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Authors(s)	Feeley, C., Bryans, A. G., Nyamdash, Batsaikhan, Denny, Eleanor, O'Malley, Mark
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The Viability of Balancing Wind Generation with Storage

C. Feeley, A.G. Bryans, *Member, IEEE*, B. Nyamdash, E. Denny, *Member, IEEE* and M. O'Malley, *Fellow, IEEE*

Abstract - This paper studies the impact of balancing wind generation with storage on the thermal plant mix and load for different levels of installed wind and storage, and under different operational strategies. Moreover, the optimal time frame to be used for the optimization of the system operation is studied and the possible revenue that can be generated by the system with wind and storage is calculated for different scenarios. It is shown that the introduction of intermittent energy resources reduces the participation of the base-load plants and increases the peaking plants, and the increasing storage dramatically increases the participation of the mid-merit plants. Furthermore, the mid-merit strategy and 24 hours time frame resulted in the best use of the system with wind and storage.

Index Terms—Energy storage, Load duration curve, Plant mix, Renewal energy resource, Wind

I. INTRODUCTION

Wind generation (WG) penetrations have increased rapidly in the last decade with wind as the fastest growing renewable energy in EU [1]. This growth is expected to continue as a result of EU policy for promotion of renewable energy sources (RES) in order to contribute for the reduction in greenhouse gas emissions [2].

WG provides a variable form of generation, with the capacity factor of a mid merit plant. Traditional thermal mid-merit plant would operate during times when the system demand and price is high; however wind generation will deliver the power in a variable and unpredictable way. Simply put, an uncontrollable intermittent source of power can not satisfy the demand for electricity and will need to be supplemented by a firm source of power.

There has been no shortage of solutions proposed in this area. Reserve power, provided by flexible, dispatchable thermal and hydro plant offers one such solution to the intermittency problem [3]. Good interconnection with a large grid [4] along with accurate forecasting techniques

would make the scheduling and dispatching of wind power an easier process [5]. Storage facilities have the potential to provide reserve and, in the case of remote wind farms offer an alternative to grid reinforcement. Furthermore, coupling wind and storage facilities in order to produce a dispatchable power output would be of significant benefit to those trading in a market system.

The EU policy for the promotion of renewable energy resources has sparked much interest in the viability of combined wind and storage facilities. The migration from conventional thermal power generators (PG) to renewable generation powered by energy sources which are variable in nature has proven to be challenging both from a system operator stand point and from a generation trading stand point. As the level of wind increases on systems, the requirement for additional peaking capacity is also increased [6]. The cost of this additional peaking capacity is estimated to be between 15-30% of the investment cost of wind. It has been suggested on many occasions that energy storage technology could be used to mitigate this problem. Energy storage systems are a proven concept and are in economically successful operation in many systems today, and provide critical system support. Greenblatt *et al* [7] compared the use of Compressed Air Electricity Storage (CAES) versus gas plant (Open Circuit Gas Turbine (OCGT) and Combined Circuit Gas Turbine (CCGT)) to produce base-load wind power. The cost competitiveness of the competing schemes was largely reliant on gas price: at low gas prices an all CCGT system is favored. As gas price increases, a large wind with CAES system provides the cheapest energy [7]. The wind with CAES system was also found to have the lowest dispatch cost; an advantageous characteristic in a market system. The benefits of the storage where transmission constraints frequently limit the power delivered by a wind farm to the grid were explored in [8]. Korpaas *et al* [9] investigate a system where storage is used to smooth wind power output to follow a production plan.

This paper will look at wind with storage system as a system resource, employed to smoothen the load and addresses the following three distinct questions. Question 1: “Storage as a system resource”, will look at how the mix of thermal plant must change with the addition of wind and storage facilitates. Question 2: “The impact of the wind and the storage on the load” considers the economic viability of using storage as a method for storing wind generation to

C. Feeley and A. G. Bryans were formally with the School of Electrical, Electronic and Mechanic Engineering, University College Dublin, Belfield, Dublin 4, Ireland and are now with ESBI and Airtricity respectively.

Batsaikhan Nyamdash, Eleanor Denny, and M. O'Malley are with the School of Electrical, Electronic and Mechanic Engineering, University College Dublin, Belfield, Dublin 4, Ireland. The corresponding author can be contacted at +353-17161857 and batsaikhan.nyamdash@ucdconnect.ie.

give it the operational characteristics of traditional thermal plant. Question 3: “Optimizing time frame for the operation of the system with wind and storage” investigates the optimal time frame that should be employed to maximize the revenue obtained by the system of wind and the storage.

