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Integrating large shares of wind energy in macro-economical cost-effective way

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ABSTRACT

The intermittent nature of wind energy poses questions on how electricity production can match the demand. The present paper analyses possible ways of achieving this goal when a large share of the energy is provided by wind. The study considers a certain share of wind energy as a target to be reached, and analyses different avenues for reaching such a target. The possible role of electricity energy storage, wind curtailment and transmission grid reinforcement is highlighted and discussed. The results show that above a certain percentage of electricity produced by wind, electricity storage becomes an economical option for integrating wind energy by reducing wind curtailments. Also, the synergy of storage and grid interconnections is highlighted.

1. Introduction

The current electrical power generation is largely based on fossil fuel power plants. Fossil-based power plants, nuclear and hydro, although differing significantly from the way their production can be regulated, can be combined in a proper way for supplying the electricity demand, which changes continuously in time. Typically, nuclear and, depending on the specific technology, coal power plants set the base-load, i.e. a minimum amount of power that can be hardly modulated. More flexible systems like gas turbines in single or combined cycle, and/or hydro power provide the electricity needed to match the demand. These units are characterized by a quick adaptation to the requested electricity production, thus they provide the so-called "flexible generation". If intermittent renewable energy (RE) contributes only marginally to the overall power production, its stochastic contribution is limited, compared to the total electricity generation. Therefore, in this case, it can be assumed that the overall electricity production is predictable and the related scheduling can be done in a reasonably easy way. An example of such a scenario is depicted in Fig. 1.

Most countries have employed for decades a power generation scenario similar to that of Fig. 1, i.e. with little contribution from intermittent RE. However, environmental concerns, together with the needs of security of energy supplies, lead some countries to push toward the production of a relevant amount of electricity from renewable resources. At European level, for example, the European Union aims at reaching 70–80% electricity from renewable by 2030, and nearly 100% by 2050 [1]. Among other ways of producing electricity from renewable energies, wind has registered the highest growth in the last few years worldwide [2].

It is widely recognized that the introduction of wind energy in a large amount is considerably changing the power generation scenario and is introducing new challenges in the power sector. One debated topic is to what extent wind and other RE will replace fossil fuel plants (e.g. [3–5]), and how much flexibility will be requested to fossil fuel plants. Intuitively, by observing Fig. 1, and adding more share of electricity from wind energy, one can easily predict at least three effects:

- The flexible generation will be more and more adjusted for compensating wind fluctuations. One typical example is the wind fall off, which can be compensated by flexible, controllable generation, e.g. gas turbines, hydro power, or biomass.
- Fossil-fuel power plants will operate for shorter time, thus decreasing their capacity factors, and increasing the related cost of electricity. This is particularly true if national regulations are in place to give priority to renewable energy (e.g. in most countries of North America, and the European Union)
- Excess of wind can be curtailed, or stored in dedicated energy storage plants (e.g. pumped hydro, compressed air energy storage, batteries, synthetic fuels, etc), or exported as electricity elsewhere.

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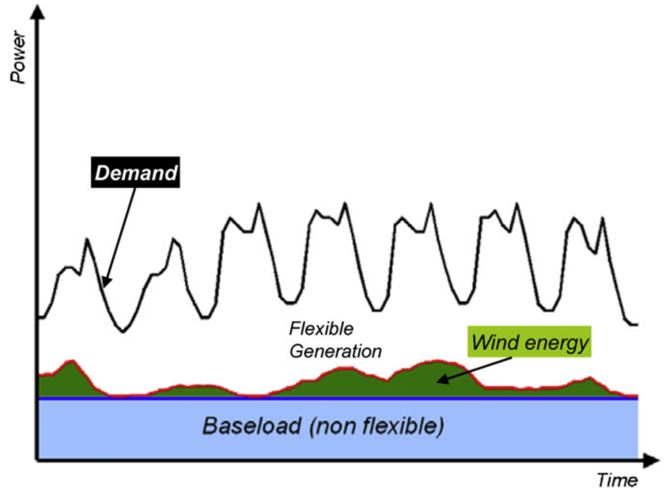

Fig. 1. Power generation versus demand for a low share of intermittent renewable (e.g. wind).

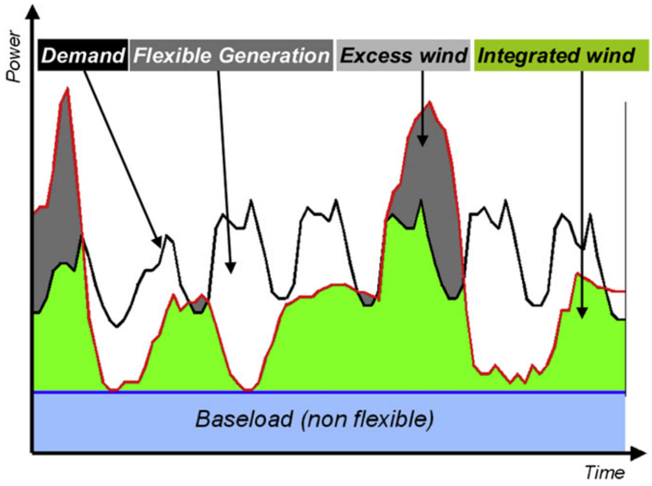

Fig. 2. Power generation versus demand for a high share of intermittent renewable (e.g. wind).

A number of studies focus on the integration of large shares of fluctuating RE in terms of feasibility and reliability (e.g. [6–10]), environmental implications ([8,11,12]), and balancing requirements due to non-precise wind forecast and other grid instabilities ([9,12–15]). Other studies focus on methodologies and tools for addressing this issue ([16,17]).

Although several options for storage are possible (e.g. electricity to chemical energy storage via synthetic fuels [18], heat storage in combination with heat pumps [19], or a combination of different technologies [20]), the present study considers electricity storage only. The study does not explicitly differentiate electricity storage technologies, but performs a sensitivity analysis of the storage efficiency and thus, accounts for different storage technologies implicitly. In this context, solutions like vehicle-to-grid ([21]), synthetic fuels production, e.g. H2 (e.g. [18]) can all be regarded as electricity storage with reduced electrical-to-electrical efficiency, due to energy use in the transportation sector. If the boundary conditions of the study are enlarged to an energy system including also the transportation sector, it is envisaged that the macro-economical optimization presented in Section 4 would appear different. However, since, at present, the electricity and transportation sectors are two different markets with different structures and mechanisms, it was decided to restrict the scope to the electricity sector only. Also, demand side management is out of the scope of the study.

