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Energy Storage:Maximising Irelands Wind Energy Potential

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by

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This Report is submitted in partial fulfilment of the requirements of the Master of Engineering in Sustainable Electrical Energy Systems of the Dublin Institute of Technology

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Declaration

I certify that this thesis, which I submit in partial fulfilment of the requirements of the Master in Sustainable Electrical Energy Systems (Programme Ref: DT704) of the Dublin Institute of Technology, is entirely my own work and that any content that relates to the work of other individuals, published or otherwise, are acknowledged through appropriate referencing.

I also confirm that this work has not been submitted for assessment in whole or part for an award in any other Institute or University.

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Abstract

Ireland plan's to generate up to 40% of its electricity from wind generation by 2020. This thesis outlines the problems that may be faced by the electricity system and illustrates the benefits that large scale energy storage can bring to the electricity system when trying to integrate large amounts of wind energy. Energy storage is currently a topical subject in Ireland as wind penetration increases and problems such as curtailment loom. This thesis outlines the storage capacities required to sufficiently aid the integration of wind energy in Ireland and outlines the value that large scale energy storage can bring to the Irish electricity system.

Models of the system load and wind generation profile are devised and wind penetration scenarios representing 13%, 20%, 40% and 60% wind penetration are developed. These wind penetration scenarios are analysed and the curtailment levels associated with them are calculated. Storage is then introduced to the system models and these are analysed. The improvements in system operation are outlined and the reduction in curtailment and required conventional generation are calculated. Popular generation adequacy assessment techniques are investigated and a generation adequacy assessment is carried out on the system models. Finally the value introduced to the system by adding the energy storage system is quantified by estimating the amount of conventional generation that has been offset by its introduction.

The analysis shows that energy storage adds little or no value to the Irish electricity system when penetration levels of wind generation are under 20%. At penetration levels of 40% and 60%, energy storage significantly increases the amount of wind energy that is absorbed by the system and reduces the levels of curtailment and required conventional generation.

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1 Introduction

1.1 Background

The Irish Government has set a binding target of 40% of the countries electricity to be generated from renewable sources by 2020. Wind Energy is expected to meet the vast majority of this target as alternative renewable energy sources are not currently suitable for large scale deployment[1]. There is currently a total of 1,459 MW's of wind energy connected in Ireland which provides approximately 14% of Ireland’s electricity requirements[2]. It is estimated that 5,900MW's of wind energy would need to installed by 2020 in order to meet the Governments target of 40% renewables[3]. There are approximately 3.9GW's of wind farm applications awaiting a connection offer from Eirgrid as part of the Gate 3 connection process and a further 11GW's of applications have been received outside of this process . It is theoretically possible for wind power to supply 100% of Ireland's electricity demands but in reality this is not practical.

The intermittent nature of wind is the biggest problem associated with wind power[4]. As the installed capacity of wind increases the problems associated with wind power become magnified. Because the wind does not always blow it cannot be solely relied upon to provide power. Alternative generation (gas powered plants etc.) needs to be available to ensure system stability. As the penetration of wind increases this alternative generation plant is increasingly generating electricity inefficiently and this mitigates the positive effects of wind power[5]. Curtailment of wind turbines also becomes an issue as wind penetration increases . Curtailment happens when the the amount of electricity generated from wind exceeds the demand requirement and thus the extra generated electricity will be wasted (or curtailed).

Energy storage systems are seen as possible solutions to these problems. Energy storage systems can be used to store electricity at times of high wind and can be discharged at time of low wind so the electricity is provided when it is needed. Energy storage may also increase the penetration levels attainable by wind energy into generation systems and reduce the amount of alternative generation required as the stored electricity will be reliable and predictable. Many storage systems are suitable for this application. The aim of this thesis is to investigate to what extent energy storage systems can increase the penetration levels attainable by wind energy in the Irish electricity generation mix.

Energy storage hit the headlines recently when the “Spirit of Ireland” group claimed that Ireland could be energy independent within 5 years[6]. The group announced that it had identified a number of glacial valleys that are suitable for developing pumped-hydro storage (PHS) plants that use the sea as the lower reservoir. The “Spirit of Ireland” announcement claimed that 2 of these reservoirs plus installing further wind capacity would enable Ireland to be energy independent. Currently only one example of a sea water PHS generating unit is operating in the world at Okinawa, Japan.

PHS systems are a mature technology. Electricity is used to pump water from a lower reservoir to a higher reservoir in charging mode. Water is released from the upper reservoir and passes through a turbine to generate electricity in discharge mode. Efficiencies are in the region of 70% - 85%[7]. PHS units have a number of applications including frequency and voltage control, black start provision and are commonly used for peak shaving and reserve[8]. Turlough Hill is currently Ireland's only PHS system. It began generating in 1974 and consists of four 73MW turbines. It has a total generating capacity of 293MW's and has a storage capacity of 1.6GWh's. Its main function is to provide ancillary services and peak shaving. There are two PHS plants currently going through the gate 3 connection process, Knocknagreenan and Kippagh Lough are both rated at 70MW. A number of other PHS systems are in various stages of planning[9].

A number of alternate energy storage systems are applicable for large scale energy storage in Ireland[10]. Compressed Air Energy Storage (CAES) works by compressing air into an underground cavern or container in charging mode and releasing this air in generating mode to generate electricity. Efficiencies of up to 54% are achievable for second generation CAES systems[11]. CAES is cheaper than other energy storage systems and is though to provide more opportunities than PHS systems. Natural gas is used in the generating process in current first and second generation CAES plants; however, third generation systems will not need to use natural gas. Gaelectric have identified a suitable site and plan to develop a 150MW CAES plant in Larne, Northern Ireland[12].

Various conventional battery storage systems such as Lead-Acid, Nickel-Cadmium and Sodium-

Sulphur as well as flow battery systems like Vanadium Redox, Polysulphide Bromide and Zinc Bromine are appropriate for large scale electricity storage systems. Efficiencies of up to 95% are achievable[13]. Various flow battery systems have been installed across the world. A feasibility study[14] was carried out with the view to installing a 2MW VRB battery system at Sorne Hill wind farm located in Co Donegal but it is unclear if this will now go ahead. Dundalk IT are currently installing a 125 kW Zinc Bromine Flow Battery Storage system that will work in conjunction with its existing wind turbine. This system is is being installed for research purposes.

Flywheels, Super capacitors, Hydrogen storage systems and plug-in hybrid vehicles are other examples of storage technologies that are applicable for use wind wind energy[15].

1.2 Thesis Outline

The overall goal of this project is to investigate if large scale energy storage can enhance the value of wind energy in Ireland. The value of wind energy can be enhanced in number of ways. Wind energy's biggest problem is its intermittency. Energy storage can possibly help to balance the intermittent nature of wind energy. Wind energy can increase its penetration levels if it becomes more predictable and dependable. Ireland's security of supply can be enhanced if the current dependency on imported fossil fuels can be reduced.

Energy storage can enhance power systems in many ways from low capacity systems(KWh's) that provide power quality control to large capacity systems(GWh's) that can provide frequency control and reserve. This project will focus on large capacity storage systems(50GWh's+). The project will model the Irish electricity system as it currently exists. Increased wind capacities will be introduced and their effects on the system will be analysed. Energy storage will then be added to the system and various storage capacities will be investigated and their effects on the system analysed. Finally the effects that energy storage have on the system will be quantified by completing a generation adequacy assessment on the system. The scope of this project is to investigate if energy storage will increase the value of wind energy and thus decrease the required amount of conventional generation needed in the Irish electricity system. Pumped-hydro storage is the storage technology that is used throughout the analysis in this project.

The initial tasks of the project involved modelling the load profile and wind generation profile of

Ireland. The Transmission System Operator of Ireland, Eirgrid, provides daily load data and wind generation data on its website and this data was used for modelling the system. Wind generation data from 2007, 2008 and 2009 was scaled to generate four wind generation profiles which represent the current installed wind generation capacity(13%), 20%, 40% and 60% penetration levels. The system was analysed with these levels of wind penetration and curtailment levels were found for each scenario. The next step of the project involved introducing energy storage into the models. The models were first analysed with storage that had no control. Various storage operational strategies and control methods were next analysed to try and maximise the value of the energy storage. Optimum storage capacities and ratings were identified for each wind generation scenario.

The final part of the project involved carrying out generation adequacy assessments on the various models. The value that increased wind penetration and energy storage could bring to Ireland is quantified by identifying the amount of conventional generation that is offset by the introduction of these systems.

2 Literature Review

2.1 Introduction

The installed capacity of wind generation in Ireland has grown considerably over the past decade[16]. Ireland currently has an installed capacity of 1,459 MW's of wind generation. The Irish Government has set a binding target of 40% of the countries electricity to be generated from renewable sources by 2020. In order to meet the 40% target set by the government, in excess 3,500 MW's of wind farms will be connected during the gate 3 process. As the penetration of wind energy grows, the problems associated with the variability of wind power become more pronounced.

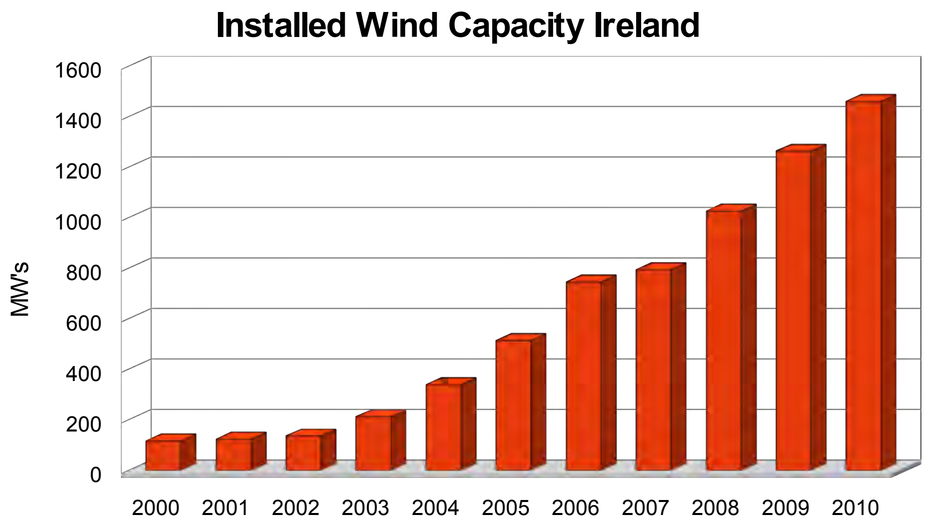

Figure 1: Ireland's installed wind capacity.

2.2 Wind Energy in Ireland

A number of studies have been carried out which investigate the impact that increased wind power penetration will have on the Irish electricity grid. The “All Island Grid Study”[17] carried out by The Department of Communications, Energy and Natural Resources looks at a number of scenarios of increased installed wind capacity in Ireland and how it will effect the electricity system. The study found that an installed capacity of 8000 MW's would provide 47% of Ireland's electricity demand. This level of installed capacity would have a curtailment level of 2.3%. A study by Ronan Doherty et all[18] found that an installed capacity of 3,800 MW's was capable of providing 22% of Ireland's energy demand. It also noted that increasing wind capacity decreases the need for base load generating plant but increases the need for peaking plant. The problems that extreme weather conditions may have on the electricity system as wind penetration increases is considered in [19]. The impact that increased wind penetration will have on reserve requirements and frequency are outlined in [20]. The “Facilitation of Renewables”[3] study indicates that the maximum penetration of wind generation that is advisable to maintain system stability is 60%. This figure is incorporated into the models that are analysed in this project.

