A stochastic model for a small energy producer with renewable sources and storage technologies[a]

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Abstract

In the last years, both renewable energy and storage technologies played an important role in the world. We develop a stochastic model whereby a small energy producer (using both traditional energy sources and wind energy, and some specific kind of storage technology) aims at meeting a part of the market demand, in order to maximize his own profits. The 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. We focus also on the role of spinning reserve, that is requested when the producer uses an intermittent energy source. An overview, of both renewable energy and storage technologies, is presented. Some results are shown, concerning the use of some types of storage technologies and both thermal and wind energy. In particular, it highlights how the model is proposed as a tool to evaluate the effectiveness of a storage technology.

Keywords: Renewable energy, Wind generation, Energy storage, Stochastic optimization.

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1 Introduction

Energy resources play an important role in the world and are considered a significant factor in economic development. During the last two decades, there has been a great deal of research on energy, especially on renewable energy technologies. 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 work we describe the most important renewable energy sources (hereafter RES) and technologies, and we identify both barriers and benefits of renewable energy penetration. The overview of renewable energies is mainly focused on wind energy, that is considered one of the most important renewable resources and the fastest growing renewable energy source in the world.

Furthermore 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.

Finally 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.

2 Renewable energy: opportunities and problems

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 for their regeneration. 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 specified 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, hydro-power, biomass, landfill gas, sewage treatment plant gas and biogases)". 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 energy sources and including renewable electricity used for filling storage systems, and excluding electricity produced as a result of storage systems"[1].

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) (see [2] and [19]). 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[2]. 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. 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[3].

Referring to the European zone, the Figure 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 [34]).

Historically, the issue of RES has been introduced first by the United

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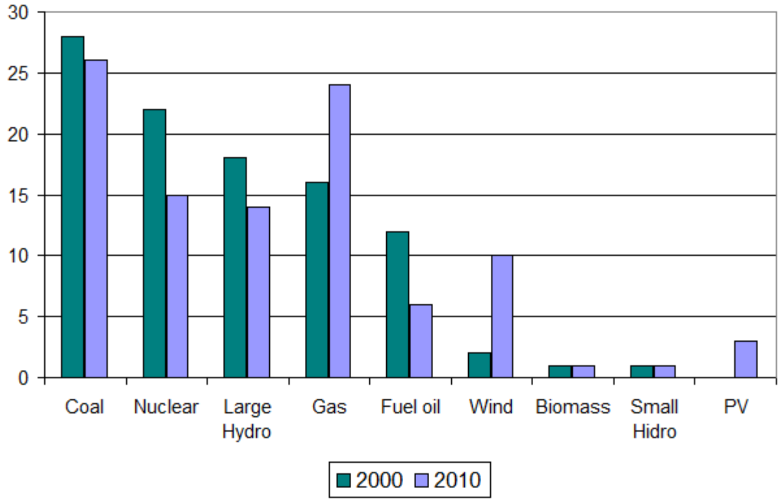
[1] Note that cogeneration (that is, the combined production of electrical or mechanical energy and heat), waste heat - recoverable from rivers, heating systems, electrical and industrial processes are also considered renewable energies.

[2] 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 [5]).

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

Figure 1: EU power capacity mix 2000-2010 (MW%)

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



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". 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[4]. 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).

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 cohe-

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[4] 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.

sion." 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. This schedule the increase of energy share from renewable sources up to 20% of the total energy from primary sources used in the EU.

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

All these factors (environmental, economic and legislative) combined with 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 hydro-power) as well as new renewable sources (small hydro, modern biomass, wind, solar, geothermal, biofuels and hydrogen), as shown in Figure2.

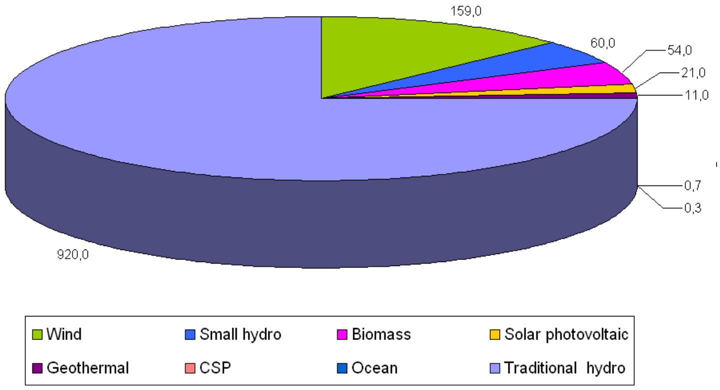


Figure 2: Renewable Electric Power Capacity, existing as of 2009

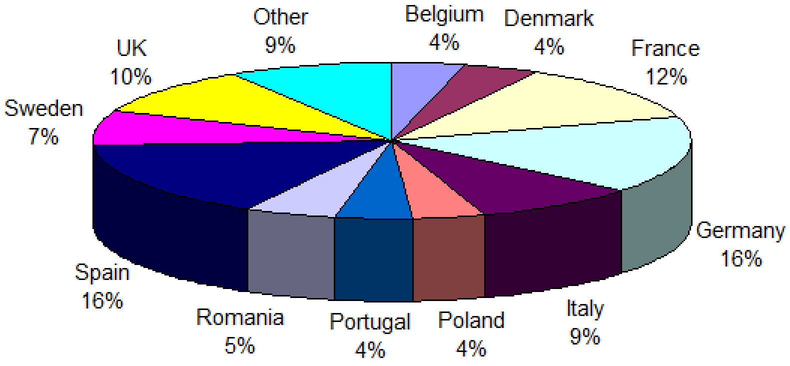
Source: author's estimated based on Renewables 2010 Global Status Report

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. 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 (see [8], [28] and [31]).

