at hour t
- $\beta_{k,t}$ the binary variable indicating if thermal unit k is started-up at hour t
- $\gamma_{k,t}$ the binary variable indicating if thermal unit k is started-up at hour t

In this formulation we suppose that the producer knows exactly how much wind power will be produced and as well as the price of energy in the future, over a planning horizon T with an hourly discretization. Therefore, the deterministic model decision variables are modelled taking into account the expected value of the variables along the scenarios considered in the stochastic model:

- $E(g_{w,t,s})$ energy provided by wind farm w at hour t
- $E(p_{t,s})$ stochastic electricity price at hour t
- $E(u_{t,s})$ percentage of spinning required at hour t
- $E(p^r_{t,s})$ spinning reserve price at hour t

We note however that $\theta_{t,s} = \{0, 1\}$ (binary variable that represents a request for spinning reserve at hour t) is replaced by a unique sequence of values indicating whether the system has required a positive amount of available spinning or not.

Therefore, considering the same constraints as in the stochastic model for each k, g and i, and for each time t, we define the objective functions of the deterministic model without considering the storage technology and considering the storage technology respectively:

$$\max \sum_{t \in T} \Big\{ \Big[E(p_{t,s}) \cdot \Big(\sum_{k \in K} q_{k,t} + \sum_{w \in W} E(g_{w,t,s}) \Big) + \Big(E(p^r_{t,s}) \cdot \sum_{k \in K} r_{k,t} \Big) \Big] - \sum_{k \in K} \big[C^v_{k,t} + \tilde{c}^{su}_{k,t,s} + c^{sd}_{k,t} \beta_{k,t} \big] \Big\} \quad (3.30)$$

$$\max \sum_{t \in T} \Big\{ \Big[E(p_{t,s}) \cdot \Big(\sum_{k \in K} q_{k,t} + \sum_{w \in W} E(g_{w,t,s}) + \sum_{i \in I} z^{-}_{i,t} \Big) + \Big(E(p^{r}_{t,s}) \cdot \sum_{k \in K} r_{k,t} \Big) \Big] - \sum_{k \in K} \big[C^{v}_{k,t,s} + \tilde{c}^{su}_{k,t,s} + c^{sd}_{k,t} \beta_{k,t} + c^{z}_{i} \cdot z^{+}_{i,t} \big] \Big\} \tag{3.31}$$

3.4 Conclusion

In this chapter we have formulated an optimization model for a small producer who needs to take her/his short-term production decisions over both traditional and wind energy. In our formulation was also provided the possibility of using some storage devices.

In the next chapter this model will be validated using a dataset referring to the Italian electricity market.

Chapter 4

Validation model and results

4.1 Introduction

The model proposed and described in the previous chapter allows to consider both traditional energy sources and wind energy, taking into account the usage of storage technologies. This allows a small producer to make decisions on energy production, to maximize its own profits while satisfying a part of the market demand.

In this chapter the model will be validated using a data set referring to the Italian electricity market.

4.2 Stochastic model data sets

In this section we describe thermal units, wind farm and storage devices data sets. Moreover, we describe the time horizon structure, and both wind resource and energy price scenarios.

4.2.1 Thermal data sets

In our analysis we consider a single small producer who owns a set of thermal power plants consisting of 5 small unit ($K = 1, ..., 5$) and one wind farm ($W = 1$). The producer acts as a price taker and aims at maximizing his profits scheduling his production over a three day time horizon with an hourly discretization. The choice of this time horizon stems from the presence of the wind resource. In fact, wind forecasts, when referred to a short term, seem to be more reliable.

The power plants are characterized by different minimum and maximum operating points, cost structures and flexibility.

To validate the model, we used a data set relative to some of the smallest Italian power plant in order to be consistent with the assumption of a small producer.

We classify power plants according to their power capacity and their different degrees of flexibility (more or less flexible). Note that while plants' flexibility is generally evaluated on a daily or weekly basis, since we adopt a three day time horizon we have to consider an hourly flexibility index that translates the available data into a unit of measurement consistent with our setting.

A summary of the main features of the considered thermal power plants is presented in Table 4.1, which describes both their minimum and maximum power capacity and their degree of flexibility. Finally we consider the initial state of each thermal plant k equal to 0 ($\gamma_0 = 0, \forall k \in K$) i.e. all thermal plants are initially OFF[1].

Table 4.2 describes the main costs of thermal power plants: production costs and start-up costs. Note that while shut down costs are set equal to 0 for each unit k, start-up costs have been proportionally reduced to make them consistent with the short time horizon under consideration. Furthermore production costs are calculated as sum of the fuel cost, CO2 emission costs and variable costs.

4.2.2 Storage data sets

A storage technology is identified by four parameters exogenously set: the efficiency coefficient ϵ, the unitary cost c_i^z its whole maximum capac-

[1]For further details see Chapter 3 section 3.2.1.

Thermal plants data				
Thermal units	minimum capacity (MW)	maximum capacity (MW)	min up-time (hours)	min down-time (hours)
1	9	22	2	2
2	30	50	4	3
3	40	60	12	6
4	20	67	12	6
5	32	68	12	6
Tot	131	267		

Table 4.1: Thermal plants data
Source: RSE

Thermal start-up and production costs (€/MWh)					
Thermal units	start-up costs	production unitary costs	current fuel unitary costs	variable unitary costs	CO2 emission unitary costs
1	5572	95.64	84.35	3.98	7.31
2	3428	77.76	61.53	3.98	12.24
3	3428	79.14	69.17	3.98	5.99
4	5572	71.95	62.55	3.98	5.42
5	5572	40.14	20.91	3.98	15.25

Table 4.2: Thermal plants costs
Source: RSE

ity $\overline{z}_i$ and its maximum hourly capacity $\overline{z}_i^u$. Therefore we can represent a storage technology as a point in $\mathbb{R}^4$. Our analysis takes into account a set of storage devices indexed by i that differ in some or all these technical features. It is worth to note that our model then represents a tool to evaluate the impact on the objective function of any given storage technology. On principle it could also allow to compute the set of points in $\mathbb{R}^4$ that represent "neutral" storage technologies i.e. with no impact on the objective function.

As references for storage technologies, we have considered several recent works, from which we have obtained data on some of the main technical features of storage devices (see [34] [33] and, for a summary, see the Table already shown at the end of Chapter 2).

Obviously, since we've focused on the case of small plants, we haven't considered large size technologies, taking into account a range of costs and efficiency parameters related to small size existing technologies. As already pointed out, also hypothetical values of cost and efficiency coefficients have been considered, as if an hypothetical storage technology was affordable for a small producer.

4.2.3 Wind data sets

We restrict ourselves to a single wind farm[2] w with a given number of rotors producing a certain amount of energy depending on wind speed that is naturally regarded as stochastic.