2.3 Energy Storage

The variable nature of wind means that it is unlikely that, at any one time, the generated electricity from wind will equal the system demand. This means that there will either be an excess of electricity, at times of high wind and low demand, or a shortfall of electricity, at times of low wind and high demand. Energy storage systems can be used to mitigate this problem. Energy storage systems can store the electricity when there is excess and can provide electricity when there is a shortfall from wind generation.

The storage technologies that area suitable for deployment with wind energy in Ireland are outlined in [21] and [10]. CAES technology is explored in [11]. Pumped-hydro storage (PHS) is though to be the most suitable energy storage technology for use with increased wind generation[22] and there appears to be significant potential for large capacity PHS in Ireland. For these reasons, PHS characteristics are used when modelling energy storage in this project. Large scale PHS operation is outlined in [8]. A significant amount of analysis has been carried out which looks at PHS systems operating in conjunction with wind generation[13, 15, 23-25]. The combined use of PHS and wind in isolated grids is analysed in [22, 26-28]. The sizing of energy storage systems is analysed in [29].

Eirgrid have carried out some studies on the merits of large scale energy storage in Ireland. The Eirgrid Storage Study[30] indicates that large scale storage only brings value to the electricity system as wind penetration exceeds 40%. The “Generation Adequacy Report 2010 – 2016”[1] evaluates the economics of storage in the Irish system. As part of this project I intend to expand on the analysis that Eirgrid have presented and provide a thorough evaluation of the benefits of energy storage to Ireland.

2.4 Generation Adequacy

The final part of the project entails outlining the benefits that storage brings to the Irish electricity system. Reliability indices such as loss of load probability(LOLP) and loss of load expectation(LOLE) are generally calculated on power systems to evaluate whether or not there is sufficient generating capacity on the system. A number of studies have incorporated wind generation into traditional generation adequacy analysis[31-34]. The sliding window technique for calculating LOLP is outlined in [35]. The various approaches for estimating the adequacy of generating systems is analysed in [36]. This thesis analyses both analytical and Monte Carlo methods for modelling the system capacity. Conventional generators are generally modelled as 2 state generators with an associated forced outage rate(FOR). Many generation adequacy assessments consider wind as a negative load for the purposes of analysing the system. Another approach is to model wind generation as a multi state generator with a number of de-rated states. The multi-state approach is outlined in [37-38]. Wind generation will be modelled both as a negative load and using the multi-state approach in the analysis of the models in this project. Generation adequacy analysis was carried out on systems that incorporate energy storage and wind in [39] and [40].

3 System Models

3.1 Load Model

Load data from the Eirgrid website was used to model the load profile. Eirgrid provide quarter-hourly load data on their website. It was decided to use the load data from 2007 as subsequent years are thought to have a skewed load profile due to the economic situation in Ireland. The load data from 2007 is considered to be a typical year[41]. The peak load and total energy consumption for Ireland declined in 2008 and 2009 due to the decline in economic activity. As outlined in the Generation Adequacy Report(GAR) 2010-2016, demand is not expected to return to 2007 levels until 2012. Scaling the load profile to simulate a load profile for 2020 was considered but it was decided that this would provide little benefit to the analysis.

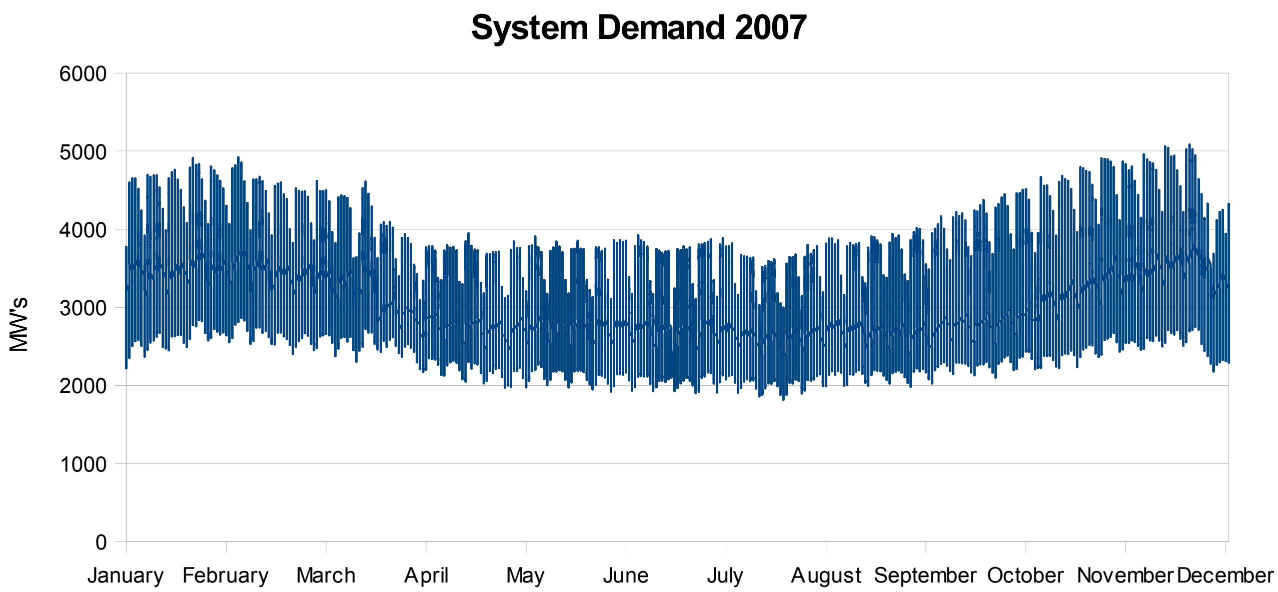

Figure 2: 2007 Load Profile

The load model has a peak demand of 5,085MW's and an average load of 3,246MW's across the year. The total demand for the year is 28.36 terawatt hours(TWh's).

3.2 Wind Generation Model

Quarter-hourly wind generation data is available from the Eirgrid website and this was used to model the wind generation profiles for this project. Data from 2007, 2008 and 2009 is used in the project models. The data for these years have capacity factors of 27.75%, 29.17% and 29.36% respectively. The capacity factor represents the actual amount of electricity generated from wind relative to the maximum possible wind generation for the year.

$$\text{Capacity Factor } 2009 = \frac{\text{Total Wind Generation for year}}{\text{Maximum Possible Wind Generation}} = \frac{3{,}758\, GWh's}{12{,}801\, GWh's} = 29.36\%$$

This data was normalised using the connected wind generation information[42]. As of the 19th of July there is 1,461.36MW's of wind generation connected in Ireland. This represents a penetration level of just over 13%. Wind generation capacities of 1,461.36MW's, 2,250MW's, 4,530MW's and 8,150MW's are modelled for this project. These represent 13%, 20%, 40% and 60% penetration levels.

The recently published “Facilitation of Renewables” report by Eirgrid[3] investigates the maximum penetration levels that wind can achieve without affecting system stability. The report suggests that system stability starts to be affected when penetration exceeds 60% but penetration of up to 80% may be possible. The 60% penetration limitation will be used for the purposes of this project. That means that wind generation can, at most, serve 60% of the load requirement at any given time.

3.3 Storage Model

The energy storage system that is modelled in this project is based on a pumped-hydro storage system. Efficiencies of pumped storage units are in the range of 70-85%[7, 43]. 80% is the generally accepted figure for pumped storage efficiency for analysis of this kind[39-40, 44-45] so it will be used for the purposes of this project. Response times for pumped storage are outlined in [8]. Pumped storage can act as primary reserve with quick response times. This project assumes a large amount of pumped storage capacity and thus a large number of turbines. Operation times are considered to be negligible. The pumping turbines are assumed to be variable speed[46], have no minimum pumping level and can operate in pumping and generating mode from one hour to the next without restriction. The pumped-hydro storage input and output will be restricted to a specified rating value. The capacity of the storage is specified at the beginning of the analysis. It is assumed that the storage facility is full at the beginning of the analysis.

The scale of pumped storage simulated in this project is very large. The Spirit of Ireland group estimate that a 4km x 4km lake would have a capacity in the range of 200GWh's[47]. Pumped storage installation costs are highly variable and site specific[48]. For the purposes of this project the benefits of energy storage will be measured by the amount of conventional generation that is offset by its introduction. This will be analysed in the generation adequacy assessment in the final part of the project.

4 Model Implementation

4.1 System with No Storage

The first stage of analysis consisted of analysing the system with no storage connected. Four wind penetration scenarios of 13%,20%, 40% and 60% are analysed for each of the wind data years. This analysis carried out in Open Office Calc. The maximum penetration level attainable for wind generation is 60% at any given time so any generation above this is curtailed. The curtailment levels are outlined for each of the penetration levels. For this analysis the wind generation profile is subtracted from the load profile to generate a conventional generation profile. This is the load profile that conventional generation will need to meet.

4.2 System with Storage

The storage system was introduced for the next stage of the analysis. The storage was initially analysed with no control. For this part of the analysis it was assumed that the system could operate with 100% wind generation and the efficiency of the pumped storage was set at 80%. The pumped storage operated by 1) storing the surplus energy if the wind power exceeded the load requirement and the storage was not full and 2) by using the stored energy if the wind generation could not meet the load requirement. The results of this analysis display the wind generation used, levels of curtailment, conventional generation required and storage operation. A number of scenarios of storage capacity and rating were investigated for the wind generation scenarios.

The next step was to introduce storage control. The main goal of the storage is to optimise the wind generation and reduce the required amount of conventional generation required. The maximum level of wind generation penetration was set to 60% for this part of the analysis. A number of different storage control scenarios were analysed along with the storage capacity and rating scenarios. Again the results of this analysis outlined the wind generation used by the system, the curtailment levels, the conventional generation required and the storage operation. This analysis gives a good overview of how the pumped storage will operate over the year. The value that the pumped storage adds to the system is analysed in the next section.

4.3 Generation Adequacy Assessment

Reliability evaluation of electricity systems is generally considered to have a 3 level hierarchical structure. Hierarchical level 1(HLI) reliability evaluation is concerned with the generation capacity evaluation of the electricity system. This is know as generation adequacy assessment. Hierarchical level 2(HLII) reliability evaluation is concerned with the transmission of electricity in the system. HLII assessment evaluates the ability of the transmission network to deliver electricity to load centres. Hierarchical level 3(HLIII) reliability evaluation is concerned with the ability of the distribution system to deliver energy to customers.

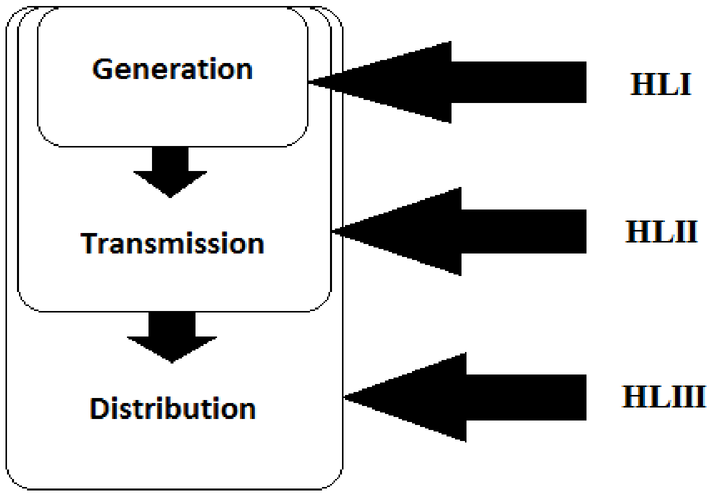

Figure 3: Hierarchical Level of Reliability Evaluation

The final part of the analysis consists of conducting a generation adequacy assessment(HLI) on the models to estimate the value that the pumped storage brings to the system. This analysis was carried out using a combination of Matlab and Open Office Calc. Generation adequacy assessments are carried out by system operators to assess whether or not there is enough generation capacity on the system to cope with expected loads requirements. System operators need to ensure that there is sufficient generation capacity on the system to cope with peak loads and to ensure that there is sufficient generation capacity in case some plant is out on maintenance or has suffered an unexpected breakdown. System operators forecast future load requirements and carry out generation adequacy assessments to plan for future system capacity requirements.

