Contribution of Energy Storage for Large-scale Integration of Variable Generation

Ana Estanqueiro[1], Atle Rygg Årdal[2], Ciara O'Dwyer[3], Damian Flynn[3],
Daniel Huertas-Hernando[2], Debra Lew[4], Emilio Gómez-Lázaro[5], Enrico Maria Carlini[6],
Eivind Solvang[2], Erik Ela[4], Juha Kiviluoma[7], Luis Rodrigues[1] and Mikael Amelin[8]
[1]LNEG (*ana.estanqueiro@lneg.pt*), [2]SINTEF, [3]UCD, [4]NREL, [5]UCLM, [6]TERNA, [7]VTT, [8]KTH

Abstract— **The amount of wind power and other time-variable non-dispatchable renewable energy sources (VRES) such as photovoltaics (PV) is rapidly increasing in the world. Several power systems in Europe are already facing a very high penetration from variable renewables which is posing concerns on the operational stability limits that are being surpassed for extreme RES generation conditions. Most transmission system operators are defining VRES limits of penetration, thus, requiring the renewable energy excess to be curtailed, exported or stored. Energy storage may play a relevant role in maximizing the long term penetration of VRES if used as a technical mean to regulate the daily, weekly and annual profiles of variable generation (VG). This paper reviews the storage technologies that are available and may be used on a power system scale and performs a cost/benefit analysis discussing their advantages and disadvantages for the integration of fast-growing renewables, such as wind power and PV.**

Index Terms— **Wind power, renewable integration, energy storage, balancing of wind power.**

I INTRODUCTION

The amount of wind power and other time-variable non-dispatchable electricity generation (VG) is rapidly increasing across the world [1]. A few power systems are already facing very high penetrations from variable renewables which, under certain situations, can surpass the system's consumption, especially during low load periods, requiring the energy excess to be curtailed, exported or stored. Energy storage has not been widely used in large power systems due to the technological and economic limitations of the storage processes. Instead, the well-known form of storing potential energy in reservoirs of hydropower stations is increasingly used to cope with the time-dependency of the VG. Also some other technologies such as heat storage have been successfully used.

The fast growing VG capacity is posing a new set of challenges to transmission systems operators (TSOs): one of the difficulties being the variability of these new renewable power sources, allied to daily and seasonal production profiles that, in most situations, do not follow the load consumption profile. Several countries already have a very high wind contribution from these sources: in 2011 Denmark had 27% wind penetration; Spain covered 17% of their electric energy demand with wind power; Portugal had a wind participation of 18% and Ireland had 16%.

In order to achieve annual wind energy contributions between 16 and 27%, these power systems have faced several periods when the contribution from wind power (and other non-dispatchable power stations) was very close to operational stability limits. The excess VG needs to be used, stored, exported or curtailed. Although curtailment of excess VG seems a solution, its time-dependent nature combined with the fast installed capacity growth, increases the benefits of energy storage. For some countries, local storage capacity becomes especially important when transmission capacity for exporting to neighbouring countries is limited. In other cases, increase in transmission capacity will allow sharing available energy storage capacity between countries. Keeping in mind the increasing role of VG in future, it is important to assess how systems with higher shares of these sources can be efficiently operated and designed without violating system security and still maximizing their penetration and VG added value. Besides reducing the need to curtail VG, energy storage may also be used for smoothing net load variations, allowing dispatchable base load units to remain operating when VRES generation is high and reducing the need to dispatch peak power units when VRES generation is low. Therefore, assessing the role and added value of energy storage, especially for well-known technologies such as pumped hydro storage, chemical batteries and district heating systems with heat storage, and future distributed options such as electric vehicle batteries, is actually of the utmost relevance for power systems with existing and planned very high VRES penetration.

The paper reviews the storage technologies that are available and may be used on a power system scale, and compares their advantages and disadvantages for the integration of fast-growing time-variable renewables, such as wind power and PV. The experiences gained and the particular challenges faced and solutions adopted are outlined for a number of different systems, ranging from trans-continental grids to island systems, and from those which are hydro- and thermal- dominated to evolving systems where variable generation, in the form of wind and/or solar generation, is increasing in capacity.

Section II of this paper presents typical wind and consumption profiles for different power systems that indicate the necessity of storage, exporting facilities or curtailment. Section III describes the energy storage technologies available that are being used among IEA Wind Task 25 members as well as the identified contribution of energy storage for VRES integration. Section IV provides a cost/benefit analysis of power system energy storage options with a particular focus on power system scale systems. Conclusions are drawn in Section V.

This paper has been written as part of the IEA Wind Task 25 "Design and operation of power systems with large amounts of wind power" collaboration (www.ieawind.org)

II PROFILES OF WIND GENERATION AND LOAD CONSUMPTION

In principle, large scale deployment of variable RES, namely wind, doesn't necessarily imply the installation and/or reinforcement of the energy storage capability. This is justified by the fact that several European countries have already experienced a pronounced growth in wind capacity without changing (or even planning) their energy storage capability. Nevertheless, the benefits of coordinating wind generation (especially for high penetrations) with hydro generation in countries and markets has been recognized and extensively utilized by most system operators that possess that capability [2].