Currently , wind energy is the fastest growing source of renewable energy. 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. The success of wind power plants in Europa can be interpreted as 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 (see [19]). In Table 1, we can see the wind power (cumulative) installed in Europe by end of 2010 while Figure 3 shows the market shares for new capacity installed during 2010.

Figure 3: EU member state market share for wind capacity 2010

Source:EWEA, Wind in power 2010 European statistics



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. Moreover, similarly to other RES, the strong interest for wind power is due to the fact that energy production is convenient in terms of costs. Indeed, given the increasing cost of fossil fuel and the decreasing cost of wind power generation, this resource is already competi-

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

tive 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. As other Renewable Sources, electricity generated from wind power is intermittent, variable (at several different time scales: from hour to hour, daily, and seasonally) and unpredictable[5]. Furthermore, wind turbines are often installed in remote sites (i.e. offshore plant), away from both energy demand and existing generators. This translates into high connection costs and the need to adapt the network topology. 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 resource cannot be used to maintain real-time reliability on the grid. All these limits, in the recent past, have reduced its economic attractiveness (see [13] and [15]). Simultaneously, 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 [28], [7] and [8]) trying to resizing the penetration limits. 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 ([21], [23]). 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. 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 [29], [17] and [30], which investigate the benefit of storage technologies in general terms, and the pa-

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[5] 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 [13], [20], [11], and [16]).

pers by [6], [9], [14] and [4], which analyse some storage technologies with specific reference to systems where wind energy is explicitly introduced. Besides [27] and [10] 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[6]. 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. In the next section we will analyse the main types of storage technologies and their characteristics.

3 Energy storage technologies: state of the art

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 [6], [14], [4], [29], [27], [17], [30] and [9]).

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.

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[6] In this case, 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.

In this section 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 [25], [18], [12], [3], [26] and [24]).

3.1 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 [12] and [26]):

- 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[7].
- 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[8].

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. Masaud et al. (see [18]) 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.

By referring to ([12] and [26]), several categories of storage technologies applications are shown in more detail in Table 3 and described following:

- **Electric supply**

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

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

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

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

- **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

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 3: Categories of Energy Storage Applications
Source: Sandia Report 2010

  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[9]. When the storage devices have enough stored energy to discharge 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.

- **Grid system**

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

  - *Transmission support*: energy storage used for transmission support improves T&D[10] system performance by compensating for electrical anomalies to improving the system performance. In order to be used for transmission support, energy storage must be

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[9] 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 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).

[10] Transmission and Distribution.

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.
  - *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.

- **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[11]. 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

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[11] 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.

    reducing demand charges and power draw during specified periods, normally during the utility's peak demand periods.

  - *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 shut-down 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.).

- **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[12]. 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.
  - *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

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

plus storage is constant[13]. 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.

3.2 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 [26]). The main examples of storage technologies can be included in listed as follows:

- 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.

Next we will describe the main existing storage technologies by referring to some of the most recent technical reports and papers on this topic (see [12], [3], [1] [18] and [25]).

3.2.1 Pumped hydroelectric energy storage

Energy can be stored by conventional hydro-power and pumped storage hydro-power facilities. A pumped storage resource is a hydro-power generating facility that stores water as potential energy during off-peak hours

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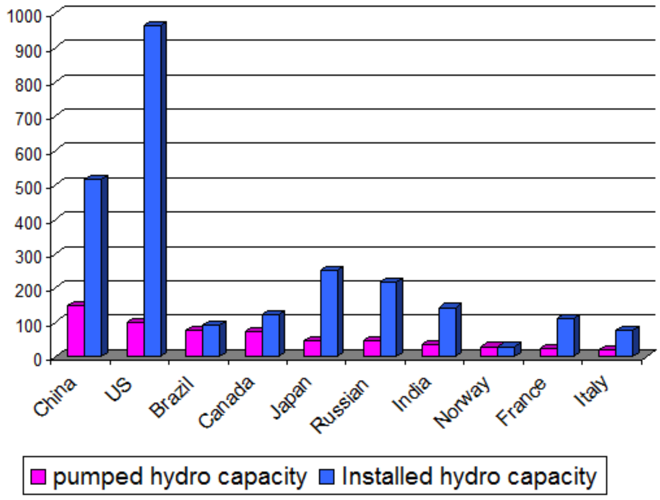
[13] The difference between renewables capacity firming, and renewables energy time-shift is that the latter involves enhancing the value of energy to increase profits and/or reduce maintenance costs.

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 4 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 [18])). 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]).

3.2.2 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

Figure 4: World-wide pumped-hydro and installed hydro capacity
Source: author's estimated based on Key World Energy Statistics, IEA, 2010



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 [25] and [6]).