Generation adequacy assessments are performed using a number of different techniques. Analytical and Monte Carlo methods appear to be the most common techniques used to evaluate generation adequacy. Analytical methods combine the load model and generation model to determine the adequacy of the system. The load model is generated using average hourly load data from previous years to generate the load profile for the required year. This profile is scaled to emulate the predicted load model for the year of analysis. The GAR 2010-2016[1] uses half hourly data while this project will use quarter-hourly data to generate the load model.

The generation model for conventional generation consists of two indices, the generator capacity and the generator forced outage rate(FOR). Every generator has the possibility of being unable to generate due to an unexpected event such as a breakdown. The proportion of time that a generator is unable to generate due to an unexpected event is know as the forced outage rate(FOR). Every generator has an associated FOR and because of this the generation capacity can never be 100% certain that it can supply the required load. A number of generators may fail simultaneously and therefore the load requirement may not be met for a certain period. The Loss of Load Probability(LOLP) is the probability that the generation capacity cannot meet the required load for a certain period. The Loss of Load Expectation(LOLE) is the expected time that the load is expected to suffer a loss of load.

$$LOLP = Pr(G < L)$$

where

$Pr -$ *probability*
$G -$ *available generation*
$L -$ *Load*

$$LOLE = LOLP \ x \ Time$$

The LOLP is calculated for any given moment in time. LOLE is the cumulated time that a loss of load is suffered. LOLE is generally used to assess the generation adequacy of a power system. The “1 day in 10 years” metric is often used as the benchmark LOLE for a system to have adequate generating capacity[49]. Eirgrid uses 8 hours a year as its standard of LOLE in Ireland. This does not mean that an outage of 8 hours a year is expected, it is the total accumulated time where a loss of load is expected. Eirgrid considers that there is excess generating capacity on the system if the LOLE is under 8 hours a year and conversely that there is insufficient generating capacity on the system if the 8 hours standard is exceeded.

There are a number of methods used to calculate the LOLE for a system. The “Stacking” or recursive method as outlined in [50] will be used for the purposes of this project. The “stacking” method is used to generate the generating units Capacity Outage Probability Table(COPT). Generating systems generally consist of a number of different generators with various generating capacities and FOR's. Generators can generally operate at various output states but for the purposes of generating the COPT generators are assumed to have two operating states,full output or zero output. The COPT is created by first considering a single generator.

Available capacity, MW	Outage capacity, MW	Exact probability, P_i	Cumulative probability, P
c	0	$1- q$	1
0	c	q	q

Figure 4: COPT with a single generating unit

Where

c is the generation units capacity

q is the forced outage rate(FOR)

A second generator is then added to the system and the COPT is recalculated. The process is repeated until all of the generators in the system are added and the final COPT is obtained. A Matlab program provided in [51] was used to generate the COPT for this project. The Matlab code can be fount in the appendix section of this report.

Below is an example of a generation system with 3 generators.

	Capacity (MW)	FOR (%)
Generator 1	100	5
Generator 2	150	4
Generator 3	50	8

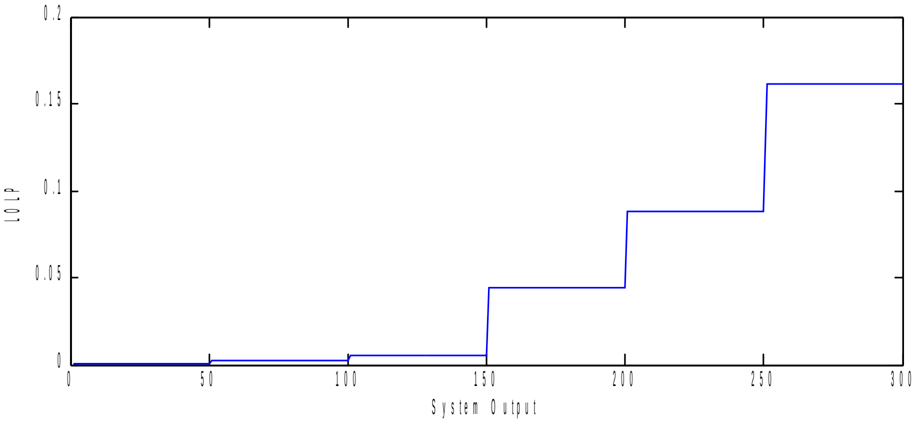

Figure 5: Loss of Load Probability Curve

System Output	LOLP
<50	1.60E-004
50 - 100	2.00E-003
100 – 150	5.04E-003
150 – 200	4.38E-002
200 – 250	8.80E-002
250 -300	1.61E-001

Figure 6: COPT for system with 3 generators

The COPT table is used along with the load profile to calculate the LOLE. For each specific hourly load value there is a corresponding LOLP value.

Time	Load (MW)	LOLP
01/01/09 00.00	178	4.38E-002
01/01/09 01.00	160	4.38E-002
01/01/09 02.00	148	5.04E-003
01/01/09 03.00	145	5.04E-003
01/01/09 04.00	175	4.38E-002
01/01/09 05.00	201	8.80E-002

Figure 7: LOLE example

There will be 8,760 LOLP values, each one corresponding to the load value for an hour of the year. These 8,760 values are summed together to get the LOLE for the system.

The program for generating the COPT table was tested for its reliability by calculating the LOLE for the IEE Reliability Test System(IEE RTS)[52] using the load profile for Ireland. The load profile for the Irish system for 2007 was scaled to have a peak load equivalent to that of the IEE RTS. The IEE RTS system has a peak load of 2,850MW. The IEE RTS modelled with the Irish load profile had a LOLE of 9.2 hours. This calculation compares favourably with the calculation of the system using the IEE RTS load profile which was found to be 9.37 hours[53]. This shows a 1.85% difference between calculated values for LOLE. Therefore we can conclude that the load profile used in this analysis is a typical load profile and that the Matlab program used is accurate.

For this project the generating capacity model for Ireland needed to be developed in order to generate the COPT. Information on the current connected generators in Ireland[54] was used to model the system. As of the 5th March 2010 there was 6,399.9MW's of generation capacity, excluding wind generation, on the Irish system which consists of 6,178.3MW's connected at the transmission network level and 221.6MW's connected at the distribution network level. Initially the system was modelled consisting of the generators connected at the transmission network level. The LOLE was calculated for this model and was found to be 0.1704 hours for the year. The GAR 2010-2016 indicates that there is almost 1,000MW's of surplus generation capacity on the Irish system currently. This is mostly down to the fact that demand was forecast to continue to increase and additional plant was added to the system to meet this. The slump in demand from 2008 onwards was not forecast and so there is surplus generating capacity on the system.

A generation portfolio that has a LOLE of close to the 8 hours a year standard will be used in this project. To achieve this some generation plant was removed from the generation portfolio. The six generation plant's that were removed from the portfolio were the four Tarbet plants and Great Island 1 and 2. The GAR 2010-2016 indicates that these plant are soon to be decommissioned so they were the first to be removed from the portfolio. This leaves the generation portfolio with 43 generating plants which have a total generation capacity of 5,480.9MW's. The forced outage rates(FOR) for the generation plants in the portfolio were given in [55]. The COPT was generated for the generation portfolio and it was found to have a LOLE of 9.05 hours for the year. This is considered to be sufficiently close to the 8 hour standard so this generation portfolio will be used as the base case for this project. The generation portfolio can be seen below. The plant that is expected to be decommissioned by 2020 are outlined. These generation plants will be the first to be removed in the following analysis.

Plant No	Station	Capacity(MW)	FOR	Decomissioned By 2020
1	Aghada1	258	0.0500	
2	Ardnacrusha1	22	0.0100	
3	Ardnacrusha2	22	0.0100	
4	Ardnacrusha3	21	0.0100	
5	Ardnacrusha4	21	0.0100	
6	Aughinish	130	0.0300	
7	Carrigadrohid	8	0.0100	
8	Cath Fall1	22.5	0.0100	
9	Cath Fall2	22.5	0.0100	
10	Cliff1	10	0.0100	
11	Cliff2	10	0.0100	
12	Huntstown2	412	0.0200	
13	Cushaling	121.5	0.0500	
14	Rhode1	51.8	0.0665	
15	Rhode2	51.8	0.0665	
16	Huntstown1	352	0.0300	
17	Lee Hydro1	15	0.0100	
18	Lee Hydro2	4	0.0100	
19	Dublin Bay	415	0.0200	
20	Marina	112.3	0.0500	
21	Moneypoint1	287.5	0.0500	
22	Moneypoint2	287.5	0.0500	
23	Moneypoint3	287.5	0.0500	
24	Pollaphuca1	15	0.0100	
25	Pollaphuca2	15	0.0100	
26	Pollaphuca3	4	0.0100	
27	West Offaly	141	0.0500	
28	Poolbeg4	460	0.0500	
29	Turlough Hill1	73	0.0100	
30	Turlough Hill2	73	0.0100	
31	Turlough Hill3	73	0.0100	
32	Turlough Hill4	73	0.0100	
33	Tynagh	404	0.0360	
34	Lough Ree	94	0.0500	
35	Aghada2	90	0.0350	D
36	Aghada3	90	0.0350	D
37	Aghada4	90	0.0350	D
38	Great Island3	108	0.0900	D
39	North Wall1	163	0.0500	D
40	North Wall2	109	0.0350	D
41	Poolbeg1	109.5	0.1000	D
42	Poolbeg2	109.5	0.1000	D
43	Poolbeg3	242	0.1200	D
	Total Capacity	5480.9		

Figure 8: Generation Plant Portfolio

Next we need to consider the addition of wind energy to the generation adequacy assessment. One technique is to consider wind generation as a load modifier. This is the technique used by Eirgrid in the Generation Adequacy Reports. This technique involved subtracting the wind profile from the load profile to generate an alternative load profile. This lower demand load profile is then analysed in the same way as shown previously.

Another popular technique is to model wind generation as a multi-state model with a number of de-rated output states. While it is acceptable to model conventional generation as a 2 state model, wind generation has to be considered differently as wind turbine output cannot be maintained at a specific stable level due to wind speed variability. Wind generation therefore needs to be modelled as a multi-state model. The multi-state model can be developed by using the wind power duration curve. Each output state of the multi-state model will have an associated probability.