We built a Matlab tool to generate wind power forecast scenarios and we provided for the possibility to change the type of rotor (considering the type Gamesa turbine), the wind farm number of rotors, and the number of turbines that could be in the "fail" state or in the "maintenance" state, to simulate the different wind power penetration. In Table 4.3 and in Figure 4.1 we can observe the technical differences between two types of rotors Gamesa and their generated power.

[2] Wind farm is defined as a group of wind turbines in the same location used to produce electric power.

Rotor	**G52**	**G58**
Diameter	52 m^2	58 m^2
Swept area	2.124 m^2	2.642 m^2
Rotational speed	14.6-30.8 r.p.m.	14.6-30.8 r.p.m.
Rotational direction	Clock Wise	Clock Wise
Weight	Approx. 10.000 kg	Approx. 12.000 kg
Nacelle weight	Approx. 23.000 kg	Approx. 23.000 kg
Cut-in speed	4 m/s	3 m/s
Cut-out speed	25 m/s	21 m/s

Table 4.3: Comparison between two Gamesa rotors
Source: Gamesa

This wind farm is actually regarded as a group of 10 wind turbines in the same location. The wind farm is supposed to employ an existing technology, with zero investment costs. Wind power has zero marginal costs as well.

To generate wind power production scenarios the hourly wind speed data from 2006 to 2007 (provided by a small Italian wind power producer) have been employed. Scenarios generation was based on Weibull distribution, which is typically used for wind forecasting (see [44]). As examples of wind speed and wind power scenarios generation, see Figure 4.2 and Figure 4.3 respectively.

4.2.4 Price data sets

In our analysis the "UNP price[3]" is the unique price on the market, and, since we have a single, price taker, small producer, we suppose that all produced energy is sold at that price.

Note however that spinning reserves are treated differently: if required they are sold at a different price. For the sake of simplicity spinning reserve price is defined introducing a mark-up over the UNP. This allows

[3]UNP= Unique National Price

Figure 4.1: Wind Power produced by Gamesa rotors

Source: author's estimated based on Gamesa data

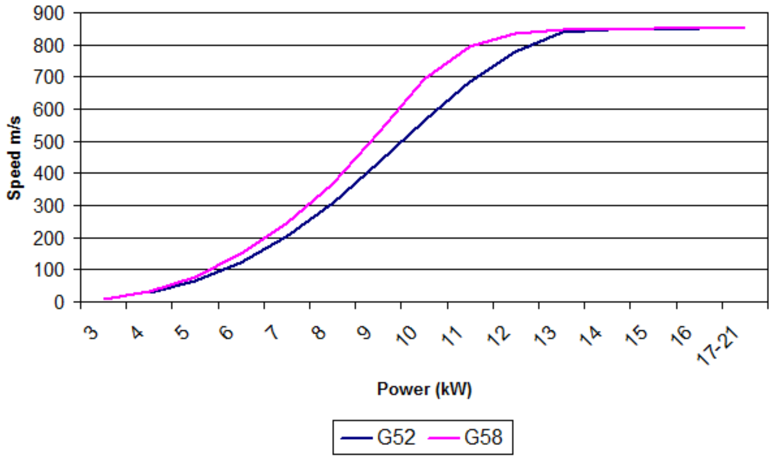


Figure 4.2: Wind scenario generation

Source: author's estimated based on a small producer data

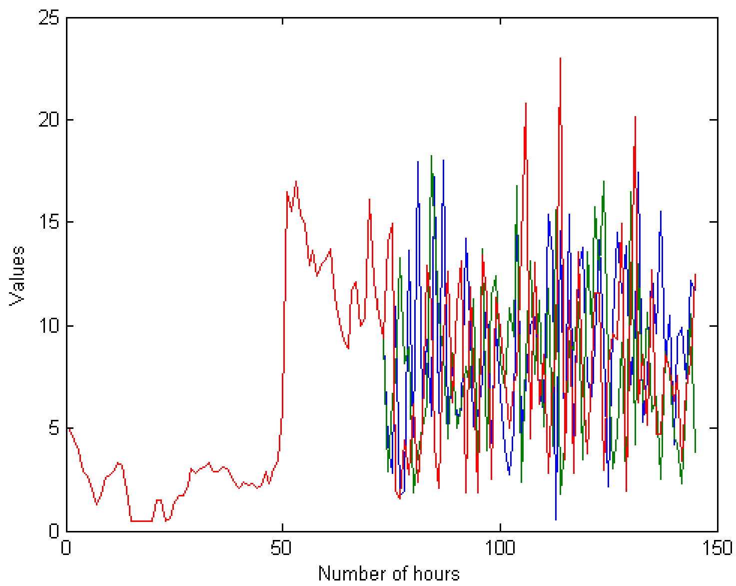
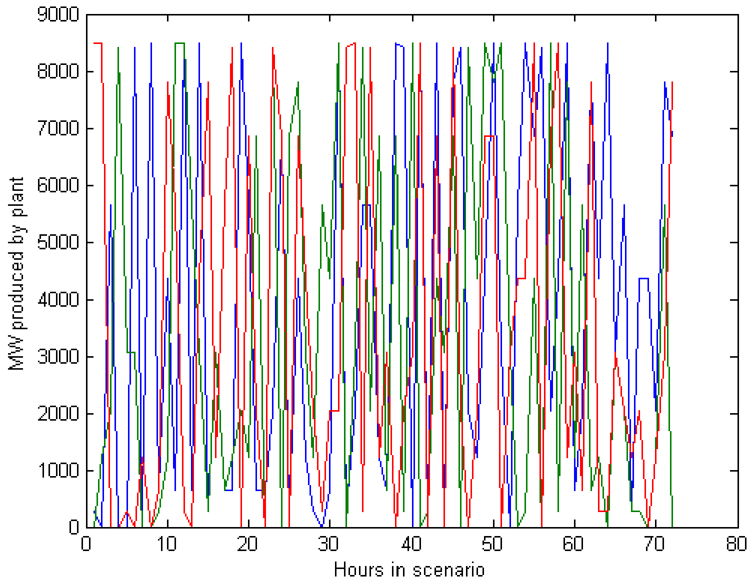


Figure 4.3: Wind production scenario generation

Source: author's estimated based on a small producer data



us to make the spinning reserve price stochastic without making the scenarios too heavy.

Price scenarios are estimated based on a linear regression, considering a time series of hourly prices from 2005 to 2010, related to GME data sets. Hourly price values of the considered six year are shown in Figure 4.4.

Let $p_{t+1|t}$ be the price at time $t+1$ forecasted at time t given the data available up to time t. Our model takes the following form:

$$p_{t+1|t} = \beta_0 + \beta_1 * p_{t-1} + \beta_2 * p_{t-168} + \sigma * \epsilon_{t+1}$$

where p_{t-1} and p_{t-168} represent, respectively, the energy price one hour before and one week before and $\epsilon_{t+1} \sim IID\ N(0,1)$. In Table 4.4 we report the values of coefficients and their p-values. Finally the value of $R\!-\!square$ coefficient is equal to 0,857359.