3.2.3 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 [18]). 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.

3.2.4 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 [18]). 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).

3.2.5 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.

3.2.6 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 [12] and [26]).

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 [18] and [26]). 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], [25] and [26]).

- **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 [26]). 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], [25] and [26]).

- **Sodium Nickel Chloride**: between high temperature battery technologies, we also mention sodium nickel chloride battery, better known as the ZEBRA battery[14]. 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 power density.

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[14] Zero Emission Battery Research Activity

The principal applications for the ZEBRA battery to date has been seen in the electric vehicle and associated sectors (see [3] and [26]).

- **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], [25] and [26]).

3.2.7 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 [12] 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.

3.2.8 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 [18]).

3.2.9 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 [22] and [18]).

3.3 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 [18]):

- 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 4.

In this table, devices are classified based on both power capacity (MW) and discharge duration (time); the price range for each device concerns 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 [26]). 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.

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

4 Stochastic model: formulation and results

In this section 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 his own profits, the producer takes advantage of a specific kind of storage technology. The aim of this part of work 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 [32]). 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 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 where the small power producer must take into account the variability of both wind resource and energy prices.

4.1 Sets, parameters and variables

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
- $\overline{c}^{su}_k$: maximum start-up cost of thermal unit k
- c^v_k: 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
- $\overline{z}^u_i$: ramp-up limit of storage device i

The stochastic parameters 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
- $p^r_{t,s}$: 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
- $r^{av}_{k,t,s}$ 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
- $z^{cum}_{i,t,s}$ 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:

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

4.2 Constraints

Our stochastic model is characterized by the following constraints:

- Thermal generator minimum generation bound:

$$q_{k,t,s} \geq \underline{q}_k \cdot \gamma_{k,t,s} \tag{1}$$

  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:

$$q_{k,t,s} + r^{av}_{k,t,s} \leq \overline{q}_k \cdot \gamma_{k,t,s} \tag{2}$$

  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[15].

- 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:

$$q_{k,t-1,s} + r_{k,t-1,s} - (q_{k,t,s} + r_{k,t,s}) \leq \delta^d_k \tag{3}$$

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[15] Given constraints 2 and 10 we also have $q_{k,t,s} + r_{k,t,s} \leq \overline{q}_k \cdot \gamma_{k,t,s}$.

otherwise the constraint reads:

$$q_{k,t,s} + r_{k,t,s} - (q_{k,t-1,s} + r_{k,t-1,s}) \leq \delta_k^u \tag{4}$$

- Thermal generator minimum up-times constraint:

$$\sum_{\tau=max(t-t_k^u,1)}^{t} \alpha_{k,\tau} \leq \gamma_{k,t,s} \tag{5}$$

  Defining t_k^u 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_k^u 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_k^u previous hours (or it was already "on").

- Thermal generator minimum down-times constraint:

$$\sum_{\tau=max(t-t_k^d,1)}^{t} \beta_{k,\tau} \leq 1 - \gamma_{k,t,s} \tag{6}$$

  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:

$$\gamma_{k,t,s} = \gamma_{k,t-1,s} + \alpha_{k,t,s} - \beta_{k,t,s} \tag{7}$$

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

  Table 5 shows a representation of constraint 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 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 [32]), since the operations would result in a cost without changing the state of the thermal unit.

$\gamma_{k,t-1}$	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 5: Feasible transition cases

- The total spinning reserve constraint reads:

$$\sum_{k \in K} r^{av}_{k,t,s} = u_{t,s} \sum_{k \in K} \overline{q}_k \tag{8}$$

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.

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

$$r^{av}_{k,t,s} \leq \overline{r}_k \cdot \gamma_{k,t,s} \tag{9}$$

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:

$$r_{k,t,s} \leq r^{av}_{k,t,s} \tag{10}$$

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

$$z^{cum}_{i,t,s} \leq \overline{z}_i \tag{11}$$

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

$$z^{+}_{i,t,s} \leq \overline{z}^{u}_i \tag{12}$$

4.3 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:

$$A_{t,s} = Q_{t,s} + G_{t,s} \tag{13}$$

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:

$$Q^{av}_{t,s} = A_{t,s} + R^{av}_{t,s} \tag{14}$$

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:

$$R^{pot}_{t,s} = \sum_{k \in K} \overline{q}_k \cdot u_{t,s} \tag{15}$$

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

$$R_{t,s} = \theta_{t,s} \cdot R^{pot}_{t,s} = \sum_{k \in K} r_{k,t,s} \tag{16}$$

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

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

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.

4.4 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:

$$Q_{t,s}^{sold} = A_{t,s}^{sold} + R_{t,s} \tag{17}$$

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

$$A_{t,s}^{sold} = A_{t,s} - \left(Z_{t,s}^{+} - Z_{t,s}^{-}\right) \tag{18}$$

Equation (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:

$$Z_{t,s}^{cum} = \sum_{i \in I} z_{i,t,s}^{cum} \tag{19}$$

with

$$z_{i,t,s}^{cum} = (1-\epsilon) \cdot z_{i,t-1,s}^{cum} + z_{i,t,s}^{+} - z_{i,t,s}^{-} \tag{20}$$

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.