The fact that wind generation has little or no power regulation capability introduces the concern of excess wind generation during periods of reduced load. That concern is amplified when some countries such as Denmark, Portugal and Spain exceeded a wind energy penetration of 15% that, as a natural consequence, led to periods when wind power and other RES (added by the required reserves) was sufficient to match the entire system demand. Moreover, several countries have already felt the need to curtail wind generation during periods of excess generation, e.g. Spain [3], while Ireland has introduced an operational limit of 50% penetration from non-synchronous sources. Other countries, where operational stability limits are guaranteed by their transmission interconnections, including Denmark and Portugal [4], have maintained wind power plants in operation with zero (and even negative) market prices.

From the above, and considering a purely energy balance approach, it becomes reasonable to conclude – apart from associated investment costs, ancillary service tariffs and market value issues – that using wind power plants in conjunction with energy storage units would be a desirable option for any power system with a relevant share of wind (and other) renewable variable generation.

To assess the value that energy storage may have for a power system with high penetration of variable RES (VRES), the characterization of VRES profiles, and their correlation with the load consumption profile should be performed. The overview of those profiles performed within IEA Task 25 countries enable to conclude that some countries have a higher correlation between wind (and other variable renewable) generation and load consumption than others. Moreover, geographical, climatic and other socio-economic constraints strongly affect the shape of the consumption load pattern. Fig. 1 depicts two typical daily profiles for consumption and wind generation in IEA Wind Task 25 countries.

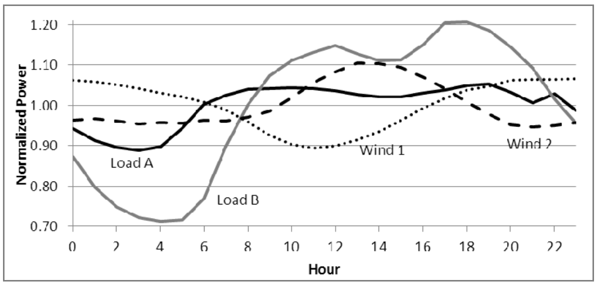

Fig. 1 Typical normalized daily load and wind generation profiles (annual data).

While countries in northern Europe, such as Norway and Finland, show a "flat" load profile (curve A) others, namely Portugal, Ireland and Spain, present a greater variation from peak to no-load hours (curve B). Although these load profiles based on annual data are naturally smoothed by the intra-annual climatic variations, when compared with the two typical wind generation daily profiles depicted, the lack of correlation between wind and load becomes clear for most countries that follow a type "Wind 1" curve and only a few, such as Ireland and Norway show a positive correlation between wind and load (Wind 2). In Ireland the correlation between the daily wind profile and the demand clearly favors wind integration in a country that operates a near isolated power system. The less marked daily wind power profiles obtained from wind power simulations in Nordic countries [5], allied to a smoother demand profile may indicate a reduced need for added energy storage.

Although energy storage usually follows a daily pattern, its full range of operation, especially for hydro storage, also addresses weekly and seasonal patterns of consumption. Fig. 2 depicts typical high VRES weekly profiles (run of river, ROR, wind and others) which periodically exceeds consumption during no load hours.

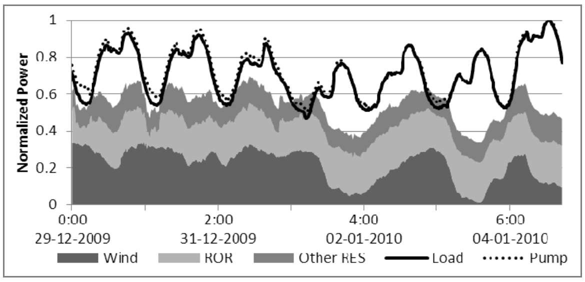

Fig. 2 Normalized weekly load and high wind generation typical profiles.

An annual pattern of load with respect to wind generation is presented in Fig. 3. It is clear that the country with load pattern B (typical of northern Europe) has a variable seasonal consumption, while the country with load A (from southern Europe) shows an almost constant pattern. For the annual profile both Nordic and Southern wind profiles show a positive correlation with consumption.

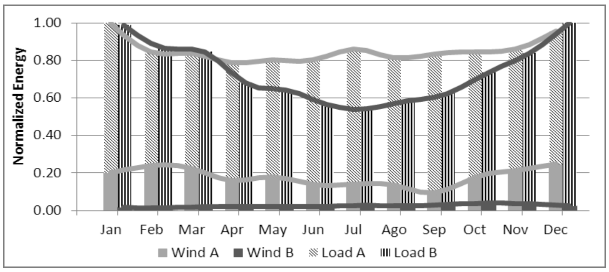

Fig. 3 Example of two normalized annual consumption and wind generation profiles.

Figures 1 to 3 highlight the daily, weekly and intra-annual load patterns that, together with the wind generation daily and seasonal variations, enable to visualize the technical difficulties in operating power systems with high wind penetration –if energy storage or import/export capacities are not available.

