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Sizing and Management of Energy Storage for a 100% Renewable Supply in Large Electric Systems

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1. Introduction

Many developed countries are moving towards a low carbon economy and are therefore demanding higher levels of renewable energy sources. These energy sources include wind, solar, biomass, etc. to supply the energy demand. Nevertheless, there are still some aspects that warrant further technical and economical feasibility studies for those renewable energy sources to be considered sustainable alternatives.

The random nature of renewable energy sources, mainly solar and wind is the major limiting factor in achieving significant penetration in any electric system. This limiting factor has different consequences depending on the ratio between the amount of renewable generation and the demand level. This has been studied by many authors from different perspectives and in many cases the key element was energy storage. For example, energy storage can be used to reduce the production fluctuations of large scale wind farms, to move a certain production amount to better remunerated periods, to reduce prediction errors to minimize penalties, to increase the power predictability, to participate in secondary power markets and to achieve fully controllable energy production through any renewable primary source. In such way, any renewable generator would offer guaranteed production and may participate in electric markets on equal terms with non-renewable generators.

Most analyses of isolated large electric systems with renewable supply and storage are performed based on energy balance results over several years (Bremen et al., 2009) (Alonso et al., 2009, 2010). This methodology has been extended in order to include real data measurements from various renewable technologies and also storages with different dynamic and rates. In particular, this method allows the resolution of multiple scenarios of renewable penetration levels, profiles, technologies, etc in order to obtain the minimum storage service that will reduce the conventional production or even satisfy a total supply of the demand through only renewable producers. This methodology has been firstly used to analyse a suitable large system: the Spanish electric system. Although Spain is electrically connected with other countries, the low rates in exchanged energy allow the simplification to consider it as an isolated system. As it will be shown, Spain offers excellent opportunities to produce large amounts of renewable production. However, the

integration will require some storage to guarantee the electrical supply meets the demand, especially in future scenarios where 100% is proposed only using renewable sources. Nevertheless, the existence of current hydro systems with huge storages strongly reduce the need of additional units.

The transition from current generating mix (renewable and non-renewable) to a likely future generation mix (with only renewable) has been also analyzed. As it will be explained, the prompt introduction of these storage systems, better if it is arranged in a very disperse way, will ease the replacement of conventional generation, starting with those units especially pollutant. Finally, some proposals of future scenarios are also presented and discussed regarding technical feasibility.

2. Random nature of renewable energy sources

Renewable energy from wind and solar sources are rapidly increasing their influence in the electric grid system worldwide. Both energy sources are uncontrollable by nature. Because of that when their contributions become important, locally and at greater scales, several and well reported grid integration problems may arise. Although energy demand and renewable production are random in nature, demand usually maintains a clear tendency that allows its reliable forecasting, especially in developed countries. For example, figure 1 shows the typical demand profile during a working and a non working day for Spain during 2010. Demand follows a similar profile experiencing variations during the year; season dependent, and also from one year to another, figure 2. These variations normally depend on the economical situation and the development level of the analyzed system. For example, 2006 Spanish electric demand versus 2005 verified an increase around 2.9%, while 2006 versus 2007 was about 3.8% (REE, 2009).
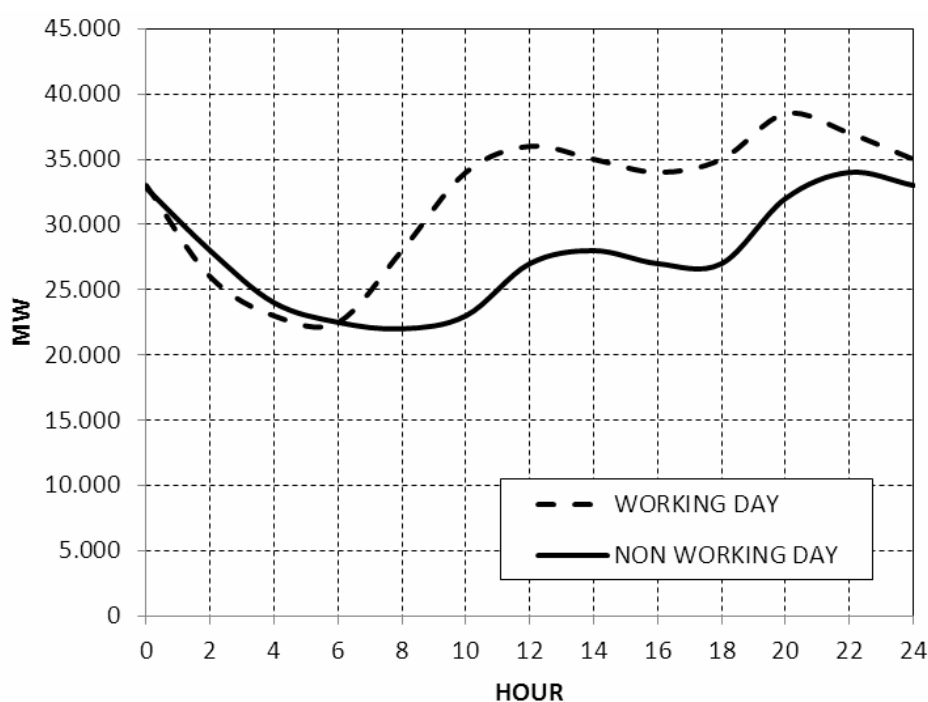

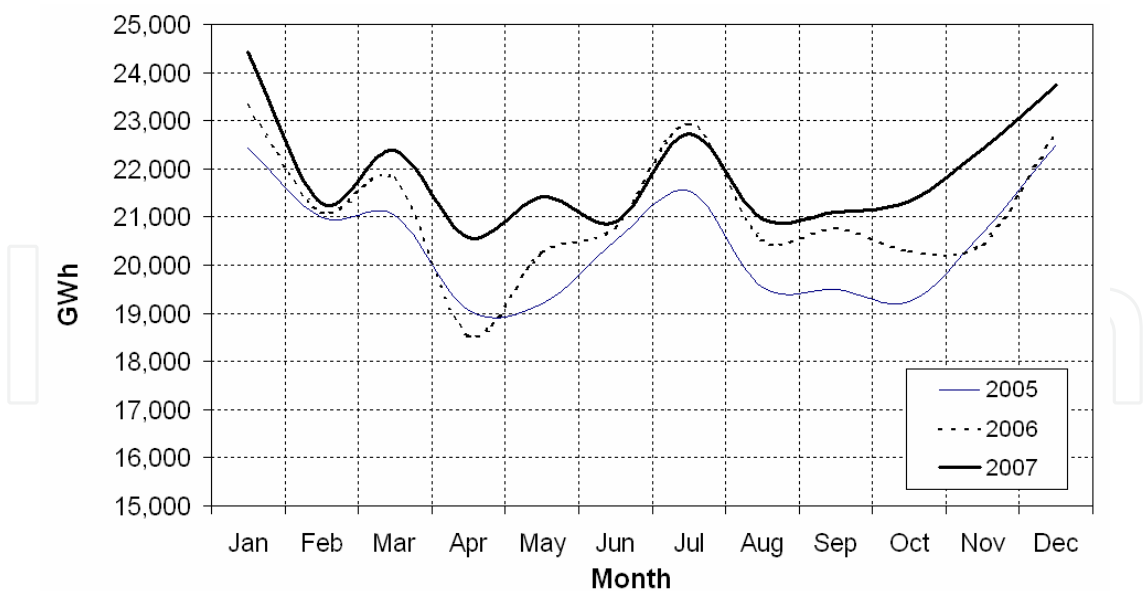Fig. 1. Example of daily electric demand in Spain (Working and non working day)

Fig. 2. Monthly demand in Spain (2005 – 2007)

In a preliminary stage the following basic balance is valid for any isolated electric system without storage.

$$
\begin{aligned}
Non\ Renewable\ Power\ &+\ Potential\ Renewable\ Power \\
&= \\
Power\ Demand\ +\ System\ Power\ Losses\ &+\ Renewable\ Power\ Losses
\end{aligned}
\tag{1}
$$

In this equation, *Non Renewable Power* represents all power contributions coming from conventional energy sources such as coal, gas, nuclear, co-generation, etc –based power plants. *Potential Renewable Power* is the power that could be produced at any moment taking into account all operative power plants of wind, solar, hydro, etc. This amount of power depends on the primary source availability and the technology efficiency. *Power demand* is the electric power demanded by users, *System Power Losses* represents power losses in lines, transformers, etc, and *Renewable Power Losses* represents the renewable power that was not transformed into the electric system. Several and important aspects are involved with this concept. The integration of all *Renewable Power Losses* during a year from now on will be called the *Renewable Energy Losses*.

A few years ago the Renewable Energy Losses were insignificant because grid operation rules in most countries were establishing priority for the new renewable sources in detriment of conventional ones. Normally local overload on some lines has been wielded to temporally stop some generators. However, nowadays several countries with high wind energy penetration have been changing the rules to allow grid operators to stop wind generation under the excuse of low quality of service or low reliability of the grid operation. Despite of the ethical debate about all these particular aspects, these new losses are becoming important and will increase during the next years unless newer grid stability solutions are provided.

The above mentioned energy losses are hard to be either calculated or estimated. Nevertheless, apart from those losses, as non-controllable renewable energy penetration increases, energy opportunity production losses due to demand limitation shall be added. It

may happen that non-controllable renewable production exceeds the electric demand and as a consequence renewable generation must be limited. Thus, *Renewable Energy Losses* are mainly due to two different causes, grid operation and over production stops (locally or globally).

Figure 3 shows normalized hourly potential productions coming from non-controllable renewable energy sources versus maximum hourly demand value. To illustrate this two different cases have been considered: Spain and Navarra. Navarra is a Spanish region with 620,000 inhabitants with a high renewable penetration level (in 2010 more than 80% of its electric demand was supplied by renewable generators). In Spain´s case it is appreciated that the potential production is always well below the demand curve (also normalized). Potential Renewable production never reaches the electric demand, which means that in principle *Renewable Energy Losses* should be zero. However, analyzing the case of Navarra; potential renewable production is higher than electric demand in a large number of hourly intervals. Assuming Navarra was an isolated electric system; non-controllable renewable plants should be stopped due to the considerably increasing *Renewable Energy Losses*.
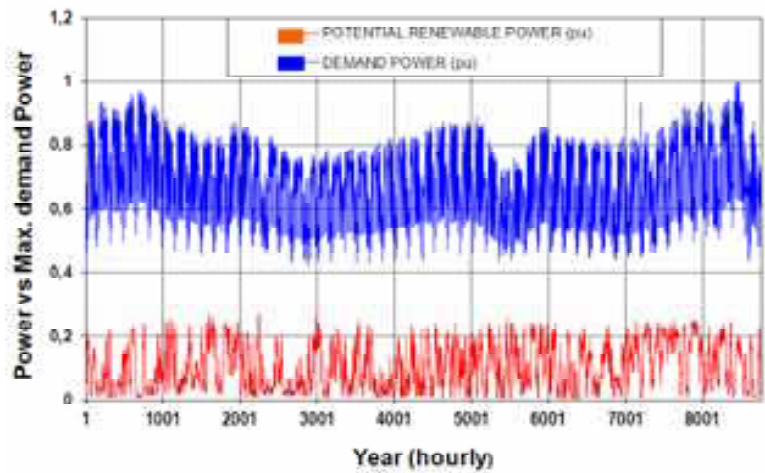
(a) Spain
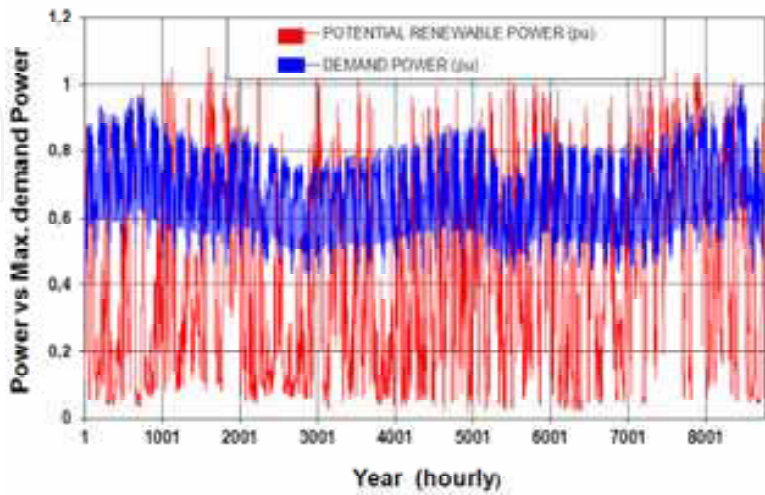
(b) Navarra

Fig. 3. Normalized Renewable Production and demand

Figure 4 shows the yearly evaluation of the *Renewable Energy Delivered to Grid* (a) and the *Renewable Energy Losses* (b) in function of the *Potential Renewable Production* versus electric demand. From now on, this last relation will be named as *RPPR, Renewable Potential Production Ratio*. In this analysis, no energy storage system of any kind was considered.