An example of price scenario generation is shown in Figure 4.5.

Regression coefficients		
Coefficient	value	p-value
β_0	1.390090	1.17 $e^{-0.25}$
β_1	0.533210	0
β_2	0.447181	0

Table 4.4: Regression coefficients

Source: author's estimated

Figure 4.4: Price time series 2005-2010

Source: GME

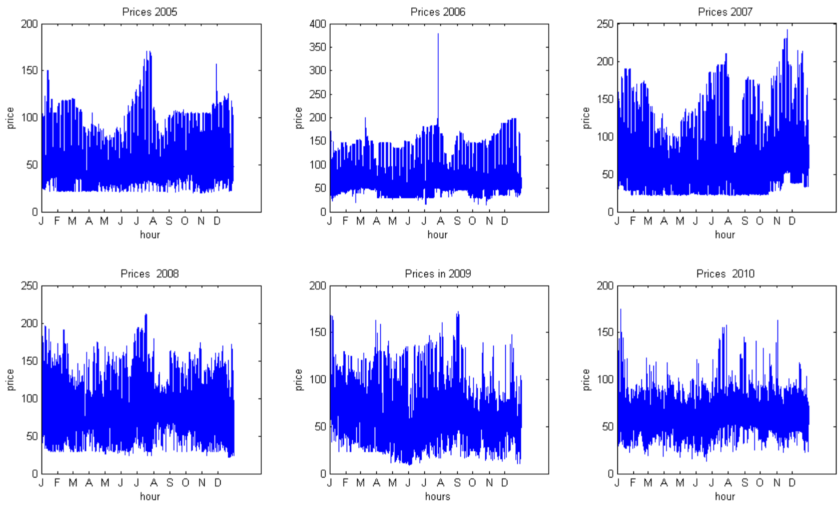
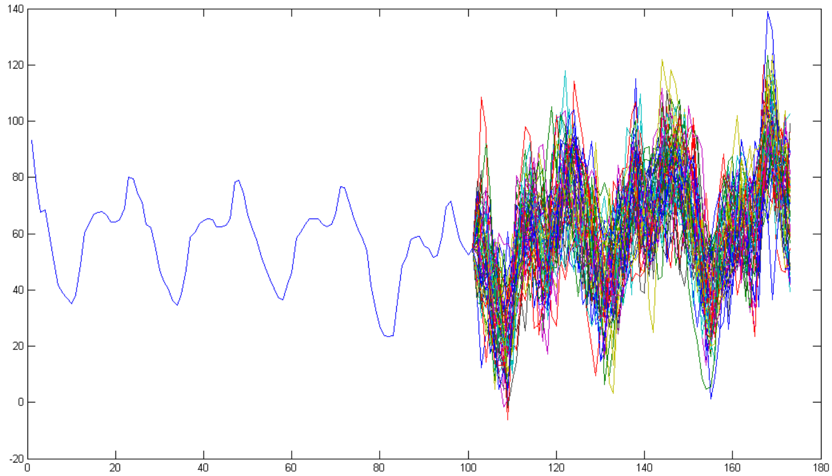


Figure 4.5: Price scenario generation

Source: author's estimated based on GME data



4.2.5 Scenarios tree generation

Energy prices and wind power production are independent random variables whose realization defines a scenario S.

Our analysis confines itself to a finite number of equally likely scenarios covering a planning horizon of three days (with an hourly discretization, then 72 hours). Finite number of possible scenarios including prices and wind data randomly created with the procedure described in previous sections. We assume that the various scenarios are equally likely.

We structure our scenarios in order to obtain a scenario tree as shown in Figure 4.6. We obtain a multi-period stage model, where the producer can take a decision at time $t = 1$ in the first node concerning the first 24 hours and can revise his decision at hour 24 for the remaining time horizon (48 hours).

In the scenario tree, each of the first two branches represents the realizations of prices and wind power production over time up to the next decision node. In the first stage we consider two possible scenarios. For the following 48 hours we consider n branches departing from each node of the second stage. Therefore, when we consider the whole time horizon, the number of possible scenarios is actually equal to $2n$. It is obvious that at each decision node the producer has just a probability distribution over the different branches departing from the node itself and has to take a decision on this basis.

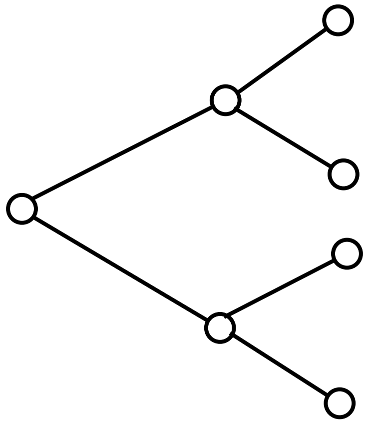


Figure 4.6: Scenarios tree representation

As example, in Figure 4.7 and Figure 4.8 we can observe respectively both 40 prices scenarios generated and 40 scenarios tree actually used for our analysis. The first graph represent the whole 40 scenarios as generated by our Matlab tool. The second one shows how the scenarios are used to create the scenario tree. Consider the scenarios as 40 different straight lines and, in order to get the first stage node, consider an average over all the scenarios. Then to get the second stage nodes divide the scenarios into two sets with identical cardinality and compute the average over the scenarios in each set. Finally, to get the third stage nodes, no further average is made.