III CONTRIBUTION OF ENERGY STORAGE FOR VARIABLE GENERATION INTEGRATION

In some high wind penetration countries (Portugal, Spain, Ireland and Denmark) there is already some experience in handling excess wind energy and other VRES during periods when generation exceeds load consumption. In others (e.g. US and Italy), the high load factor of transmission lines with periodic occurrences of local grid congestion makes storage almost mandatory due to an increased growth in installed wind capacity. For a particular system the challenges for integrating large amounts of VRES depend mainly on:

- how often and how deep the demand valleys occur and their correlation with variable RES production;
- the flexibility of other power sources;
- management of grid congestion;
- possibilities of trade with neighbouring systems.

Major challenges to balance wind power and other VRES occur in situations when the share of wind power is high (often in windy, low load situations), trading with neighbours is limited and the flexibility from other power stations is constrained. An important factor is also whether it is necessary (required) to maintain large power reserves.

This section highlights different approaches of IEA Wind Task 25 countries towards using storage capacity as a means to optimize wind integration while adding value for VRES energy, with most relevant power system's data being presented in Table I.

TABLE I
POWER SYSTEM, VRES AND ENERGY STORAGE DATA FOR IEA WIND TASK 25 COUNTRIES

	Power System Installed Cap. (GW)	Wind Cap. (GW)	Max Instant. Wind Pen. (%)	Min. Load (GW)	Import/ Export Cap. (GW)	PHS(i) (GW)	Other Storage (GW)
Portugal	17.9	4.2	85	3.4	1.30	2.0	n.a.
Ireland	11.06	2.1	~ 50	2.3	0.95 / 0.80	0.29	0.10[1]
Finland	17	0.2	16.8(3)	26.4	3,8 / 2.3(2)	-	-
Norway	32	0.5			5	1.3	
Sweden	36	3			9.4	-	
Italy	118	7	16	22	8\3	4.0	0.25 (4)
Spain	100.1	21.1	60	18.2	3.6 / 2.6	~ 5.0	
US	~ 980.0	39.0	56(5)			22.0	

(1) proposed compressed CAES
(2) of which 0.4/1.4 outside of Nordic countries
(3) including Denmark
(4) proposed batteries storage
(5) on an hourly basis, in a specific Bal. Area

A. Portugal and Spain

Portugal conducted a review in 2007 of the deployed hydro capacity versus the existing potential having in mind the growing installed capacity of wind power and other non-dispatchable VRES. This study, PNBEPH [6] characterized in detail the technical, environmental, social and economic conditions of 25 plants (including plants already operating and new projects) and identified 10 plants to be repowered and/or constructed that enable to increase 1.1 GW the hydro capacity to be installed by 2020 to reach 6.95 GW. Of those, eight new/repowered hydro power stations will be reversible with a total new pumping capacity of 800 MW, that will add up to the already existing 1.2 GW in 2011.

In Spain, the proposed PHS developments for the next years are 3 GW of new PHS in 2020, from potential projects amounting to nearly 6 GW between pure PHS and mixed inflow PHS (using reversible turbines).

Table II [7] illustrates recent very high penetration situations in the Iberian countries of wind and other sources with no power regulation capability (e.g. run of the river plants, industrial CHP with IPP contracts and PV power stations). As it is clear from this table both the Portuguese and the Spanish systems - that share a common electricity market, MIBEL - have been operated several periods with more than half of its demand covered by wind generation, with record values in Portugal reaching 85% on the 13th of November 2011 and in Spain on the 6th November, 2011 with 59.6 % of the instantaneous demand fed by wind. In Spain wind power supplied 20.8 % of the demand during the month of March, 2011, making it the technology with the highest energy produced during that month, while in Portugal during the autumn/winter (from November to March) the monthly energy penetration has been systematically above 25% since 2009.

TABLE II
IBERIAN EPISODES OF HIGH SHARES OF WIND AND OTHER RES (AVERAGE HOURLY POWER).

	Day	Min. Load [MW]	Min. Load & Pump (no exports) [MW]	Max. Wind Power [MW]	Max. Non-regul. Power [MW]	Max. Wind Penetr. [%]	Max. Penetr. Non-reg. P (incl. PHS. & export) [%]
Portugal	15.Nov.09	3708	4365	2785	3958	70%	78%
	31.Oct.10	3862	4137	3182	4093	75%	90%
	15.May.11	3727	4206	3115	3811	81%	102%
	13.Nov.11	3835	4401	3694	5011	85%	117%
Spain	24.Nov.08	20700	24200	9.300	17000	45%	35,5%
	8.Nov.09	19000	21950	10250	13700	54%	42,8%
	10.Nov.10	22900	25900	11300	15800	50%	41,8%
	6.Nov.11	20800	23500	12000	13400	58%	47,3%

In 2010 Spain experienced 200 hours of curtailed wind generation with an estimated curtailment of 0.6% of the annual wind resource. The studies, conducted by REE, forecast for 2020 a frequency of occurrence of these situations ranging from 400 to 1400 hours, and the curtailment of 1 to 6% of the primary resource of VRES, this already including the expected installation of new PHS. Similar studies show for Portugal in 2020 an excess of RES generation totaling 457 GWh that will represent a curtailment of 65 hours at full power if no added storage is assumed (484 hours of partial power). Planned PHS for 2020 has the capacity to avoid RES curtailment in 39% of those periods. In both Spain and Portugal these high levels of wind penetration were possible thanks to several factors, such as a good monitoring (and some control capability) from wind generation aggregation centers, the possibility to issue curtailment set points to all wind farms (Spain), the possibility to export part of the RES production surplus, and the contribution of PHS to increase the system load, as well as the existence of bilateral contracts between wind power and hydro plants (Portugal).