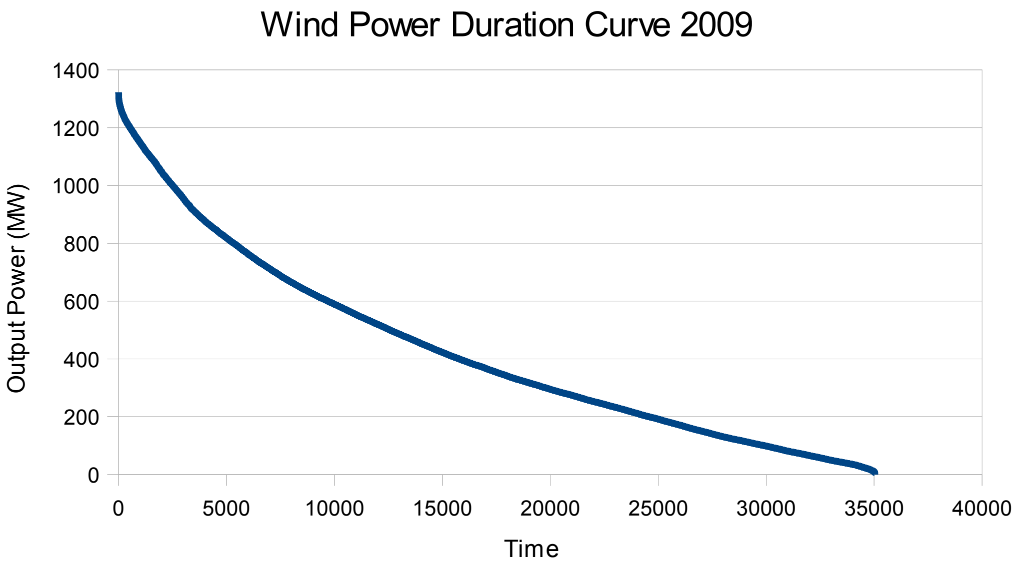

Figure 9: Wind Power Duration Curve

The above wind power duration curve is for 2009. The time on the x-axis represents the 35,040 quarter-hourly wind power output's for the year 2009. From this plot we can develop the multi-state model for wind generation. The rounding method for simplifying the multi-state model is discussed in [38]. The wind power duration curve is divided into suitable power output bands and the probability that the wind power will be generating at that power band is calculated. Simplified multi-state models and the appropriate number of output band states is discussed in [31]. Below is a simplified example of a multi-state model for the above wind power output curve with 6 output state bands.

Output (MW)	Probability
0	0
300	0.44
600	0.29
900	0.17
1200	0.09
1500	0.02

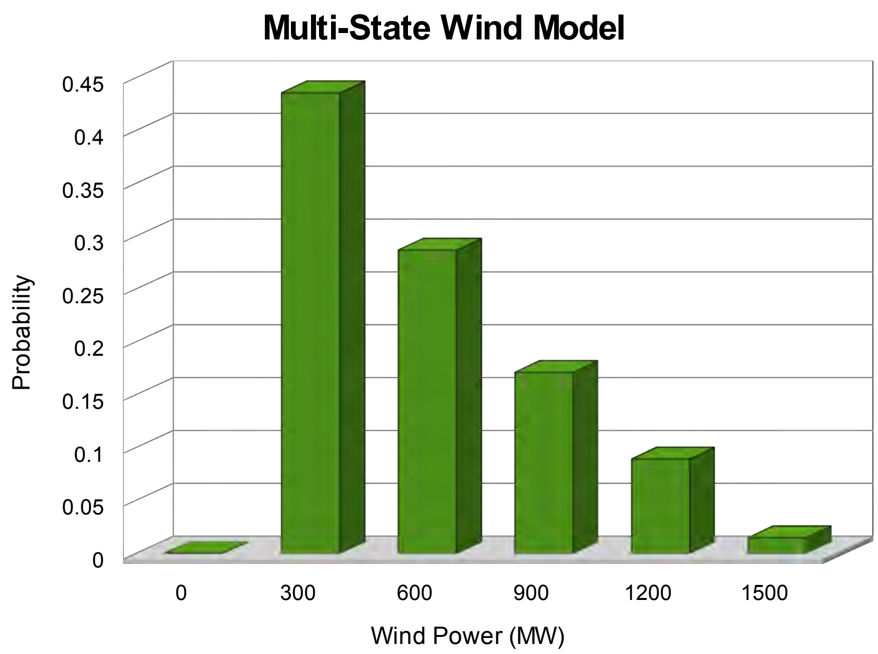

Figure 10: 6 Step Multi-State Wind Power Model

The multi-state models in this project will consist of bands of 50 – 100MW's depending on the wind generation capacity. This multi-state model is combined with the generation portfolio and a new COPT is generated to simulate the system with wind power. The LOLE is then calculated in the same way as previously described. The wind power data used in this project already incorporates forced outages and maintenance outages. For the purposes of this project, both the load modifier technique and the multi-state model technique will be used in the analysis.

The final part of the analysis is to incorporate the storage into the generation adequacy assessment. The load modifier technique and the multi-state model technique will be modified and incorporated into the generation adequacy assessment. The load modifier technique can easy incorporate the storage system into the model. The storage analysis generates a "Conventional Generation" profile for each combination of scenarios analysed. This "Conventional Generation" profile is the power that conventional generation has to contribute to the system i.e. the load profile for conventional generation. This load profile will be analysed like previously done for the system with no wind generation or storage. Generators will be taken out of the generation portfolio one at a time until the LOLE of the system is equal to that of the system with no wind power or storage. The amount of generation taken out of the generation portfolio will indicate the value that wind generation and energy storage have brought to the system.

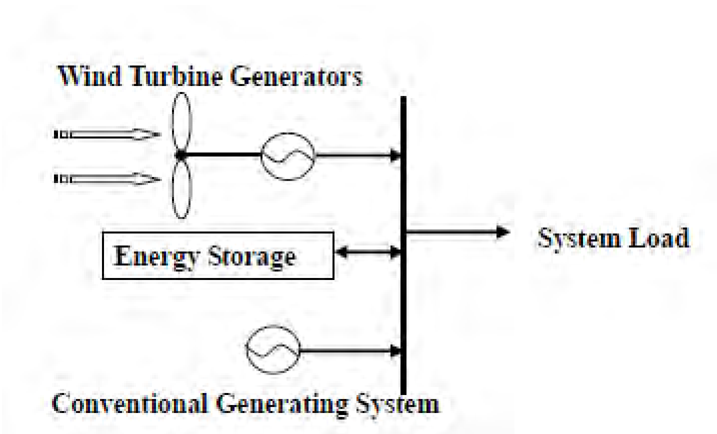

Figure 11: Model of System with Energy Storage

The multi-state model for wind power and storage will be similar to the model with just wind power. If the energy storage has sufficient energy to generate at full load and is not in pumping mode then the rating of the energy storage will be added to the generated wind power for that hour. If the energy storage is in pumping mode then the energy used by it will be subtracted from the wind profile for that hour. A Wind-Energy Storage hybrid power duration curve will be developed and a multi-state Wind-Energy Storage model will be generated like previously done for the system with just wind energy.

5 System Analysis

5.1 System with no Storage

The first model to be analysed was the model of the system with conventional generation and wind generation. Four scenarios of wind generation penetration of 13%, 20%, 40% and 60% were simulated for the years 2007, 2008 and 2009. Installed wind generation capacities of 1,461.36MW's(Wind 1), 2,250MW's(Wind 2), 4,530MW's(Wind 3) and 8,150MW's(Wind 4) were needed to achieve the stated penetration levels. For these penetration levels to be achieved from the stated installed capacities it was assumed that the electricity system could run with 100% wind generation.

	2007	*2008*	*2009*
Wind 1	12.49%	13.13%	13.22%
Wind 2	19.24%	20.22%	20.35%
Wind 3	38.00%	39.97%	40.07%
Wind 4	56.98%	60.13%	60.16%

Figure 12: Wind Penetration Levels (100% wind)

The 60% maximum wind penetration scenario was now introduced and the penetration levels were recalculated. This means that wind generation can only account for 60% of the load requirement at any one time.

	2007	*2008*	*2009*
Wind 1	12.49%	13.13%	13.22%
Wind 2	19.16%	20.13%	20.23%
Wind 3	32.78%	34.64%	34.32%
Wind 4	42.33%	44.38%	44.72%

Figure 13: Wind Penetration Levels (60% wind)

We can see from the above that wind generation is unaffected by the 60% maximum wind constraint until the penetration level reaches 20%. As you would expect, the “Wind 4” scenario is greatly affected by the introduced constraint. This 60% maximum wind constraint will be applied to all of the following analysis unless stated otherwise.

Below an example of the system operation across the year can be seen in Figure 14. Figure 15 shows the operation of the system for week 1 of the year. In both of these plots the contributions of wind generation and conventional generation to meet the load requirements are illustrated.