II. STORAGE SYSTEMS

A. General information and existing storage facilities

The profitability of any storage scheme operating within a market will depend on two key factors; the price differential that occurs across its hours of charging and discharging and the round trip efficiency of the plant. Any gains made from this price arbitrage must also be substantial enough to cover the large capital costs associated with large scale energy storage. Figure 1 shows the impact of the wind turbine and the storage facility on the load for a sample day. Use of wind, lowers the load for the system. The storage was charged during the night time by the wind power (WP) and if WP is not enough to charge the storage, conventional generator (CG) is used to charge, when the demand and price of electricity are low. Furthermore, stored energy in the storage facility is discharged when the demand and price are high during the day time.

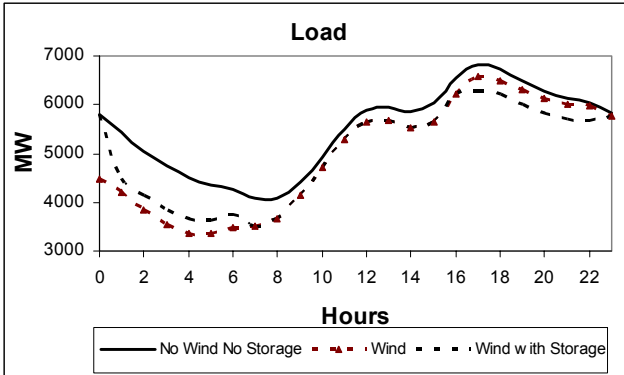


Figure 1: Impact of the wind turbine and the storage facility on the load.

Examples of the feasible large scale storage units are CAES and Pumped hydro electricity storage (PHES) and detailed information are given below.

B. Compressed air electricity storage

Unlike conventional gas turbines that consume about 2/3 of their input fuel to compress air at the time of generation, CAES pre-compresses air using the low cost electricity from the power grid at off-peak times. This stored energy is later used along with some gas fuel to generate electricity as needed. Key features of a CAES plant are fast cold start times, fast ramp rates and high part load efficiency. Fuel use is 30-40% that of a combined turbine (CT). The compressed air is often stored in appropriate underground

mines or caverns created inside salt rocks. As is true of most large scale storage facilities, the capital costs of CAES are typically large and highly site specific.

TABLE I. AVAILABLE CAESS

Type of Cavern	Rock	Salt	Aquifer
Turbo-machinery (\$/kW)	439	425	414
Storage (\$/kWh)	30	1.1	8
Hours of storage	10	10	10
Capital cost (\$/kW)	739	436	494

C. Pumped hydro electricity storage

Pumped hydro uses two water reservoirs, separated vertically. During off peak hours water is pumped from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. Pumped storage has a typical round trip efficiency of 70%. It is important to consider that the charge energy is produced by and large by base-load thermal plant. If the charge energy is generated with an efficiency of 40%, and PHES has a round trip efficiency of 70%, this reduces the overall efficiency of fuel burnt to 28%. Capital costs are high and depend on the suitability of the development site (estimated at \$1100/kW to \$2000/kW). It is the most widespread energy storage system in use on power networks, its main applications are for energy management, frequency control and provision of reserve.

Other small storage units that are not discussed in this paper are batteries (Polysulfide Bromide Flow Battery, Vanadium Redox Flow Battery, Zinc Bromine Flow Battery, Sodium Sulfur Battery, Lead-Acid Battery, Metal-Air Battery and Lithium ion Battery), and flywheels

III. METHODOLOGY

In this paper, 2006 Irish system marginal price¹ is chosen as a normal system marginal price and the forecast 2010 Irish demand profile [10] is used to predict the demand leveling and the forecast of 2010 Irish wind profile² is used to predict the wind energy.

Question 1: Storage as a system resource

A model was built that sought to plot how the optimum plant mix adapted itself to varying levels of wind power penetration. First task was to set criteria for defining the best mix of base-load, mid-merit and peak plants. For the purpose of the paper following assumptions are made:

Assumption 1. Upper limit of base-load plant allowable on a typical system was defined as the MW figure above which demand rises 85% of the time. This ensures base-load plant maintains a high capacity factor.

Assumption 2. Peak plant requirement was defined as the

¹ Eirgrid Transmission System Operator. Available: www.eirgrid.ie

² All Island Website. Available: www.allislandproject.org

MW figure which demand rises 15% of the time.

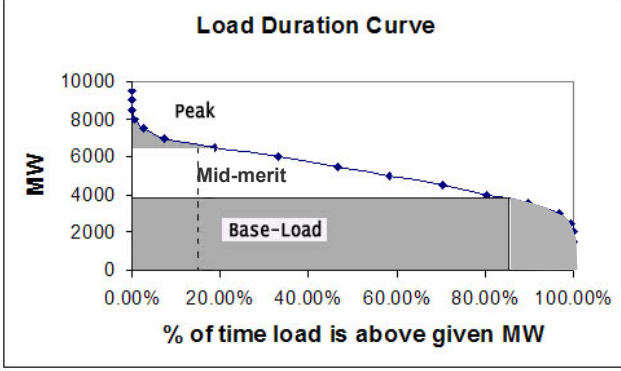


Figure 3. Load Duration Curve.