4.5 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:

$$C_{k,t,s}^{v} = c^{v} \cdot (q_{k,t,s} + r_{k,t,s}) \tag{21}$$

where c^v is unitary cost of produced energy.

Referring to start-up costs we consider the following stochastic variable and parameters[16]:

- $c_{k,t,s}^{su}$ 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

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

We consider the start-up cost $c^{su}_{k,t,s}$ $\forall k \in K$, 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:

$$c^{su}_{k,t} = \overline{c}^{su}_k \cdot (1 - e^{-\frac{t}{b_k}}) \tag{22}$$

where $\overline{c}^{su}_k$ is the maximum start-up cost and b_k is an arbitrary parameter. The final equation is obtained iteratively. We write the equation 22 at time $t-1$ as:

$$c^{su}_{k,t-1} = \overline{c}^{su}_k \cdot (1 - e^{-\frac{t-1}{b_k}}) = \overline{c}^{su}_k - \overline{c}^{su}_k \cdot e^{-\frac{t-1}{b_k}} \tag{23}$$

Combining equation 22 and 23 we obtain:

$$\begin{aligned} c^{su}_{k,t} &= \overline{c}^{su}_k (1 - e^{-\frac{-(t-1+1)}{b_k}}) = \overline{c}^{su}_k (1 - e^{-\frac{t-1}{b_k}} e^{-\frac{1}{b_k}}) = \\ &= \overline{c}^{su}_k - \overline{c}^{su}_k e^{-\frac{t-1}{b_k}} e^{-\frac{1}{b_k}} + \overline{c}^{su}_k e^{-\frac{1}{b_k}} - \overline{c}^{su}_k e^{-\frac{1}{b_k}} = \\ &= \overline{c}^{su}_k - \overline{c}^{su}_k e^{-\frac{1}{b_k}} + \overline{c}^{su}_k e^{-\frac{1}{b_k}} (1 - e^{-\frac{t-1}{b_k}}) = \\ &= \overline{c}^{su}_k (1 - e^{-\frac{1}{b_k}}) + e^{-\frac{1}{b_k}} c^{su}_{k,t-1} \end{aligned} \tag{24}$$

and starting by 24 we derive the start-up costs linear equation for every scenario s and every hour t with $t \geq 1$[17]:

$$c^{su}_{k,t,s} \geq e^{-\frac{1}{b_k}} \cdot c^{su}_{k,t-1,s} + (1 - \gamma_{k,t-1,s}) \overline{c}^{su}_k \cdot (1 - e^{-\frac{1}{b_k}}) - \alpha_{k,t-1,s} \cdot \overline{c}^{su}_k \tag{25}$$

with

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

where $\overline{c}^{su}_k$ 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 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 $\overline{c}^{su}_k$. When a start-up operation takes place (i.e. $\alpha_{k,t,s} = 1$), the start-up cost will

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[17] For the case $t = 0$ we obviously consider equation 22. Therefore $c^{su}_{k,0} = 0$

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:

$$c^{su}_{k,t,s} \cdot \alpha_{k,t,s} \tag{26}$$

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

$$\tilde{c}^{su}_{k,t,s} = c^{su}_{k,t,s} - \bar{c}^{su}_{k} \cdot (1 - \alpha_{k,t,s}) \tag{27}$$

with

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

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 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 $\tilde{c}^{su}_{k,t} = c^{su}_{k,t}$[18].

4.6 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:

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[18] 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.

$$\max \sum_{t\in T} \Big\{ \sum_{s\in S} \pi_s \Big[\Big(p_{t,s} \cdot \Big(\sum_{k\in K} q_{k,t,s} + \sum_{w\in W} g_{w,t,s} \Big) \Big) + \Big(p^r_{t,s} \cdot \sum_{k\in K} r_{k,t,s} \Big) - \sum_{k\in K} \left(C^v_{k,t,s} + \tilde{c}^{su}_{k,t,s} + c^{sd}_{k,t,s} \beta_{k,t,s} \right) \Big] \Big\} \quad (28)$$

In the second case we 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:

$$\max \sum_{t\in T} \Big\{ \sum_{s\in S} \pi_s \Big[\Big(p_{t,s} \cdot \Big(\sum_{k\in K} q_{k,t,s} + \sum_{w\in W} g_{w,t,s} + \sum_{i\in I} z^-_{i,t,s} \Big) \Big) + \Big(p^r_{t,s} \cdot \sum_{k\in K} r_{k,t,s} \Big) - \sum_{k\in K} \Big(C^v_{k,t,s} + \tilde{c}^{su}_{k,t,s} + c^{sd}_{k,t,s} \beta_{k,t,s} + c^z_i \cdot z^+_{i,t,s} \Big) \Big] \Big\} \quad (29)$$

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.

4.7 Model validation and results

4.7.1 Model data sets

In our analysis we consider a single small producer who owns a set of thermal power plants consisting of 5 small units ($K = 1, ..., 5$) 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[19]. Power plants are characterized by different minimum and maximum operating points, cost structures and flexibility. To validate the model and be consistent with the assumption of a small producer, we make use of a data set on five of the smallest Italian power plant. 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

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[19] The choice of this time horizon stems from the presence of the wind resource. Indeed, wind forecasts, when referred to a short term, seem to be more reliable.