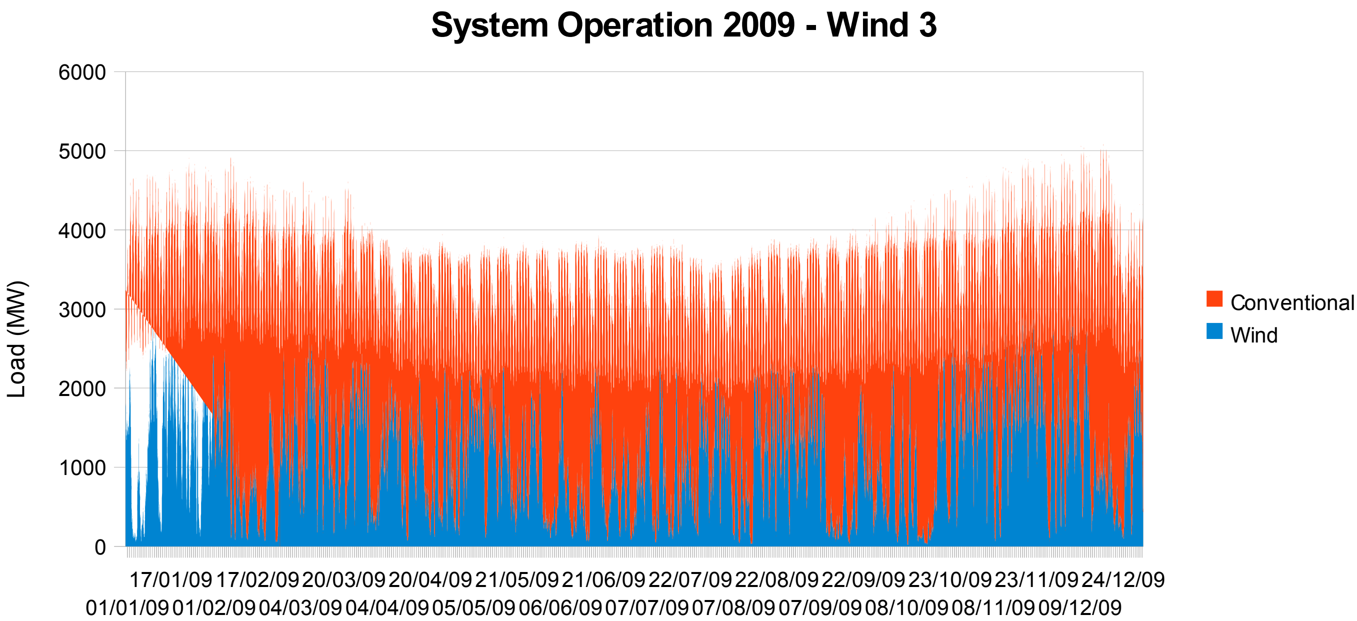

Figure 14: System Operation for 2009 – Wind 3

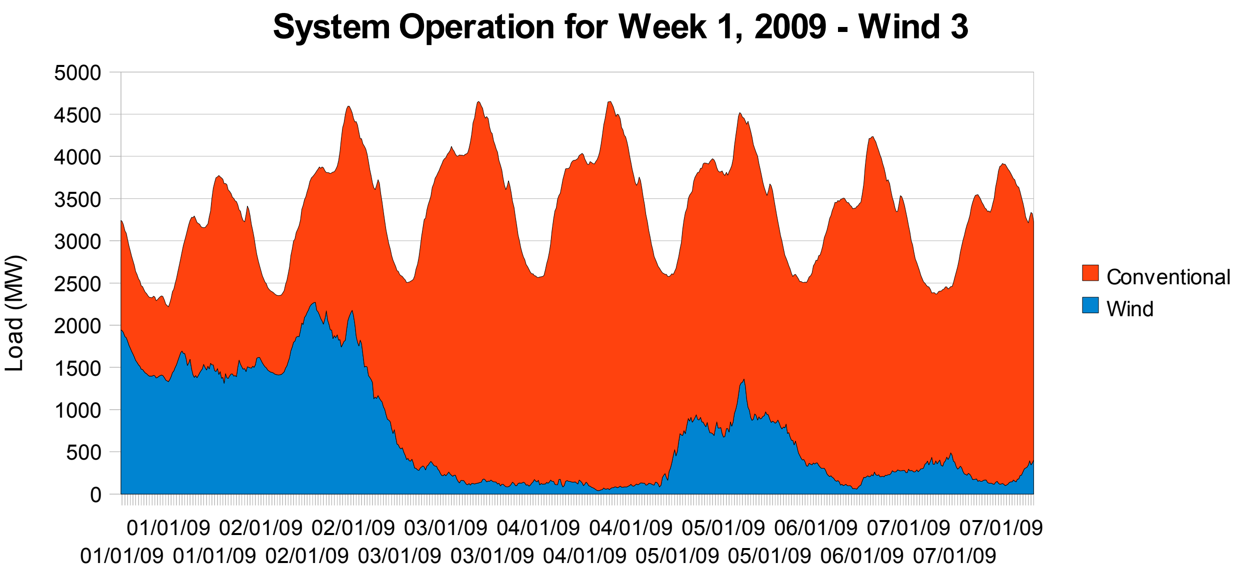

Figure 15: System Operation for Week 1, 2009 – Wind 3

Finally the curtailment levels associated with the wind penetration scenarios were calculated. We can see that there is very little curtailment on the system up until the penetration level exceeds 20%. The 60% penetration scenario(Wind 4) has an excessive amount of curtailment associated with it.

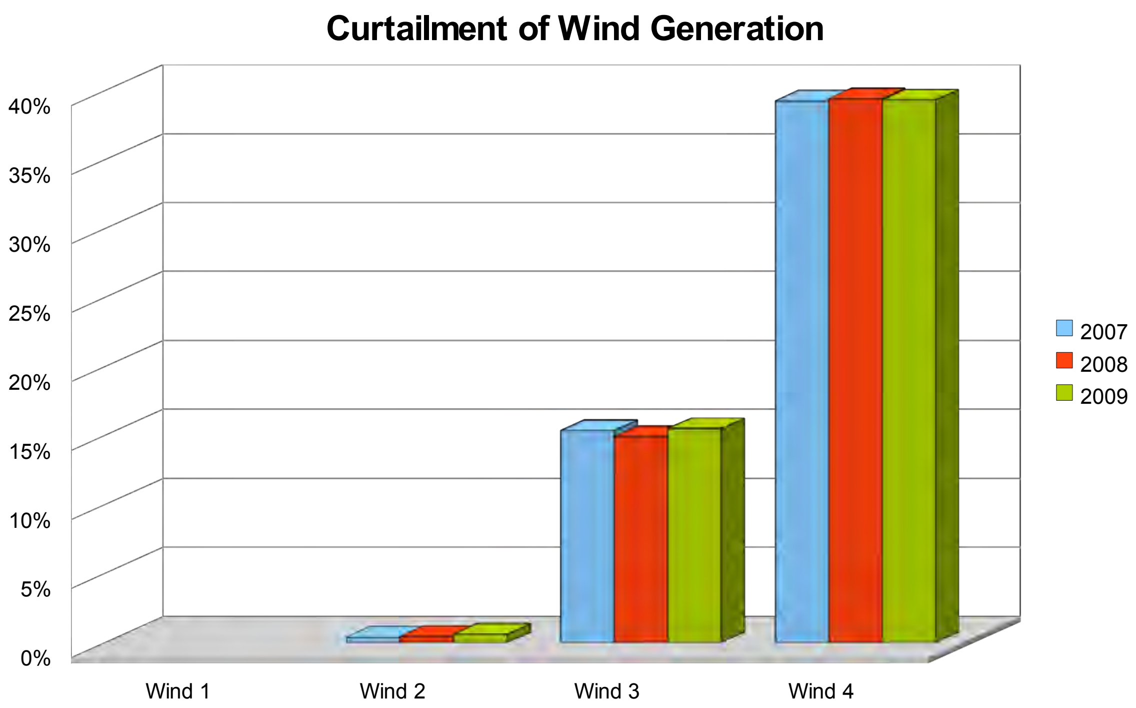

Figure 16: Curtailment of Wind Generation

5.2 System with Pumped-Hydro Storage

The next step of the analysis involved introducing the storage system to the models. The storage that was initially introduced had no associated control characteristics. The storage operated by the following rules; 1) The surplus energy is stored if the wind power generation exceeds the load requirement and the storage is not full and 2) The stored energy is used if the wind generation could not meet the load requirement and the energy storage is not empty. For this initial analysis of the storage system it is assumed that the system can operate with 100% wind generation. The first task was to find the optimal storage rating for the storage system. For this the storage capacity was fixed at 200,000GWh's and the rating value was changed to find the optimal storage rating for each wind generation scenario.

The first scenario to be analysed was the “Wind 1” scenario. The Wind 1 scenario corresponds to the current installed wind generation capacity in Ireland of 1,461.36MW's.

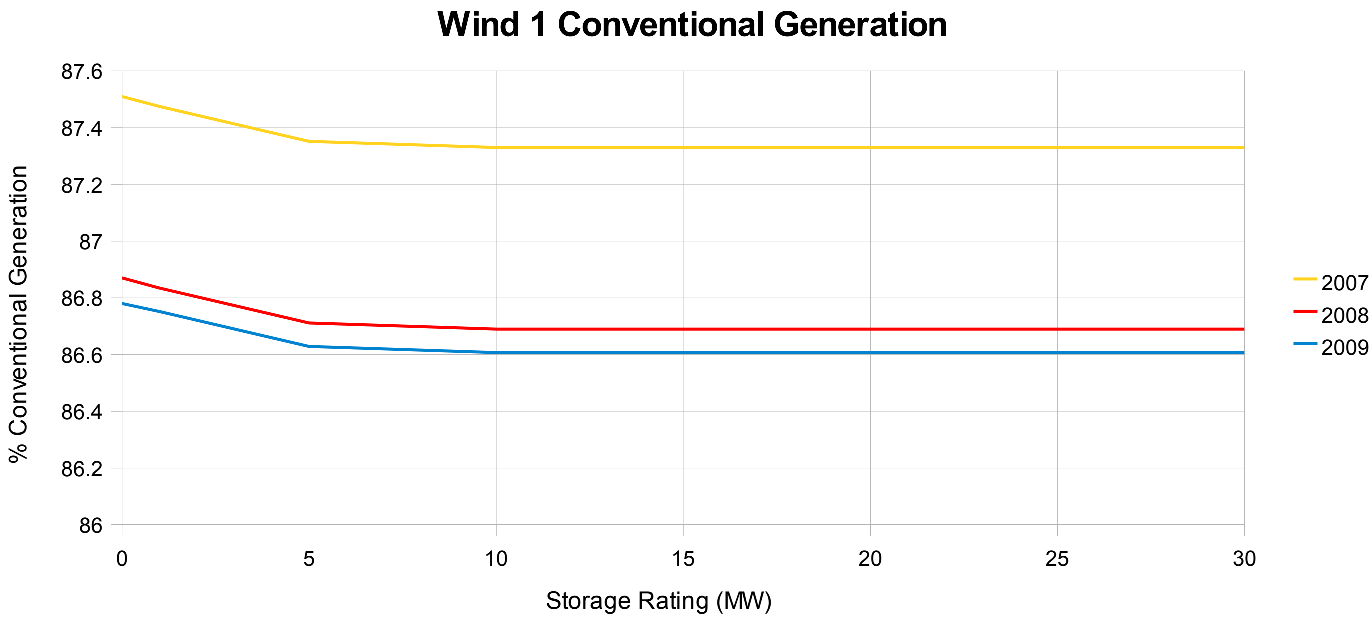

Figure 17: Storage Rating Analysis for the “Wind 1” Scenario

Figure 17 plots the contribution that conventional generation supplies to the load requirement. We can see that as the the storage rating increases the contribution that conventional generation supplies to the load decreases. This value levels off as the storage rating approaches 10MW and larger storage ratings provide no further benefit to the system. It can be concluded that 10MW is the optimal storage rating for the “Wind 1” scenario. The “0” storage rating corresponds to the system with no storage. It can be seen that the introduction of storage to the system reduces the amount that conventional generation contributes to the system by approximately 0.2%.

In figure 18 the “Wind 2” scenario is analysed. Here it can be seen that the optimal storage rating is also 10MW. The introduction of storage to this scenario reduces the contribution of conventional generation by 0.21%.