Assumption 3. Mid-Merit plant requirement was calculated as the balance of MW required to cover demand given the above definitions of base-load and peak.

Because of their low marginal costs, introduced intermittent sources of power displace the base-load power. The storage facility is charged by the wind farm if the wind energy is enough to charge it, otherwise the balance is charged by the power from conventional PG.

During the night, storage is charged ($P_{store,t} < 0$) when the demand and the price of the electricity are low and during the day, stored energy is released when the demand and the price are high ($P_{store,t} > 0$).

Net demand profile ($\hat{P}_{load,t}$) with wind and the storage is calculated in the following way: a wind profile ($P_{wind,t}$) was subtracted from the demand profile ($P_{load,t}$) and the storage profile was added ($P_{store,t}$), hence the MW figures of allowable base-load, mid-merit and peak plant are found and the total energy supplied by the base-load (P_{base}), mid-merit ($P_{mid-merit}$) and peaking plants (P_{peak}) are calculated:

$$\hat{P}_{load,t} = P_{load,t} - P_{wind,t} + P_{store,t}$$

$$P_{base} = \sum_{t=1}^T (P_{base,t}) \quad P_{base,t} = \begin{cases} P_{85\%} & \text{if } \hat{P}_{load,t} \geq P_{85\%} \\ \hat{P}_{load,t} & \text{if } \hat{P}_{load,t} < P_{85\%} \end{cases}$$

$$P_{peak} = \sum_{t=1}^T (P_{peak,t})$$

$$P_{peak,t} = \begin{cases} \hat{P}_{load,t} - P_{15\%} & \text{if } \hat{P}_{load,t} \geq P_{15\%} \\ 0 & \text{if } \hat{P}_{load,t} < P_{15\%} \end{cases}$$

$$P_{mid-merit} = \sum_{t=1}^T (\hat{P}_{load,t} - P_{base,t} - P_{peak,t})$$

Where T is number hours in one year, $P_{85\%}$ is MW that

the load is above for 85% of the time, $P_{15\%}$ is MW that the load is above for 15% of the time.

This was repeated for the increased levels of installed wind capacity from 0MW to 7800MW and increased levels of installed storage capacity (0MW to 3600MW) for different levels of the installed wind capacity. Based on the results found, effect of the wind with storage on the plant mix is calculated as a fraction of the total load.

Question 2: Impact of the wind and the storage on the load

A number of different operational strategies for the storage facility to improve the revenue of the wind generation are considered: “Base-load Strategy” a flat 24 hours generation profile (Figure 4a), “Mid-merit Strategy” generating during 12 daylight hours (Figure 4b) and “Peak Strategy” generating during the 6 hours of the highest demand (Figure 4c). The storage system employed in this model could either be PHES or CAES and is allowed different charge and discharge capacities.

The model seeks to maximize revenue by only selling power to the grid when the market price is favorably high. In this question WP is *only* used to charge the storage facility.

For all those 3 strategies the wind resource is available over 24 hours ($P_{wind,t}$). Depending on the operating strategy employed, power ($P_{del,t}$ - shown as a controlled wind output in the figure 4a, 4b and 4c), will be delivered to the grid from the storage over the 6 highest priced hours (peak power), or 12 daylight hours (mid merit) or evenly over 24 hours (base load).

If in any hour $P_{wind,t} > P_{del,t}$ the surplus energy is stored and likewise, if $P_{del,t} > P_{wind,t}$ the energy deficit will be supplied from the storage system. In this manner a schedule of operation is computed for the storage facility, $P_{store,t}$:

$$P_{store,t} = P_{del,t} - P_{wind,t}$$

If $P_{store,t} < 0$, then $P_{store,t}$ is a charge for the storage.

If $P_{store,t} > 0$, then $P_{store,t}$ is a discharge from the storage.

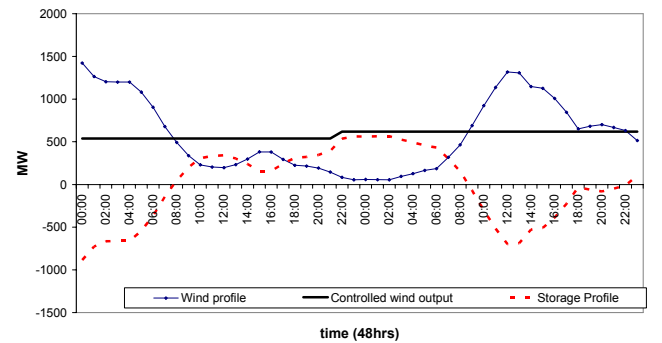


Figure. 4a. Production schedule of operating according to the base-load strategy.