B. Ireland

In Ireland, wind provided 16% of electricity demand in 2011 and is targeted to rise to 37% by 2020. From Jan – Nov 2010 ≈1% of total available wind energy was curtailed (26 GWh), mostly in the second half of the year. This was due to the combination of Turlough Hill (pumped storage) station being offline since July 2010 (leaving no storage capability on the Irish system), an increase in installed wind capacity (+200 MW) and an increase in capacity factor for the wind generation (20% up to 25%), and the 50% system non-synchronous penetration limit operational rule for stability reasons [8-9].

Recent studies on a 2020 scenario have shown the unprofitability of merchant storage units participating in energy arbitrage under current market conditions [10-11], despite reduced curtailment in high wind scenarios. Due to high capital costs and low round-trip efficiencies, storage was not economically justified until ≈50% of energy was supplied by wind [10], ignoring alternative options such as demand side management and improved wind forecasts. Additional opportunities arising from storage, including fast start up and response times, remain to be evaluated. For example, the significant reserve contribution which can be provided by storage (particularly at low load) could permit operation with less synchronous generation online, although concerns arising from lower system inertia may result [8]. Indeed, additional value streams may improve the business case for storage. A current review of ancillary services payments in Ireland [8], against a background of increased flexibility requirements from high wind penetrations, may provide an opportunity for storage.

B. USA

There is interest in energy storage in the USA, to accommodate VRES and for other reasons, and a number of PHS projects are actively being developed. One of the Balancing Areas (BAs) with the highest penetration of wind is Xcel's Public Service of Colorado which sees a 12-13% annual average wind penetration which can reach 55-56% on an hourly basis. They are pursuing a move to faster interchanges with neighboring BAs to help them accommodate the wind variability and reduce wind curtailment. Incidentally their 10% wind integration study showed that using their 300 MW pumped hydro unit to balance net load instead of load would reduce their wind integration costs by 26% [12].

PHS, like many other storage technologies, also provide a number of valuable services besides providing energy at high need times, which may often allow them further value streams than what is received from energy arbitrage. Pumped storage plants also can provide very valuable secondary control reserve on automatic generation control. This service has a very high value in the regulation markets, which can often include prices of over US$50 per MWh. The demand for this service may also increase based on the increase of VRES penetrations increasing the need. The service may also be evolving to one that incentivizes faster and more accurate response, both providing additional value streams for pumped storage [13]. However, it is important to note, that in the U.S. the majority of PHS plants are fixed speed pump technology. This means that when the wind power is high and the technology would likely be operating in pump mode, it would not be able to regulate the frequency or support balancing. Many efforts have shown that variable speed pumped hydro technology can take advantage of more value streams by eliminating this constraint [14].

As VRES penetrations increased, the PHS utilization and revenue sharply increase at 30% wind and 5% solar penetration level (see Fig. 4 [15]) due to extreme forecast errors that drive large spot price spreads. In this high renewable case, the PHS earns $3.8M annually. However, this is still several times less than needed to recover costs for a new PHS plant in the U.S.

D. Finland, Norway and Sweden

The synchronous power system of Finland, Norway and Sweden is integrated in an international electricity market. Most of the larger hydro power plants have reservoirs, where the storage capacity is ranging from a few hours of generation to seasonal storage. Pumped storage hydro is not common in the Nordic area. However, balancing of wind power can instead be performed in the conventional hydro power units, by decreasing hydro generation during windy periods (storing more water in the reservoirs) and vice versa. The balancing capacity of the conventional hydro power is considerable; the total storage capacity of the reservoirs is approximately 121 TWh, which can be compared to that in 2010 the total wind power generation in the three countries was 4.6 TWh.

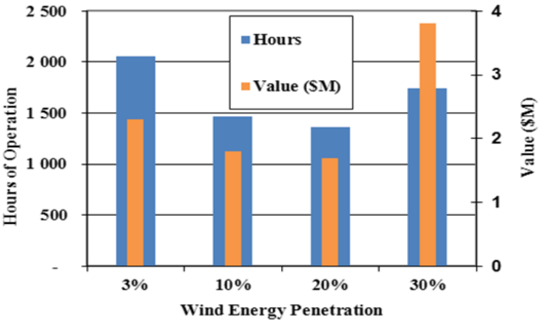

Fig. 4. Annual hours of operation and price arbitrage revenue earned for a new 100 MW PHS plant in Arizona in WWSIS [15] for 3%, 10%, 20% and 30% wind energy penetration in the study footprint with an imperfect (state-of-the-art) forecast.