(a) Yearly Renewable production delivered to grid
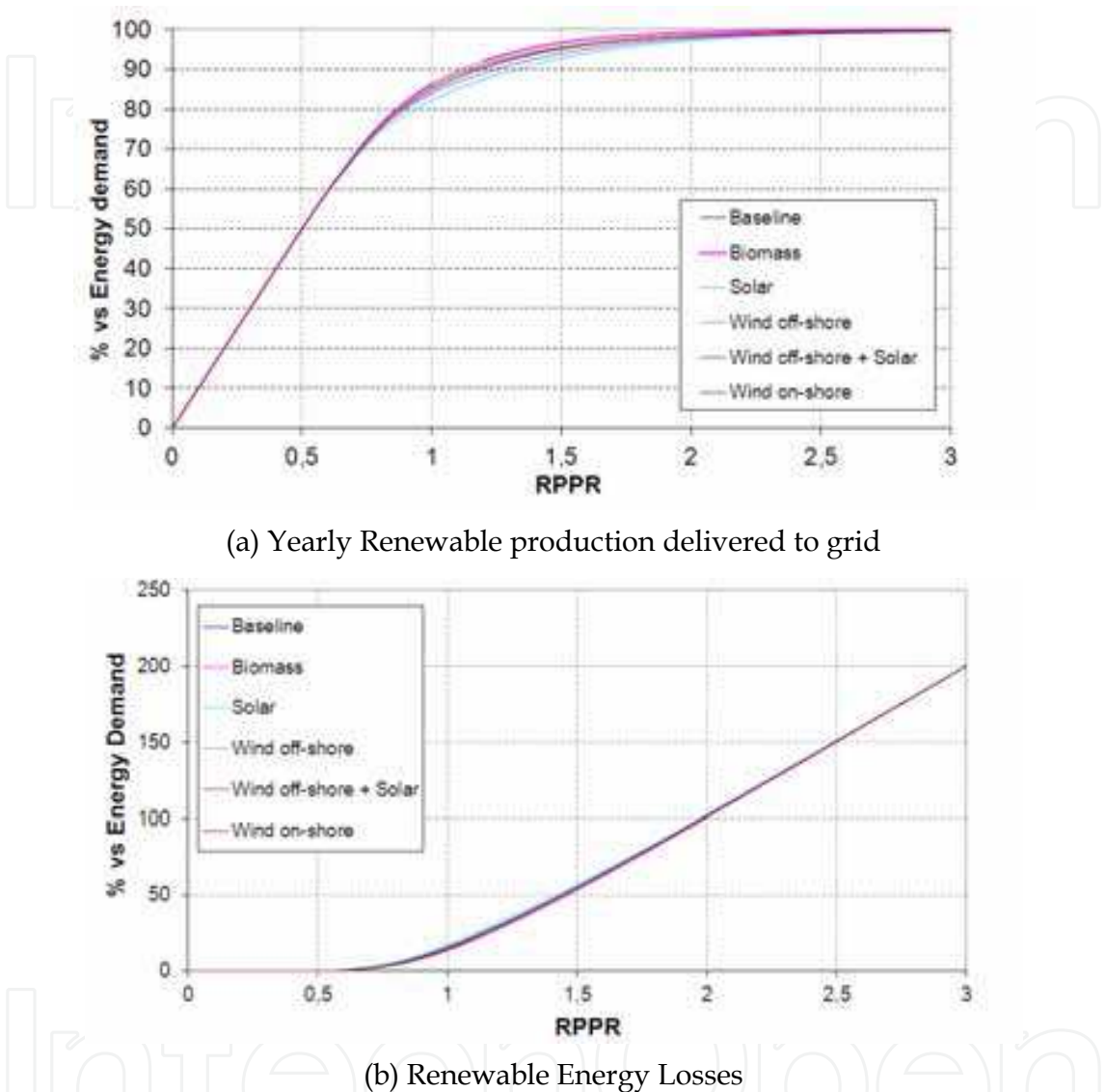

(b) Renewable Energy Losses

Fig. 4. Normalized index at different *RPPR*

Therefore, this graph is showing a hypothetical substitution of non-renewable energy with renewable in an isolated electric system. Different combinations of likely on-shore wind, off-shore wind, solar, biomass and hydraulic power plants were included in these renewable mixes (large hydraulic power plants were not considered). Every combination is built up using a differently scaled data series of real production of each technology. Trought this way it is possible to prepare combinations where one or two technologies get highlighted; according to different and likely future perspectives that seem to consider more feasibility on some technologies than others. Detailed contribution of each renewable technology for any combination will be defined later in section 4.2.3. For instance, renewable mix named "Baseline" includes all technologies according to current levels of each one in Spain. For

higher *RPPR* levels this set of series is scaled according to available official development plans (Spanish Ministry of Industry, 2010) and some assumptions. However, the mix named "Solar" was prepared to follow a different tendency. For low *RPPR* the combination of technologies is the same as in the Baseline case, but as the *RPPR* is increased the high solar power contribution is highlighted with respect to the baseline case becoming the more relevant renewable influence. Same concepts apply to the rest of combinations already prepared. Although results depend on the specific production mixes and demand profiles used, no big differences have been found as it can be seen in figure 4. It is remarkable that only very big ratios of *RPPR* achieve complete demand fulfillment without storage systems, which then involves extremely huge *Renewable Energy Losses*, besides of an unacceptable cost effective energy. This aspect can also be seen in figure 5 where the minimum *RPPR* to get a 100% renewable-based supply for every combination of renewable technologies has been presented. The main reason for those big *Renewable Energy Losses* is the necessity of stopping a lot of renewable production plants as demand is lower than available production. Even though current scenarios of renewable production differ considerably with correspondents shown on figure 4, clearly it is appreciated that not only renewable production plants will be required, but additional elements to optimize the global energy management such as energy storages.
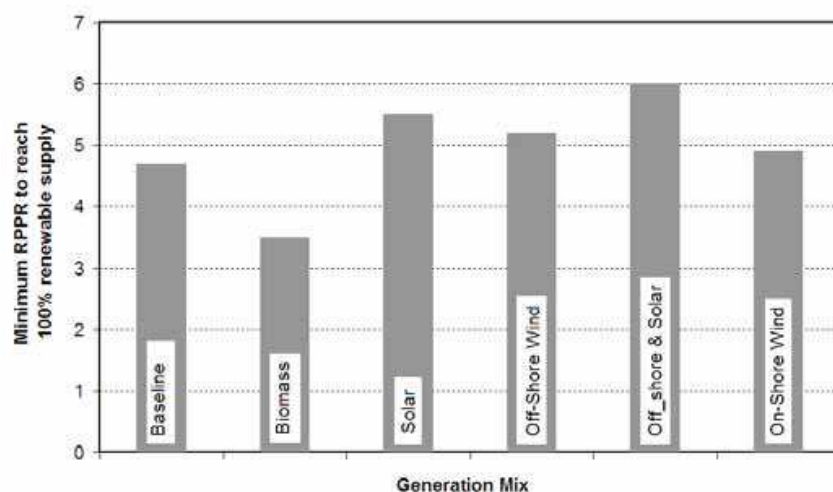

Fig. 5. Minimum *RPPR* to get a 100% renewable-based supply for different combinations of renewable technologies.

According to the results exposed in figure 4 and 5 the following conclusions can be obtained:

- Renewable real production does not fulfill the electric demand within a reasonable renewable overproduction. Analyzing extrapolations of real electric systems with high penetration of renewable producers (without any storage) to guarantee the demand excessively large and unviable *RPPR* levels (large renewable system) are required. Higher levels of off-shore generators seem to diminish the variability (Tipping & Sinclair, 2009) thus, improving the demand tracking capabilities with lower *RPPR*.
- *Renewable Energy Losses*, become considerable with *RPPR* ratios higher than 0.5. Those losses are only consequences of a potential renewable production that is higher than the electric demand. Actually, *Renewable Energy Losses* may be higher than those shown on the graph, since grid operators may reduce renewable generation arguing low

reliability of the operation. For the Spanish electric system, figure 3, *Renewable Energy Losses* are negligible since current *RPPR* ratio is still very small. However, for Navarra with a *RPPR* higher than 0.6 in 2009, in case this region was electrically isolated a 5% of renewable losses should be expected.

-   The distance between the *Real Renewable Production* (Inst. Demand supply line) and the 100% line is the percentage of the required non-renewable energy contribution. For a certain future free of non-renewable generators this energy should be based on controllable renewable energy (biomass, hydro, H_2 plants, etc.). However, in most countries it will not be feasible to get this amount of controllable renewable production. Therefore to get the 100% renewable target for most *RPPR* a great amount of non-controllable production would be required, which again would produce excessive *Renewable Energy Losses.*

Renewable Energy Losses and the necessary controllable renewable energy may also be strongly reduced for any *RPPR* when energy storages are included in the electrical equation. As it will be demonstrated such energy storages are not necessarily huge. Besides, renewable based systems are usually presented on a highly dispersed basis across the territory and a system of smaller and strategically distributed storages may definitely increase the global operation, performance and reliability. For example, the combination of a wind power plant and a relatively close to site storage under a common control system makes possible the operation of the whole system like a controllable power plant. Thus, combined solutions may offer a similar performance to actual conventional plants, opening new technical features for a better integration and also new possibilities on the electric market. The analysis about how different storage systems may help with the integration of more renewable production is the main objective of the following study. This analysis has been extended to the ideal situation of a total demand supply only with renewable producers.