Therefore, the focus is on the economical trade-off between wind curtailment, electricity storage and new transmission lines. A model for assessing such a trade-off from a macro-economical point of view is defined and presented. Two different drivers are considered in the analysis:

1) Maximizing the use of renewable energy (wind curtailment minimization)
2) Minimizing costs

2. Definition of the energy scenarios

In some countries, the power generation scenario is quickly moving from that of Fig. 1 to that of Fig. 2, i.e. with a non-negligible amount of electricity provided by intermittent renewable energy.

At European level, for example, all Member States of the European Union agreed to produce 20% of their energy from renewable sources, by 2020 [22]. Each Member State submitted its agenda to reach such a target. More recently, even more ambitious targets were set for some Member States of the European Union (Table 1).

It should be noticed that, although for most EU countries the targeted wind share is below 35% by 2030 (with the exception of Denmark, targeting 39.1%), the integration problem should be considered at regional, rather than national level. For example, Table 1 shows that in 2010, the average share of electricity from wind in the EU27 countries was 5.3%, but in some countries it was as high as 24% (Denmark) or 9.4% (Germany). A further analysis to the German wind production in 2010 shows that there were areas where electricity production from wind power was higher than 40% [25].

In the present study, five European countries are considered, namely, Germany, The Netherlands, Denmark, the United Kingdom and Spain. These countries have been chosen due to their ambitious targets for 2030, in terms of wind power generation. The selection of a Southern European country (Spain) allows for investigating the role of long distance cross-border transmission lines that connect two geographical areas subject to different climates.

As explained in Section 4, real data have been collected for wind speed and electricity demand, while base-load and wind penetration are set arbitrarily and varied in the analysis. Such an approach results to be useful for a “what if” scenario analysis.

3. Modeling approach

The present model considers as an input a certain share of electricity from wind to be integrated into a generic generation/consumption area. This approach reflects the current wind, and, more in general, renewable energy deployment plans that some countries might put in place for power generation. This means that, for example, if a certain country sets as a target a certain percentage of electricity produced from wind energy, the results of the present model will suggest the most cost-effective way of reaching such a target.

The domain of application is a generic power generation area, composed of a number of different generation technologies, producing electricity at a certain time “*t*”. The time domain is discretized into a certain number of hours, “*i*”. The generators are grouped as follows (Figs. 1 and 2):

- Base-load. This is defined as the lowest threshold of power generation, and represents the cumulative minimum load

Table 1
Status and target of EU Member States in terms of electricity production from wind energy.

Country	2010 [23]	2020 [24]			2030 [24]		
		Wind production (GWh)	Electricity demand (GWh)	Wind share (%)	Wind production (GWh)	Electricity demand (GWh)	Wind share (%)
Finland	0.5%	2530.0	93237.7	2.7%	4299.0	95377.6	4.5%
France	2.3%	44865.0	493763.3	9.1%	73275.0	545772.6	13.4%
UK	3.2%	81043.0	372160.0	21.8%	107286.0	394326.8	27.2%
Italy	3.4%	18465.0	355540.7	5.2%	30600.0	399071.8	7.7%
EU27	5.3%	399210.0	3218090.8	12.4%	643895.0	3517342.3	18.3%
Germany	9.4%	103009.0	567497.5	18.2%	175702.0	584512.2	30.1%
Ireland	10.1%	5702.0	30784.6	18.5%	9276.0	35169.1	26.4%
Spain	14.4%	57355.0	309009.1	18.6%	118350.0	361541.8	32.7%
Portugal	14.8%	10180.0	54219.1	18.8%	15601.0	63395.1	24.6%
Denmark	24.0%	12027.0	36553.1	32.9%	15374.0	39367.6	39.1%

below which the generating system cannot be operated, unless some base-load units are switched off. This is also sometimes referred to as minimum stable generation (MSG). Typically, nuclear and, to a lower extent, coal plants contribute most to the base-load. For modeling purposes, base-load generation is represented by one single value (power or % of total installed power), constant for a certain period of time (typically months or years).

- Flexible load. This is the total power that can be adjusted from one specific hour to the following one. It includes the cumulative power plant quota that can be modulated. Gas turbines in open and combined cycles, and peakers in general contribute most to it, while nuclear and some types of coal power plants provide a marginal contribution. In the present model, transient operations within 1 h are neglected. This means that the capability of the power plants to reach the required output levels, in terms of start-up/shut-down time and ramp rates, as well as the admissible number of start/stop operations during a certain time span, is beyond the scope of the present study.
- Electricity storage. Electricity storage can act as a generator, when in discharging mode, and as a load, when in charging mode.
- Wind energy. This is conveniently divided in wind energy integrated into the system as electricity and electricity potentially available but not integrated, i.e. curtailed wind energy. The sum of these two quantities is the available wind energy:

$$E^W_{\mathrm{av}}(i) = E^W_{\mathrm{int}}(i) + E^W_{\mathrm{curt}}(i), \tag{1}$$

where $E^W_{\mathrm{av}}(i)$ is the electricity from wind potentially available during the ith hour, $E^W_{\mathrm{int}}(i)$ the related electricity from wind integrated into the system and dispatched to the end-users, and $E^W_{\mathrm{curt}}(i)$ is the curtailed wind energy. The available wind energy is calculated from wind statistics and empirical data from wind turbine manufacturers (cf. Section 4).

Since wind speed measurements are usually taken at a few tens of meters over ground or sea level [26] and most wind turbine hub heights are around 100 m, the wind speed at hub height of the wind turbine is estimated knowing the measured wind speed at measurement level. A power law is commonly applied to the vertical distribution of the wind speed [27]:

$$v = v_0(h/h_0)^p, \tag{2}$$

where v_0 is the measured wind speed, h_0 the measurement height over ground or sea, and v is the estimated wind speed at hub height h. The power law exponent p is specified by the atmospheric stability and the roughness of the surface. Typical values of p found in the literature are outlined in Table 2. The power law exponent depends considerably on the location and the terrain type, hence its roughness. According to [28], a value of $p = 1/7$, corresponding to neutral stability conditions [29], is adequate for realistic but conservative estimates of the wind speed.

For the empirical data, a typical 2 MW wind turbine power curve is adopted (Fig. 3).