The Nordic hydropower system has a large potential regarding capacity upgrading and pumped storage. Due to environmental concerns and political directives, this potential consists mainly in increasing the capacity of existing power plants and constructing pumping systems between existing reservoirs.

There are several barriers related to large-scale peak-power expansions. From the local environment point of view, several concerns have to be made according to regulations in the plant license. For example, ramping of power and reservoir level must be kept within the given limits. Depending whether the outflow is to a river, restrictions can also apply to maximum and minimum flow. It is clear that trade-offs must be sought between the need for increased balancing services and local environmental considerations.

Using hydro power for balancing of wind power would cause some challenges concerning short-term planning and operation. The largest reservoirs are generally located in the upper part of the river system. Hence, there is a risk that the smaller reservoirs are being filled up if there are several consecutive days with large wind power generation, resulting in a situation there many power plants in practice become run-of-the-river. Another problem is that there are time constraints in the hydrology of a river system. Assume that water is released from a large reservoir during an hour with low wind power generation. This water will after a few hours of travel time reach the next hydro power plant. If this power plant has a small reservoir, it might be necessary to use the water for generation in order to avoid spillage, even if wind power generation has increased by that time. These challenges should however be manageable for with good wind forecasts and improved planning tools.

Heat use is responsible for a large share of primary energy consumption in Nordic countries and therefore presents a large potential for power system flexibility. In order to get any benefits for the power system, heat (or cool) has to be produced with electric resistance heaters, heat pumps, or combined heat and power (CHP) plants. A combination of electric resistance heaters and heat storage can be a relatively inexpensive way to deal with the low residual demand situations. A heat storage with an electric heater can decrease boiler fuel use more than a plain electric heater could do by providing room for the excess heat during periods of low power prices.

Kiviluoma and Meibom [16] evaluated the benefits of heat storages for wind power integration with a generation planning model. All other things being equal, the availability of heat measures (electric resistance heaters, heat pumps, and heat storages) in district heating networks increased the cost-optimal share of wind power considerably (from 35 % energy penetration to 47 % in case where no low cost base load power was available and from 12 % to 15 % where low cost nuclear power was available). In both cases, the heat measures caused a drop in the average cost of electricity of about 2.5 €/MWh. The heat demand that was subject to new investments was about 27 TWh whereas the electricity demand was about 113 TWh.

The main barrier for heat storage is the availability of storage opportunities besides the competitiveness of electricity in heating, which will improve when fuels get more expensive. Storing hot water is rather inexpensive in large containers and therefore district heating systems or some forms of industrial heat use are prime targets. Heat storage in individual households is less economic, since the smaller containers are more expensive per kWh and the containers will require expensive real estate. Well-insulated houses could also offer some buffer and could be important especially for PV integration where the generation pattern is typically shorter (daily) than for wind (often couple of days).

E. Italy

Terna's power system had 334.840 GWh of annual energy in 2011 with a structure of approximately 60% gas or oil based, nearly 15% of conventional hydro, 14% of coal. The remaining 11% of energy is coming from other (4%), solar (4%) and wind (3%). There is no nuclear energy in this region.

Terna has pure PHS units (Table I). Fast loading emergency, flexibility, and opportunity to meet peak load consumption are some of the benefits of storage. Storage is dispatched by the producer based on their own strategy and market conditions. Accordingly, storage is paid for the ancillary services in the energy market. The balancing market is partly used for this purpose.

In the future due to economic incentives, significant amounts of VRES, including bio-energy, solar, wind and others will be added to the Terna system. In 2020 it is expected in operation 13 GW of wind and about 30 GW of solar plants, mainly concentrated in the central south of Italy.

To face this new challenge, in the next years, Terna will start to install about 250 MW (about 900 millions Euro of investments) of Battery Energy Storage Systems to allow a better integration of VRES (see Fig. 4) mainly in the 150 kV grid management and dispatching to:

- avoid VRES curtailment in case of exceeding generation respect to grid transport capacities, by storing the excess of energy in secure conditions to be used later, out of network congestion's periods;
- compensate the RES variable generation by increasing primary and tertiary reserve availability.

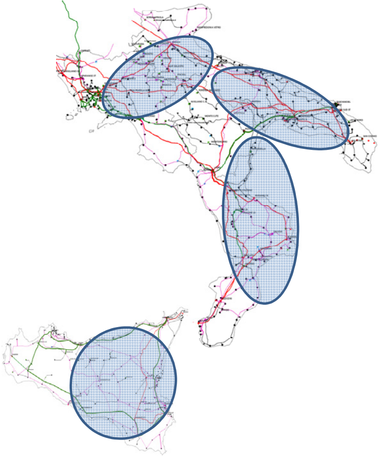

Fig. 4. Key geographical characteristics in the south of Italy for installation of storage batteries.