3. Analysis methodology

A mathematical model properly defined offers the possibility to explore opportunities of higher integration levels of renewable sources in large and isolated electric systems using energy storages. Therefore, equation (1) must be completed with the storage contributions as it is established on equation (2). Here, *Storage Power* responds to control system needs and can be positive or negative, producing the corresponding decrement or increment of the storage energy level. This power must also satisfy the condition of a long term integral tendency to a constant value (steady state operation). Of course, the storage model also must include limits in power and levels to represent real systems.

$$\textit{Non Renewable Power } + \textit{ Potential Renewable Power}$$
$$= \qquad\qquad (2)$$
$$\textit{Power Demand } + \textit{ System Power Losses } + \textit{ Renewable Power Losses } + \textbf{\textit{Storage Power}}$$

The mathematical modeling of these systems requires power sources (renewable and non renewable), power sinks (demand and losses), storages and a set of control rules. Renewable power sources can be modeled using scalable power profiles depending on the specific technology. This approach will increase the reliability of the whole modeling, especially if said power profiles are based on real production measurements (Acciona Remote Control

Centre, 2010) recorded over the years on a number of existing power plants. Power demand profiles, series, etc, are usually available from grid operators (REE, 2010), while storage dynamics are usually simple involving a few global parameters. Control or management rules may also be quite complex, in particular when forecasting and territory distribution are considered. The complete model should be appropriate to describe current scenarios but, more importantly, to advance as much as realistically possible future opportunities. Of course, this approach does not consider likely improvements in future renewable technologies thus offering lower performance solutions. This chapter introduces some basics about the mathematical model and real data used in these studies. In any case, both the modeling process and analysis has been carried out considering the following and important directives:

- To guarantee the electrical demand at any moment.
- To minimize the non-renewable production.
- To minimize *Renewable Energy Losses*.
- To offer reliable solutions based on stationary multi-annual study.

The simulation platform may be prepared to work with two storages: hydro-based and a generic solution of reversible storage. The process to get in and out in this reversible storage is also performed by generic electric power drives. In this way it is avoided to mention any specific technology: water, batteries, heat, compress-air, etc. The future seems to be opened to most of these technologies, although size and grid penetration of every one will finally depend on aspects such as technical development, economical ratios, environmental or territorial limitations, etc (Price, 2010). Water-based storage size is fixed according to real plants already in operation in Spain and only power drivers (pumps and turbines) are available to be changed for further analysis. However, reversible storages have parameters for storage size, power drives, performances, etc. Both storages can operate together coordinately. The program includes a set of rules to determine when and how much a specific storage shall work. The decisions for that are taken considering current levels of energy on each storage, the required turbine power (or drive out power), etc. In any case, the main objective of such rules is to offer globally as much available storage as possible and also help to increase as much renewable energy as possible. The system also offers parameters to freely setup levels of different renewable producers: solar, wind, biomass, etc. Therefore, the whole system shows programmed results suitable for exploring current and future renewable-based electric systems with any grid penetration level.

3.1 Renewable power profiles

Renewable power sources have been modeled using production measurements recorded from a number of real power plants (Acciona Remote Control Centre, 2010). These facilities have been in operation in Spain for years and include solar, on-shore wind, biomass and hydro sources. For every different plant there was available several years of hourly-based series of power production. All data were arranged and compiled technology by technology in order to prepare independent time-series during a *normal year*. Thus, this equivalent or normal year was determined to represent a set of years in terms of average and standard deviation production. The final result was a set of hourly-series of renewable power production by technology also capable to be scaled to any power. This set of models has been very useful to determine the sensitivity of storage systems depending on the specific composition of renewable power mixes.

Off-shore hourly-series were calculated using ocean wind speed measurements and power curves of most promising multi-megawatt off-shore wind turbines. However, for other important renewable technologies, like tidal waves, geothermal, etc, it was not available neither time series nor reliable technical information to produce useful data. Therefore, due to the huge potential of these technologies (García & Linares, 2005) better future perspectives are expected than already obtained.

All available hourly-series of real measurements were obtained from databases property of Acciona Energy. This company is also owner of large renewable systems covering a total of 8,500 MW. Most facilities have been running for years providing invaluable data of renewable production, losses and other technical aspects of great importance.

3.2 Simulation basis

The simulation program has been setup to simulate the operation of a large electric system over several years until steady-state is reached. This program includes several preparatory stages prior to the running of the multi-annual simulation:

1. Setup. Definition of the global system size by means of some parameters:
   a. Renewable Potential Production Ratio (RPPR).
   b. Reversible storage size and power.
   c. Renewable mix. Weighting factors are available for every renewable technology. Through them a specific profile of the global mix can be established. For example, it is possible to prepare a renewable mix to strengthen the influence of solar generators, or off-shore influence, etc. Therefore, a set of different mixes with distinct characters can be specifically prepared which are useful for sensitivity analysis.
2. Initialization. Setting up of initial values on all state variables, focused to get as close as possible to the steady state.
3. Simulation of one year. The electrical system is simulated hour by hour using the algorithm in figure 6. This complex decision-making model is based on equation (2) where physical system limits (pump or turbine rates, storage size and current level, yield factors, etc) and control rules are also included. These rules are based on the set of directives introduced before which basically try to maximize renewable production with minimum storage.
4. Steady state analysis. This one year simulation will be continuously run until steady conditions are reached. The program also includes options to simulate demand and production variations over the years according to statistical information. In order to get representative results at least three years with different data should be executed (Acciona Remote Control Centre, 2010).

The algorithm in figure 6 clearly distinguishes two situations depending on the potential renewable production with respect to the demand. For potential over production it is necessary to check whether the remaining energy can be stored. In this sense, limiting factors are a full storage or insufficient pump power. On the other hand, energy deficit can be compensated using stored energy, when available, or conventional production. The program establishes priority over the stored energy to minimize non renewable contributions. Bearing in mind that also turbines have a limit on their power rate. Besides basic magnitudes such as energy storage level, other important magnitudes are also evaluated on every simulation step, in particular the *Non Renewable Contribution* and the *Renewable Energy Losses*.
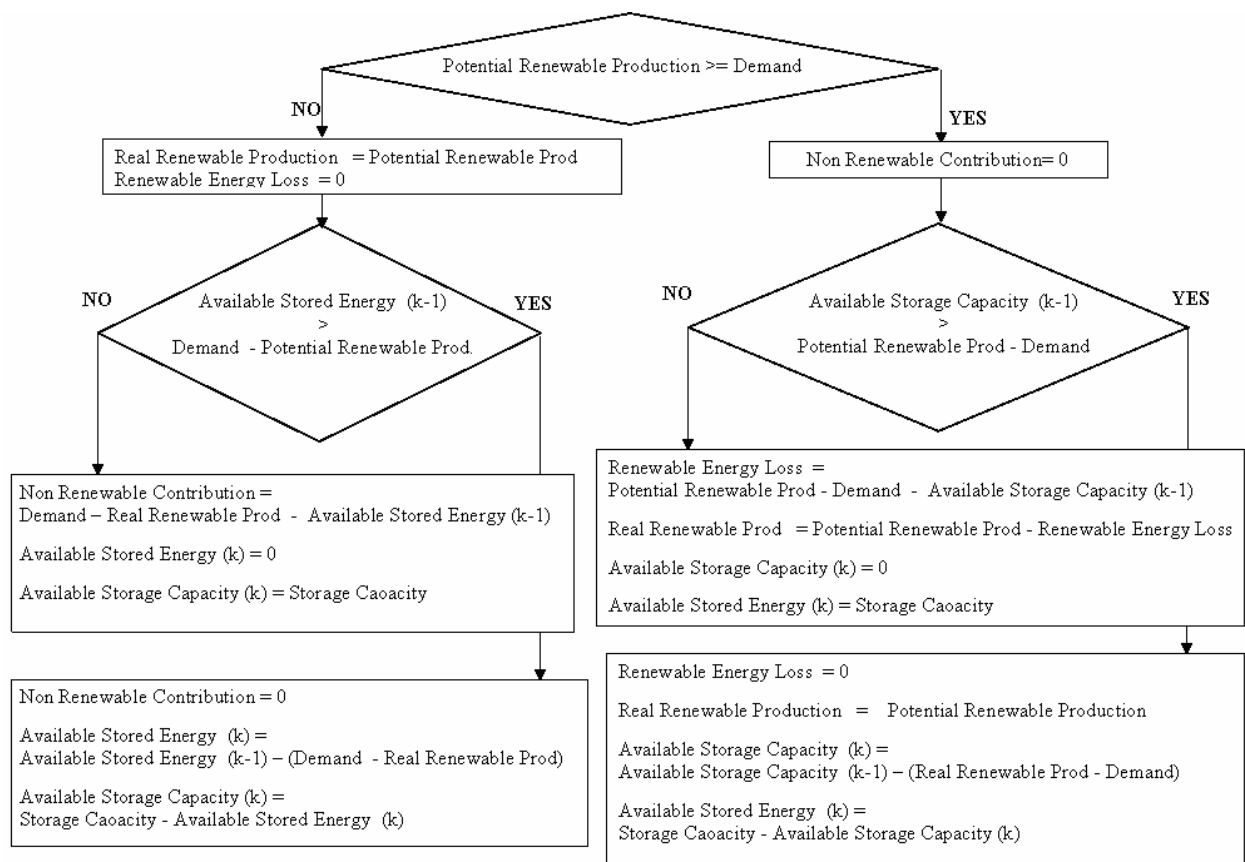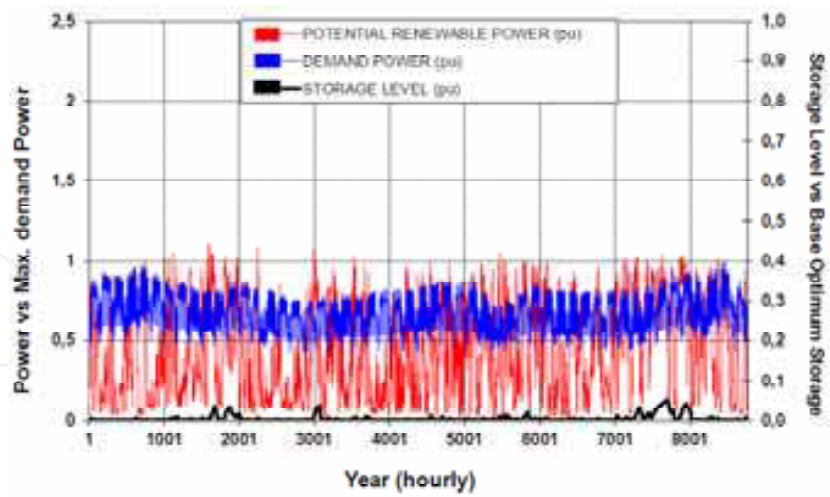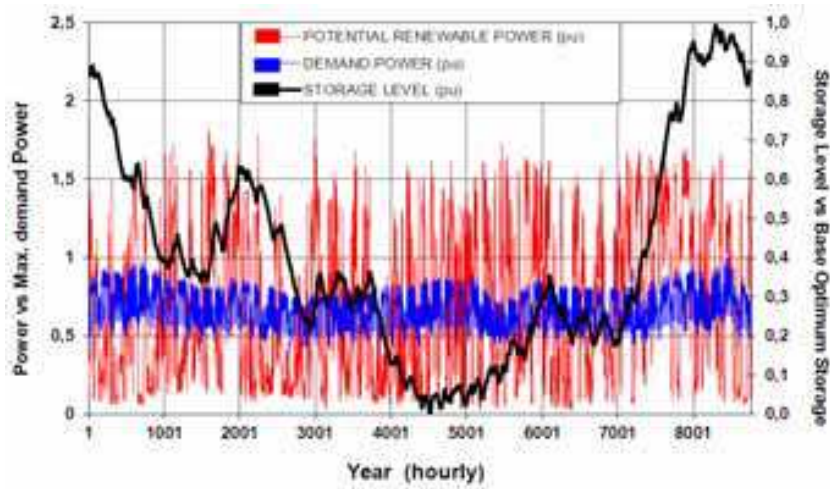
Potential Renewable Production >= Demand

NO   YES

Real Renewable Production = Potential Renewable Prod
Renewable Energy Loss = 0

Non Renewable Contribution= 0

NO   Available Stored Energy (k-1)   YES
                          >
            Demand - Potential Renewable Prod.