The combination of the generation technologies (base-load, flexible load, wind and electricity storage), together with import/export need to match the electricity demand, which represents the electricity hourly requested by all the end-users of the generation/consumption region under consideration:

$$D(i) = E^W_{\mathrm{av}}(i) - E^W_{\mathrm{curt}}(i) + E^{BL} + E^{FG}(i) + E^{ST}(i) + E^{TL}(i), \tag{3}$$

where $D(i) > 0$ is the electricity demand during the ith hour, $E^{BL} > 0$ is the electricity produced by the base-load in 1 h, $E^{FG}(i) \geq 0$, $E^{ST}(i)$, and $E^{TL}(i)$ are the electricity produced by flexible load, the electricity produced (when $E^{ST}(i) > 0$) or consumed (when $E^{ST}(i) < 0$) by energy storage, and the electricity received (when $E^{TL}(i) > 0$) or sent (when $E^{TL}(i) < 0$) over the transmission lines from/to another generation region during hour i, respectively.

As already mentioned, no control of the demand is considered in this study, i.e. no demand side management is assumed to be in place.

The model does not consider possible congestions in the electrical grid within a certain generation area, but it focuses solely on total electricity demand and supply. For this reason, a copper plate assumption for the generating region is used [31].

One boundary condition of the model is that a certain amount of wind energy is consumed during a certain period of time. Using (1), such a boundary condition is written as:

$$T = \sum_{i=1}^{n} E^W_{\mathrm{int}}(i) = \sum_{i=1}^{n} E^W_{\mathrm{av}}(i) - \sum_{i=1}^{n} E^W_{\mathrm{curt}}(i), \tag{4}$$

where T is the target of electricity from wind to be integrated within n hours. Such a value is typically expressed as a percentage of the overall electricity consumed in a certain area, e.g.:

$$T = c \cdot \sum_{i=1}^{n} D(i) \tag{5}$$

with $0 \leq c \leq 1$.

Table 2
Power law exponents.

Power law exponent p	Terrain type	Source
0.23–0.31	Rolling	[28]
0.18	Hilly	[28]
0.11	Offshore	[30]

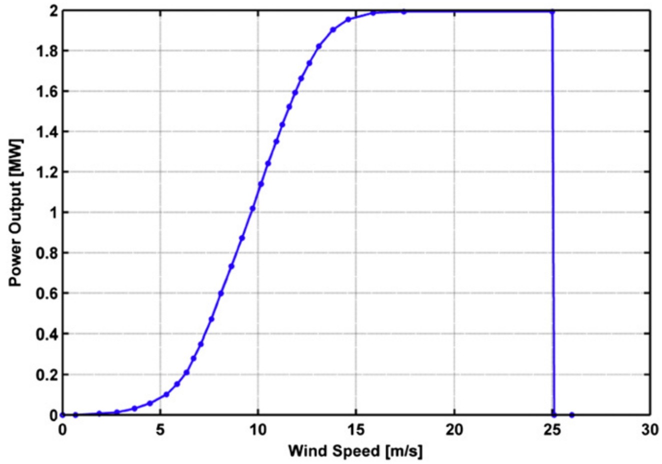

Fig. 3. Wind turbine power curve.

Expression (4) shows that for achieving a certain target *T*, it is possible to either increase $E^{W}_{\mathrm{av}}(i)$ (i.e. installing more or larger wind turbines), or to reduce wind curtailments, $E^{W}_{\mathrm{curt}}(i)$. However, as expression (3) shows, for given $D(i)$ and E^{BL}, even when $E^{FG}(i)=0$, the increase of $E^{W}_{\mathrm{av}}(i)$ might lead to an increase of $E^{W}_{\mathrm{curt}}(i)$, unless more electricity storage for charging and/or more transmission capacity for export are available. This means that a certain target of electricity produced by wind can be achieved either by oversizing the wind installation, and accepting a larger amount of wind curtailment, or by installing electricity storage and transmission capacity with neighboring regions that will allow for a better integration of wind into the grid, and, ultimately, for a reduced number of installed wind generators. Mathematically, this means finding the optimal combination of installed wind turbines, electricity storage, and transmission lines.

From an economical point of view, an optimal combination of wind oversizing, storage, and grid installation is to be found.

The optimization is conducted in two steps:

- Operational optimization (scheduling): to maximize the integrated electricity from wind, for a given E^{BL}, $E^{W}_{\mathrm{av}}(i)$, and $D(i)$. This is equivalent to minimizing the energy generated by the flexible generators. From (3), this is:

$$\mathrm{Min}\sum_{i=1}^{n}E^{FG}(i)=\mathrm{Min}\sum_{i=1}^{n}\Big[E^{W}_{\mathrm{curt}}(i)+D(i)-E^{W}_{\mathrm{av}}(i)-E^{BL}-E^{ST}(i)-E^{TL}(i)\Big]. \tag{6}$$

Equation (6) defines the optimal values, hour by hour, of $E^{FG}(i)$, $E^{ST}(i)$, and $E^{TL}(i)$.

- Cost optimization: to find the optimal combination in terms of investment cost of installed capacity of electricity storage, transmission, and wind turbines, for a certain value of integrated electricity from wind, *T*.

$$\mathrm{Min}\left|f\left(P^{ST},P^{TL},P^{W}\right)\right|_{\sum_{i=0}^{n}E^{W}_{\mathrm{int}}(i)=T}, \tag{7}$$

where P^{ST}, P^{TL}, P^{W} represent the installed power of electricity storage (for a given discharge time), transmission line, and wind power. The following relationship between *P* and *E* must be respected:

$$E^{j}\leq\int_{0}^{1\mathrm{hour}}P^{j}dt \tag{8}$$

with $j = ST, TL, W$. In expression (8) the equal sign applies when the hourly capacity factor is equal to 1.

In addition, for storage in discharge mode, the following applies:

$$0\leq\sum_{i=1}^{n}E^{ST}(i)\leq P^{ST}\cdot n_{\mathrm{st}}, \tag{9}$$

where n_{st} is the number of hours the storage can discharge at its maximum power. For simplicity, n_{st} is referred to as “storage time” in the following. In addition, although not explicitly indicated in the previous expressions, it is assumed that the storage discharges less energy than that it has charged before. The ratio of these two quantities is called the storage efficiency.

Fig. 4 depicts a schematic representation of the calculation steps.

4. Results and discussions

Equations (6) and (7) are solved for different values of integrated wind targets (*T*) and base-load (E_{BL}), given wind speed statistics and load demand $D(i)$ of five European countries, namely, Germany, Denmark, The Netherlands, The United Kingdom, and Spain. Wind speed data are retrieved from the National Climatic Data Center [32]. The measurement stations are selected considering their availability and number of hours with missing or corrupted data. Table 3 summarizes the number of selected stations for each country. The results presented in this section refer to wind data of 2009. Wind speed data sensitivity is reported in Section 4.1.1.