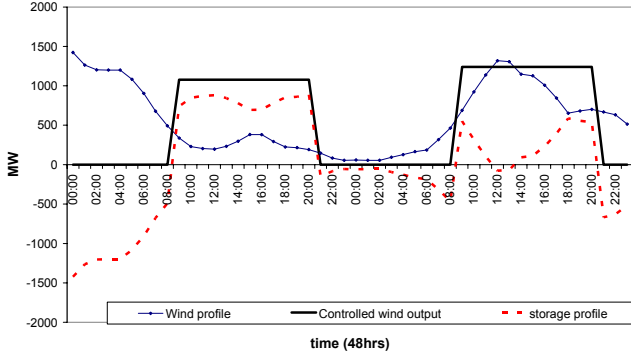


Figure 4b: Production schedule of operating according to the midmerit strategy.

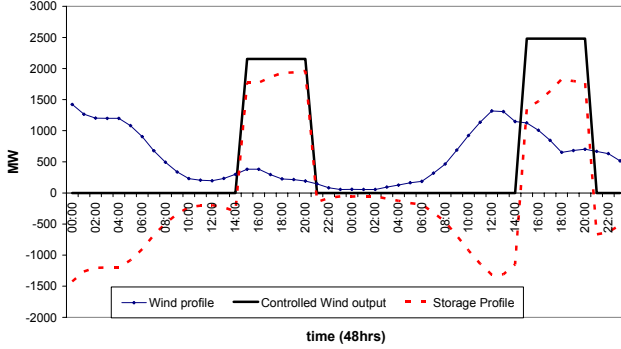


Figure 4c: Production schedule of operating according to the peak strategy.

The model is such that the expected controlled wind output ($E\{P_{del,t'}\}$) per hour, when the system is supplying energy, is total energy that can be generated by the wind per time frame divided by the number of hours when the storage is supplying power.

$$E\{P_{del,t'}\} = \frac{\sum_{t=1}^T P_{wind,t}}{\tau}$$

Where t' is the hours when the storage is supplying energy and τ is the number of hours that the storage supplies energy.

Potential output ($P_{t'}^*$) of the system is the energy that can be supplied per hour, when the storage is supplying, is equal to the expected output if the available power at time t in the system of wind farm and storage exceeds the expected output otherwise it is equal to the available power at time t .

$$P_{t'}^* = \begin{cases} E\{P_{del,t'}\} & \text{if } \sum_{t=1}^{t'} P_{store,t} + P_{wind,t'} \geq E\{P_{del,t'}\} \\ \sum_{t=1}^{t'} P_{store,t} + P_{wind,t'} & \text{if } \sum_{t=1}^{t'} P_{store,t} + P_{wind,t'} < E\{P_{del,t'}\} \end{cases}$$

Actual energy supplied is the level of supply that takes into account of the demand. It is equal to the potential output if the demand is more than $P_{t'}^*$, otherwise it is equal to the demand itself (system supplies only what is demanded).

$$P_{del,t'} = \begin{cases} P_{t'}^* & \text{if } P_{t'}^* \leq X_{t'} \\ X_{t'} & \text{if } P_{t'}^* > X_{t'} \end{cases}$$

Where $X_{t'}$ is the demand at time t' .

The storage facility is considered to be 100% efficient in this research.

Question 3: Optimizing time frame for the operation of the system with wind and storage

Storage systems normally operate on a daily bases to take advantage of the daily difference in price; however wind generation is known to vary over longer periods. Optimized operational schedule for the longer time frame may reduce the revenue of the system.

An algorithm was developed to optimize the level of output of wind with storage regarding to the demand and wind energy availability. For this purpose the expected output was re-optimized in terms of the different time frames. For example: for two days peak strategy, τ (the number of hours that the storage supplies energy) is 12 instead of 6 and T' (length of the time frame) is 48 hours instead of 24. The following figures will illustrate these algorithms clearly.