NO   Available Storage Capacity (k-1)   YES
                          >
            Potential Renewable Prod - Demand

Non Renewable Contribution =
Demand – Real Renewable Prod - Available Stored Energy (k-1)

Available Stored Energy (k) = 0

Available Storage Capacity (k) = Storage Caoacity

Renewable Energy Loss =
Potential Renewable Prod - Demand - Available Storage Capacity (k-1)

Real Renewable Prod   = Potential Renewable Prod - Renewable Energy Loss

Available Storage Capacity (k) = 0

Available Stored Energy (k) = Storage Caoacity

Non Renewable Contribution = 0

Available Stored Energy (k) =
Available Stored Energy (k-1) – (Demand - Real Renewable Prod)

Available Storage Capacity (k) =
Storage Caoacity - Available Stored Energy (k)

Renewable Energy Loss = 0

Real Renewable Production = Potential Renewable Production

Available Storage Capacity (k) =
Available Storage Capacity (k-1) – (Real Renewable Prod - Demand)

Available Stored Energy (k) =
Storage Caoacity - Available Storage Capacity (k)

Fig. 6. Hour-by-hour energy balance algorithm.

Figure 7 shows examples of a same baseline case (defined later) simulated at different *RPPR*. In all of the time-graphs the results in the last year of simulation are presented (steady conditions). As it can be observed, normalized potential renewable and demand power with respect to the maximum power demand are shown. These graphs also show the storage level normalized with respect to the maximum storage (obtained for case with *RPPR* =1.0). As it can be observed, for low *RPPR* (figure 7.a) during most part of the year the renewable production gets below demand and on a limited number of occasions the storage is used. Moreover, the lack of energy must be covered by conventional generators. However, for higher *RPPR*, figures 7.b and 7.c, the influence of the storage becomes relevant opening the possibility of demand fulfillment without conventional contribution (100% renewable supply). Figure 7.b corresponds with a critical point where the yearly potential renewable production exactly generates the yearly demand. In this situation to assure the demand power a huge storage with a high powered pump or turbine is continuously required. Nevertheless, as the *RPPR* increases (for example, in figure 7.c for *RPPR* = 1.2) smaller sized storages will be necessary to fulfill demand. In this figure, the minimum storage to satisfy demand is just 30% of the required in critical situations. It is verified that the higher the *RPPR* the lower the optimum storage but also the higher the *Renewable Energy Losses*. (balance renewable overproduction, energy storage size).

(7.a) *RPPR* = 0.64

(7.b) *RPPR* = 1.0
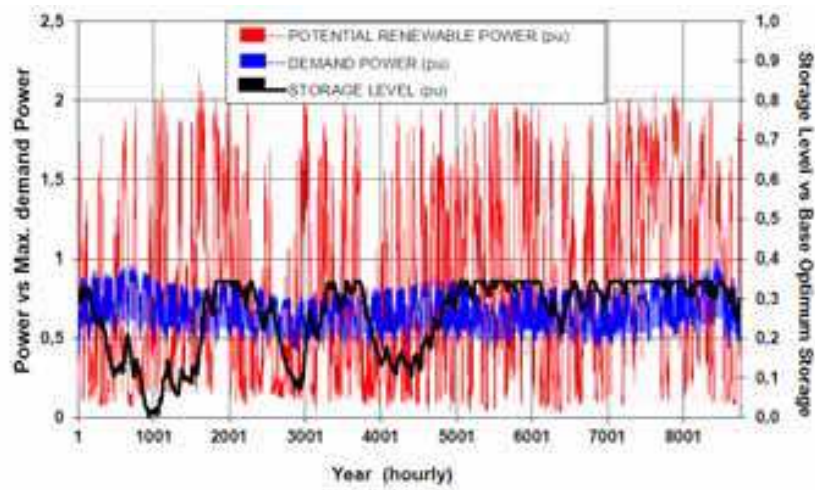
(7.c) *RPPR* = 1.2

Fig. 7. Normalized renewable production, demand and energy stored at different *RPPR*.

3.3 Critical Storage Curve

The minimum storage required to optimize the renewable production (reduction of potential losses) while minimizing the conventional contribution changes depending on the *RPPR* (figure 7). It is possible to determine the optimal storage for any *RPPR* following the procedure explained before. Figure 8 shows an example of this optimal storage for a generic electric system. This curve will be named from now on as *Critical Storage Curve*, and as it can be observed there are two different ranges:

- *RPPR* ≤ 1: Within this range the renewable potential production does not reach the demand energy. However, there are no *Renewable Energy Losses* and the non renewable contribution gets minimized (figure 8, point 1).
- *RPPR* ≥ 1: Within this other range it is feasible to fulfill the electric demand just with renewable energy. Non renewable contribution is not necessary. However, *Renewable Energy Losses* are produced for *RPPR* higher than 1 (figure 8, point 4).

For *RPPR* =1 it was verified that the non renewable contribution and the *Renewable Energy Losses* were both zero although a huge storage seemed to be required. For *RPPR* higher than 1, above the *Critical Storage Curve* (figure 8, point 5) storage is higher than the minimum required. However, below the critical curve (figure 8, points 2 and 3) the storage capacity is not enough to assure minimal values of non renewable contribution and *Renewable Energy Losses*. Point 0 corresponds to very low *RPPR* values where no storage is required to optimize the potential renewable production. This is a consequence of very limited production sequences with no overproduction at any moment during the year. A similar situation was shown on figure 3 a. Another remarkable point is 6, which correspond with very high *RPPR* values. In this unfeasible situation, no storage is required because the minimal renewable production is always over the demand at any moment. However, almost all potential production will become *Renewable Energy Losses*. A similar situation was pointed out in figure 4 for very high *RPPR* levels. Moreover, different renewable combinations, like those shown in figure 5, will produce different *Critical Storage Curves*. Therefore, this curve can be used to compare the tendency of different future scenarios with different renewable mixes. More specifically, this tool reveals important information about likely storage needs and their dependency on the *RPPR* and the specific renewable mix. Thus, offering a particular vision today, about the best politics or incentives in renewable investments for the future.
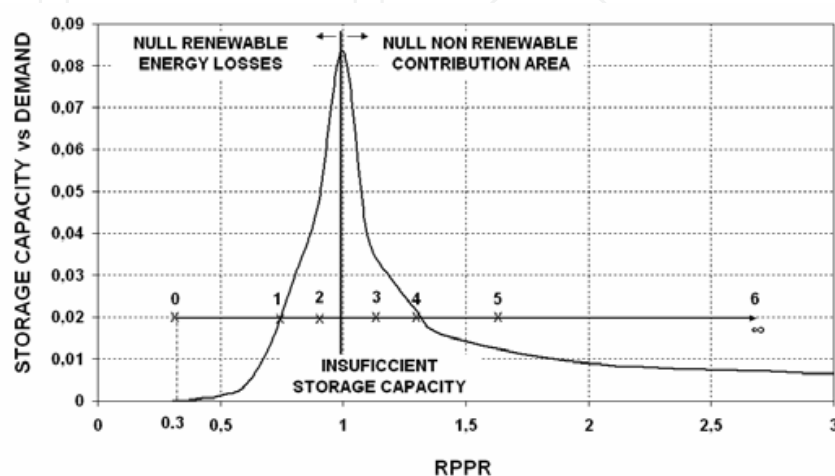

Fig. 8. Normalized *Critical Storage Curve* at different *RPPR*

3.3.1 Sampling time influence

In order to verify the reliability of the results obtained, several analyses have been performed. The first one attempts to determine the minimal measurement interval advisable (monthly, daily, hourly, etc). Figure 9 shows the *Critical Storage Curve* calculated with different measurement intervals. As it were foreseen, monthly measurement intervals lead to significantly lower storage than the obtained with shorter intervals (daily, hourly). This is a consequence of a higher percentage of renewable production directly satisfying the demand with respect to analyses performed with lower sampling times. *Critical Storage Curves* calculated in hourly and daily measurement intervals basis differ minimally. Even when using ten-minute sampling data the *Critical Storage Curve* is nearly the same as those calculated based on daily or hourly data. As a consequence of this analysis, it was decided to perform all analyses always based on hourly series as it was mentioned before.
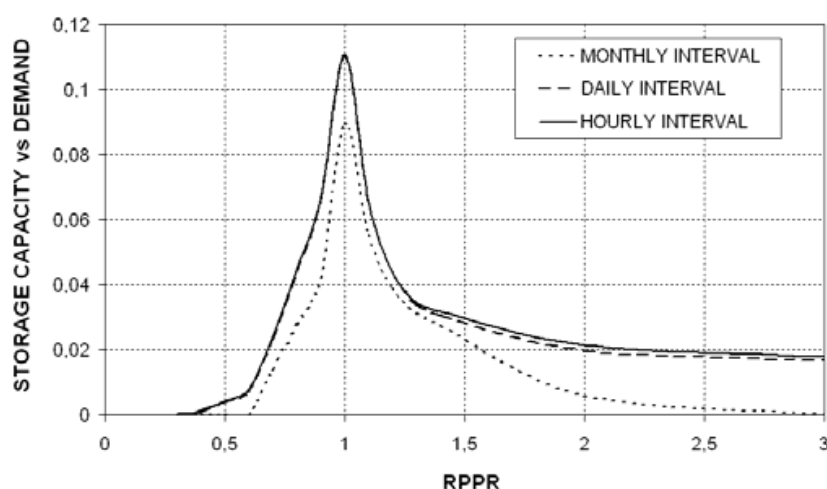
Fig. 9. *Critical Storage Curve* for different sampling times

3.3.2 Wind profile influence

The optimal energy storage sizing depends on both demand and renewable production profiles. However, demand profiles present a certain hourly and yearly regularity as it was shown previously, while renewable production profiles may be very different according to locations and scales (the lower the scale the higher the difference). In order to show such dependence, *Critical Storage Curves* for a typical demand profile and four real wind production profiles (Acciona Remote Control Centre, 2010) have been calculated, figure 10. These wind productions correspond with four wind farms placed in different Spanish regions. In this figure it is clearly appreciated that such difference may be very relevant. When comparing wind farm "S" and "T" at *RPPR* = 1, the required storage capacity for wind farm "S" is almost twice the required for wind farm "T". Also the analysis has been performed for a case which considers an average production profile of the four wind farms mentioned previously and which represents the expected evolution in wider regions. This profile's results are much smoother when it is compared with the independent wind farms, which in turn also leads to smaller storage requirements ("VRST" curve).
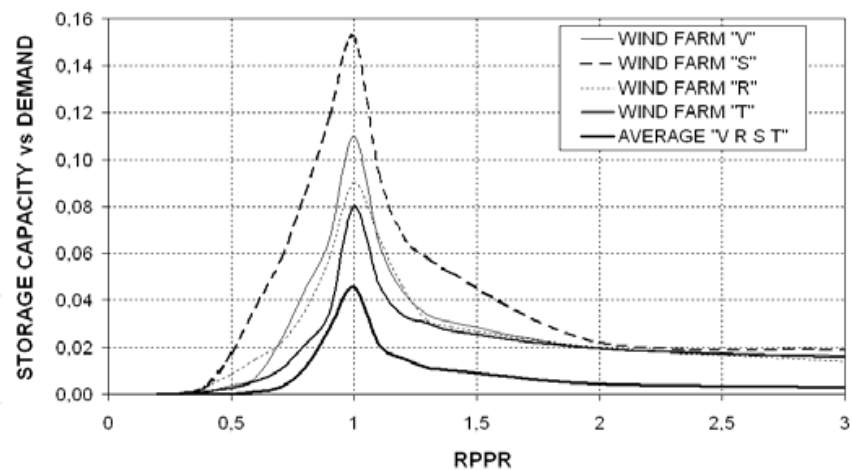
Fig. 10. Influence of different wind generation profiles.