Figure 4.7: Actual price scenario generation

Source: author's estimated based on GME data

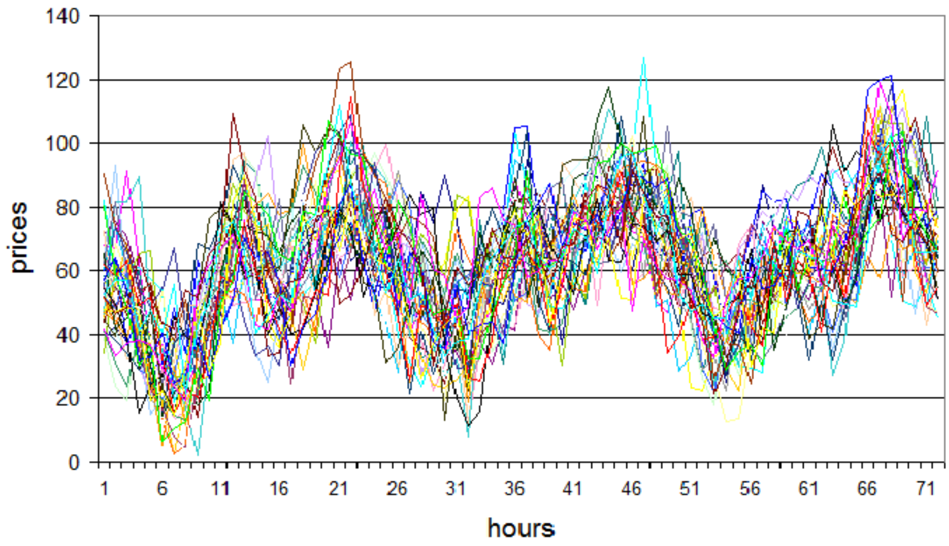
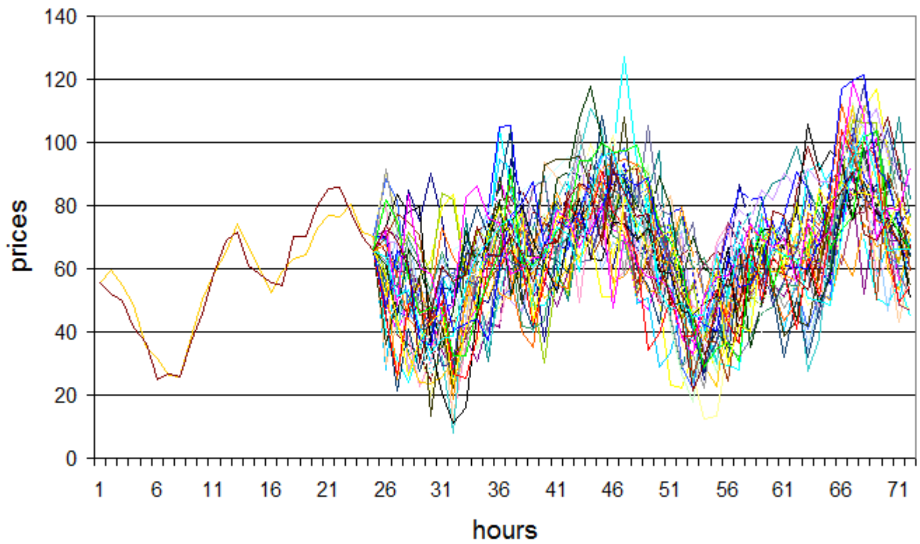


Figure 4.8: Tree scenario generation

Source: author's estimated based on GME data



4.3 Model validation

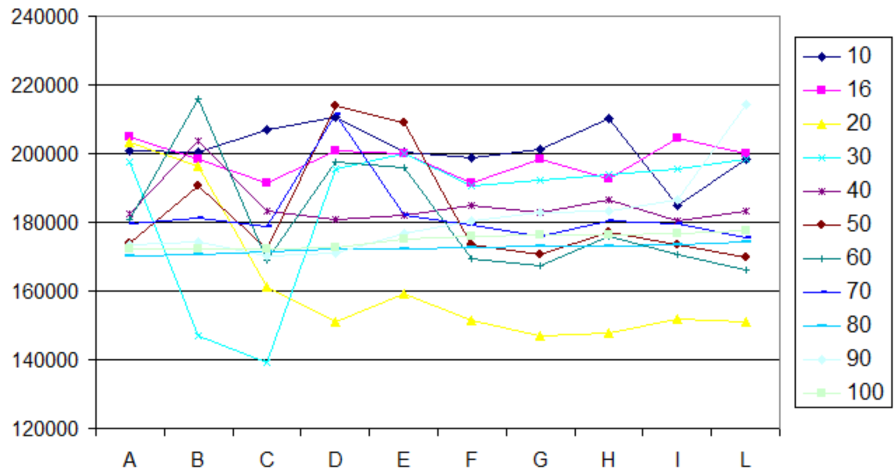
As already pointed out, we analyse a three-day planning horizon, with an hourly discretization ($T = 1, ...t, ..., 72$) considering both prices and hourly wind power production as stochastic.

Note that we have considered just 40 equally likely scenarios over a planning horizon T. To justify this choice we analysed changes in the value of the objective function by generating different scenarios (cases: $A, ..., L$) and increasing the number of scenarios ($10, ..., 100$) (see Table 4.5).

We note that the values of the objective functions do not change significantly when we increase the number of scenarios (as shown in Table 4.5 and Figure 4.9). Also the average of hours "on", the average of produced spinning reserves and the average amount of storage remain almost constant.

Figure 4.9: Objective function values

Source: author's estimated



On the other hand, we noticed that computational time increases significantly with an increasing number of scenarios. For these reasons we chose to perform our analyses with 40 scenarios.

	Different scenarios									
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**L**
10	200,740	200,363	207,064	210,563	200,542	198,644	201,276	210,317	184,841	198,376
16	204,994	198,312	191,293	200,715	200,127	191,245	198,473	192,648	204,403	200,155
20	203,409	196,349	161,105	150,983	159,336	151,520	146,893	147,600	151,735	151,038
30	197,541	146,756	139,049	195,397	199,951	190,689	192,185	193,847	195,454	198,538
40	182,318	203,695	183,451	180,866	182,043	184,997	182,819	186,592	180,324	183,355
50	173,789	190,456	172,428	214,008	209,153	173,609	170,485	177,139	173,660	169,645
60	180,644	215,787	168,920	197,524	195,934	169,319	167,173	175,896	170,581	165,967
70	179,668	181,220	178,804	211,411	181,952	179,163	175,942	180,365	179,636	175,684
80	170,097	170,433	171,354	172,403	172,436	172,586	173,038	173,122	173,424	174,203
90	173,337	174,416	170,140	170,983	176,698	180,567	182,685	183,126	186,467	214,329
100	172,166	172,204	172,345	172,779	174,974	176,041	176,219	176,474	176,903	177,577

Table 4.5: Objective function values

Source:author's estimated

4.3.1 Thermal production results and the role of spinning reserves

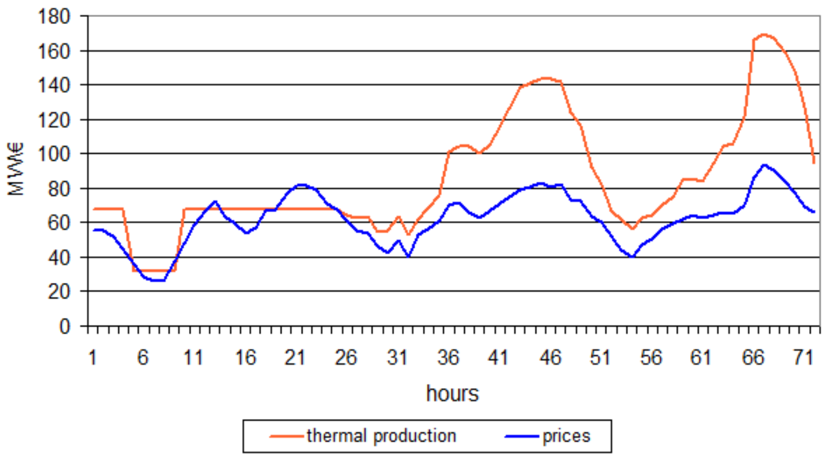
This model allows to determine optimal thermal production, representing a tool for the producer to take scheduling decisions that maximize his profits.