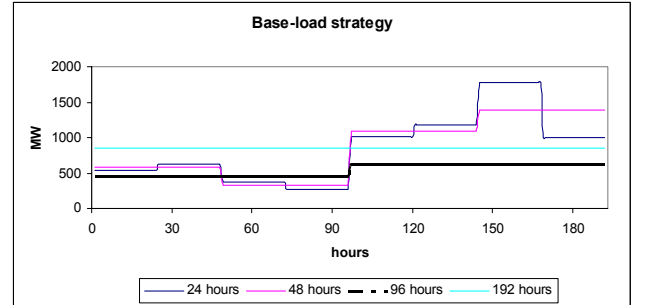


Figure 5a: Base-load strategy for different time frames

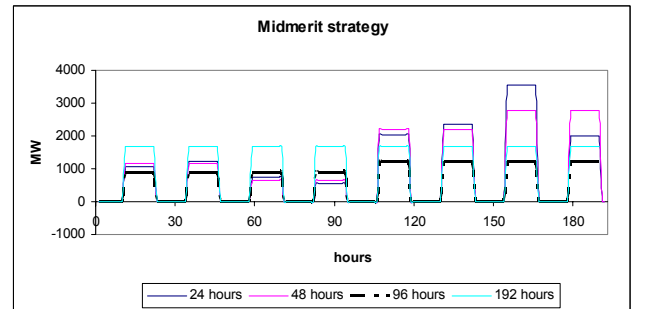


Figure 5b: Mid-merit strategy for different time frames

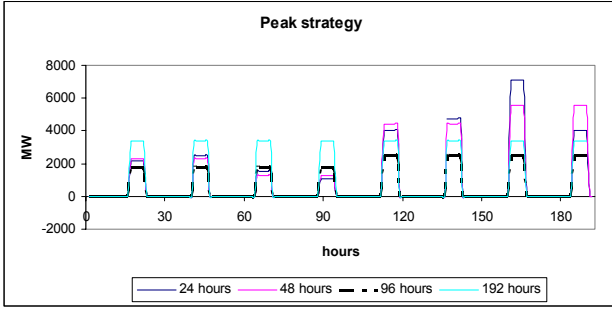


Figure 5c. Peak strategy for different time frames

To compare the merits of each strategy the 2006 Irish system marginal price ($S_{price,t}$) was chosen as a “normal” system marginal price. The gross revenue was calculated according to the product of $P_{del,t}$ and $S_{price,t}$.

$$Rev = \sum_{t=1}^{T'} (P_{del,t} \times S_{price,t})$$

In this method the storage capacity and size is not constrained, therefore it will show the required storage size as a maximum of the total discharge occurred within 24 hours.

$$\text{Required storage size} = \max \left\{ \sum_{t_i=1}^{24} P_{store,t_i} \text{ if } P_{store,t} > 0, i=1 \dots 365 \right\}$$

IV. RESULTS

Question 1: Storage as system resource

A diverse portfolio of generating units helps to ensure a secure supply of electricity. Firstly, it is prudent not to be overly reliant on one fuel source. Secondly, to follow a fluctuating demand curve, a mix of cheap base-load plant, cycling mid-merit and expensive peaking units is required. Obviously, if a system could support large amounts of cheap CCGT and coal plant this would reduce overall system costs.

In the model, maximum load was 9225MW and minimum was 3525MW when there is no wind and storage. The effects of increasing wind and increasing storage are shown in Table II. Base-load plant is displaced by wind and the requirement for load following mid-merit and peaking plant increased.

It can be seen from Table II that with no wind on the system, base-load power represents 76% of the total load of the year. When the installed capacity of wind is increased up to 7800MW, the share of the base-load decreased down to 8% and the participation of peaking plants increased from 1% to 35%. Moreover, the load duration curve becomes steeper as the wind capacity increases which implies that the share of the base-load decreases as wind on the system increases (Figure 6abc). When the storage capacity is increased, the use of peaking plants decreases

slightly and the use of the mid-merit plants increase significantly for all levels of the wind capacity.

TABLE II
EFFECT OF WIND FARM AND STORAGE FACILITY ON THE PLANT MIX

Installed Capacity of the Storage		Installed Capacity of the Wind				
		0	600 MW	1200 MW	1800 MW	3600 MW
0	Base-load	76%	80%	83%	80%	56%
	Mid-merit	23%	19%	17%	19%	43%
	Peak	1%	1%	1%	1%	2%
1950MW	Base-load	71%	77%	79%	77%	48%
	Mid-merit	28%	22%	20%	22%	51%
	Peak	1%	1%	1%	1%	1%
3900MW	Base-load	62%	67%	69%	68%	38%
	Mid-merit	36%	31%	30%	31%	61%
	Peak	2%	1%	1%	1%	1%
7800MW	Base-load	8%	12%	13%	13%	10%
	Mid-merit	57%	57%	59%	60%	65%
	Peak	35%	30%	28%	27%	26%