3.3.3 Influence of storage power drives

Any energy storage system is necessarily equipped with drives to in and out power. These drives have limited powers that play an important role for the whole system's efficiency. Moreover, the efficient use of the storage will depend on the drive's power. Drives rated very low will not be able to pump or turbine, in the case of water, the necessary power; which finally will imply increasing system losses (renewable generators that must be stopped) or increasing the contribution of non-renewable generators (not enough turbines to meet demand). Figure 11 shows the dependence of the power drives on the *Critical Storage Curve*. As it can be observed, as the drive power diminishes the curves move towards the right-hand side. This means that more renewable contribution will be needed to compensate losses. But more importantly, the right part of the curves does not mean anymore zero conventional contribution. In fact, the *Critical Storage Curve* just represents the best storage that corresponds with the rated drive power. Besides, the intrinsic efficiency of these drives is also important as some real technologies do really have low rates; introducing a new element to worsen the situation. Therefore, the drive powers limits and efficiency must be clearly taken into consideration in further analyses due to notable influent results.
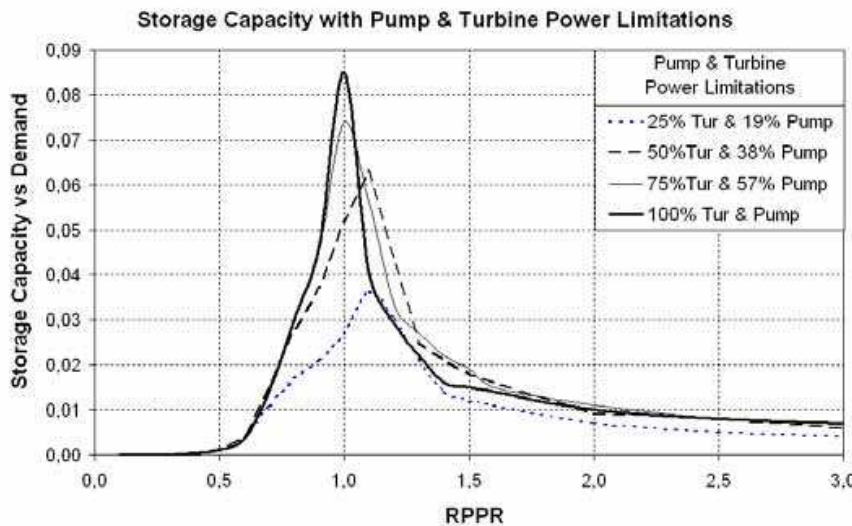

Fig. 11. Influence of storage drives limit power.

4. Energy storage analysis in large isolated electric systems

4.1 Introduction of the study case. Spain

Spain had in 2010 a population of 47 million inhabitants in an area of 504,790 km², and a total electrical demand of 251.43 GWh (REE, 2009). In this country, renewable sources (including large hydro) suppled 31% of the total electrical energy demand in 2009. Thus, the *RPPR* for Spain in 2009 was around 0.31; however, this number does not correlate with real renewable production due to the different curtailments introduced in various nodes as a consequence of power limitations.

Spanish electric system is connected to the European electric grid through France and Andorra, to the African grid through Morocco, and finally with Portugal. The total energy flow along those connections is just 3.2% of the Spanish electric demand (REE, 2009). Therefore, in order to analyze how energy storage may optimise the total renewable production, Spain has been considered an isolated electric country.

Figure 12 shows the geographical and climatic map. Spain has a variety of regions: mountainous, plains, long shore perimeter, etc., being the general climate continental, with some regions being mediterranean, oceanic, etc

(a) geography   (b) climate

Fig. 12. Maps of Spain.

Spain offers excellent features for the basis of this study for the following reasons:

- Spain presents a high development level in all economic sectors. Its electrical demand profile can be considered representative of a modern, industrial and diverse society.
- Spain currently has a diversified renewable energy production comprising high levels of wind, solar, hydro, mini-hydro, biomass, etc.
- Due to its condition of being one of the leader countries in renewable generation, several years of complete hourly production data from many renewable generators in various technologies are available. For example, wind power hourly series are available since 1992.
- There are two different energy storage systems already available: classic hydro and reversible storage. The first type includes all classic hydro generators without pump systems only based on rain water. These systems include huge water storage able to supply rated power during several weeks. The total storage capacity of these systems is around 7.1% of the yearly Spanish electric demand while the current power installed is 16,657 MW (17.8% of the total power installed) [3]. The second type corresponds with

reversible storage systems (turbine plus pump) with a total capacity of around 74,201 MWh, which represents 0.03% of the yearly electric demand. Power drives are rated at 6% of the maximum demand power during a year (around 45 GW).

- Geography and climate of the country are very diverse among the different constituting areas. The South of the country is especially suitable for solar (photovoltaic and Thermo-solar plants) while the north of the country may concentrate most biomass plants. However, wind power is abundant and available across the whole country. The same applies for hydro although the north concentrates more facilities. Table 1 show how many times the potential renewable resource of each technology could satisfy the Spanish electric demand (according to the situation during 2009) (García & Linares, 2005).

Renewable Technology	Potential satisfaction of the electric demand (times)
Thermo-Solar	31.8
Photovoltaic	4.44
Wind on-shore	7.34
Wind off-shore	1.1
Waves	0.9
Hydraulic	0.1

Table 1. Theoretical potential renewable resources in Spain.

4.2 Baseline critical storage curve

A Baseline case has been defined basically according to the current mix of renewable producers, table 2. It includes a set of hourly series taken from real measurement productions (solar, wind and Biomass) and also calculated from meteorological information (wind off-shore). For future scenarios these data series have been scaled increasing the global potential production according to known official (Spanish, Ministry of Industry, 2010) plans of renewable developments for the future. As it can be observed, these plans concede good opportunities for solar developments although not very optimistic ones for biomass plants.

Renewable Technology	Current power (year 2010, MW)	Hypothetical Power for RPPR = 1.3
Solar (PV & Thermal)	3,700	60,000
Wind on-shore	19,000	40,000
Wind off-shore	-	10,000
Biomass	2,000	10,000

Table 2. Baseline definition

The *Critical Storage Curve* for the baseline case is presented in figure 13.a. This curve presents the strictly minimum reversible-type storage for every *RPPR*. Therefore, large existent hydro storages currently spread throughout the country were not included in this analysis because there are not reversible in power. Their influence is crucial as it will be shown but they need a new set of operation rules to efficiently work with reversible storages. Figure 13.b shows the minimum required drive power to be installed in

accordance with the critical storage. Due to system power losses (power drives losses particularly), the minimum *RPPR* for 100% renewable supply is around 1.1 instead of 1.0 (critical). Nevertheless, around these numbers both storage size and driver power presents unfeasible values.
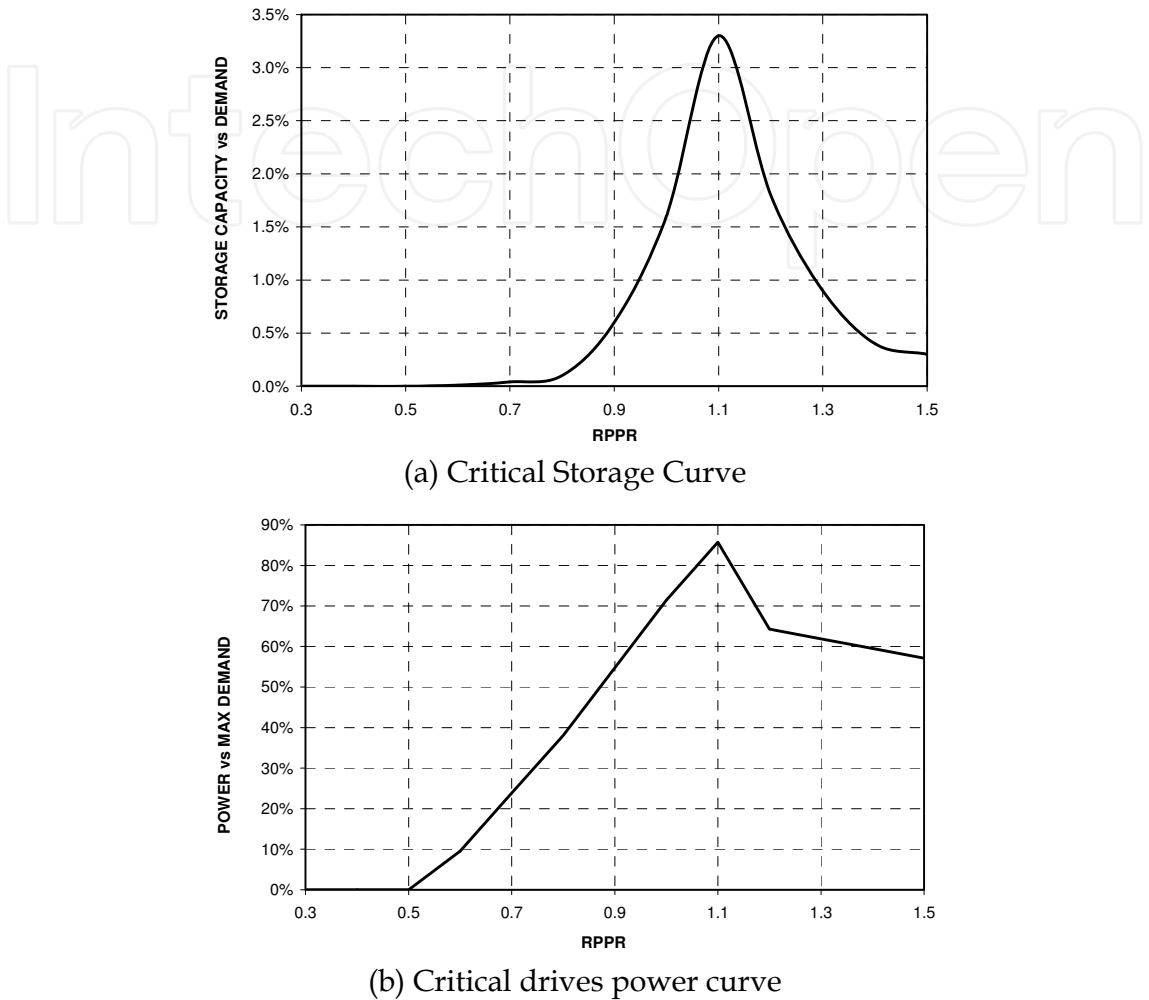

(a) Critical Storage Curve

(b) Critical drives power curve

Fig. 13. Critical Storage and Power Curves for baseline case.