The main elements considered in the model (presence of spinning reserves, wind power production and storage) can be enabled or disabled to evaluate their effect on both scheduling of production and objective function values.

As a first case we consider thermal output net of both spinning reserves production and storage. Average total thermal production over different scenarios, related to this case, is shown in Figure 4.10.

Figure 4.10: Thermal production and prices

Source: author's estimated



As expected, production and price values agree: an increase in hourly prices is reflected by an increase in thermal production. Straight lines in the production graph need more care: note that in initial hours, when prices are very low, thermal production stems from only one thermal plant identified by number 5, which produces at its minimum capacity. This evidence might be regarded as counter intuitive: despite its unitary production cost, equal to 40.14€, is higher than the average market price[4], still thermal plant 5 produces. This seems due to the fact that if it was turned off then we should wait six hours to turn it on and this start up operation would imply a start-up cost, both loosing and decreasing profits in next hours characterized by high prices. When hourly prices increase still just the fifth thermal plant is ON, now producing at its maximum capacity: on one hand plants number 3 and 4, being OFF since time $t = 1$, cannot be turned on due to their minimum down constraints; on the other hand, prices are still too low to make the activation of thermal plants 1 and 2 profitable given both unitary production costs and start-up costs.

We analyse a second case to evaluate the effect of the introduction of spinning reserves on thermal production and scheduling decisions.

On principle, when we allow for spinning reserves we expect two distinct effects: first, given the chance to sell energy at a higher price, the producer might decrease his actual production reserving production capacity to accomplish future requests. This might depress the value of expected thermal production given that reserved production capacity might remain unused.

On the other hand spinning reserves introduce an incentive to turn on more thermal plants in order to exploit this new chance with a positive impact on the expected value of thermal production. These incentive are hidden in our model since spinning reserves are assumed to be mandatory, and the producer decides not whether to reserve production capacity but how this production capacity is to be reserved i.e. which thermal plants are to be devoted to spinning reserves production.

In Figure 4.11 the first effect is clearly reflected by the production level at hour 10 and 11 when still just thermal plant 5 is on and positive spinning reserves are required.

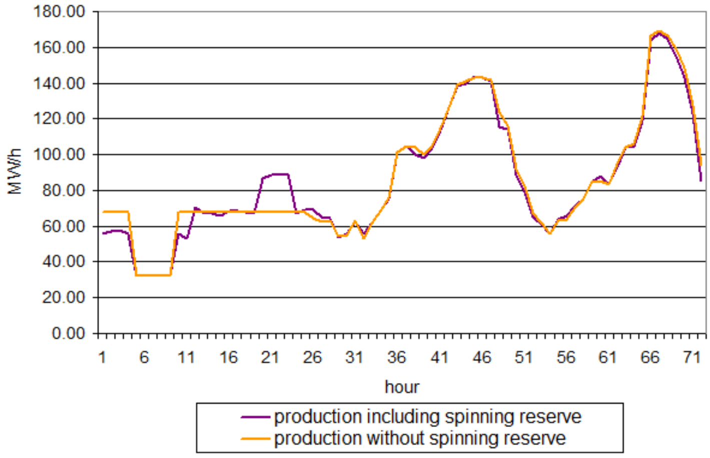
Note however that in some scenarios, the presence of mandatory spinning reserves forces the producer to activate a second thermal plant[5]. This

[4]Average market prices from hour 5 to hour 9 range from a minimum of 25.85€ up to a maximum 37.61€.

[5]In more details thermal plant 4 is activated at hour 12; interestingly the crucial tech-

Figure 4.11: Thermal production with/without spinning reserves

Source: author's estimated



choice, while forced, seems to allow the producer to exploit the future increase in prices, an increase that is more evident here than in the case with just thermal production, since spinning reserves are sold at a higher price.

However, since the required amount of spinning reserves is not chosen by the producer, with no surprise we observe in the data that the value of the objective function is lower when spinning reserves are considered: activating thermal plant 4 implies a start-up cost that, even if smoothed over at least 12 hours, increases the unitary cost. This has an obvious implication: given the set of electricity prices we have considered, there is no incentive for the producer to reserve enough productive capacity. The role of the regulator is then essential to gain market balance or, at least, his absence would imply a higher cost (i.e. higher prices) to get the same result.

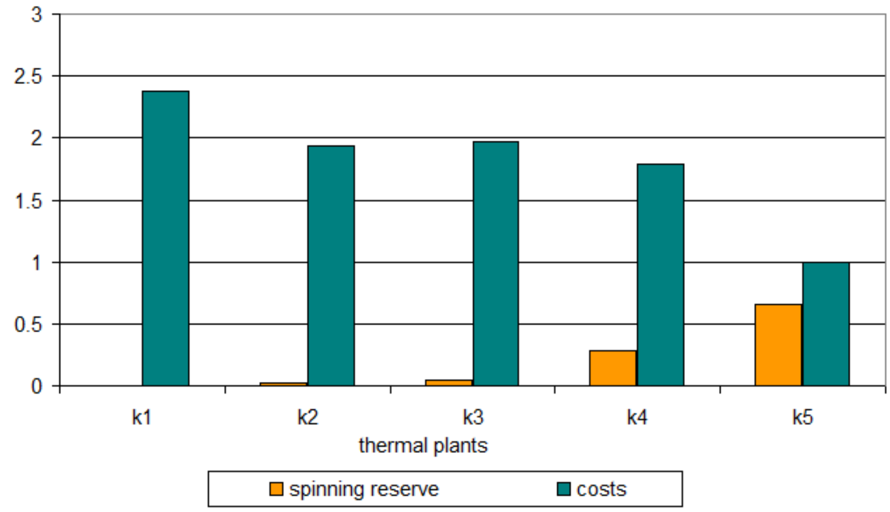
Producer's choices when he has to decide how to accomplish the spinning reserves requirement are represented by graph in Figure 4.12 where unitary production costs of each thermal plant are compared to the per-

nical feature leading the decision maker is then thee unitary production cost given that thermal plant 4 has the second highest start-up cost among the thermal plants OFF at hour 12.

centage of required spinning reserves actually reserved by that plant. As expected, the lower the unitary production cost the higher the share of reserved spinning reserves.