Hourly load demand data are retrieved from the transparency platform of the European Network of Transmission System Operators for Electricity (ENTSO-E) [33]. Since data of the total load was not available for all 5 countries for the year 2009, data are calculated starting from the electricity fluxes measured at the transmission level. This is also referred to as “vertical network load” [34]. Vertical network load data are collected by transmission system operators (TSO) and are publicly accessible, whereas load data,

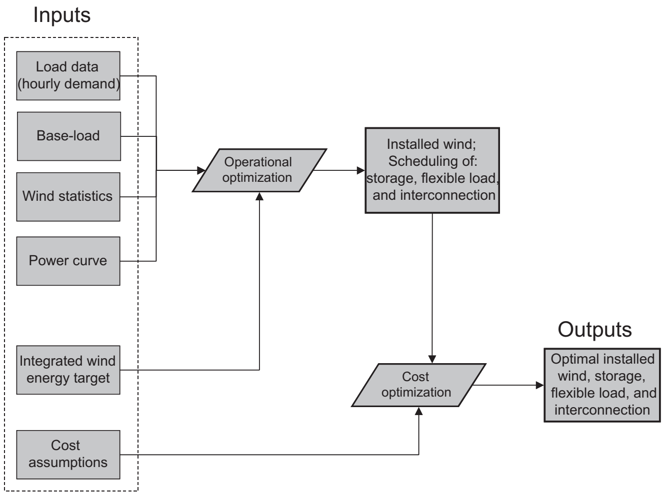

Fig. 4. Schematic representation of the calculation process.

Table 3
Number of selected measurement stations.

Country	Number of stations
Germany	22
Denmark	37
Spain	17
The Netherlands	25
The United Kingdom	22

particularly residential load data, are measured by distribution utilities and are rarely available.

Equation (6) is solved using a linear programming approach, as well as a heuristic approach. The comparison of the two approaches shows that the results differ for less than 0.1% [35]. Due to the reduced computational cost, the heuristic algorithm is used.

Electricity storage capacity is assumed to be 20 h, and the related efficiency 70%.

Cost assumptions are shown in Table 4.

It should be noticed that, given the very low marginal cost of operating wind turbines, storage and transmission, the minimization of the investment costs provides for a good indication of the most economical option, also in terms of cost of electricity. Also, if not indicated otherwise, wind cost is assumed to be 2070 €/kW representing a weighted average for a possible future wind energy scenario. In Section 4.1.1, the effect of this assumption and the related wind cost is analyzed.

4.1. Results for a single generation/consumption area with no import/export

If no import or export is considered, cost minimization must be researched in the appropriate trade-off between wind turbine oversizing and storage installation for a certain target of total electricity to be produced from wind, T. By solving Equation (6) for different values of c of Equation (5), the values of electricity storage and wind turbines to be installed provide for ∞^1 combinations. These are depicted in Fig. 5 as iso-lines for different values of c, considering the wind statistics of Denmark and $E^{BL} = 20\%$ of the total Danish electricity demand ($\sum_{i=1}^{n} D(i)$) in 2009. In analogy, the iso-lines representing the total investment costs are depicted. Graphically, the solution of Equation (7) is the tangent of the iso-cost lines to the iso-c curves. In Fig. 5, the electricity storage to be installed is normalized to the peak demand, and the wind turbine oversizing is expressed by the oversizing ratio (OR), defined as the wind produced ($\sum_{i=1}^{n} E_{av}^{W}(i)$) over the total electricity demand ($\sum_{i=1}^{n} D(i)$):

$$\mathrm{OR} = \frac{\sum_{i=1}^{n} E_{av}^{W}(i)}{\sum_{i=1}^{n} D(i)} \tag{10}$$

Table 4
Cost assumptions.

Technology	Costs	Reference
Electricity storage	Cost (€/kW) = $a + bx$, where x is the storage time (h), $a = 493$ (€/kW), and $b = 75$ (€/kWh)	[36]
Onshore wind	1500 €/kW	This study
Offshore wind	2500 €/kW	[23,37]
Transmission line	Cost (€) = $184y_1 + 1180y_2$, where y_1 is the installed power (kW), and y_2 is the length (km) multiplied by the power (MW)	[38]

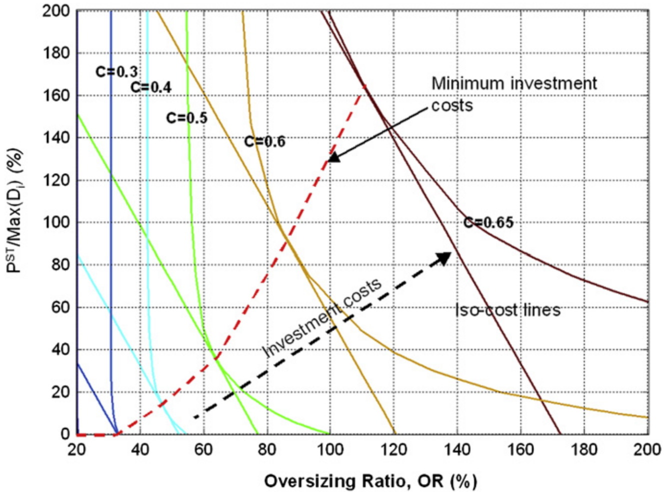

Fig. 5. Graphical representation of the cost minimization problem.

by combining Equations (10) and (5), the following is derived:

$$\frac{\mathrm{OR}}{c} = \frac{\sum_{i=1}^{n} E_{av}^{W}(i)}{T}. \tag{11}$$

For a certain given c, when $\mathrm{OR} > c$, $\sum_{i=1}^{n} E_{av}^{W}(i) > T$, i.e. wind turbine oversizing needs to compensate for wind curtailment and/or electricity storage efficiency. For $\mathrm{OR} = c$ there is no wind curtailment or storage. This last case is typical for low shares of wind energy and is not presented in Fig. 5.

Fig. 5 shows that above a certain target of electricity to be produced by wind (c), electricity storage becomes economical, compared to a mere installation of more wind turbines. This result does not take into account for possible grid congestions within the generation/consumption area (copper plate assumption), but it only reflects the mismatch between wind energy generation and electricity demand.

Fig. 6 shows, for the five countries considered in the study, the electricity storage requirements for different shares of wind, c, minimizing the overall investment costs.