4.2.1 Influence of large hydro storages

Current large hydro plants are usually operated under market-based rules or on grid operator needs. However, the existing set of plants conform a huge energy storage that can be operated to improve the integration of the rest of renewable technologies. These strategies have been included on the simulation platform explained before. Therefore, now the system includes two different storages: hydro-based and reversible. The control rules for each one have been coordinated in order to make the most efficient use of both storages at any instant. Logically, behind such rules there is a general objective to maximise the renewable production, reducing losses and conventional contributions. Figure 14 shows the *Critical Storage Curves* when the large hydro storage is also considered. As it can be observed, the new reversible storage is now clearly smaller than the previous case, figure 13. This reduction also affects the required drives power as demonstrated on the curve in figure 15. Both reductions also imply fewer losses moving the whole curve towards the left-hand side.
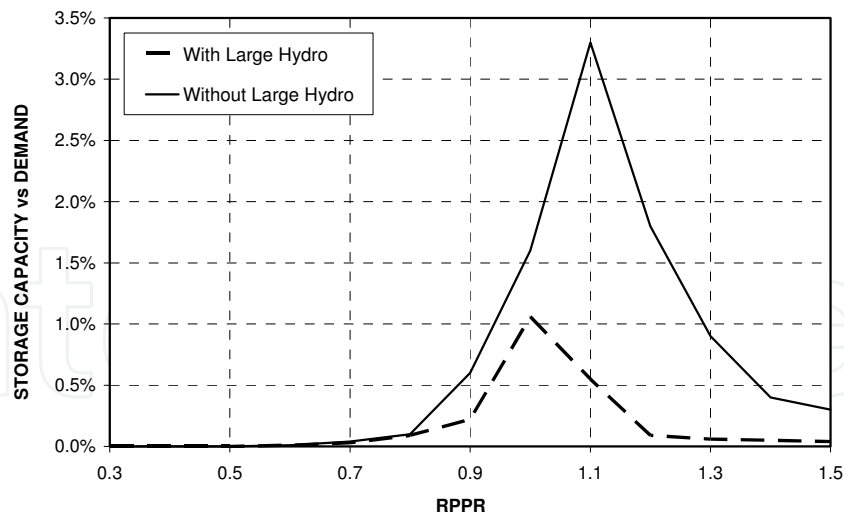
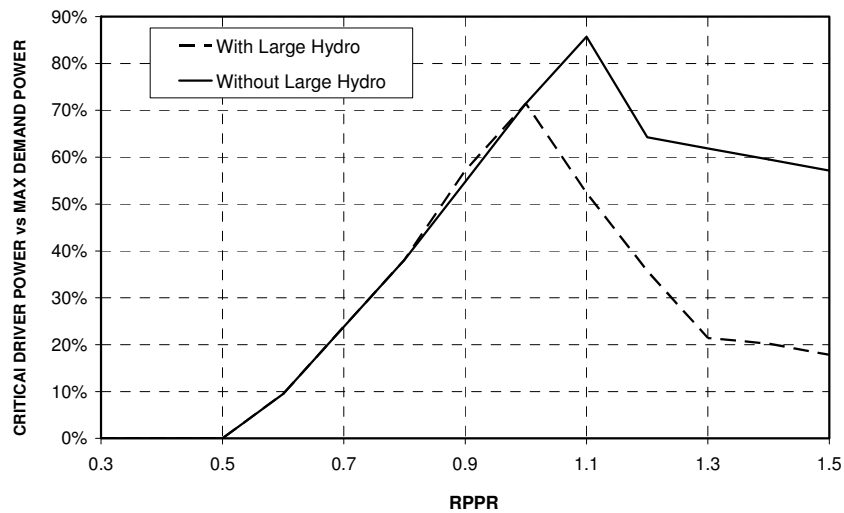Fig. 14. *Critical Storage Curves* for baseline case.

Fig. 15. Critical Power Drives for baseline case.

A 100% renewable scenario requires *RPPR* over 1.1 to be technical and economically feasible. A reasonable value according to all curves shown on figure 14 and 15 could be around *RPPR* = 1.3. Table 3 summarizes the difference between both scenarios (with and without large hydro). As it can be observed, the efficient and coordinated use of current large hydro systems strongly reduces the need for large reversible storages, both in size and power. Moreover, an over sizing like the one proposed in table 3 (*RPPR* = 1.3) should lead to a global reversible storage need which is only twice the existing one. Considering that such increment in renewable contribution from current rates to the correspondent for *RPPR* = 1.3 may take some decades, the proposed increment in storages could clearly be feasible.

The positive influence of current large hydro storages can be incremented if some more actions were taken. Particularly interesting is the possibility of increasing turbine ratings of the whole system. Current power is around 16.6 GW but some plants still admit additional powering to reach a maximum of around 20 GW. Figures 16 and 17 show the influence on the critical storage and power curves respectively due to an increase in uniquely large hydro power.

RPPR = 1.3	Reversible Storage Capacity vs Yearly Energy Demand	Drives Power vs Max Demand Power
No large hydro storage	0.9%	62%
Large hydro storage (7,1%)	0.06%	21%

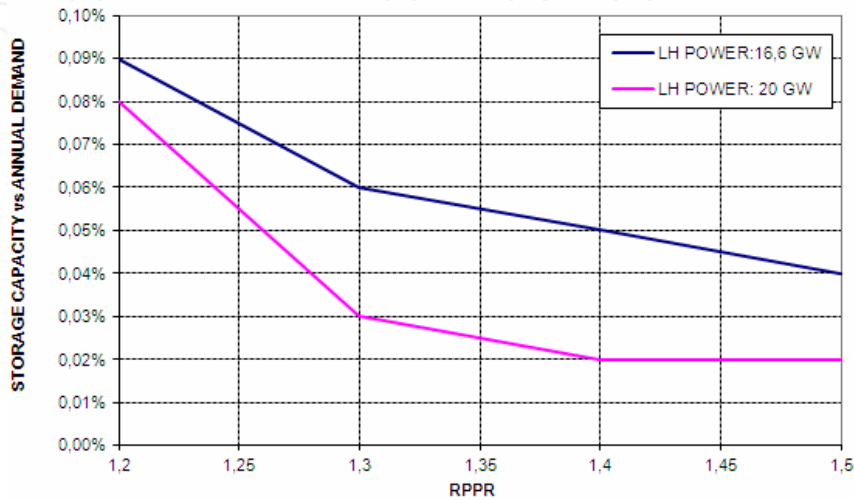Table 3. Reversible storage and power requirements considering large hydro.

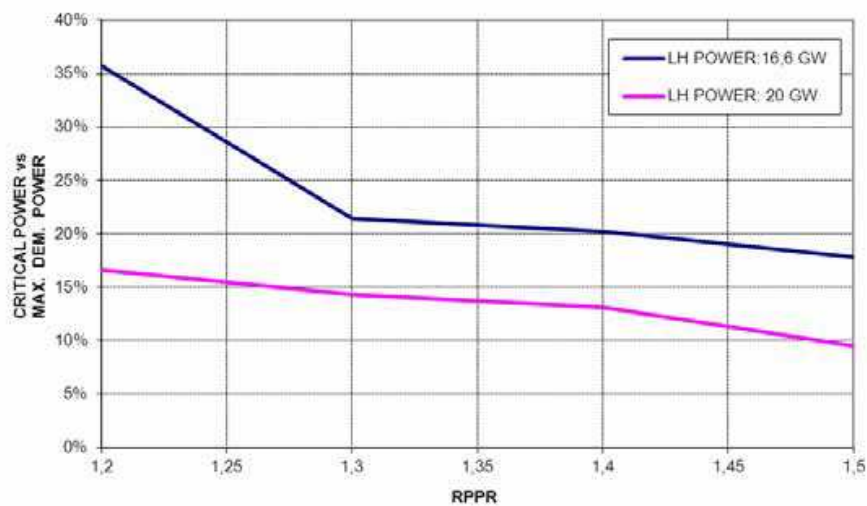Fig. 16. *Critical Storages Curves* for baseline case depending on large hydro power.

Fig. 17. Critical Power for baseline case depending on large hydro power.

Table 4 summarises the influence of higher turbine power ratings at *RPPR* = 1.3. Again a notable reduction of reversible storage needs is observed. Moreover, with the proposed turbine empowering, already available reversible systems should almost be enough. This hypothetical scenario with 20 GW large hydro turbine ratings makes it almost possible to achieve a 100% renewable supply with the existing hydro pump storage system. It should be enough to increase power in such systems from the current 4 GW to around 6 GW. Moreover, enormous technical improvements within R&D divisions have taken place over the last decade that offer commercial power plants of up to 50 MW the ability to deliver

energy peaks during 60 minutes. A proper distribution of these units would fulfil the required storage and also improve the system efficiency (locally and globally) although some control complications may arise.

RPPR =**1.3**	**Reversible Storage Capacity vs Yearly Energy Demand**	**Drives Power vs Max Demand Power**
Large Hydro Power: 16.6 GW	0.06%	21%
Large Hydro Power: 20 GW	0.03%	14%

Table 4. Reversible storage and power requirements depending on large hydro power.

4.2.2 Influence of demand control

Demand control is sometimes used by grid operators in order to compensate energy unbalances under certain circumstances. These techniques require fast communications and commitment with some users which receive economical compensation for this service. This possibility has been explored in order to understand the influence on the proposed renewable-based system for any RPPR. The demand control algorithm establishes a daily schedule with the percentage of demand to be shared among different intervals throughout the day. The decisions are made using the forecasting of the renewable production (already available in simulation). In this way, on every hour the best relation between demand and available renewable production is established. This method offers the better perspectives that can be expected with demand controls as such because it uses perfect information. Thus, these results should be considered as a theoretical maximum positive influence. Figures 18 and 19 show the critical storage and power curves respectively depending on different ranges of demand control over the daily demand (0%, 15% and 30%). The first conclusion is the little influence that seems to offer demand control implementation. For *RPPR* = 1.3, the likely benefits maybe do not compensate the complication introduced in these demand control programs. However, further analysis with other demand control politics should be made to get definitive conclusions.
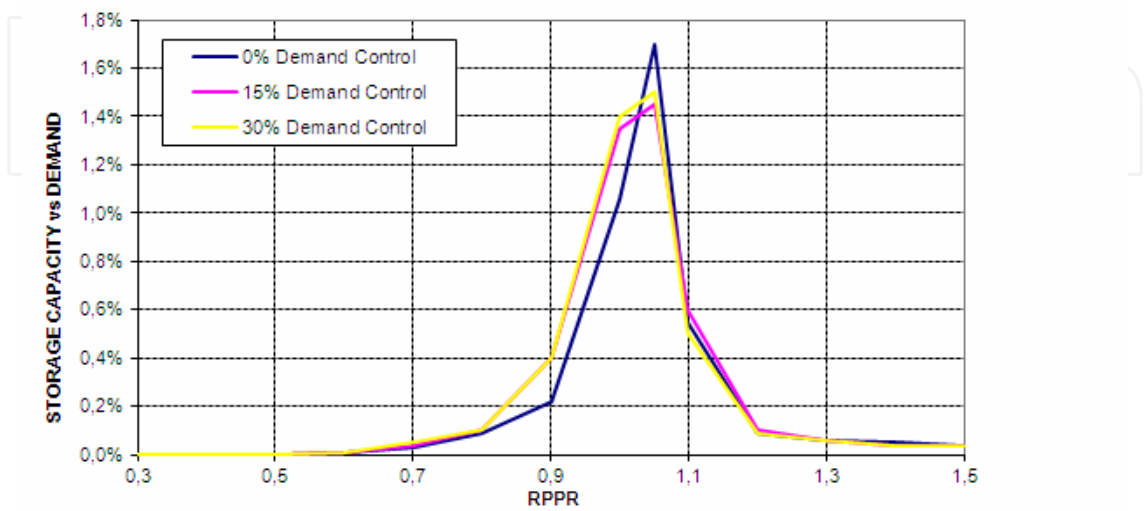