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 6, 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. Table 7 describes the main costs of thermal power plants: that is, production costs and start-up costs. Note that while shut down costs are set equal to 0 for each unit k, start-up costs are proportionally reduced to make them consistent with the short-time horizon of our model. Furthermore production costs are calculated as sum of the fuel cost, CO2 emission costs and other variable costs.

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 6: Thermal plants data
Source: RSE

In our analysis a storage technology is identified by four parameters exogenously set: the efficiency coefficient ϵ, the unitary cost c_i^z, its whole maximum capacity $\overline{z}_i$ and its maximum hourly capacity $\overline{z}_i^u$. Therefore we can represent a storage technology as a point in $\mathbb{R}^4$. We take into account a set of storage devices indexed by i that differ in some or all these technical respects. It is worth noting that our model then represents a tool to evaluate the impact of any given storage technology on the objective function. In theory, it could also allow computing the set of points in $\mathbb{R}^4$ that represent "neutral" storage technologies i.e. with no impact on the objective function. As for storage technologies, we draw data on some of the main technical features of

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 7: Thermal plants costs
Source: RSE

storage devices from several recent works (see [26] and[25]). Table 4 presents a summary of the data on which our model is based. Obviously, since we focus on small plants, we consider a range of costs and efficiency parameters strictly related to small-size technologies, while abstracting from other large-size specific technologies. As already pointed out, also hypothetical values of cost and efficiency coefficients are considered, on the assumption that a hypothetical storage technology is affordable for a small producer.

We restrict ourselves to a single wind farm[20] w endowed with a given number of rotors and producing a certain amount of energy depending on the wind speed, which is modelled as stochastic. We build a Matlab routine to generate wind power forecasting scenarios. In order to simulate different wind power penetration, we allow for the possibility to vary the type of rotor (considering the type Gamesa turbine), the number of rotors, as well as the number of turbines that could be in the "fail" state or in the "maintenance" state. 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) are employed. Scenarios generation is based on Weibull distribution, which is typically used for wind forecasting (see [33]). Figure 5 and Figure 6 show examples of wind speed and wind power scenarios generation respectively.

In our analysis the "UNP price[21]" is the price set by the market and,

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

[21] UNP= Unique National Price

Figure 5: Wind scenarios generation

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

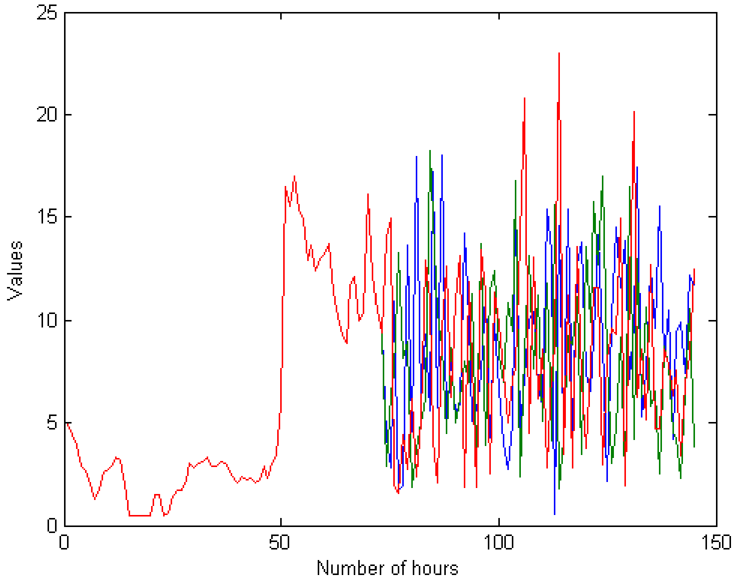
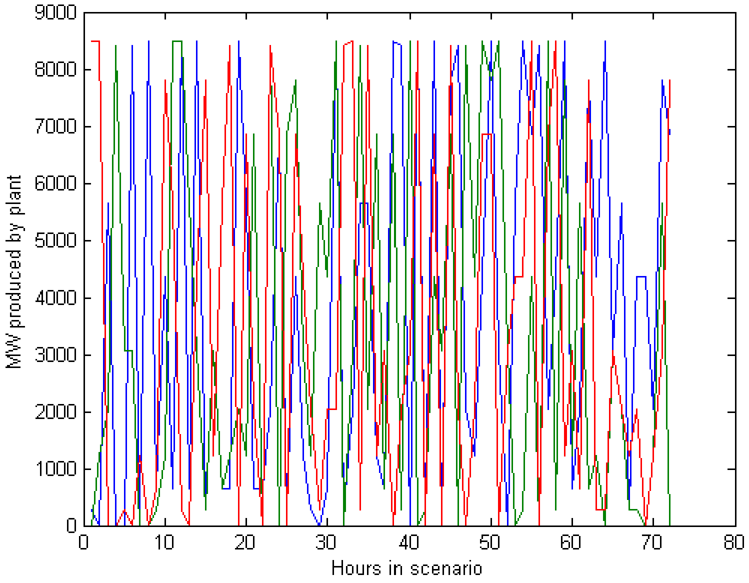