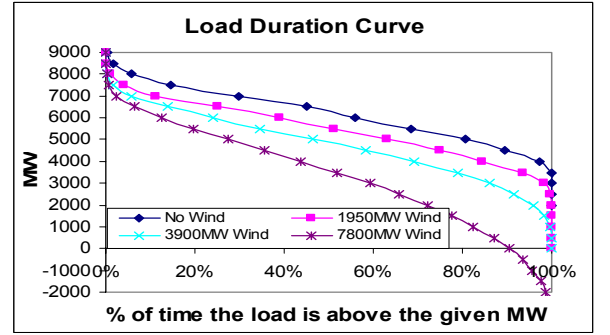


Figure 7a. Load Duration curve: No storage facility

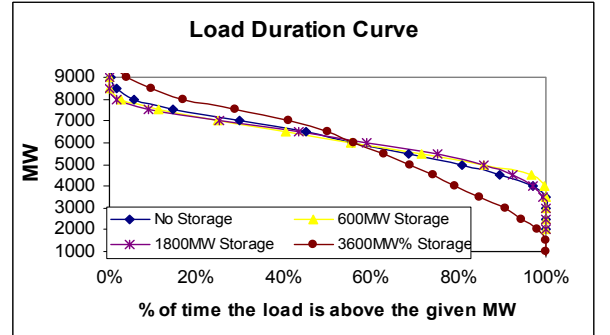


Figure 7a. Load Duration curve: No wind farm

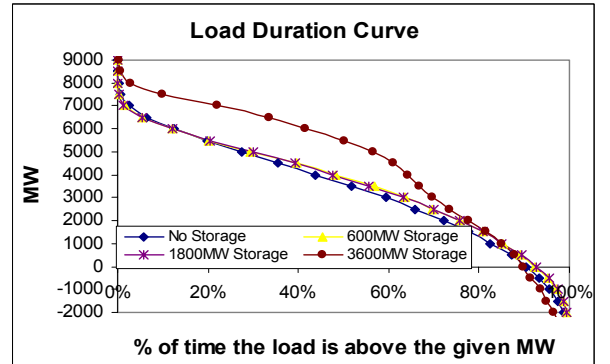


Figure 7d. Load Duration curve: Installed capacity of the wind farm 7800MW

Combined effect of the wind and storage on the system reduces the use of base-load plants, and increases the use of mid-merit and peaking plants compared to the no wind and no storage scenario.

Table II demonstrates that storage systems could be used to reduce the need for expensive peaking plant on the system with wind. However, it significantly increases the participation of the mid-merit plant and decreases the base-load plants. Therefore depending on the capital and operational costs of the wind farm and storage system, these could be used to offset the additional costs wind power places on a system.

Moreover, the effect of the storage is to decrease the maximum load and increase the minimum load. As the size of the storage increases until the point where the maximum load becomes the minimum and the minimum becomes the maximum (Figure 6a and 7) the use of the mid-merit plants decreases and the use of base-load plants increases. From that point the use of the base plants rapidly decreases while the use of the mid-merit plant rises. Because maximum load decreases beyond the minimum load, which implies that the MW that base plants work decreases, hence the participation. At the same time the minimum load increases beyond the maximum load, hence the use of mid-merit as the use of the peak-plants will still be low.

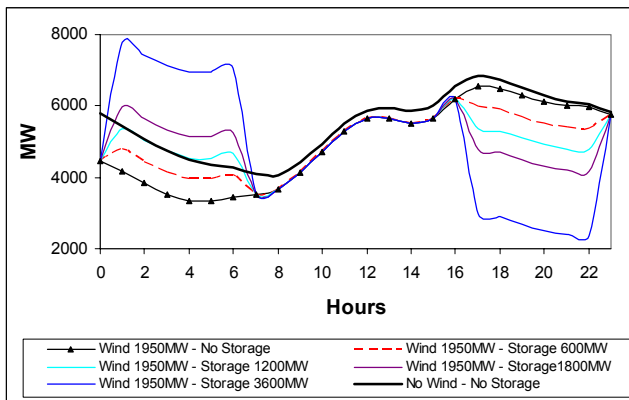


Figure 7. Impact of the storage on the load

Question 2: Impact of the wind and the storage on the load

In areas of weak grid connection, a wind power producer may be forced to curtail his power output on a regular basis or may be unable to fully exploit the wind resource available. Storage may be useful in realizing the full potential of a wind farm site. If operating in a market system that exhibits high within day price volatility, the power producer may wish to use storage to follow a production schedule that would result in the highest revenue.

Wind power is used to charge the storage as it is generated when storage is not supplying any power, while it is sold directly to the grid when storage is supplying. As it is figure 6a base-load strategy reduces the load at all time and the peak strategy decreases the load significantly only when storage is supplying energy. The mid-merit strategy

smoothen the load.