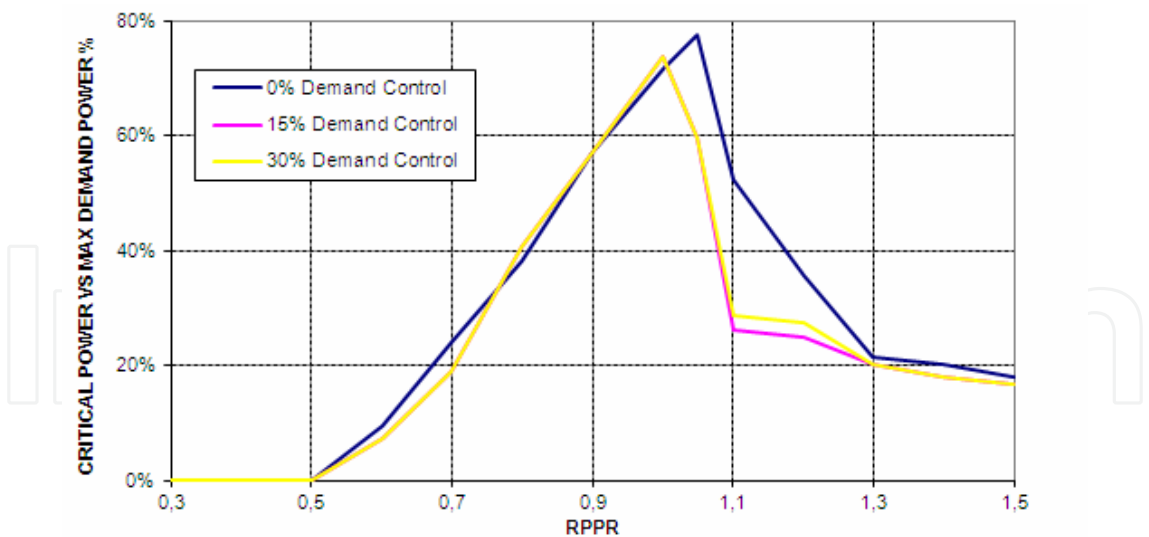Fig. 18. *Critical Storages Curves* for baseline case under Demand Control.

Fig. 19. Critical Power for baseline case under Demand Control.

4.2.3 Influence of the renewable mix generation

The analysis of potential renewable capabilities in Spain sorted by technology (table 1) evaluated by (García & Linares, 2005) opens multiple likely future scenarios of renewable mixes. The evolution in one and another direction will depend on many aspects such as political decisions, economical or technological incentives, etc. In that sense, one aspect that also should be considered for incentives could be the influence on future storage needs. As it will be demonstrated storage size or drive power is influenced by the mix characteristics for a same *RPPR*. Figure 20 shows the evolution of the total power installed by technology during several years, from 2000 until 2009. This graph also presents proposals of hypothetical extrapolations of likely future mixes according to known development plans (baseline) or other assumptions that concede higher development opportunities to some technologies.
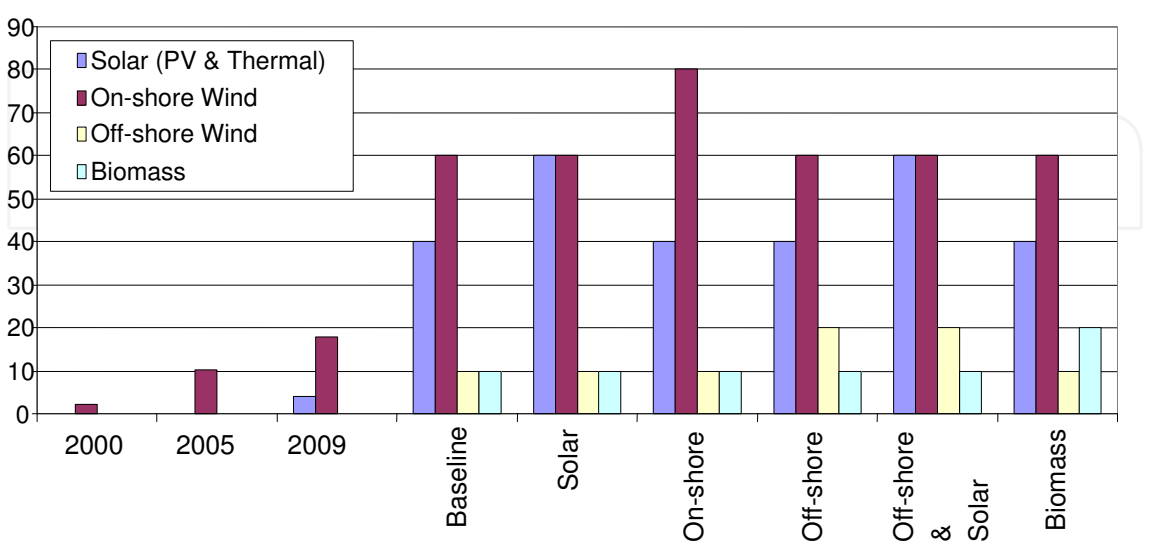

Fig. 20. Renewable mix generation scenarios.

The *Critical Storage Curve* of all renewable mixes has been calculated for two different large hydro powers: 16.6 GW (current) and 20 GW (hypothetical). Results are exposed in figure 21 where several aspects could be highlighted:

- All renewable mixes show a similar tendency offering good opportunities to reduce storage size as the *RPPR* or hydro power increases.
- Biomass case seems to offer the better opportunities to reduce future needs of storage. In fact, the higher the influence of controllable renewable producers the lower the storage needs. Consequently, more incentive of these technologies should be seriously considered.
- In general, greater hydro powers lead to lower storage needs. However, the differences are in some cases very little, being also important the characteristics of the renewable mix. In fact, around *RRPR* = 1.3 almost all mixes confluent on a narrow range of storage size, where only the Solar case seems to be out of range.
- Solar contribution must be increased for future systems. However, above certain levels the opportunity to reduce storage size or power diminishes considerably. This means other technologies become more relevant. Nevertheless, it is important to remember that in all mixes of figure 20, the expected contribution of this technology has been planned considerably high and above 40 GW, a rating that means around 1 kW per habitant to be installed.
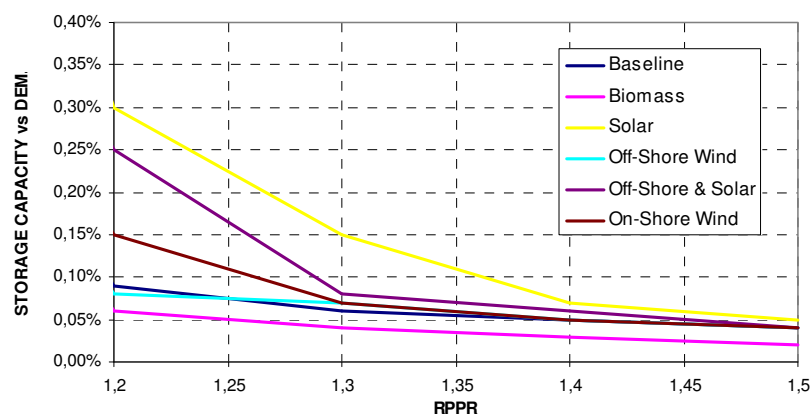
Large Hydro Power: 16,6 GW
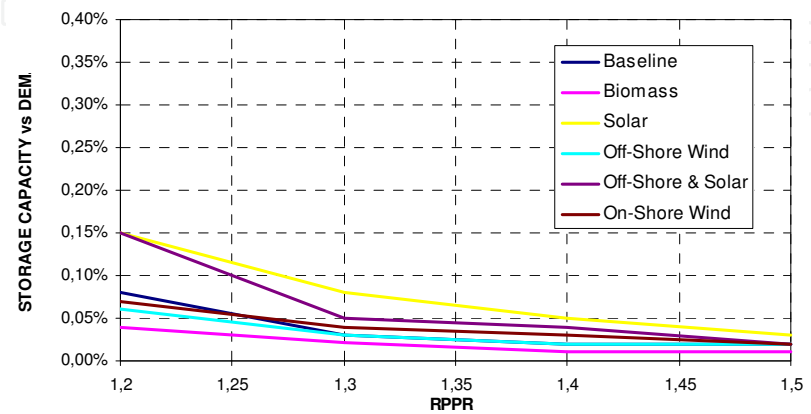
Large Hydro Power: 20 GW

Fig. 21. *Critical Storage Curves* for 6 renewable combinations and 2 large hydro powers.

5. Transition process

The transition towards a 100% renewable–based electric system starting from the current situation has critical implications and a lot of questions to be answered. Some of these questions could find a reasonable and acceptable answer through the analysis already made. The required renewable system, to guarantee the electric supply, seems to be clearly feasible in terms of natural resources. Moreover, the final system power to be installed in generators, storages, etc also seems to be feasible and surely justifiable from an economic perspective. However, there are also political and economic implications with pollutant technologies still pending to be cleared up, aspects that are beyond the scope of this analysis. Some official and non official plans (García & Linares, 2005) seem to consider a total substitution of current generation plants in around 40 years. Thus, the new renewable system must be planned today to reach the desired point in time. Therefore, it is important to have some

(a) No hydro empowering
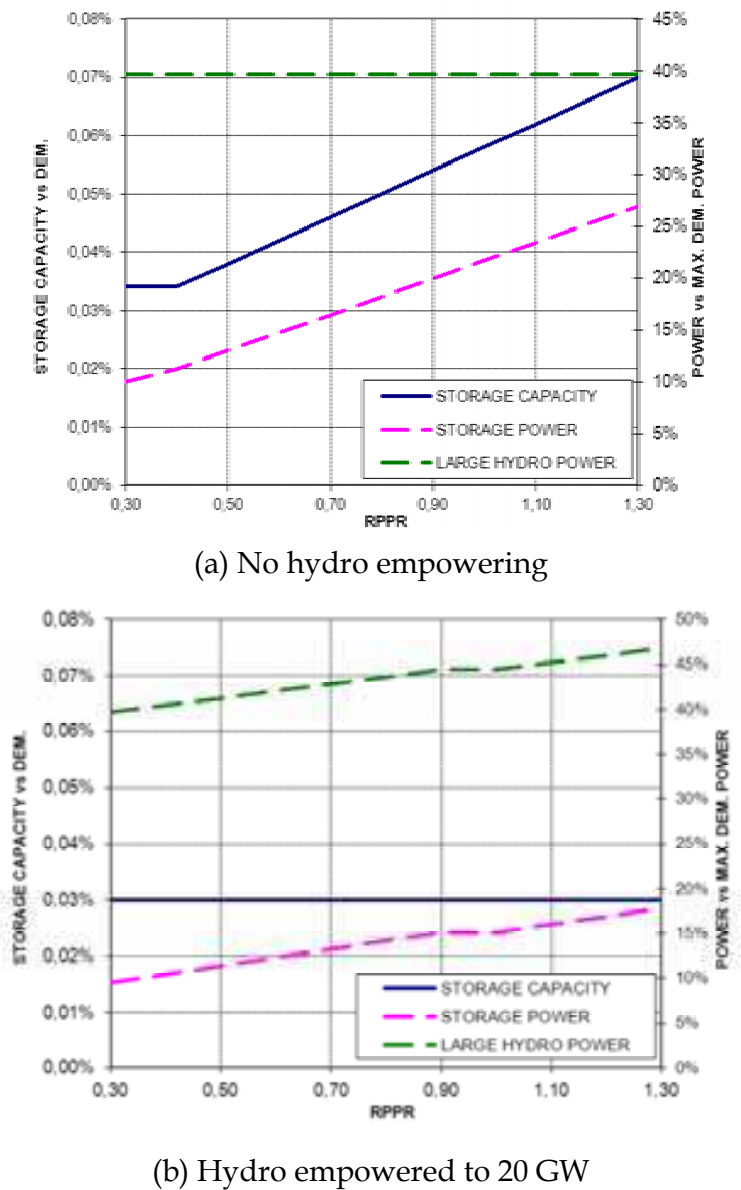
(b) Hydro empowered to 20 GW