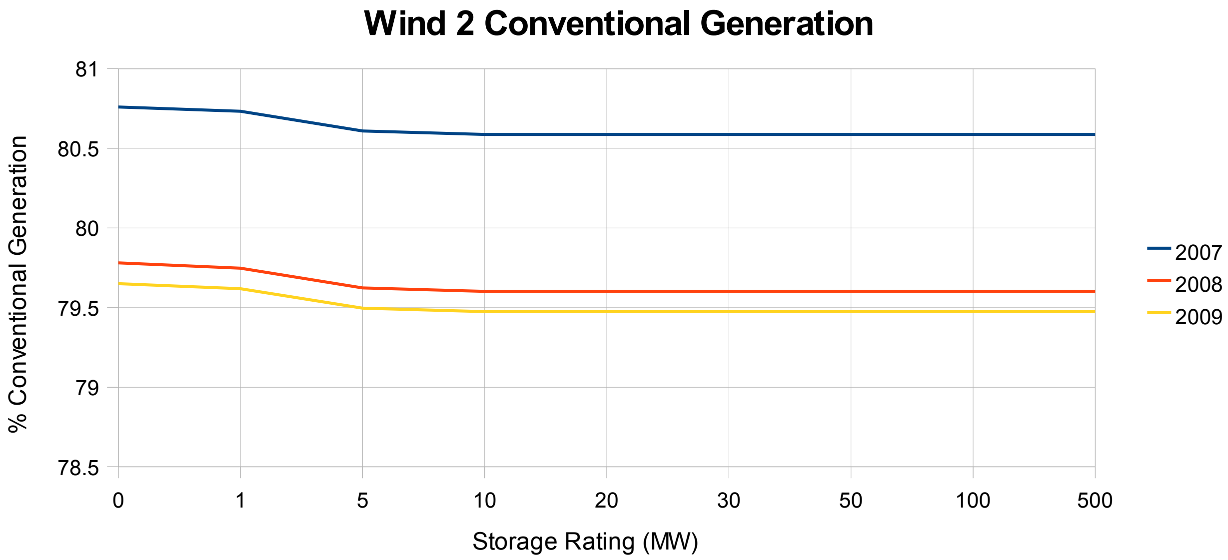

Figure 18: Storage Rating Analysis for the "Wind 2" Scenario

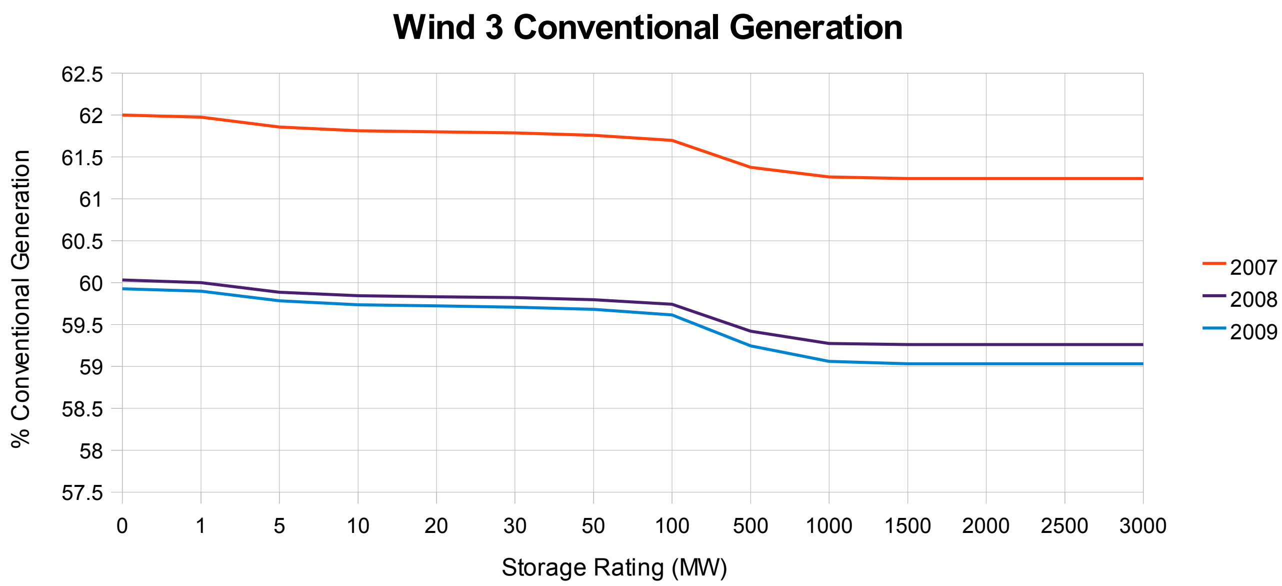

Figure 19: Storage Rating Analysis for the "Wind 3" Scenario

Figure 19 analyses the "Wind 3" scenario. Here it can be seen that the optimal storage rating is reached at about 1500MW. The introduction of storage to this scenario reduces the contribution of conventional generation by between 0.76% and 0.9%.

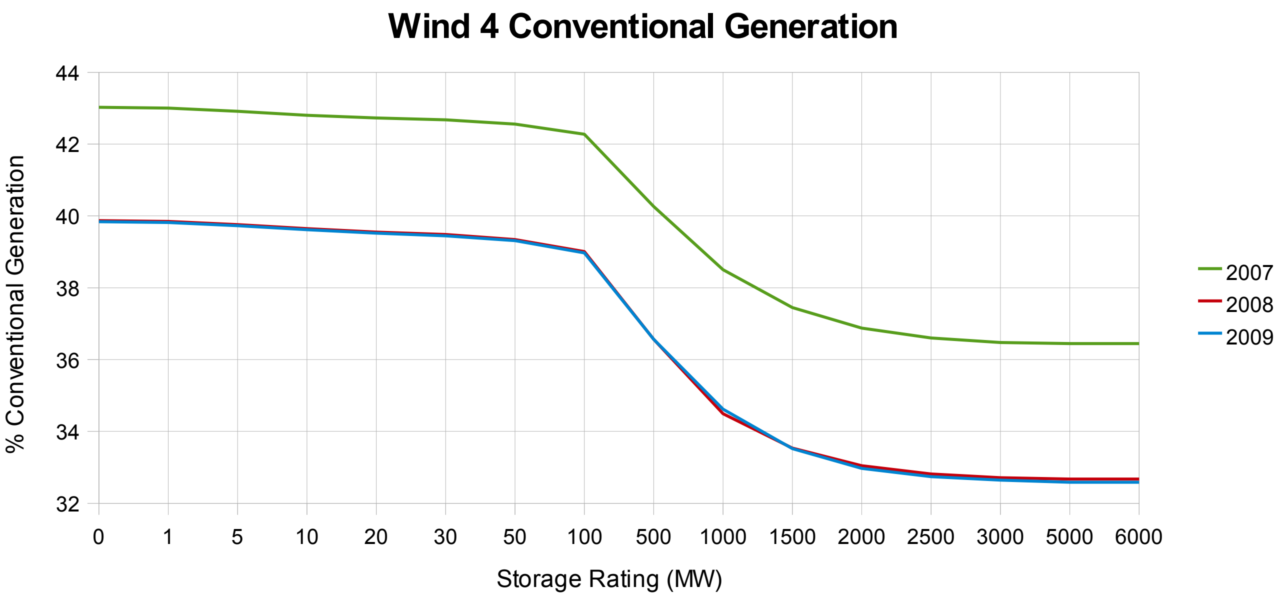

Figure 20: Storage Rating Analysis for the "Wind 4" Scenario

Figure 20 shows the analysis of the "Wind 4" scenario. Here it can be seen that the optimal storage rating is reached at 3000MW's. The introduction of storage to this scenario reduced the contribution of conventional generation to the load requirement by between 6.58% and 7.25%.

From the above analysis it can be seen that the introduction of storage starts to make a big contribution to the system as the penetration on wind increases(>40%). Storage contributes little to the system at low levels of penetration(<20%). The system was analysed with each wind scenario combined with its optimal storage rating. Each storage unit has a capacity of 100 hours at peak load. The analysis for 2009 is shown in figure 21. The percentage of load that each component met is displayed.

	Wind 1	*Wind 2*	*Wind 3*	*Wind 4*
Wind	13.22%	20.35%	40.07%	60.16%
Conventional	86.77%	79.64%	59.08%	32.97%
Storage	0.01%	0.01%	0.85%	6.86%

Figure 21: System Analysis 2009

The 60% penetration limit on wind generation was reintroduced to the analysis. The system was again analysed with no control features but with the 60% wind penetration limit reimposed. The results for 2009 can be seen in figure 22. It can be seen that there is little of no effect on the “Wind 1” and “Wind 2“ scenarios. The conventional generation required by the system increases slightly for the “Wind 3” scenario. The contribution that the storage makes to the system increases significantly while the direct wind contribution decrease as would be expected. There is a significant increase in the conventional generation required by the system under the “Wind 4” scenario. The direct wind generation contribution decreases while the contribution from the storage system increases.

	Wind 1	Wind 2	Wind 3	Wind 4
Wind	13.22%	20.23%	34.62%	44.72%
Conventional	86.77%	79.76%	59.78%	45.02%
Storage	0.01%	0.02%	5.60%	10.26%

Figure 22: System Analysis 2009 with 60% constraint introduced

Control features were then introduced to the storage system. The control features were introduced to optimise the operation of the storage. The control features aim to maximise the wind generation by minimising curtailment and also minimising the conventional generation needed on the system. It is also important to try to minimise the peak level of generation required by the conventional generation as this has a large bearing on the generation adequacy assessment. The main control features that were introduced aim to maximise the energy contained within the storage facility once a threshold storage capacity has been reached. The storage continues to operate normally once the storage capacity is above this threshold level. The system control comes into operation when the storage capacity level drops below X% of full capacity. When this happens the storage control prioritises the charging of the storage. Y% of the load is then satisfied by the wind generation and the remaining wind generation is used to charge the storage facility. The aim of this control feature is to satisfy a certain percentage of the load requirement whilst also charging the storage facility which has been depleted.

The minimum storage threshold(X) was initially set to the same figure as the storage capacity so the optimal value of (Y) could be found. The "Wind 1" and "Wind 2" scenarios were ignored for this analysis as it has been seen previously that energy storage has little effect on the operation of these models.

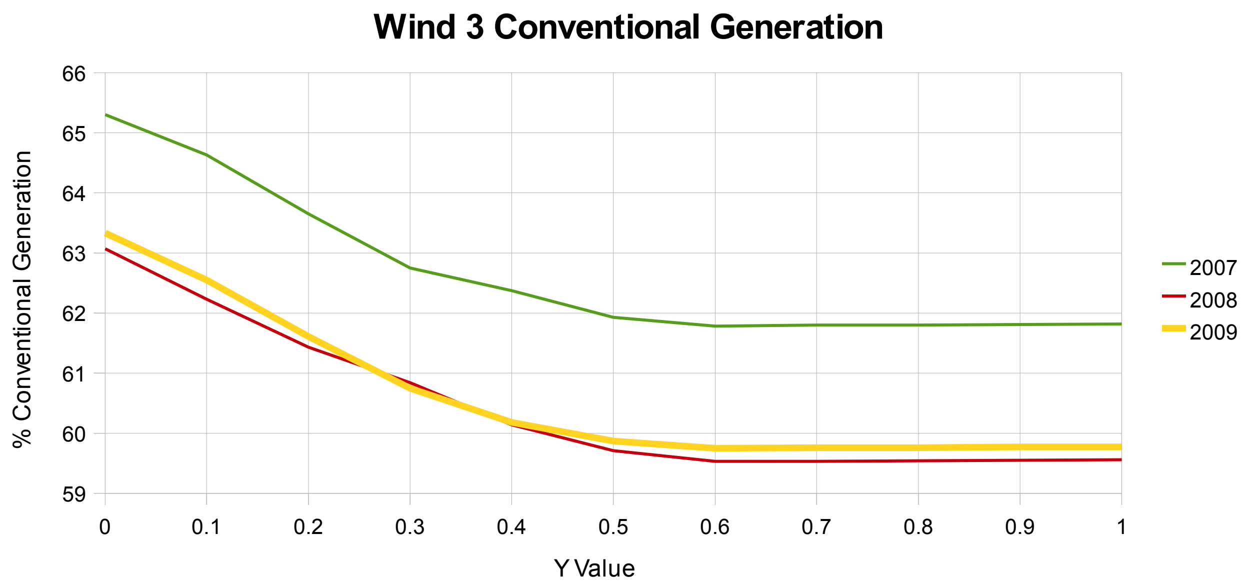

Figure 23: Estimation of Optimal "Y" Value (1-Wind 3)