Figure 4.12: Spinning reserves produced and unitary costs

Source: author's estimated

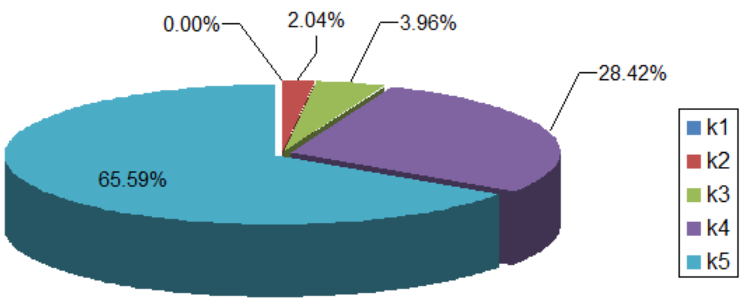


However this point might be tricky: we expect the producer to follow a precise ordering when deciding how to share required spinning reserves among active thermal plants.

In more details, he should first produce the optimal quantity with the lowest cost thermal plants, and then he should devote to spinning reserves the active thermal plants with higher unitary costs. This fact is not clear from Figure 4.13, given that we consider an average over the scenarios, while it is evident if we consider the example in Tables 4.6 and 4.7, that singles out to different scenarios at different hours.

Figure 4.13: Spinning reserves produced by each thermal unit

Source: author's estimated



Scenario 1, hour 26				
thermal unit	status	maximum production (MW)	actual production MW/h	spinning allocation MW/h
1	OFF	22	0.00	0.00
2	OFF	50	0.00	0.00
3	OFF	60	0.00	0.00
4	ON	67	20	15.22
5	ON	68	68	0

Table 4.6: Spinning reserve allocation

Source: author's estimated

Scenario 2, hour 35				
thermal unit	status	maximum production (MW)	actual production MW/h	spinning allocation MW/h
1	OFF	22	0.00	0.00
2	OFF	50	0.00	0.00
3	OFF	60	0.00	0.00
4	ON	67	20	13.39
5	ON	68	68	0

Table 4.7: Spinning reserve allocation
Source: author's estimated

4.3.2 Storage technology results

When wind energy is considered, a stochastic element, on the offer side, is introduced. We expect storage technologies to allow the producer to accomplish demand stochasticity[6] and to redefine his production scheduling over time. The producer has a chance to exploit an expected future increase of the market price (remember that our producer is a price taker so no production choice has an impact on the market price at any hour) by lowering the amount of energy sold today, storing part of his production and selling his stored energy at a future date when a higher price is expected. This role of storage is reflected by Figure 4.14, representing storage distribution over time[7].

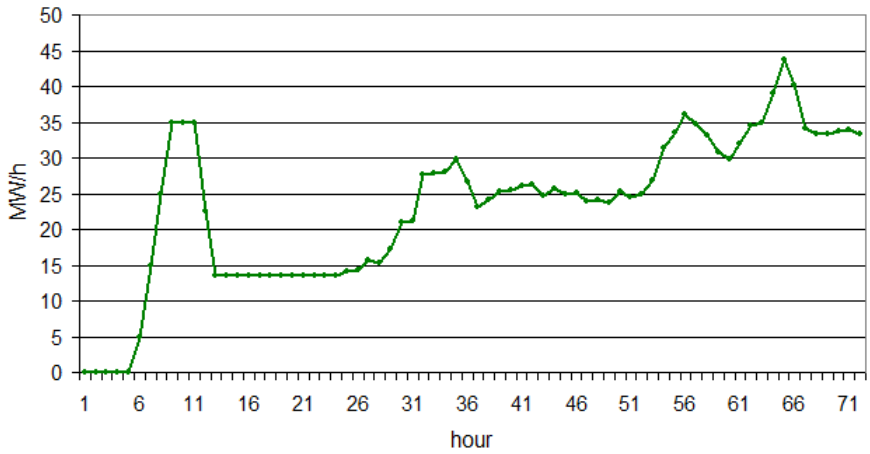
Therefore it seems obvious that the introduction of a storage technology would increase the value of the objective function. We can see this effect considering a fixed storage technology characterized by specific parameters and coefficients: maximum capacity $\overline{z}_i = 50MW$, maximum hourly capacity $\overline{z}_i^u = 10MW$, efficiency coefficient $\epsilon = 0.9$, unitary cost $c_i^z = 10$€. In this case, enabling or disabling various elements of the model,

[6] In our case, since we consider a small producer this effect is neglected.

[7] As previously stated, since we consider average values over the scenarios, some information might be concealed. Note however that a logic time schedule is respected: first energy is stored, then it is used to increase production.

Figure 4.14: Cumulated storage

Source: author's estimated



the value of the objective function in cases where the storage technology is used is always higher than cases in which is not used. This is shown in Table 4.8 where the following cases are considered:

- **case a**: only thermal production with mandatory spinning reserve;
- **case b**: only thermal production without mandatory spinning reserve;
- **case c**: both thermal and wind power production, with mandatory spinning reserve;
- **case d**: both thermal and wind power production, without mandatory spinning reserve.

Obviously, the higher is the cost of a storage technology, the lower is its (positive) impact. In fact, we can observe that, depending on different technology, we have a different values of objective function. Then, we can evaluate which hypothetical pairs of costs and efficiency coefficients make

	storage	NO storage
case a	111,098.59	110,044.74
case b	116,017.96	114,966.32
case c	204,174.19	203,109.93
case d	209,098.96	208,043.18

Table 4.8: Role of storage technology
Source: author's estimated

profitable the use of storage devices. In our case, being a small producer, the costs must be very low and the efficiency coefficient very high.

An example is shown in Figures 4.9 and 4.10, which consider the following cases respectively[8]:

- **case a**: storage device with $\overline{z}_i = 50MW$ and $\overline{z}_i^u = 10MW/h$;
- **case b**: storage device with $\overline{z}_i = 20MW$ and $\overline{z}_i^u = 2MW/h$.

Objective function values								
ϵ \ cost	10	15	20	25	30	35	40	45
0.9	188,271	187,773	187,520	187,416	187,366	187,337	187,330	187,326
0.8	187,475	187,386	187,349	187,336	187,329	187,326	187,326	187,326
0.7	187,360	187,340	187,331	187,327	187,326	187,326	187,326	187,326
0.6	187,337	187,329	187,327	187,326	187,326	187,326	187,326	187,326

Table 4.9: Objective function values with storage (case a)
Source: author's estimated

[8]These values refer to the model that include both thermal and wind power production

Objective function values								
ϵ \ cost	10	15	20	25	30	35	40	45
0.9	187,515	187,416	187,365	187,344	187,333	187,328	187,326	187,326
0.8	187,356	187,337	187,330	187,328	187,327	187,326	187,326	187,326
0.7	187,332	187,329	187,326	187,327	187,326	187,326	187,326	187,326
0.6	187,328	187,326	187,326	187,326	187,326	187,326	187,326	187,326

Table 4.10: Objective function values with storage (case b)
Source: author's estimated

We note the same effect investigating the average amount of storage on different scenarios, as shown in Tables 4.11 and 4.12.