Moreover, batteries are characterized by removable, modular and flexible installations; these characteristics allow installations in a wide variety of sites and the possible replacement depending on the needs that could arise in the medium/long term. Thus, these systems are particularly suitable to deal with the critical issues above.

The project is particularly strategic for VRES integration. Moreover, it represents the first steps to reduce congestions relieve on transmission systems, facilitates electrical exchanges between EU member States of Central South Europe and Mediterranean area to develop the strategic energy corridor 2(North South electricity interconnections in Western Europe). It also has a positive impact for corridor 3 (North South electricity interconnections in Central and South Eastern Europe) for the completion of the Mediterranean Ring with the Energy Community Countries and ensure a greater RES integration [17].

IV COST-BENEFIT ANALYSIS OF ENERGY STORAGE IN IEA TASK 25 COUNTRIES

In Norway a simplified estimate of costs for the various cases presented in [18] is given based on figures from the Norwegian regulator NVE. The costs are approximately adjusted to the level of detail of the study in [18] since only very rough indications of the main factors affecting the costs are known / publicly available.

The total cost of capacity upgrades of 12 existing hydropower stations in the main scenario (11.2 GW) is approximately 3.625 M€. All cases are power plants constructed with new tunnels to an existing upstream reservoir and to the downstream outflow into an existing reservoir, a fjord or the sea. This gives an average cost of approximately 325 €/kW. The average for the pumped storage power plants is approximately 365 €/kW and for hydro storage power plants approximately 290 €/kW.

The figures for individual cost elements provided for Norway are very uncertain. The totals can be used as a cost estimate, most likely as a lower bound, since costs are typically underestimated rather than overestimated. Initial feedback received on these cost estimates indicates that they are underestimated by approximately 10% (at least) for expansion upgrades due to the combination of new pumping storage facilities and expansion upgrades. Additional costs for upgrades of the electrical components of the generators should be added to these estimates if the capacity expansion upgrade and the new pump storage unit are combined into the same facility.

The costs apply to stations with an output voltage up to 420 kV. Any costs for connection to the central transmission grid, and any necessary reinforcements or expansion of the central transmission grid will be additional, as well as connection costs (HVDC converters, etc.) and HVDC cables for the international links. Order of magnitude cost estimates for upgrades in the central transmission grid in Norway are given in [19]: upgrades of capacity for overhead lines (420 kV) ~0.7 M€/km; AC submarine cable 6-10 M€/km; new transformer station 25-35 M€.

Finland reports a relevant potential from heat for energy storage and VRES balancing. Table III shows the estimated costs for different sizes and technologies, ranging from district heating to domestic applications.

TABLE III
HEAT STORAGE COSTS [20]

	Very large (District heating)	Large (Network of houses)	Small (single house)
Technology	Pit/Borehole	Large steel tank	Hot water storage tank
Heat Storage (m^3)	50000	5000	1
Cost [€/MWh] (estimated* mean, correlates with size)	900	4600	60000
Resistance heater	>10 MW	~1 MW	1-10 kW

** Cost estimates based on average temperature difference of 30 C (E.g. heat usage return temperature 50 C and outgoing temperature 80 C). Cost for single house storage tanks is based on quotes in internet stores.*

In the US, a recent study for the Department of Energy (DOE), has investigated the costs of energy storage [21], with the main results presented in Table IV.

TABLE IV
COST AND PERFORMANCE ASSUMPTIONS [21]

Technology	Power Sub-system Cost [$/kW]	Energy Storage Sub-system Cost [$/kWh]	Round-trip Ef. [%]	Cycles
Advanced Lead Acid Batteries	400	330	80	2000
Sodium/sulphur Batteries	350	350	75	3000
Lead-acid Bat. with Carbon-enh. Electr.	400	330	75	20000
Zinc/bromine Batteries	400	400	70	3000
Vanadium Redox Batteries	400	600	65	5000
Lithium-ion Batteries (Large)	400	600	85	4000
CAES(1)	700	5	N/A (70)	25000
Pumped hydro	1200	75	85	25000
Flywheels (high speed)	600	1600	95	25000
Supercapacitors	500	10000	95	25000

(1)CAES – Compressed air energy storage

Although there is a considerable dispersion of costs (real and estimated), among the IEA Wind Task 25 countries, it is particularly relevant to assess and compare the levelized costs of energy (LCOE) for different power system-scale energy storage technologies depicted in Fig. 5. It is to be noted that LCOE was calculated using a methodology according to [22] for a case study of a 100 MW power plant, operating 2000 h at full capacity annually, using only investment costs. O&M was neglected for all technologies and the lifespan of PHS and CAES was assumed to be 50 years, and 10 years for batteries and EVs.

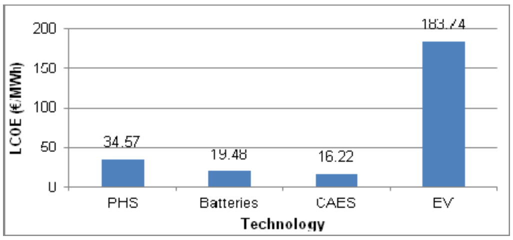

Fig. 5. IEA Wind Task 25 Levelized Cost of Energy (LCOE) for selected power system scale storage technologies: Pumped hydro storage (PHS); batteries (slow charge); CAES; Electric vehicles (EV) with fast charging systems.