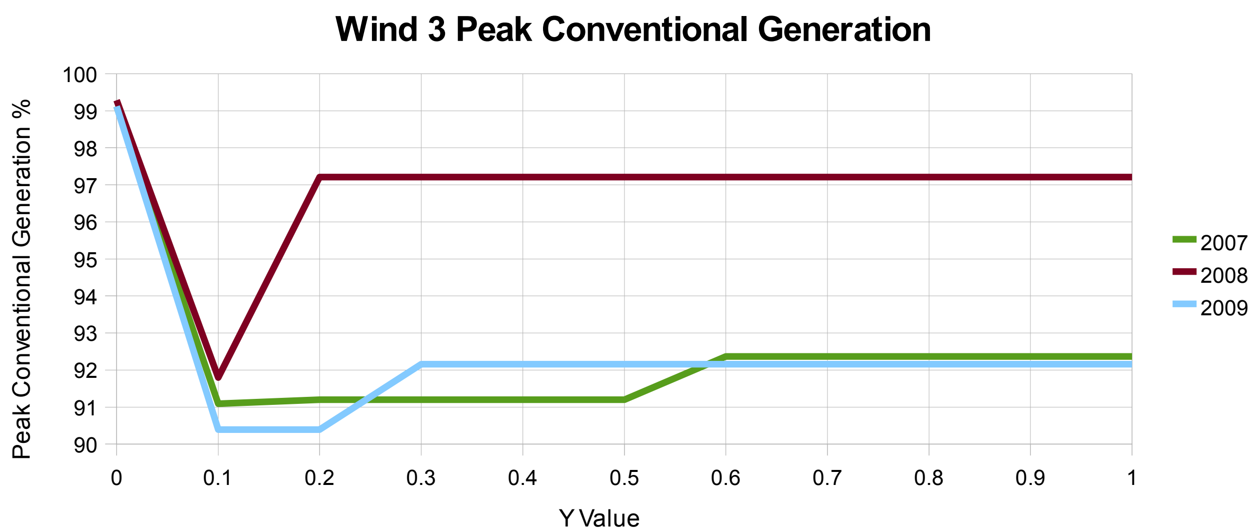

Figure 24: Estimation of Optimal "Y" Value (2 –Wind3)

Figures 23 and 25 illustrate the contribution that conventional generation makes to the system with varying “Y” values. In both “Wind 3” and “Wind 4” scenarios the optimal “Y” value from the perspective of offsetting conventional generation is 0.6. This 0.6 value represents 60% of the load requirement being met by the generated wind while the remaining 40% concentrates on charging the storage facility. Figures 24 and 26 illustrate the peak conventional generation value as a percentage of the total load requirement across the year as the “Y” value varies. The optimal “Y” value is less clear from this viewpoint. The peak conventional generation point is dependant on the peak load and the wind generation and storage states so is not directly affected by the “Y” value. The 0.6 optimal “Y” value as observed from the conventional generation plots is acceptable to provide an optimal peak generation value.

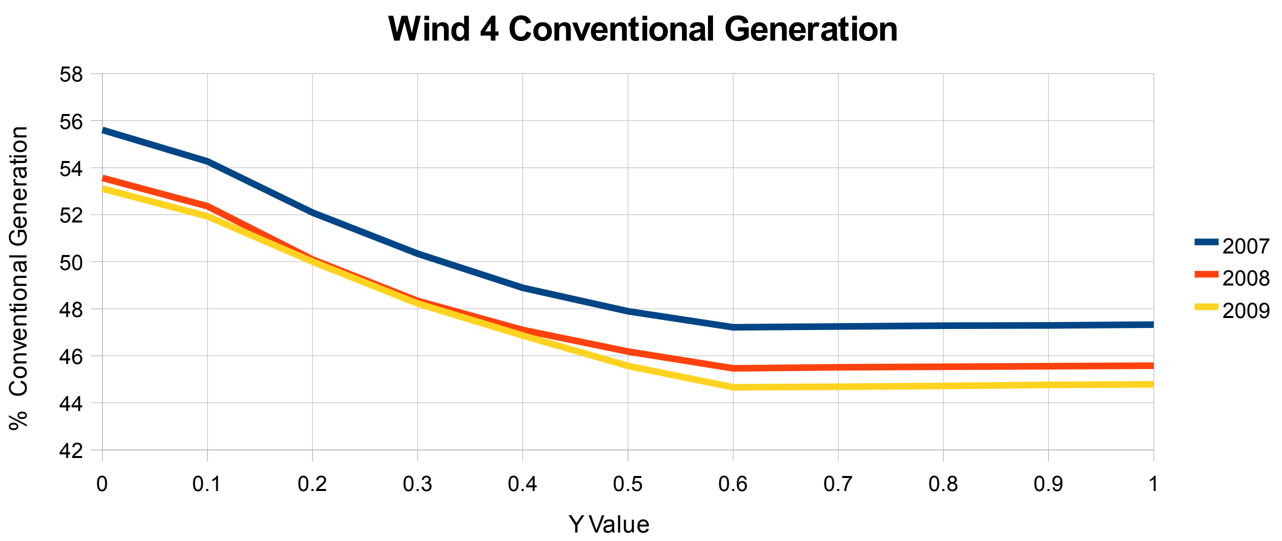

Figure 25: Estimation of Optimal “Y” Value (1-Wind 4)

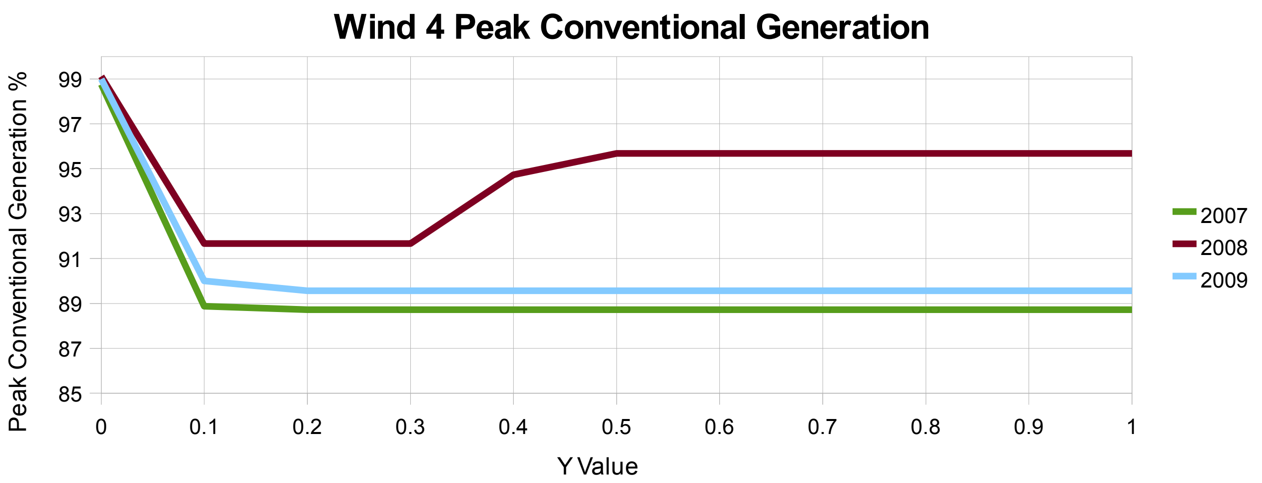

Figure 26: Estimation of Optimal “Y” Value (2-Wind 4)

The optimal minimum storage capacity threshold value(X) was next to be calculated. It was found that for all wind penetration scenarios that the optimal value of "X" was the maximum storage capacity value that had been used in the previous analysis to find the optimal "Y". The conventional generation contribution to the system increased linearly as the value of "X" was decreased. The value of "X" has no bearing on the peak conventional generation value. An example of the operation of the system with wind generation scenario "Wind 3" and storage with control for the month of January can be seen in Figure 27. Figures 28 and 29 plot the storage facility capacity level and the curtailment for January 2009 also.

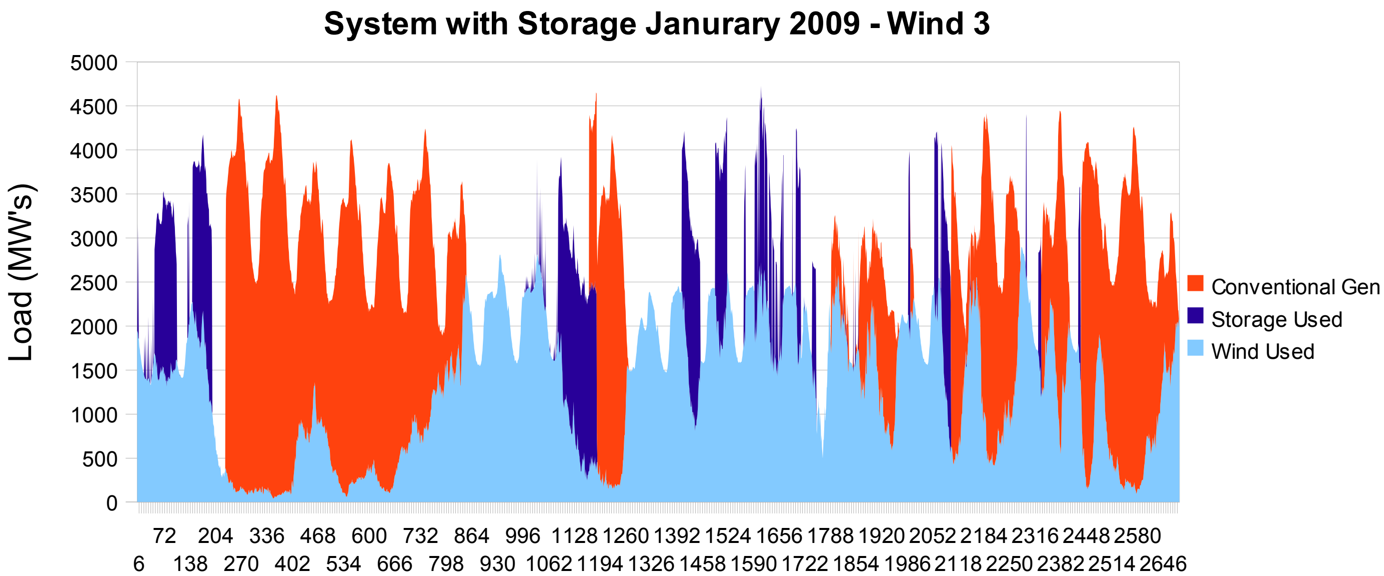

Figure 27: System operation example

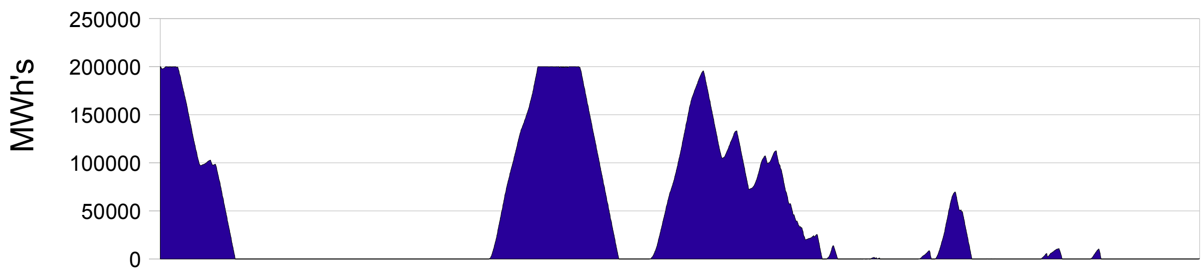

Figure 28: Reservoir Capacity Level January 2009 – Wind 3

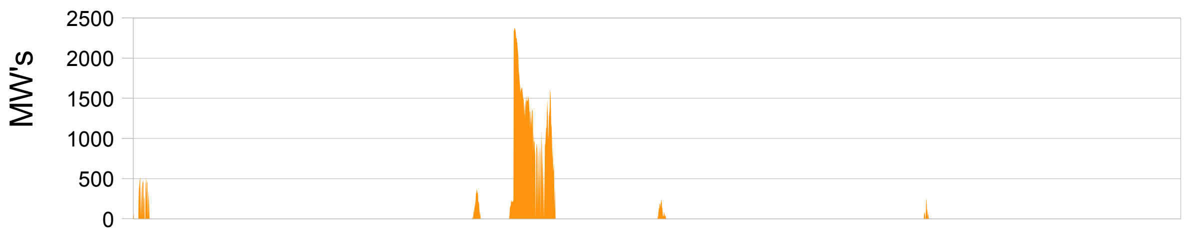

Figure 29: Curtailment Level January 2009 – Wind 3

The models of system with storage were then compared with the models of the system with wind generation and no storage to evaluate the value that storage brings to the system. The configurations of storage rating and capacity are outlined in figure 30.