Average amount of storage (MW/h)								
ϵ \ cost	10	15	20	25	30	35	40	45
0.9	129.25	70.50	29.75	14.00	6.25	3.25	1.25	0.00
0.8	26.25	11.75	4.75	1.75	1.00	0.25	0.00	0.00
0.7	7.00	2.50	1.25	0.50	0.00	0.00	0.00	0.00
0.6	2.25	0.75	0.15	0.00	0.00	0.00	0.00	0.00

Table 4.11: Average amount of storage (case a)
Source: author's estimated

It is worth noting that only electricity prices (actual and expected) determine the amount of storage. This can be seen comparing prices and storage choices at hour 6 in scenarios 20 and 21 (see Table 4.13). In scenario 21 prices are lower than in scenario 20 determining an incentive to increase the amount of storage.

Average amount of storage (MW/h)								
ϵ \ cost	10	15	20	25	30	35	40	45
0.9	25.85	14.10	5.95	2.80	1.25	0.65	0.25	0.00
0.8	5.25	2.35	0.95	0.35	0.20	0.05	0.00	0.00
0.7	1.40	0.50	0.25	0.10	0.00	0.00	0.00	0.00
0.6	0.45	0.15	0.00	0.00	0.00	0.00	0.00	0.00

Table 4.12: Average amount of storage (case b)
Source: author's estimated

Scenario	price (€)	storage (MW/h)
20	31.49	0
21	24.95	10

Table 4.13: Storage choices
Source: author's estimated

Note that the role of spinning reserves in defining storage choices is neutral. Again this result seems to be logic. Suppose that, in order to meet the demand of spinning reserves, the producer decided to increase his current production instead of reserving production capacity. Obviously, this choice would imply no advantage or disadvantage if spinning reserves were actually required. If not required, the extra production could be carried to the next hour $t+1$ and sold or, again, used to satisfy the demand of spinning reserves. However, the non-zero cost of storage, would imply a higher unitary cost of this production.

Finally, we note that an increase in wind energy production at any hour t do not increase stored energy (unless whole thermal production was stored and the maximum storage level was not reached). This because an increase in wind energy production would just determine a lower unitary production cost (wind energy has zero cost), without modifying the incentive structure of the producer that is influenced just by the difference between prices at different points in time. Suppose (p_t, c_t) and (p_{t+1}, c_{t+1}) are, respectively, the energy price and the unitary cost at time t and at time $t+1$. Producer's incentive to increase storage depends on the difference between the unitary profit at time t, given by $(p_t - c_t)$ and the expected unitary profit at time $t+1$ given by $\left(p_{(t+1)|t} - c_t\right)$ where $p_{(t+1)|t}$ represents the energy price at time $t+1$ forecasted at time t. If wind power production increased at time t, this difference would remain identical.

We have observed that the choice of the optimal amount of storage seems to depend on market prices only. This might to confine the role of renewable energy in determining the amount of storage since when wind power production is introduced there is no change in price structure. This minor role of wind power production seems ingrained to the structure of our model since a small producer can sell any quantity with no impact on the market price. A big producer could regard a storage technology a more useful tool given that he faces two additional problems: first he might face the need of storing an extra wind power production, whose amount is not the result of a producer's choice. Second, he has to accomplish a stochastic demand. But while the role of storage in accomplishing stochastic demand would be independent of the production technology, the presence of RES and, in particular, wind power production would increase the role of storage due to the intrinsic stochasticity of wind energy itself. Both this aspects are not considered in this setting, where price is given and demand can be regarded as infinite.

On the other hand, results show that when increasing the amount of stored energy, the value of the objective function increases, and thus the producer profit.

Conclusions

Renewable energy seems to be an inevitable choice for sustainable economic growth. Today, wind energy is the fastest growing source of renewable energy. Wind power has low costs and its environmental impact is relatively minor, compared to the impact of traditional energy sources. However, electricity generated from wind power can be highly variable at several different timescales: from hour to hour, and on a daily, and seasonally base. Therefore, like other electricity sources, wind energy must be "scheduled". Wind power forecasting methods are used, but predictability of wind output remains unsatisfactory for short-term operation. In this setting we introduce the role of storage devices in increasing the producer's profit and promoting the use of renewable energies.

In this work two aims have been accomplished. First we develop a model that allows a small producer to make his decisions in an integrated system including different elements: thermal units constraints, spinning reserves, variability of both wind resource and energy prices, and storage technologies, within a stochastic setting. The producer's best decisions can be made considering the different possible scenarios over a short time horizon.

Second we have focused on storage technologies (considering the cases defined by different combinations of hypothetical costs and efficiency coefficients), trying to prove when a storage technology is profitable.

Using the storage the producer has a chance to exploit an expected future increase of the market price by lowering the amount of energy sold today, storing part of his production and selling his stored energy at a future date when a higher price is expected. Obviously, the higher is the cost of a storage technology, the lower is its (positive) impact. We saw that, depending on different technology, for some pairs of efficiency coefficient and cost, the storage technology is affordable even for a small producer. In our case, since we consider a small producer being a small producer, the costs must be very low and the efficiency coefficient very high.

Finally, we have observed that the choice of the optimal amount of storage seems to depend on market prices only. Therefore an increase in energy production, even considering wind energy at zero cost, would result in an increase of stored energy. This minor role of wind energy seems ingrained to the structure of our model, since a small producer can sell any quantity with no impact on the market price.

Bibliography

[1] D. Allen, C. Brown, J. Hickey, V. Le, and R. Safuto. Energy storage in the new york electricity markets. Technical report, New York Independent System Operator, March 2010.

[2] D. Amatucci, F. Vestito. Lo sviluppo di fonti energetiche innovative per la realizzazione di ambienti urbani sostenibili. Technical report, Cittalia Fondazione anci ricerche, 2009.

[3] J. N. Baker, T. J. Pears, and C. Morris. Electrical energy storage - current state-of-the-art, applications and barriers to implementation in electrical power systems. Technical Report 6473, EA Technology Consulting, November 2010.

[4] G. Barbose, C. Goldman, and B. Neenan. A survey of utility experience with real-time pricing. Technical report, Ernest Orlando Lawrence Berkley National Laboratory, 2004.

[5] S. Barsali. Battery storage contribution towards the cost effectiveness of wind generation in small system. University of Pisa, Italy, 2005.

[6] A. Bartolazzi. *Le energie rinnovabili*. Ulrico Hoepli Editore, Milano, 2006.

[7] A. Berizzi, C. Bovo, and C. Chemelli. Flessibilizzazione della domanda di energia elettrica: ricognizione internazionale e prospettive nazionali. Technical report, Fondazione Politecnico di Milano, 2006.