V CONCLUSIONS

Analysis from planning and operational data of IEA Wind Task 25 participating countries indicates that the operation of power systems with small to moderate variable renewable energy deployment doesn't require energy storage capacity. However, when power systems reach high integration levels - which may be assumed above an annual wind energy penetration of 15% - several power systems rely on PHS to minimize spillage of primary renewable energy and increase security of supply. In the future, operational situations of extreme variable RES penetrations, such as those recently reported by Portugal (>100%) Spain (58%) and Ireland (>50%), will force extensive curtailment of variable RES by 2020.

A major trend detected within this overview is that the benefits of storage systems regarding system security, optimization of RES integration for reducing curtailment, and reduction of variable generation costs are extremely valued from a technical perspective, but generally not valued by energy markets.

Energy storage has been reported in the past as an extremely expensive option for aiding the integration of variable renewables. A simple calculation of LCOE for selected power system-scale energy storage technologies enable it to be concluded that most available technologies present adequate costs, if a minimum capacity factor is ensured. That leads to the conclusion that energy storage systems will be very beneficial both technically and economically, under very high wind penetration (and other variable sources, such as PV or run of the river systems) that guarantee a sufficiently high need for energy storage (instead of curtailment), and not an adequate economic solution for small to medium VRES penetration, unless critical technical constraints of power system operation are present.

A conclusion forwarded by most countries is that market mechanisms and incentives must be developed in order to allow large scale cross-border exchange of balancing and ancillary services. A challenge to overcome is the existence of different day-ahead markets in Europe, as well as in the US. Important requirements to address in the near future are:

- Lowering entry barriers for new actors through equal rules in all countries;
- Harmonize laws, regulations and rules in order to ease market operation, having in mind high variable RES penetration scenarios;
- Market recognition of the flexibility required for secure operation of the system;
- Competition from alternative sources of flexibility, including demand side management, HVDC and flexible conventional generation units.

ACKNOWLEDGMENTS

The authors would like to acknowledge Gary Jordan, Rui Pestana and Peter Meibom, for their contributions to this work.

REFERENCES

[1] IEA Wind 2010 Annual Report. ISBN 0-9786383-5-2. Available at http://www.ieawind.org/IndexPagePOSTINGS/IEA%20 Wind%202010 %20AR_cover.pdf, last accessed 14.11.2011)

[2] IEA Task 24 “Integration of Wind and Hydropower systems – final report. (to be published)

[3] S. Martín-Martínez, E. Gómez-Lázaro, A. Vigueras-Rodríguez, A. Molina-García, M. Milligan, E. Muljadi, “Participation of wind power plants in the spanish power system during events” , IEEE PES GM 2012, , 22-25 Sept, San Diego

[4] Estanqueiro, A, C. Mateus, R. Pestana (2010). “Operational Experience of Extreme Wind Penetrations”. in 9th Intern. W. Large-Scale Integ. of Wind Power into Power Systems and Transm. Networks for Offshore WPPs, 2010, Québec City, pp 371-383.

[5] T. Aigner and T. Gjengedal “Modelling wind power production based on numerical prediction models and wind speed measurements,” in Power System Computational Conf. 2011, Stockholm, 2011, pp. 1–7.

[6] PNBEPH (2007). Hydrologic Nat. Plan for Dams with high Potential (in Port.). (available at http://pnbeph.inag.pt/np4/documentos.html,last accessed 15.11.2009).

[7] Estanqueiro, A. et al. Energy Storage for Wind Integration: Hydropower and other contributions, IEEE PES GM 2012, 22-25 Sept, San Diego.

[8] "Ensuring a Secure, Reliable and Efficient Power System in a Changing Environment," EirGrid; SONI, 2011.

[9] EirGrid. http://www.eirgrid.com

[10] Tuohy, A., O’Malley, M. (2011). Pumped storage in systems with very high wind penetration, Energy Policy 39(4), pp. 1965-1974

[11] Nyamdash, B., Denny, E., O’Malley, M. (2010). The viability of balancing wind generation with large scale energy storage, Energy Policy 38(11), pp. 7200-7208.

[12] Parsons, B., et al, 2006. Grid Impacts of Wind Power Variability: Recent Assessments from a Variety of Utilities in the United States, National Renewable Energy Laboratory, CP-500-39955, Golden, CO.

[13] Frequency Regulation Compensation in the Organized Wholesale Power Markets, Order No. 755, FERC Stats. & Regs. Issued October 2011.

[14] MWH, "Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest," Prepared for the U.S. Army Corps of Engineers Northwest Division Hydroelectric Design, August 2009.

[15] GE Energy, 2010. Western Wind Solar Integr. Study, NREL, SR-550-47434, Golden, CO.

[16] J. Kiviluoma and P. Meibom, "Influence of wind power, plug-in electric vehicles, and heat storages on power system investments," Energy 35(3), pp. 1244-1255, March 2010.