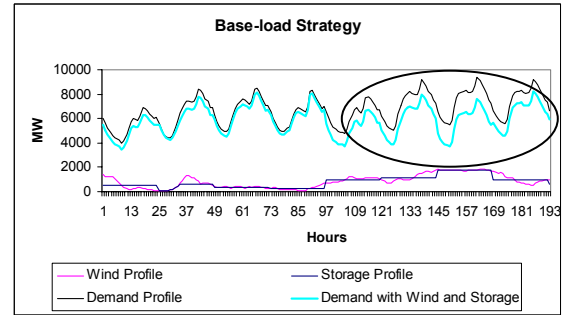


Figure 8a. Impact of controlled wind output on the load: Base-load strategy

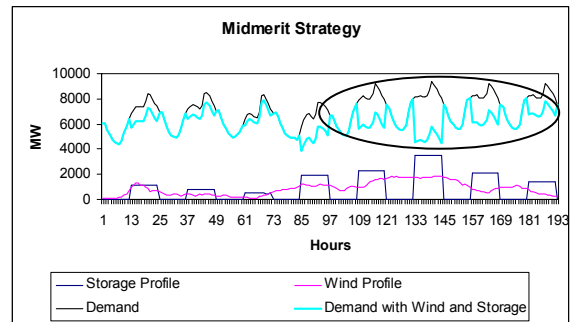


Figure 8b. Impact of controlled wind output on the load: Mid-merit strategy

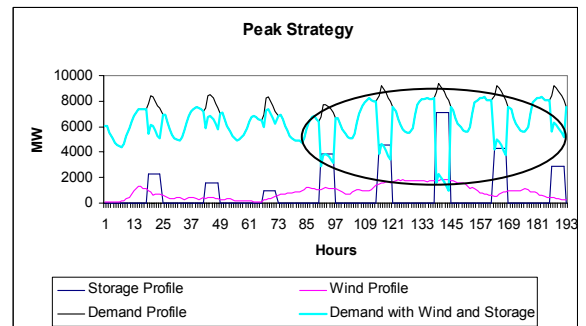


Figure 8c. Impact of controlled wind output on the load: Peak strategy

Question 3. Optimizing time frame for the operation of the system with wind and storage

There are, of course, differences in the demand profile, and consequently energy prices, for week days and week ends. Both wind and demand also display seasonal variations. It is important to investigate the most appropriate time frame over which to cycle the storage unit. Therefore, the operational strategies of the system with 1950MW wind and storage was optimized by the time frames of 24 hours day, 48 hours, 96 hours and 192 hours (Table III and Figure 9abc) and it was compared to the scenario with 1950MW wind with no storage.

From Table III we can surmise that a 24 hour cycle time makes best use of the storage unit as it shows the revenue collected is the highest compared to other time frames. Moreover, table IV shows that the 24 hours time frame requires the smallest storage facility apart from the when

peak strategy was employed.

TABLE III
EFFECT OF INCREASING TIME FRAME ON THE REVENUE GENERATED BY EACH STRATEGY COMPARED TO NO STORAGE SCENARIO (MILLION €)

	Peak	Mid-Merit	Base-load	No storage
24 hours	498.12	500.31	469.81	467.19
48 hours	496.31	499.57	470.57	467.19
96 hours	496.46	498.23	470.85	467.19
192 hours	492.16	495.95	467.02	467.19

TABLE IV
EFFECT OF INCREASING TIME FRAME ON THE STORAGE SIZE REQUIRED BY EACH STRATEGY COMPARED TO NO STORAGE SCENARIO (MWh)

	Peak	Mid-Merit	Base-load	No storage
24 hours	32874	22281	6924	0
48 hours	32309	28061	15510	0
96 hours	33254	27833	18085	0
192 hours	32317	28500	25495	0

The main causation of this result is that variation in the controlled wind profile is less when longer time frame was used rather than 24 hours. Hence, there will be greater probability of actual output not meeting the expected output and, shortage of supply will occur. Thus, the operation of the system can't gain any benefit from the price variation.

From the figures, we can see that storage operational schedule is often interrupted when 48, 96 and 192 hours optimisation used (Figures 9a,b,c) rather than 24 hours optimisation due to the lack of stored energy in the storage facility.

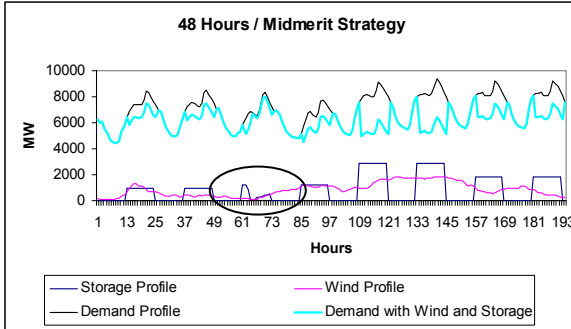


Figure 9a. Impact of controlled wind output on the load: Mid-merit strategy – 48 hours time frame