Electricity storage starts to be economical for wind shares varying from about 30% for The Netherlands, Denmark, and Germany, to about 40% for Spain. For wind penetration as high as

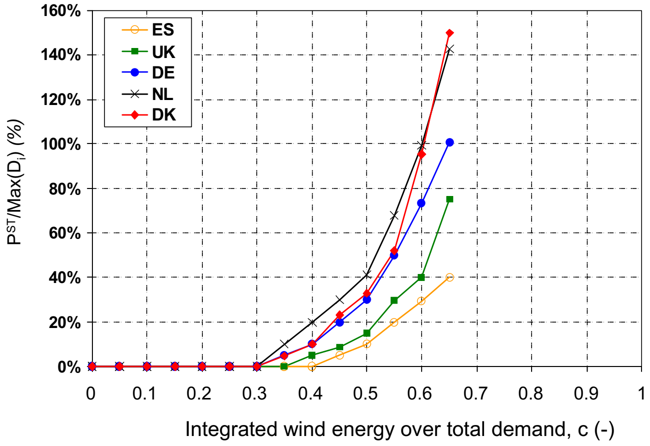

Fig. 6. Electricity storage requirements for different targets of wind energy, base-load = 20% of total demand, and storage time = 20 h.

50% of the total energy demand, the storage requirements vary significantly from country to country. The differences are mostly driven by the correlation between electricity demand distribution and the wind speed variation in time. This suggests that storage requirements need to be quantified at regional level, and cannot be generalized. The copper plate assumption makes the data of Fig. 6 the minimum requirements. In fact, values as high as 30–40% of wind production at local level, might result in limited values for an entire country (cf. Section 2). Therefore, in some areas, the need for electricity storage might appear well before the values of 30–40% wind penetration is achieved. Also, more storage needs might be required in case of possible grid congestions. This last aspect, however, is beyond the scope of the present study.

4.1.1. Sensitivity analysis

The first variable considered in this analysis is the efficiency of the storage, as shown in Fig. 7 for Denmark and 20% base-load. When the storage efficiency decreases, the amount of storage to be installed does not change significantly. However, the amount of wind to be installed increases. Such an increase is due to the wind turbine oversizing required to compensate for the loss of electricity in the storage. Therefore, although the storage efficiency does not have a direct impact on the overall storage capacity to install, it impacts the overall investment costs and, ultimately, the cost of electricity. By considering a wind share $c = 0.5$ in Fig. 7, for example, an increase of storage efficiency from 50% to 85% would reduce the need for installed wind power by about 8 points percentage.

Fig. 8 shows the effect of electricity storage power and energy capacity. This is represented as storage energy capacity (kWh) over daily average electricity demand for different storage times, as a function of the wind power installed, for a certain share of wind, c ($c = 0.5$ in the case of Fig. 8). In this case, no cost optimization is performed, thus the Fig. 8 refers only to the relationship between installed wind power and storage installation.

On the x-axis, the wind oversizing is represented as the installed wind power over the peak demand, rather than with the OR defined in (10). This is for underlining the required installed wind power with respect to the peak demand. In analogy, the electricity storage capacity is normalized to the average daily consumption of electricity. The first information emerging from Fig. 8 is that the installed capacity of wind power needs to be at least 150% the peak demand to satisfy 50% of the demand, and storage cannot decrease this value. Such a value is solely driven by the relatively low capacity factor of wind turbines. Fig. 8 shows the effectiveness of electricity storage in reducing wind curtailments as more storage is installed. When it comes to distinguish between power and number of storage hours for a certain installed energy capacity, there is an optimum around 5 h of storage. The reduced installed power associated to a further increase of the storage time for the same energy capacity would reduce the ability to capture wind power peaks. On the other hand, a low number of hours would not allow the system to charge/discharge for a sufficient number of hours.

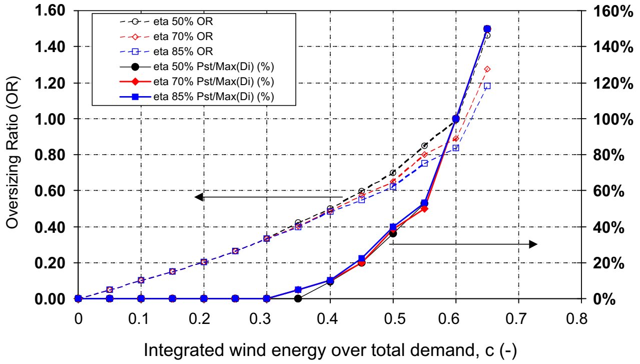

Fig. 7. Effect of electricity storage efficiency on storage requirements and wind installed capacity.

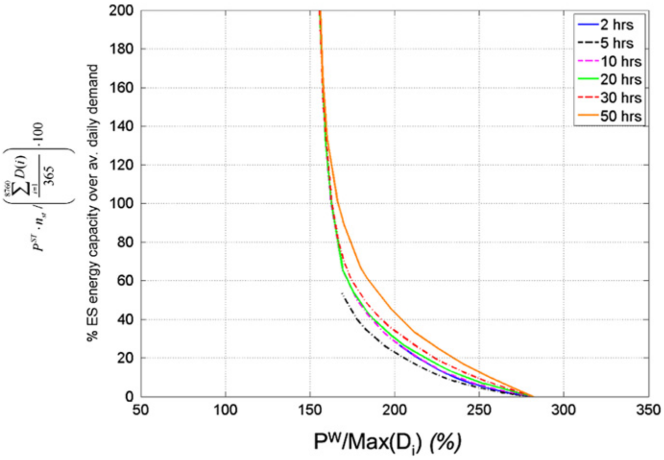

Fig. 8. Relationship between energy storage capacity and installed wind power, for different storage times, $c = 0.5$, and base-load 20% for Denmark wind and demand data.

As already mentioned, Fig. 8 does not consider any cost minimization, thus, Fig. 9 reports the optimal combination of storage time and power, for achieving a certain value of c, and minimizing the investment costs.

As far as wind data distribution is concerned, Fig. 10 shows the effect of wind characteristics on the storage requirements. In particular, wind data for Denmark from 2005 to 2010 are used to compute the electric energy storage requirements in terms of installed power as a percentage of the peak demand. As Fig. 10 shows, the yearly change in wind profile has a quantitative impact for wind penetration higher than 50–55%, while the general trend stays unchanged.