Fig. 22. Proposals of reversible and hydro storages evolution possibilities.

clear numbers that help to define targets. During this study some numbers have arisen like a final RPPR around 1.3 and storages not really much more capable than current systems. The transition to such final system seems to require simply the implementation of more renewable plants coordinated with the decommissioning of existing ones, sensibly starting first with those more dangerous, pollutants and older. In any case, during this process the intermediate electric system must guarantee the supply which will have several implications as the following study will show. Figure 22 shows a proposal of increasing storages (both reversible and hydro) as the RPPR is going to be increased. The evolution of required storages power or size will be different if large hydro plants decide to increase the turbine power. If no additional power is to be installed, (figure 22.a) the reversible storage must be increased in size and power. On the contrary (figure 22.b), only the reversible power should be increased. Certainly, in this sense final decisions will also depend on likely economic advantages.

Figure 23 shows a hypothetical sequence of the different energy supplies during the transition process. Four different energy sources fulfill the electric demand for any *RPPR*:
1. Generation coming from conventional base plants (nuclear and coal mostly)
2. Generation coming from conventional controllable plants (gas, fuel, etc)
3. Renewable generation instantaneously delivered to the grid.
4. Renewable generation delivered to the grid through the storage.

Fig. 23. Transition process with baseline case and 16,6 GW hydro power.

While the reduction of the conventional energy contribution maintains a gradual shape, unfortunately controllable conventional power plants must be maintained operative in order to assure peak demands. Figure 24 shows the sequence of conventional plants decommissioning correspondent with the process proposed in figure 23 for two different renewable mixes (wind and Biomass). Here it can be appreciated that only when *RPPR* values reach 0.9 a considerable controllable conventional power can be diminished, irrespective of the renewable mix. The energy produced for such plants is progressively decaying but must be operative because of power peaks needs. This would certainly require special economic incentives and politics to be feasible. Nevertheless, in this sense the situation in figure 24 corresponds with the two extreme cases richer in wind and biomass than the baseline case. Anyway, most controllable conventional plants can be slightly changed to use biofuel, biogas, etc. improving the total biomass service while fulfilling the required power to cover demand peaks.
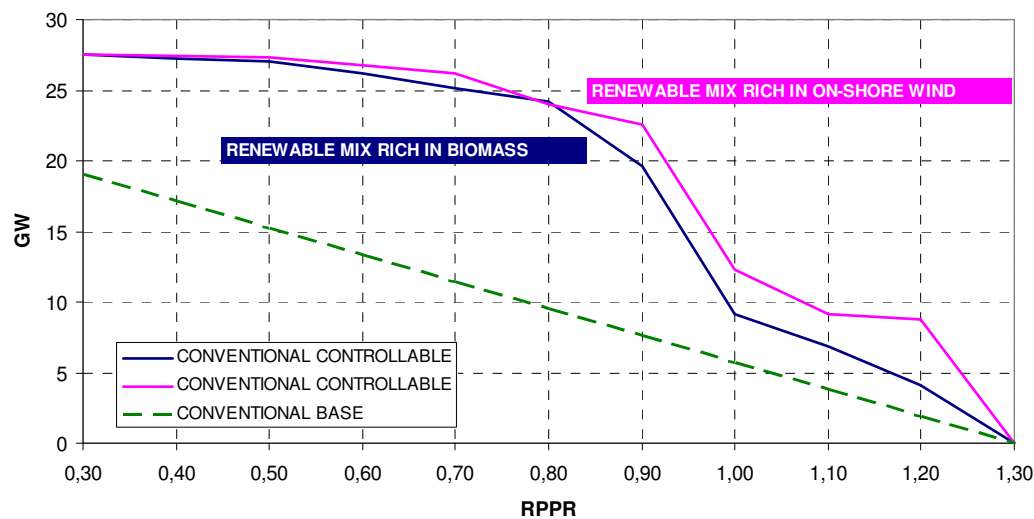

Fig. 24. Conventional power plants decommissioning sequence for two mix renewable generation scenarios.
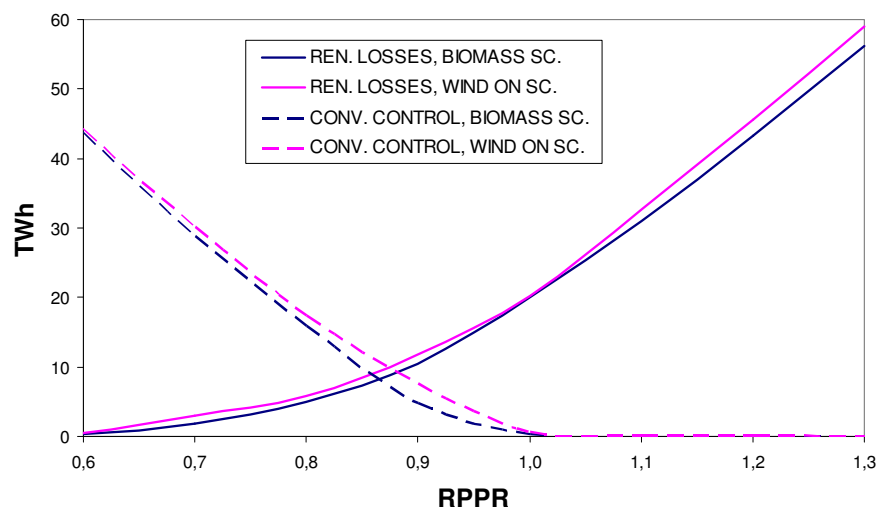

Fig. 25. Renewable energy losses and controllable conventional generation. Transition process.

During this transition certain inefficiencies must be admitted, such as increments in *Renewable Energy Losses*. Figure 25 shows extreme results (again for those combinations richer in wind and biomass than the baseline case) of these losses together with the evolution of the expected controllable conventional energy. The Biomass case requires from any *RPPR* value the minimum controllable conventional generation and creates the minimum renewable losses comparing with any other renewable mixes.

6. Conclusions

The use of storage systems is essential to allow future higher grid integration levels of renewable energy. Even a total substitution of current conventional generators to achieve a 100% renewable supply seems to be technically feasible. The Spanish electric system has been used as a base case for this study, due to the significant and diverse renewable energy technologies already installed and the high renewable resource available. However, the ratings per capita in Spain regarding electrical demand and renewable resources availability (hydro power, equivalent sun hours, wind on-shore and off-shore, biomass, etc) can be compared with a lot of countries with different levels of development. Therefore, most of the conclusions obtained from of these studies could also be extended for those in other countries and regions. The following ones are remarkable:

- Large hydro storage systems available in many countries may reduce significantly the reversible storage capacity needed to reach 100% renewable supply. However, in places without this possibility it will be advisable to plan a highly distributed reversible storage system. Two benefits would be expected: reduced transport losses and easier integration of these systems in both remote and civilised areas.

- The renewable mix clearly influences the size and drives power of reversible storages. Current political incentives should take care of these implications for future planning, especially regarding biomass systems because they offer the better opportunities to reduce future storage needs. Biomass also helps to smooth the transition from current to higher renewable systems.

- Increasing renewable rates will need the operation of storages accordingly for better grid integration. Both systems, hydro-based and reversible, must be adapted and coordinated to support and service such integration. In this moment the level of renewable production is relatively low without requiring storage service. However, countries like Spain with important levels of wind-based renewable production should already start to take care for future close needs.

- Above certain renewable integration the theoretical reversible storage needs are strongly reduced. Penetration levels around *RPPR* = 1.3 seems to offer good technical perspectives although final decisions will also be made considering the economic or environmental implications.

- The transition from current electrical systems, mostly based on non-renewable sources, towards 100% renewable should be carefully planned. As it has been pointed out, depending on the future renewable mix, available hydro, available renewable resources, etc, the storage system, the electrical transport and transmission system, the communications and other important aspects should be determined.

For years the never ending debate about the feasibility of a 100% renewable-based electric system has been taking place worldwide. This work has had the intention to clarify as much

as possible in that sense, completing contributions of many other personalities and institutions. The study here devised offers good perspectives for future renewable energy developments. Moreover, from the point of view of technical feasibility some important aspects have been explored and analysed, seeking good opportunities and a path to be followed for a successful change.

7. Future research lines

Several research lines have been opened as a consequence of this work. Some of them related with technical aspects that still need more study or detail, such as new, more capable control techniques (especially forecasting), improvement of the simulation platform, influences of grid ancillary services, total and local effect of the dispersion of producers and storages, etc. However, other lines related with economic issues have also arisen becoming quite relevant. Technically, the proposal here exposed has developed a lot of points to defend it but, it is necessary to complement it with economic arguments. During the last years an important work to sustain the renewable option in regulated or free markets has been presented by many authors (Makarov et al. 2009). One basic analysis, introduced in (García & Linare,2006), compares the current electric system costs with respect to one only based on renewable energy, where important aspects are revealed that strongly support. However, one interesting line to be followed in future research will try to characterise the opportunities of a hypothetical electric company that makes use of the storage in order to maximise benefits. Market conditions, financial costs, etc must be determined for optimal economic exploitation.

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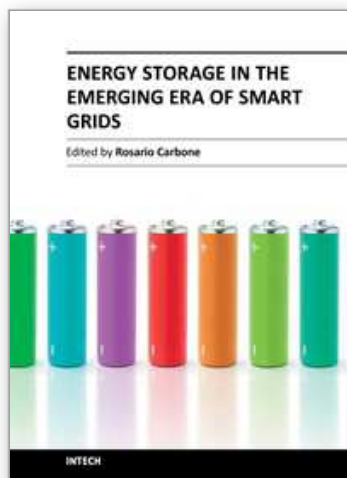
Energy Storage in the Emerging Era of Smart Grids

Edited by Prof. Rosario Carbone

Reliable, high-efficient and cost-effective energy storage systems can undoubtedly play a crucial role for a large-scale integration on power systems of the emerging "distributed generation" (DG) and for enabling the starting and the consolidation of the new era of so called smart-grids. A non exhaustive list of benefits of the energy storage properly located on modern power systems with DG could be as follows: it can increase voltage control, frequency control and stability of power systems, it can reduce outages, it can allow the reduction of spinning reserves to meet peak power demands, it can reduce congestion on the transmission and distributions grids, it can release the stored energy when energy is most needed and expensive, it can improve power quality or service reliability for customers with high value processes or critical operations and so on. The main goal of the book is to give a date overview on: (I) basic and well proven energy storage systems, (II) recent advances on technologies for improving the effectiveness of energy storage devices, (III) practical applications of energy storage, in the emerging era of smart grids.

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