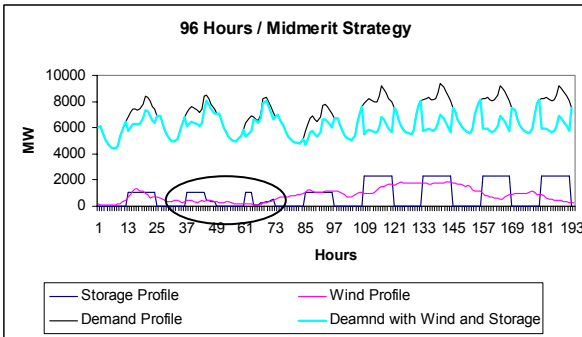


Figure 9b. Impact of controlled wind output on the load: Mid-merit strategy – 96 hours time frame

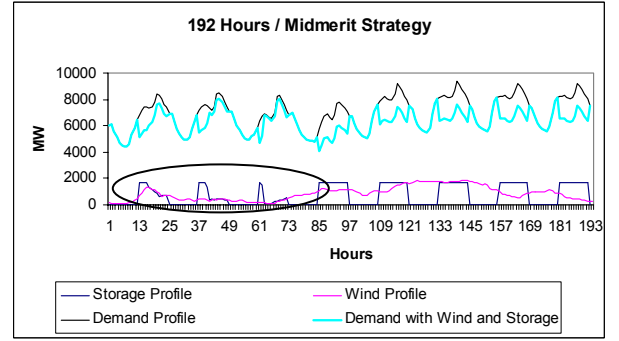


Figure 9c. Impact of controlled wind output on the load: Mid-merit strategy – 192 hours time frame

Additional “No storage case” was examined here to compare with the operational strategies (Table III). For different time frames, no storage scenario is worse than scenarios with storage on the system as it is generating the lowest revenue and it is due to the fact that wind follows a diurnal pattern, and is likely to be producing slightly more power during higher priced daylight hours than off peak at night. Therefore the storage facility is availing the best use of the wind as it is in table II. Furthermore, from table IV, we can see that as the operational time becomes fewer, the storage capacity is increased.

Here we used perfect wind forecast and 100% efficient storage, thus, the results may overestimate the benefits of storage. Further work to examine the net profit of the system with wind and storage is in progress and the provisional results suggest that the net profits are highly sensitive to the installed storage size and the capital and operation costs.

V. CONCLUSION

This paper looked at three questions: ‘Storage as a system resource’, ‘Impact of the wind and storage on the load’, and ‘Optimizing the time frame for the operation of the system with storage’.

Firstly, the impact of the wind and the storage on the plant mix was examined, and it was found that as wind increased use of the base-load plant decreased substantially and use of mid-merit plants increased. The use of the peaking plants increased due to the introduction of the intermittent energy resource. Moreover, the use of mid-merit plants increased as storage increased.

Secondly, the impact of the wind with storage on the load was studied for three operational schedules (base-load, mid-merit and peak). It was found that the effect of base-load strategy is just to decrease the load at all times by a small amount, the peak strategy decreased the load by large amount when there was high wind power. But, mid-merit strategy has more smoothening effect on the load as it decreased the load for longer when demand is high and kept the load at its level when the demand is low.

Thirdly, different time frames were compared in term of the revenue generated by the system. Based on the result 24

hours optimization was the most effective compared to longer time frames and mid-merit strategy optimized at 24 hours time frame generated the highest revenue by the system of wind with storage.

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VII. BIBLIOGRAPHIES



Claire Feely graduated with a BE in Mechanical Engineering in 2005. She continues to participate in research work within Electricity Research Centre, University College Dublin.



A. Garth Bryans (M'05) graduated with a BSc in Marine Biology & Oceanography in 2003, an MSc in Applied Physical Oceanography from the University of Wales, Bangor and a PhD from Queen's University Belfast in 2006.



Batsaikhan Nyamdash received a BA degree in Business Administration and Applied Mathematics from Khan-Uul Institute, Ulaanbaatar, Mongolia, in 2002, Higher Diploma in Economics Science and MA in economics from University College Dublin, Ireland, in 2006 and 2007, respectively.



Eleanor Denny received a B.A. degree in Economics and Mathematics, an M.B.S. degree in Quantitative Finance and a Ph. D. on wind generation integration in 2000, 2001 and 2007 respectively. She is currently a research lecturer in the School of Electrical, Electronic and Mechanical Engineering at University College Dublin and has research interests in renewable generation integration, distributed energy resources and system operation.



Mark O'Malley received B.E. and Ph. D. degrees from University College Dublin in 1983 and 1987, respectively. He is the professor of Electrical Engineering in University College Dublin and is director of the Electricity Research Centre with research interests in power systems, control theory and biomedical engineering. He is a fellow of the IEEE.