An important factor defining the integration of wind energy is the base-load installed, which can be regarded as the flexibility that a generation fleet has. Fig. 11 shows that decreasing the base-load from 40% to 20% for the case of Danish wind data of 2009 and its load profile, the amount of wind energy that can be integrated for a certain storage installation would be almost doubled. It should be

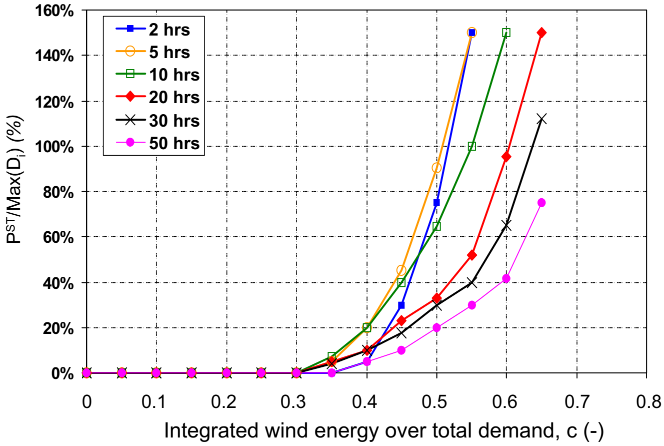

Fig. 9. Electricity storage power and number of hours requirements for integrating a certain amount of wind energy, c, and minimizing the investment costs.

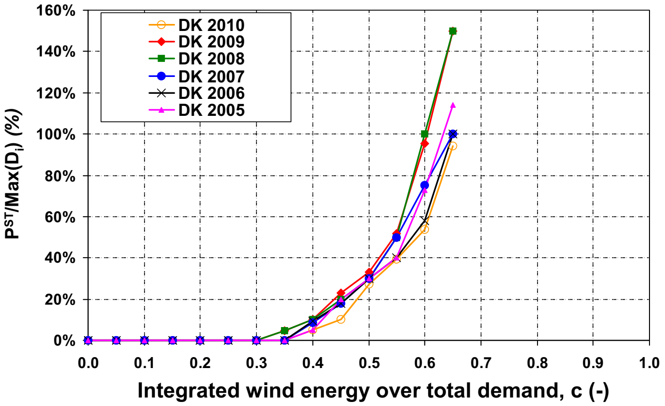

Fig. 10. Electricity storage power for integrating a certain amount of wind energy, *c*, for Danish wind profiles from different years.

reminded, however, that the storage need is the result of a cost minimization and no cost is associated to a decreased installed base-load. This is equivalent to consider that an increased power generation flexibility would be possible with no additional costs. Although there is no doubt that increased power flexibility would favor the integration of wind energy and, more in general, of fluctuating RE, a more detailed analysis of the costs associated to such an increase is required.

Finally, it is interesting to notice that even in the case of no base-load installed (completely flexible generation), there would still be a need for electricity storage for wind penetration higher than 45% of the total energy ($c = \sim 0.45$). For such a high wind penetration, in fact, the installed wind power with no storage would be so high that wind production alone would be higher than the demand $D(i)$ for several hours. In this case, even with a base-load of 0%, the wind curtailments are not economical compared to electricity storage.

The optimum electricity storage required for the different scenarios discussed so far relies on the cost assumptions described in Table 4. In order to investigate the impact of those assumptions, four different cases are defined (Table 5). Two cases analyze the influence of different cost assumptions of wind and two cases analyze that of storage.

The results of the cost sensitivity are presented in Figs. 12 and 13. The first diagram shows the optimum electricity storage power installed for different wind costs (blue lines) and storage costs (green lines) compared to the base case assumption (red curve). The correspondent cost saving achieved by the installation of storage are reported in Fig. 13. It can be seen that when the electricity storage becomes cheaper ("low storage") or the wind installation costs are higher ("high wind") the optimum solution foresees more electricity storage installed, which allows a higher cost reduction compared to the base case. On the contrary, when storage becomes expensive ("high storage") or wind is cheaper ("low wind"), the optimum electricity storage power installed is decreased with a consequent reduction of the cost saving that can be achieved. Besides these obvious conclusions, the most important outcome is that the influence of different cost assumptions on the final results is rather limited. In fact, Fig. 12 confirms that electricity storage starts to be economical always from a similar wind share of 30–35% and different curves behave similarly with increasing penetration. Also the cost savings achieved with storage in Fig. 13 do not change dramatically.

Table 5
Cost sensitivity scenarios.

Cost (€/kW) = $a + bx$, where x is the storage time (h)	Power related (a)	Energy related (b)
	EUR/kW	EUR/kWh
Reference wind	2070	0
High wind	2500	0
Low wind	1500	0
Reference electricity storage	493	75
Low electricity storage	400	50
High electricity storage	1000	100

4.2. The role of interconnections

In this case, Equations (6) and (7) are solved for two different generation/consumption zones. Contrarily to the previous case, both $E^{TL}(i)$ and $P^{TL}(i)$ are not set to zero. Also, energy conservation between two areas is set:

$$\left[E^{TL}(i)\right]_{\text{zone 1}} + \left[E^{TL}(i)\right]_{\text{zone 2}} + E^{\text{Losses}}(i) = 0, \forall i \in [1, n]. \tag{12}$$

In the present study, only one interconnection between two zones is considered, i.e. if zone 1 is connected to zone 2, there is no additional connection to a further zone 3. Under this condition, the number of possible combinations for the five selected countries is ten. The scenario definition is based on the correlation of the wind

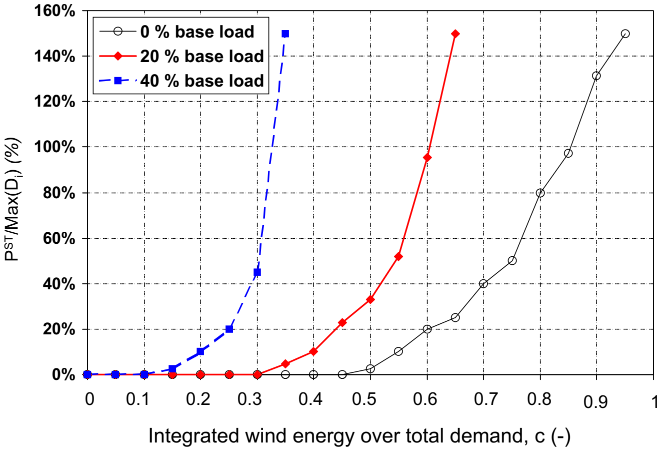

Fig. 11. Effect of base-load on required electricity storage. Wind and demand data relative to Denmark in 2009.