	Wind 1	Wind 2	Wind 3	Wind 4
Storage Rating (MW's)	10	10	2000	2000
Storage Capacity (MWH's)	1000	1000	200000	200000

Figure 30: Storage Configuration

		Wind 1 (%)	Wind 2 (%)	Wind 3 (%)	Wind 4 (%)
2009					
Wind Only:	Conventional Generation	86.78	79.77	65.68	55.28
	Wind	13.22	20.23	34.32	44.72
Wind + Storage:	Conventional Generation	86.61	79.47	59.75	44.66
	Wind + Storage	13.39	20.53	40.25	55.34
2008					
Wind Only:	Conventional Generation	86.87	79.87	65.36	55.62
	Wind	13.13	20.13	34.64	44.38
Wind + Storage:	Conventional Generation	86.69	79.6	59.53	45.47
	Wind + Storage	13.31	20.4	40.47	54.53
2007					
Wind Only:	Conventional Generation	87.51	80.81	67.22	57.67
	Wind	12.49	19.19	32.78	42.33
Wind + Storage:	Conventional Generation	87.33	80.59	61.78	47.21
	Wind + Storage	12.67	19.41	38.22	52.79
	Average % Increase in Wind Generation	1.38%	1.28%	16.90%	23.78%

Figure 31: Comparison of system with and without storage

Curtailment Levels		Wind 1	Wind 2	Wind 3	Wind 4
	2009				
	Wind Only:	0%	0.61%	15.50%	39.34%
	Wind + Storage:	0%	0%	1.97%	24.98%
	2008				
	Wind Only:	0%	0.44%	14.92%	39.41%
	Wind + Storage:	0%	0%	1.02%	25.56%
	2007				
	Wind Only:	0%	0.40%	15.36%	39.26%
	Wind + Storage:	0%	0%	1.77%	24.39%

Figure 32: Curtailment levels with and without storage

It can be seen from Figures 31 and 32 that storage adds considerable value to the "Wind 3" and "Wind 4" wind generation scenarios. Storage adds little or no value to the "Wind 1" and "Wind 2" scenarios. To quantify the value added to the system by introducing storage Generation Adequacy assessments were carried out on the models.

5.3 Generation Adequacy Assessment

The generation portfolio to be used in this analysis was introduced in chapter 4. The wind generation scenarios will be combined with this generation portfolio and a generation adequacy assessment will be carried out on these models. The storage will then be introduced to the models and again a generation adequacy assessment will be carried out on the models. The LOLE calculated for the generation portfolio alone was fount to be 9.05 Hours. The LOLE calculations for the load modifier technique can be seen in figure 34. Figure 35 shows the LOLE for the models with storage present.

	2007	*2008*	*2009*
Wind 1	1.3896	1.3062	1.2576
Wind 2	0.9609	0.9201	0.6477
Wind 3	0.4688	0.5090	0.2147
Wind 4	0.2042	0.2764	0.0907

Figure 33: LOLE for wind models Load Modifier Technique

	2007	*2008*	*2009*
Wind 1	1.3896	1.3062	1.2576
Wind 2	0.9609	0.9201	0.6477
Wind 3	0.2412	0.5047	0.2140
Wind 4	0.0592	0.2616	0.0541

Figure 34: LOLE for wind + Storage models Load Modifier Technique

Next generators were removed from the generation portfolio until the LOLE was roughly equal to the LOLE of the generation portfolio without wind generation or storage, 9.05 hours. The first generators to be removed were the generators that are expected to be removed from the grid by 2020. The value that storage has brought to the system can be quantified by the size of the generation units that are removed to maintain the same LOLE.

Wind 1	*2007*	*2008*	*2009*
LOLE	7.09 Hours	6.74 Hours	7.15 Hours
Generation Ofset	Poolbeg1	109.5	
	Poolbeg2	109.5	
		219MW	

Figure 35: Wind 1 Offset Generation

Wind 2	*2007*	*2008*	*2009*
LOLE	7.9 Hours	7.57 Hours	6.78 Hours
Generation Ofset	Poolbeg1	109.5	
	Poolbeg2	109.5	
	Poolbeg3	242	
		461MW	

Figure 36: Wind 2 Offset Generation

Wind 3	*2007*	*2008*	*2009*
LOLE	9.32 Hours	10.44 Hours	9.76 Hours
Generation Ofset	North Wall1	163	
	North Wall2	109	
	Poolbeg1	109.5	
	Poolbeg2	109.5	
	Poolbeg3	242	
		733MW	

Figure 37: Wind 3 Offset Generation

Wind 4	*2007*	*2008*	*2009*
LOLE	10.33 Hours	11.07 Hours	9.96 Hours
Generation Ofset	Aghada3	90	
	Aghada4	90	
	Great Island3	108	
	North Wall1	163	
	North Wall2	109	
	Poolbeg1	109.5	
	Poolbeg2	109.5	
	Poolbeg3	242	
		1021MW	

Figure 38: Wind 4 Offset Generation

LOLE calculations are slightly different to the 9.09 hours LOLE for the generation portfolio. The LOLE calculations are within an acceptable range to identify then amount of conventional generation that is offset by the addition of storage to the system.

6 Conclusion and Further Study

6.1 Conclusion

This thesis illustrates the benefits that large scale energy storage can bring to the Irish electricity system as its wind penetration increases. The initial tasks in undertaking the project involved modelling the load and wind profile for Ireland. Data freely available on the Eirgrid website was used to do this. Four wind generation scenarios where then modelled based on the generated wind profile. These wind generation scenarios represented penetration levels of 13%, 20%, 40% and 60%. The Irish electricity system was then modelled with these wind penetration scenarios. Curtailment levels were outlined for each wind generation scenario.

A basic pumped-hydro storage system was first introduced to the models to estimate the optimal operational characteristics for the storage system. A more complex pumped-hydro storage system was then implemented which had control features. These control features aimed to optimise the storage facility and to minimise the amount of conventional generation needed by the system. It was assumed that the efficiency of the storage system was 80%. As the storage system being modelled was large scale and would involve multiple variable speed turbines, the minimum pumping constraint was neglected. It was also assumed that the pumping system could operate in pumping and generating mode from one hour to the next. This would not be the case in a real life pumped-hydro storage system.

The system was again modelled incorporating the storage system. The storage control was optimised to provide maximum wind energy absorption and to minimise the conventional generation required by the system. Results from analysing these models show that the energy storage system provides little or no benefit to the system with wind penetration levels below 20%. Storage provides considerable value to the system with wind penetration levels of 40% and 60%. The storage system enables wind generation to further penetrate the generation mix and drastically reduces curtailment of generated electricity. The level of conventional generation required by the system is also reduced with the introduction of the storage system.

Finally a generation adequacy assessment was carried out on the system incorporating the energy storage to estimate the value that it adds to the system. A generation portfolio needed to be established to mimic the Irish system. The current conventional generation portfolio in Ireland was modelled and the LOLE of 0.1704 hours for the year was calculated for the system. For the purposes of this project a generation portfolio that had a LOLE equal to the “8 hours a year” Eirgrid standard was preferred for the base case scenario. To achieve this, individual generation plant were removed from the portfolio one by one until the standard was achieved. The final portfolio that was used in this project had a calculated LOLE of 9.05 hours. This was considered sufficiently close to the “8 hour” standard.

A number of techniques for performing a generation adequacy assessment on systems with wind generation and storage were analysed and the “load modifier” technique was used for the purposes of this project. This is the technique used by Eirgrid when incorporating wind generation into their generation adequacy assessments. The generation adequacy indices were outlined for each of the wind generation and storage scenarios. These indices were recalculated for the system to estimate the value that each energy storage scenario brings to the system. To do this, generators were removed from the generation portfolio until the LOLE equalled that of the base case scenario. The value added to the system by the introduction of energy storage is quantified by the amount of generation that is removed from the base case generation portfolio to achieve the original LOLE. Due to the nature of the generation portfolio and the preference of removing older generation plant from the system first, the exact LOLE of the base case was not achieved for each scenario but the results illustrated are sufficiently close to estimate the value added to the system by introducing energy storage.

6.2 Further Study

This thesis provides an analysis of the benefits that large scale energy storage can bring to the Irish electricity system. The storage models in the analysis makes a number of assumptions and neglect some of the constraints associated with pumped-hydro storage. A more comprehensive pumped-hydro storage model would yield more accurate and realistic results. The pumped storage system in this project is optimised to maximise the integration of wind generation and to minimise the conventional generation required by the system. Realistically it is unlikely that pumped-hydro storage systems would be operated in this way. A storage model which is optimised to generate maximum profits would provide a contrasting model to the one used in this project.

The “load modifier” technique that is used in the generation adequacy assessment shows some limitations as the penetration of wind and energy storage increases and other techniques may be more appropriate for estimating the generation adequacy of a system with wind generation and large scale storage. A detailed financial analysis of the system with and without storage would further illustrate the benefits of introducing large scale energy storage into Ireland.

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Appendices

Matlab Program to Generate COPT

Below is a MATLAB program that computes the exact distribution function of S. The program performs the following steps.

Step 1

Find the distribution function of S when we have one station in the system. This function is stored in g1. g1 is a vector of length C_1 and value FOR_1. Note that g1(i) = $G_1(i)$, $i = 1, \ldots, C_1$.

Step 2

Add the next station. (The first time, $i = 2$.) Based on equation (2), displace the values of g1 by adding C_i zeroes at the beginning of g1. The size of g1 is now $C_1 + \ldots + C_i$. Call this vector g1dis. Then multiply g1dis by $1 - FOR_i$. This is the second term of the right hand side of the last line of equation (2). The first term is obtained by adding to g1 (the distribution function of the system when there are $i - 1$ stations), C_i ones at the end of g1, and multiplying the resulting vector by FOR_i. The sum of both terms is called g2; this is the distribution function from 1 to $C_1 + \ldots + C_i$ of the system when there are i stations.

Step 3

Repeat Step 2 until all the stations have been added ($i = n$). With this method, we obtain all the values of $G_n(x)$, $x \le \sum_{j=1}^{n} C_j$. The values are the components of vector g2 at the end of the process, so that g2(i) = $G_n(i)$. The size of g2 at the end of the process is $\sum_{j=1}^{n} C_j$.

```
n=length(pow);
g1=[forest(1)*ones(size(1:pow(1)))];
for i=2:n;
g1dis=[zeros(size(1:pow(i))) g1];
g1=[g1 ones(size(1:pow(i)))];
g2=forest(i)*g1+(1-forest(i))*g1dis;
g1=g2;
end;
```

pow is a 1 x 80 vector containing the stations' capacities in megawatts.

forest is a 1 x 80 vector containing the estimated *FOR*s.

g1 is a 1 x C_T vector containing the theoretical distribution function.