Figure 6: Wind power production scenarios generation

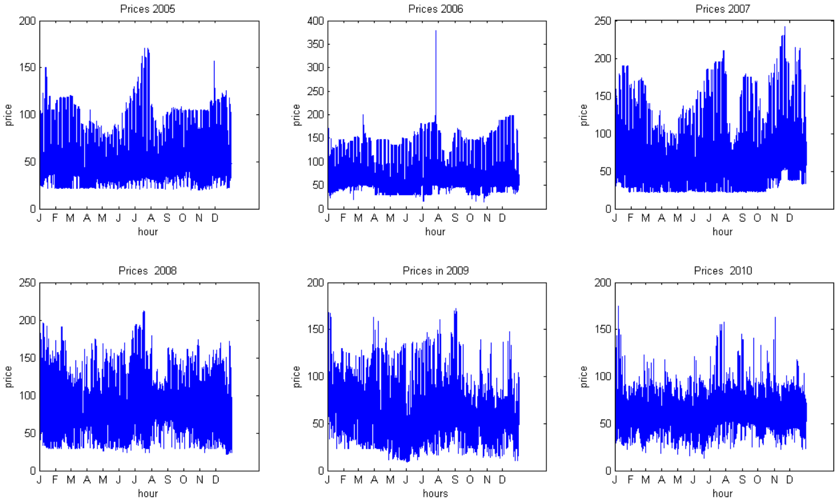
Source: author's estimated based on a small producer data



since we have a single, price taker, small producer, we assume that all the 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, the spinning reserve price is defined by introducing a mark-up over the UNP[22]. 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 over the reference years are shown in Figure 7.

Figure 7: Price time series 2005-2010

Source: GME



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

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

where p_{t-1} and p_{t-168} represent, respectively, the energy price one hour before and one week before and $\epsilon_{t+1} \sim IID\ N(0,1)$. An example of price scenario generation is shown in Figure 8.

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 (created with the procedure described above) covering a planning horizon of three days (with an hourly

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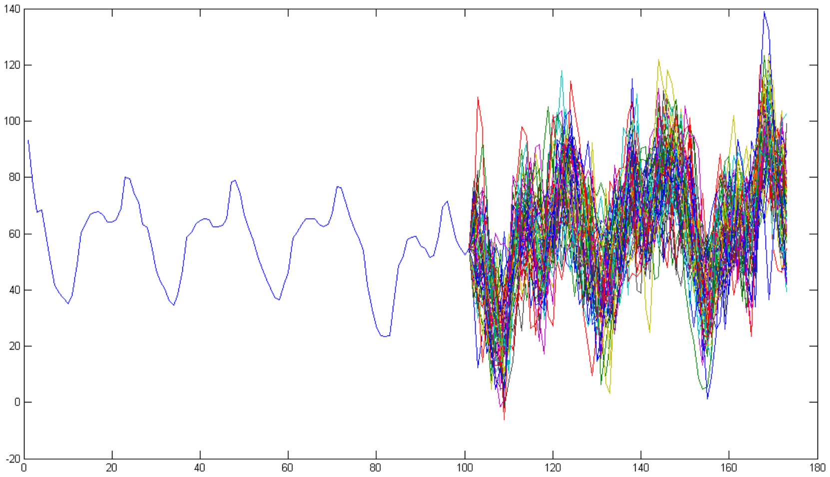
[22] This allows us to treat the spinning reserve price stochastically without making the scenarios too heavy.

Figure 8: Price scenario generation

Source: author's estimated based on GME data



discretization, that is 72 hours). We structure our scenarios in order to obtain a scenario tree. 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 straightforward to notice that at each decision node the producer has to make a decision on the grounds of the probability distribution over the different branches departing from the node itself. To validate our model, we consider 40 equally likely scenarios over a planning horizon T, representing prices and wind data randomly.

4.7.2 Results on spinning reserve and storage

The model sketched in the previous section is meant to determine the optimal thermal production decisions, that allows the producer to 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 production scheduling 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 9. As expected, production and price values move in the same direction: an increase in hourly prices is reflected by an increase in thermal production. Straight lines in the production graph need to be carefully: note that at the beginning, when prices are very low, thermal production is generated only by one thermal plant identified by number 5, which produces at its minimum capacity. Note that, despite its unitary production cost, equal to 40.14€, being higher than the average market price[23], thermal plant 5 continues to produce. This evidence might be regarded as counter intuitive, but it is not if we consider the fact that if the thermal plant was turned off then we should wait six hours to turn it on again and this start-up operation would imply a start-up cost, thus decreasing profits in next hours characterized by high prices. Even when hourly prices increase we can observe that only the fifth thermal plant is ON, now producing at its maximum capacity. On the 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 compared to unitary production costs and start-up costs to make the activation of thermal plants 1 and 2 profitable.

We analyse a second case to evaluate the effect of the introduction of spinning reserves on thermal production and scheduling decisions. In principle, when we introduce spinning reserves we would expect two distinct effects to be at work. On the one hand, given the opportunity to sell energy at a higher price, the producer might decrease his actual production, thus reserving production capacity to meet future requests. This might depress the value of the expected thermal production given that the reserved production capacity might remain unused. On the other hand, spinning reserves create an incentive to turn on more thermal plants in order to exploit the positive impact that this new opportunity has on the expected value of thermal production. These incentives 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 much of this production capacity has to be reserved, i.e. which thermal plants are to be devoted to spinning reserves production. In Figure 10 the first effect is clearly reflected by the production level at hour 10 and 11 when only thermal plant 5 is on and spinning reserves are required.