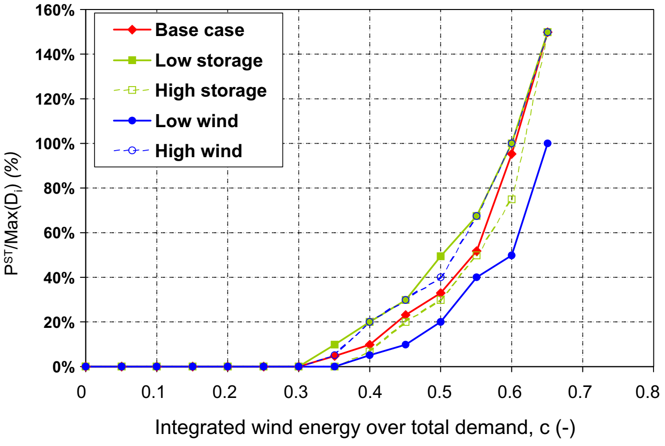

Fig. 12. Cost sensitivity. Costs assumptions in each scenario are in Table 5.

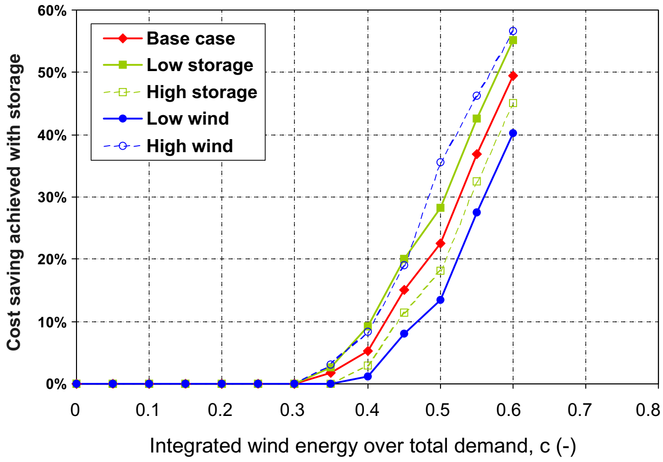

Fig. 13. Cost saving achieved by installing the optimum storage capacity indicated in Fig. 12.

power infeed of the countries under consideration. Therefore, the correlation coefficient of the wind infeed of all combinations of the five countries mentioned above is calculated. By indicating with $x = x_1, x_2, \ldots x_n$, and $y = y_1, y_2, \ldots y_n$ the wind data time series of a country 1 and a country 2, the correlation coefficient is defined as:

$$\rho(x,y) = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\left[\sum_{i=1}^{n}(x_i-\bar{x})^2\cdot\sum_{i=1}^{n}(y_i-\bar{y})^2\right]^{0.5}}, \tag{13}$$

where $\bar{x}$ and $\bar{y}$ are the mean values of the series x and y.

Fig. 14 presents the aggregated wind cross-correlations (blue circles) of each combination of countries versus the corresponding distances between the geographic centers. The data are fitted with an exponential curve of the type

$$\rho = e^{(-d/a)}, \tag{14}$$

where a is a constant, and d the geographic distance defined as the distance between the geographic centers of the areas spanned by the wind speed measurement locations within each country [39,40]. The geographic center is determined through three-dimensional vector addition of the measurement station geographic coordinates. The resulting value for a is 686.86 km, which is in good agreement with [39] (a = 500 km) and [40] (a = 723 km).

In the following, results are presented for the two most and least correlated zones, namely Germany–Denmark, with $\rho = 0.7726$, and Spain–UK, with $\rho = 0.0284$.

When connecting a relatively small country like Denmark with larger countries like Germany and Spain, the power exchange volume of the first would be negligible compared to the energy demand of the second ones, and so would be the effect. In order to assess the effect of connecting uncorrelated and correlated areas, independently from their sizes, the consumption of Denmark is scaled in order to yield the same annual energy consumption as the larger country it is connected to, e.g. Germany. The transmission capacity requirements are always referred to the system, but normalized to the average load of one country. Since the objective of this study is to analyze storage and transmission requirements at a system level, it will not be distinguished between different installed storage capacities in the two countries. In the case of storage, it is considered together as a sum.

Fig. 15 shows the optimum electricity storage power over average demand that is required to achieve different wind shares by minimizing total investment costs, in combination with the interconnection line and in the case there is no interconnection between the two countries. The corresponding cost savings achieved by the two options are shown in the same graph (dashed lines). In analogy, Fig. 16 is showing the interconnection capacity requirements and corresponding cost savings.

The following important differences can be noticed between well correlated and low correlated areas:

1. In well correlated areas (e.g. Denmark–Germany), the installation of interconnections does not reduce the need for electricity storage. Such a situation can be explained by the very little effect that a transmission line can produce in reducing the imbalance between demand and supply in case of excess or deficit of wind. In fact, if such a situation occurs in one area, it is very likely that the same is in the other area as well, thus making the effect of the transmission negligible. On the other hand, if wind profiles are less correlated, like the case of Spain and the UK, the need for electricity storage can be reduced by interconnections. Despite the high costs of the interconnections for distant countries like the UK and Spain, such an option is still more economical than electricity storage alone, due to the cost of storage and the related energy losses in the storage itself. Although other issues might arise for the construction of

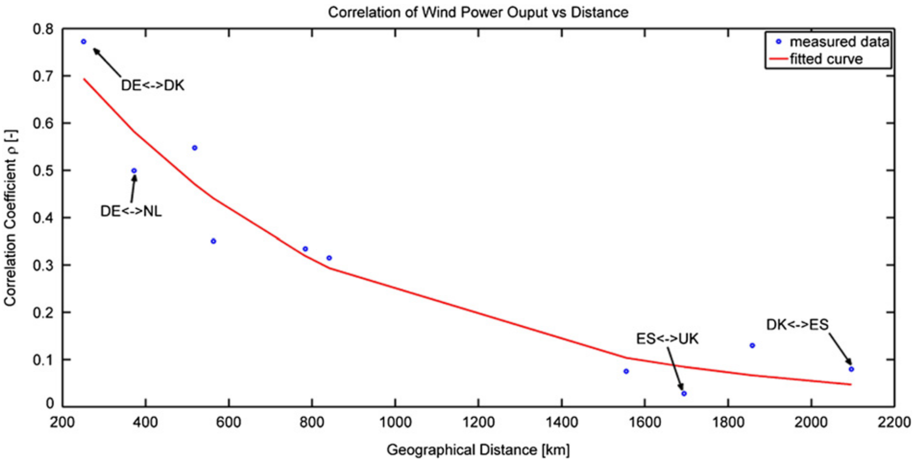

Fig. 14. Wind data correlation coefficients of the five countries considered.