[8] S. Borenstein. The long-run efficiency of real-time electricity pricing. *The Energy Journal*, 26:93–116, 2005.

[9] S. Borenstein and S. P. Holland. On the efficienty of competitive electricity markets with time-invariant retail prices. *The RAND Journal of Economics*, 36:469–493, 2005.

[10] C. Bullough, C. Gatzen, C. Jakiel, M. Koller, A. Nowi, and S. Zunft. Advanced adiabatic compressed air energy storage for the integration of wind energy. In *EWEC 2004*, London, 2004.

[11] C. Chemelli and W. Grattieri. Demand response: technology requirements for an emerging business. Technical report, CESI Ricerca, Power System Economics Dept., Milan, Italy, 2006.

[12] C. Chemelli and D. Moneta. Partecipazione della domanda ai mercati dell'energia: valutazione di casi internazionali di successo e di strumenti idonei al superamento delle barriere esistenti. Technical report, CESI, 2006.

[13] E. A. DeMeo, W. Grant, M. R. Milligan, and M. J. Schuerger. Wind plant integration. *IEEE Power and Energy Magazine*, 3:38–46, November-December 2005.

[14] E. A. DeMeo, G. A. Jordan, C. Kalich, J. King, M. R. Milligan, C. Murley, B. Oakleaf, and M. J. Schuerger. Accomodating wind's natural behavior. *IEEE Power and Energy Magazine*, 5:59–67, November-December 2007.

[15] P. Denholm and R. Sioshansi. The value of compressed air energy storage with wind in transmission-constrained electric power system. *Energy Policy*, 37:3149–3158, May 2009.

[16] P. Denholm and R. Sioshansi. The value of compressed air energy storage with wind in transmission-constrained electric power systems. *Energy Policy*, 37(8):3149–3158, August 2009.

[17] T. Domínguez, M. de la Torre, G. Juberías, E. Prieto, R. Rivas, and E. Ruiz. Renewable energy supervision and real time production control in Spain. In *Papers ICREPQ'08*, 2008.

[18] J. Eyer and Corey G. Energy storage for the electricity grid: Benefits and market potential assessment guide. Sandia report, Sandia National Laboratories, February 2010.

[19] A. Fabbri, T. Gómez San Román, J. R. Abbad, and V. H. Méndez Quezada. Assesstment of the cost associated with wind generation prediction errors in a liberalized electricity market. *IEEE Transaction on Power System*, 20:1440–1446, August 2005.

[20] J. García-González, R. Moraga, L. Matres, and A. Mateo. Stochastic joint optimization of wind generation and pumped-storage units in an electricity market. *IEEE Transactions on Power Systems*, 23(2):460 – 468, May 2008.

[21] E. Hirst. Integrating wind output with bulk power operations and wholesale electricity markets. *Wind Energy*, 5:19–36, January/March 2002.

[22] J. Jørgensen, C. Möhrlen, B. Ó Gallaghóir, K. Sattler, and E. McKeogh. Hirpom: Description of an operational numerical wind power prediction model for large scale integration of on- and offshore wind power in Denmark. In *Global Windpower Conference and Exhibition*, Paris, France, April 2002.

[23] P.D. Lund and J.V. Paatero. Energy storage options for improving wind power quality. In *Nordic wind Power Conferenc*, Finland, May 2006.

[24] S. H. Madaeni and R. Sioshansi. The impacts of stochastic programming and demand response on wind integration. submitted to Energy Systems.

[25] S. H. Madaeni and R. Sioshansi. Using demand response to improve the emission benefits of wind. submitted to Environmental Science and Technology.

[26] T.M. Masaud, Keun Lee, and P.K. Sen. An overview of energy storage technologies in electric power systems: What is the future. In *North American Power Symposium (NAPS)*, September 2010.

[27] P. Menna. *L'Energia Pulita*. Il Mulino, 2003.

[28] Niels I. Meyer. Learning from wind energy policy in the eu: Lessons from Denmark, Sweden and Spain. *European Environment*, 17:347–362, 2007.

[29] S. Moura, Pedro and Anibal T. de Almeida. Large scale integration of wind power generation. In S. Rebennack, P. M. Pardalos, M.V.F. Pereira, and N.A. Iliadis, editors, *Handbook of Power System*, pages 95–119. Springer, 2010.

[30] R. Palgrave. Innovation in concentrating solar power. *Renewable Energy Focus*, 9(6):44–49, December 2008.

[31] A. Pantaleo, A. Pellerano, and M. Trovato. Tecnical issues for wind energy integration in power system: Projections in italy. *Wind Engineering*, 27:473–498, 2003.

[32] C. Peieper and H.Rubel. Revisiting energy storage. Technical report, The Boston Consulting Group, 2011.

[33] D. Rastler. Electricity energy storage technology options. Technical report, Electric Power Research Institute (EPRI), December 2010.

[34] RSE. L'accumulo di energia elettrica. Technical report, Ricerca sul Sistema Energetico - RSE Spa, 2011.

[35] R. Sioshansi. Evaluating the impact of real-time pricing on the cost and value of wind generation. *IEEE Transactions on Power Systems*, 25(2):741 – 748, 2010.

[36] R. Sioshansi. Increasing the value of wind with energy storage. *The Energy Journal*, 32(2):1–29, 2010.

[37] R. Sioshansi and R. W. Short. Evaluating the impacts of real-time pricing on the usage of wind generation. *IEEE Transactions on Power Systems*, 24(2):516–524, May 2009.

[38] J. C. Smith, M. R. Milligan, E. A. De Meo, and B. Parson. Utility wind integration and operating impact state of the art. *IEEE Transaction on Power System*, 22:900–908, August 2007.

[39] P. Sullivan, W. Short, and B. Nate. Modeling the benefits of storage technologies to wind power. *Wind Engineering*, 32:603–615, December 2008.

[40] H. Sun, J. Wang, S. Guo, and X. Luo. Study on energy storage hybrid wind power generation systems. In *World Congress on Engineering*, volume 2, 2010.

[41] USDE. Benefits of demand response in electricity market and recommendations for achieving them. Technical report, U.S. Department of Energy, 2006.

[42] UWIG. Utility wind integration state of the art. Technical report, Utility Wind Integration Group, 2006.

[43] M.T. Vespucci, M. Innorta, E. Allevi, and M. Bertocchi. Models for short term scheduling of hydro-thermal resources in a liberalized electric energy market. Report dmsia@unibg.it 3, University of Bergamo, 2007.

[44] W. Weibull. A statistical distribution function of wide applicability. *J. Appl. Mech.-Trans ASME*, 18(3):293–297, 1951.

[45] J. Wilkes and J. Moccia. Wind in power: 2010 european statistics. Technical report, EWEA: The European Wind energy association, 2011.