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

Figure 9: Thermal production and prices

Source: author's estimated

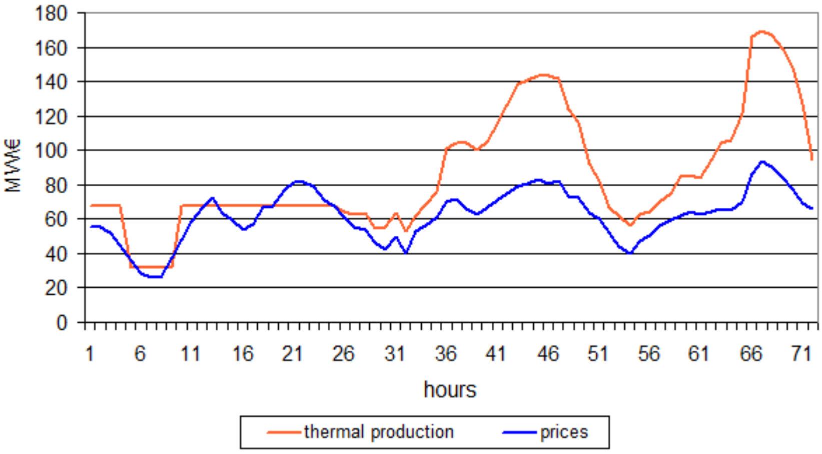
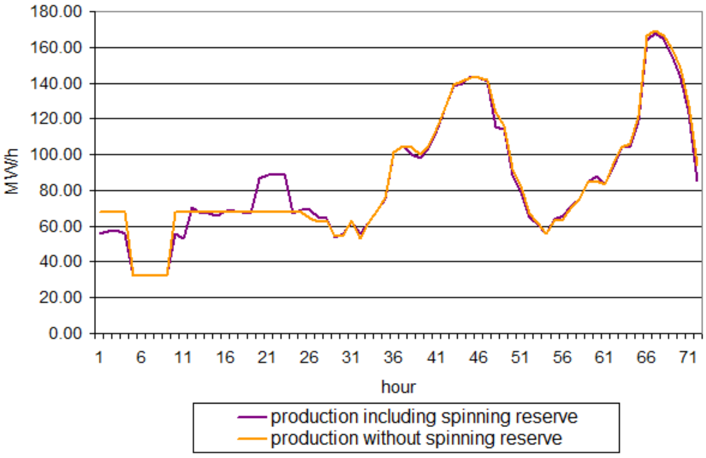


Figure 10: Thermal production with/without spinning reserves

Source: author's estimated

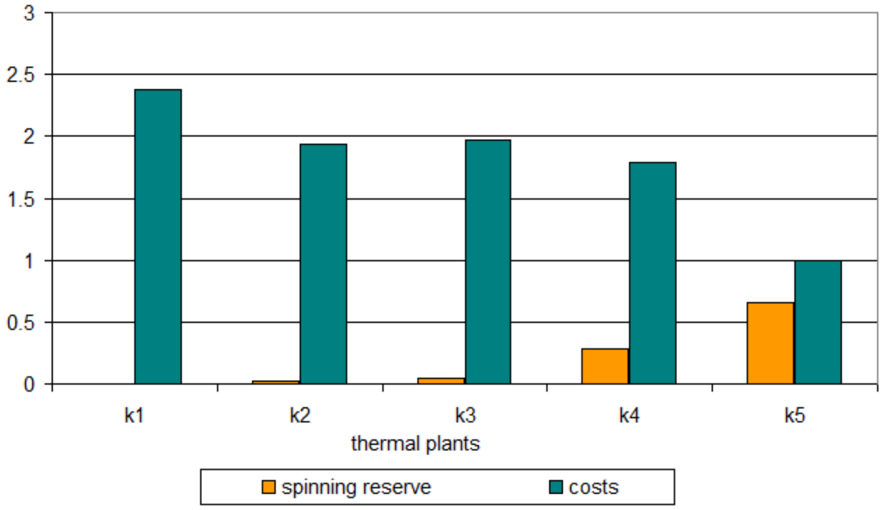


Note that in some scenarios, the presence of mandatory spinning reserves forces the producer to activate a second thermal plant. This choice, while forced, seems to allow the producer to exploit the future increase in prices, an increase that is more evident here than in the previous case, since spinning reserves are sold at a higher price. However, since the required amount of spinning reserves is not chosen by the producer, the data show 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 consider, there is no incentive for the producer to reserve enough productive capacity for spinning reserves. The role of the regulator is then essential to gain market balance, as his absence would imply a higher cost (i.e. a higher price) to get the same result.

Producer's decision on how to meet the spinning reserves requirement are represented in Figure 11, where unitary production costs of each thermal plant are compared to the share 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 11: 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 devote to spinning reserves the active thermal plants with higher unitary costs. This reasoning is not straightforward if we consider an average value over different scenarios, while it is evident if we consider the example shown in Table 8 and Table 9, which singles out two different scenarios at different hours.