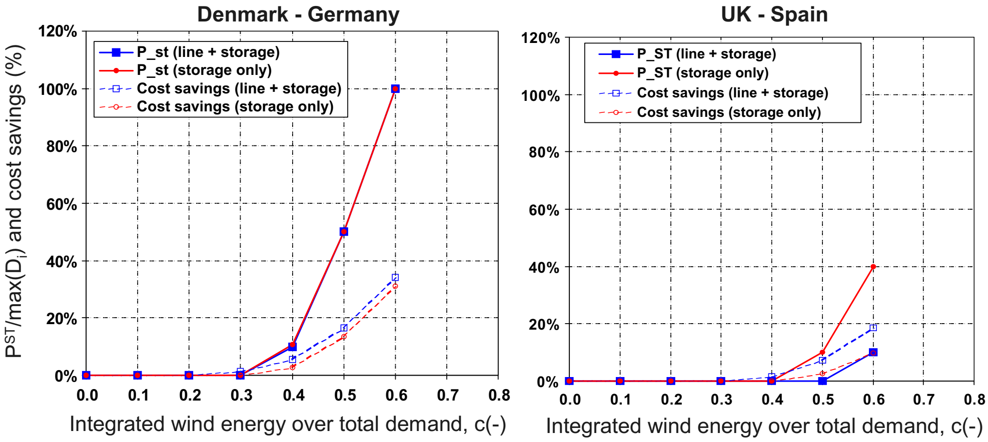

Fig. 15. Electricity storage requirements for Denmark and Germany interconnected (left), and UK and Spain interconnected (right).

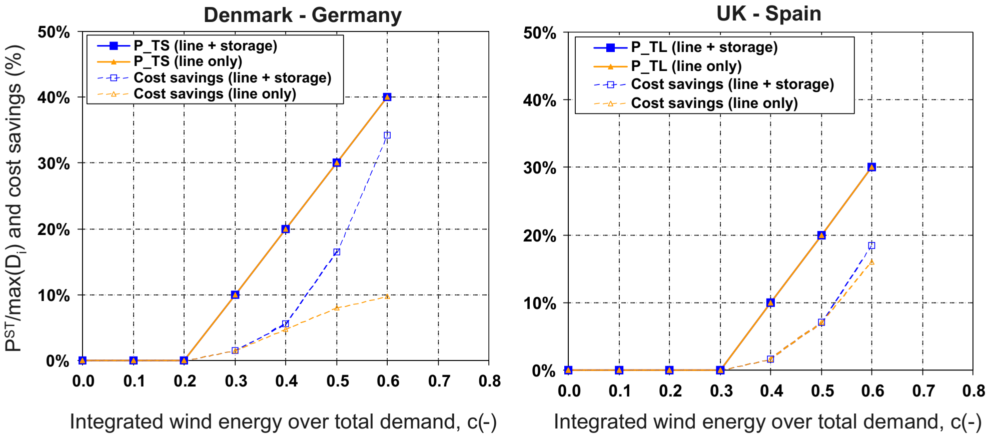

Fig. 16. Interconnection requirements for Denmark and Germany interconnected (left), and UK and Spain interconnected (right).

such long distance lines (including political ones), the analysis of these issues is out of the scope of the present study.

2. The installation of electricity storage does not appear to influence the transmission line requirements.
3. As the penetration of wind increases, interconnections are the first to appear as cost-effective solutions for wind integration (compare Figs. 15 and 16), as a result of the cost of interconnections (Table 4). In the case of Germany and Denmark interconnections start being economical at 20% wind penetration, compared to 30% of UK and Spain. Such a result is due to higher costs of interconnections given the longer distance.

Finally, Fig. 17 shows the additional wind energy that can be integrated with electricity storage and interconnections in comparison with the base case, where neither storage nor interconnections are in place. The synergy between storage and interconnections is much more marked for weakly correlated countries

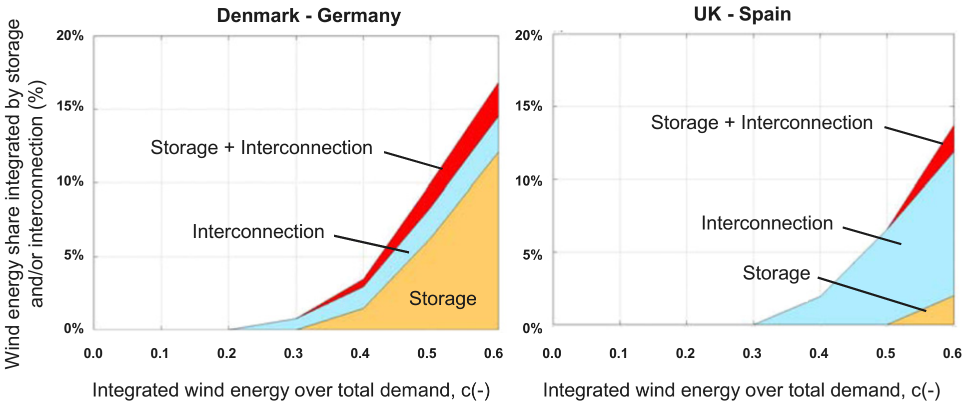

Fig. 17. Additional wind energy integrated due to storage and interconnection, with respect to the case with neither storage nor interconnections.

(UK–Spain), but it starts appearing at higher wind penetration, due to the cost of the interconnection related to the long distance.

5. Conclusions

The present paper illustrates a mathematical model for assessing the benefits of electricity storage in a power generation scenario with different levels of wind penetration and installed base-load. The model is applied to five European countries characterized by wind speed and annual electricity demand data.

The results show that installation of electricity storage reduces the overall investment costs for achieving a certain target of energy produced by wind. Such an economical advantage is due to the reduced investment cost associated to a reduced installed wind capacity for achieving the same wind energy share. The storage requirements depend on several factors, being the amount of base-load one of the most influential. This result indicates the importance of flexibility of thermal power plants, as wind penetration increases. However, even with 0% base-load, there is still a threshold of wind energy penetration, above which electricity storage is economical.

The fundamental role of interconnections is also highlighted, particularly for areas with weak wind profile correlation. As wind penetration increases, interconnections are the first to appear economical. The threshold above which these are economical depends mostly on the costs of transmission and on wind profile correlation between the interconnected areas.

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