[17] EC EIP Energy Infrastr. Pack. Priority Electricity Corridors. Annex1,Regulation guidel. for trans-European energy infrastructures. (available at http://ec.europa.eu/energy/infrastructure/consultations/20120620_infrastructure_plan_en.htm, last accessed 15.09.2012).

[18] E. Solvang, A. Harby and Å. Killingtveit,. "Increasing balance power capacity in Norwegian hydroelectric power stations", TR A7195, SINTEF Energy Research, CEDREN, February,

[19] "Energiutredningen – verdiskaping, forsyningssikkerhet og miljø" (Norges offentlige utredninger [Norwegian official Energy review], (in norwegian), ISSN 0333-2306 ; NOU 2012: 9)

[20] Technology Data for Energy Plants, Danish Energy Agency and Energinet.dk, p. 182, June 2010

[21] Schoenung, S. “Energy Storage Systems Cost Update, A Study for the DOE Energy Storage Systems Program” Sandia National Laboratories, April 2011. Available at: http://prod.sandia.gov/techlib/access-control.cgi/2011/112730.pdf

[22] IEA & NEA, 2010. Projected Price of Generating Electricity - 2010 Edition. Available at: http://www.iea.org/textbase/nppdf/free/2010/projected_costs.pdf (last access at 15th September 2012].

BIOGRAPHIES

Ana Estanqueiro received her degree in Power Eng. from the UTL/IST in 1986 and M.Sc (1991) and PhD (1997) in Mech. Eng. She is researcher at LNEG (1987) and Invited Prof. at the Univ. of Lisbon. Interests are dynamic models of WPP and operation of power systems with high RES. Pres. PT.IEC/CTE88, del. to IEA.Wind, EERA-Wind, EII-Wind.

Atle Rygg Årdal received his M.Sc. degree in Electric Power Engineering from the Norwegian University of Science and Technology in 2010. He is currently employed as a researcher with SINTEF Energy Research in Trondheim, where he is focusing on grid integration of offshore wind.

Ciara O’Dwyer received B.E. and M.E. degrees from University College Dublin in 1996 and 2011. She is currently studying for her PhD at University College Dublin, with research interests in energy storage.

Damian Flynn is a senior lecturer in power engineering at University College Dublin. His research interests involve an investigation of the effects of embedded generation sources, especially renewables, on the operation of power systems. He is also interested in advanced modelling and control techniques applied to power plant.

Daniel Huertas-Hernando Daniel has a Ph.D. in Theoretical Solid State Physics from TUDelft and worked as Postdoc. Researcher at Yale Univ. and NTNU before joining SINTEF in 2009. At SINTEF he works on grid connection of large scale offshore wind, wind forecast uncertainty, balancing of VRES generation, market integration and system operation.

Debra Lew graduated with a MS and PhD in Applied Physics from Stanford University, CA, and with BS degrees in Physics and Electrical Engineering from the MIT, MA. Debra presently works as a Senior Engineer in the Transmission and Grid Integr. Group at NREL, with focuses on integration of variable generation into the power system.

Erik Ela received the MS degree in power systems engineering at the Illinois Institute of Technology and is a research engineer at the National Renewable Energy Laboratory.

Eivind Solvang is a senior research scientist at SINTEF Energy Research in Trondheim. He received his MSc. degree in Electric Power Engineering from the Norwegian Institute of Technology, Trondheim, in 1976. He is mainly working with technical-economical optimization of maintenance and reinvestments, lifetime modelling and asset management.

Emilio Gómez Lázaro received the Electrical Eng. and Ph.D degrees in the Techn. Univ, of Valencia, in 1995 and 2000. He is Associate Prof. in the Univ. of Castilla-La Mancha, head of the Renewable Energy Research Institute. He is a member IEA Task25, IEC TC88 WG27, TPWIND. Main interest are modeling of RES power plants and power system operation with large amounts of renewables

Enrico Maria Carlini is Head of Disp.&Op. C/S, It.(TERNA), M.Sc. El. Eng (FC H (Planning PS). HE ha worked in security analyses on It TN EU intercom. systems, system planning. Expert in cross-border cap.ass, EU cong. man. and regulatory issues. He is chairman of IEC - TC99 and Deputy Convenor of ENTSO-R RG Cont C/S Eur for system development.

Juha Kiviluoma is a Senior Scientist and Team Manager for Wind Integration at VTT, Finland. Main interest is economic int. of variable power generation. Juha uses and develops stochastic unit com. models and gen. plan. models, incl. data for PHS, EVs and heat storages with electric heating.

Luis Rodrigues received the degree in Electrical Eng from the Federal Univ. of Santa Catarina (2009). He joined LNEG in 2010, with research interests in grid integration of RES.

Mikael Amelin is assistant prof. in the Elect. Power Systems Lab at the School of Electr. Eng. of KTH, Stockholm. He received his MSc, lic. and doctors degrees from KTH in 1997, 2000 and 2004 respectively. Interests include Monte Carlo techn, analysis and modelling of electricity markets, and rural electr. in developing countries.