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 8: 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 9: Spinning reserve allocation
Source: author's estimated

When wind energy is considered, a stochastic element, on the offer side, is introduced. We expect storage technologies to allow the producer to meet demand stochasticity[24] and to redefine his production scheduling over time. The producer has a chance to exploit an expected future increase of the market price[25] 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

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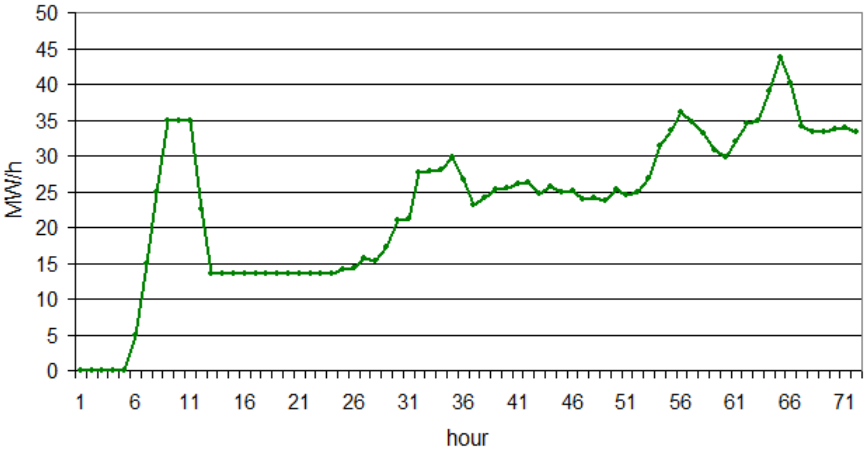
[24] In our case, since we consider a small producer this effect is neglected.

[25] Remember that our producer is a price taker, hence no production choice has an impact on the market price at any hour.

is expected. This role of storage is reflected in Figure 12, which depicts storage distribution over time. As previously stated, since we consider average values over different scenarios, some information might have ignored. Note, however, that a logic time schedule is respected: first energy is stored, then it is used to increase production.

Figure 12: Cumulated storage

Source: author's estimated



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 $\epsilon = 0.9$ and unitary cost $c_i^z = 10$€. In this case, enabling or disabling various elements of the model, profits are always higher when the storage technology is used. This is shown in Table 10, 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.

	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 10: Role of storage technology
Source: author's estimated

Obviously, the higher the cost of a storage technology, the lower its (positive) impact. In fact, we can observe that, depending on different technologies, we obtain different values for the objective function. Then, we can evaluate which hypothetical pairs of costs and efficiency coefficients make profitable the use of storage devices. In the case of a small producer, the costs must be very low and the efficiency coefficients very high. An example is shown in Figure 11 and Figure 12, which consider the following scenarios respectively[26]:

- **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								
cost ϵ	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 11: Objective function values with storage (case a)
Source: author's estimated

We note the same effect when we look at the average amount of storage on different scenarios, as shown in Tables 13 and 14.

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[26] These values refer to the model that considering both thermal and wind power production.

Objective function values

cost ϵ	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 12: Objective function values with storage (case b)
Source: author's estimated

Average amount of storage (MW/h)

cost ϵ	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 13: Average amount of storage (case a)
Source: author's estimated

Average amount of storage (MW/h)

cost ϵ	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 14: Average amount of storage (case b)
Source: author's estimated

It is worth noting that only electricity prices (actual and expected) determine the amount of storage. This can be seen by comparing prices and storage choices at hour 6 in scenarios 20 and 21 (see Table 15). In scenario 21 prices are lower than in scenario 20, thus determining an incentive to increase the amount of storage. Note that the role of spinning reserves in defining storage choices is neutral. Again this result seems to be straightforward. 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 nor 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.

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

Table 15: Storage choices
Source: author's estimated

Finally, we note that an increase in wind energy production at any hour t do not increase stored energy (unless the whole thermal production was stored and the maximum storage level was not reached). This because an increase in wind energy production would just cause a lower unitary production cost (wind energy has zero cost), without modifying the incentive structure of the producer, who is influenced just by the price difference at different points in time. Let (p_t, c_t) and (p_{t+1}, c_{t+1}) be the energy price and the unitary cost at time t and at time $t+1$, respectively. The 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 $\left(p_{(t+1)|t} - c_t\right)$ and 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 observe that the choice of the optimal amount of storage seems to depend on market prices only. This might confine the role of renewable energies in determining the amount of storage, as when wind power production is introduced there is no change in price structure. This minor role of wind power production seems ingrained in the structure of our model, since a small producer can sell any quantity with no impact on the market price. On the contrary, a big producer could think of a storage technology as of a more useful tool, given that he faces two additional problems. First, he might need store an extra wind power production, whose amount is not the result of his decision. Second, he has to meet a stochastic demand. However, while the role of storage in meeting the stochastic demand is independent of the production technology used, the presence of RES and, in particular, of wind power production increase the role of storage due to the intrinsic stochasticity of wind energy itself. Both this aspects are not considered in this setting, where prices are given and demand can be regarded as infinite.

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

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