Wind Powered Generation

An analytical framework to assess generation cost implications

June 2007

Background

Over the last number of years, some distinct trends have emerged within the generation market in Ireland. New generation capacity is being added to the system at a rapid rate, with 2213 MW being added (and 335 MW removed) since 2001, when the total exported capacity was 4821 MW. This new generation capacity is predominantly of two types; 1130 MW of gas-fired combined cycle gas turbine (CCGT) plant, and 781 MW of wind powered generation (WPG).

This trend is forecast to continue into the future with a further 1260 MW of CCGT plant and 1000 MW of WPG likely to be added by the end of 2010. Under such conditions Ireland's generation portfolio would be heavily biased towards CCGT and WPG, with the remainder of the portfolio being made up of some open cycle gas turbine (OCGT), coal, peat and hydro generation capacity.

What effect will such a portfolio have on the performance of the Electricity Supply Industry (ESI)? ESI performance is often measured in terms of three performance indicators: security of supply, price competitiveness and impact on the environment. The constitution, reliability, capital and operating costs of the generation portfolio will have a major impact on these performance indicators and overall efficiency of the ESI.

This paper examines the generation cost implications of various levels of WPG and the amount of CO_2 which is likely to be displaced under a number of plausible scenarios. Security of supply is held constant across all scenarios examined, thus allowing the cost comparison to be made on a like-for-like basis from a security of supply perspective. Scenarios have not been equalised on emissions or sustainability basis. Thus the effects of increasing levels of WPG for two of the three ESI performance indices (price competitiveness and the environment[1]) are evaluated while the third (security of supply) is held constant. Notwithstanding the environmental and non-economic benefit of WPG[2], from a generation cost perspective it will be seen that the economic case for wind is largely driven by the relative cost of WPG and the main alternative power generation technology, i.e. gas fired generation.

In this paper the relative generation costs are calculated within the following framework:

- The cost of fossil fuels (mainly gas).
- The ability of wind to displace thermal generation capacity, while maintaining supply security.
- The capital cost of wind generation plant.

EirGrid, Ireland's transmission system operator, has used up-to-date information and modelling techniques to forecast the economic cost implications for operation of the generation portfolio with levels of WPG varying from 0 to 3500 MW. As this evaluation is based on a comparison of total portfolio capital and operating costs, it offers a more accurate representation of the cost/benefits of integrating WPG into the power system than simply comparing the capital and operating costs of a wind-farm with other candidate plants. While the direct capital and operating cost comparison approach is often favoured due to its simplicity, it tends to ignore (or, at least, only partially deals with) the interactions between the different generation types within the portfolio.

[1] *The impact on the environment is evaluated only in terms of the reduction in CO2 levels.*

[2] *This report does not focus on the many issues surrounding WPG which do not readily lend themselves to economic evaluation, e.g. Sustainability, scenic impact, etc.*

Inputs and methodology

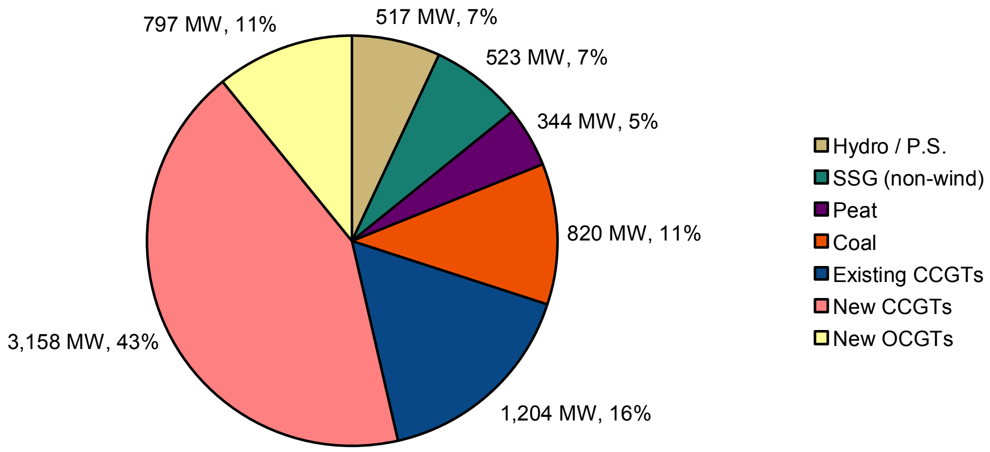


Figure 1 Plant mix in the "No Wind" reference case

Based on a model of Ireland's power system when peak demand is expected to be 6500 MW[3], a portfolio of plant sufficient to ensure compliance with the generation adequacy standard[4] was determined. This portfolio comprises CCGT, OCGT, coal, hydro, SSG (small scale generation such as small biomass-fired plant), peat and pumped storage plant. The constitution of this portfolio is illustrated in **Figure** 1 No WPG was included, as this case is used to provide base-line costs against which the incremental benefit (or cost) of adding WPG to the portfolio can be evaluated.

To this base-line case different amounts of WPG were added. The addition of WPG improves the security of supply position. Therefore for each level of WPG added an appropriate amount of the original portfolio's capacity was removed in order to return the system to the same level of security of supply as before the WPG was added, thus making all results directly comparable from a generation adequacy perspective.

It is important to note that the reduction in conventional capacity is comparatively small (1 MW of wind displaces less than 1 MW of conventional plant). This unequal relationship exists due to the fact that wind generation is limited to a low capacity factor[5] (the maximum capacity factor for WPG in Ireland is less than 45% and the average level is 35%) and, more importantly, is subject to periods of generally low output due to very high or low wind speeds covering a large geographical area across the country.

As 1 MW of wind does not offer the same contribution towards generation adequacy as

[3] This peak demand is expected to occur in the period 2012 to 2014. The corresponding customer energy consumption is 38,500 GWh.

[4] The Generation Adequacy Standard for Ireland is 8 hours Loss of Load Expectation per year. For more detail, refer to the Generation Adequacy Report 2007-2013

[5] The capacity factor of a generation plant is the ratio of the actual output to the maximum potential production. If a plant operated at maximum output for 6 months of the year and zero for the other six months, then its capacity factor would be 50%.

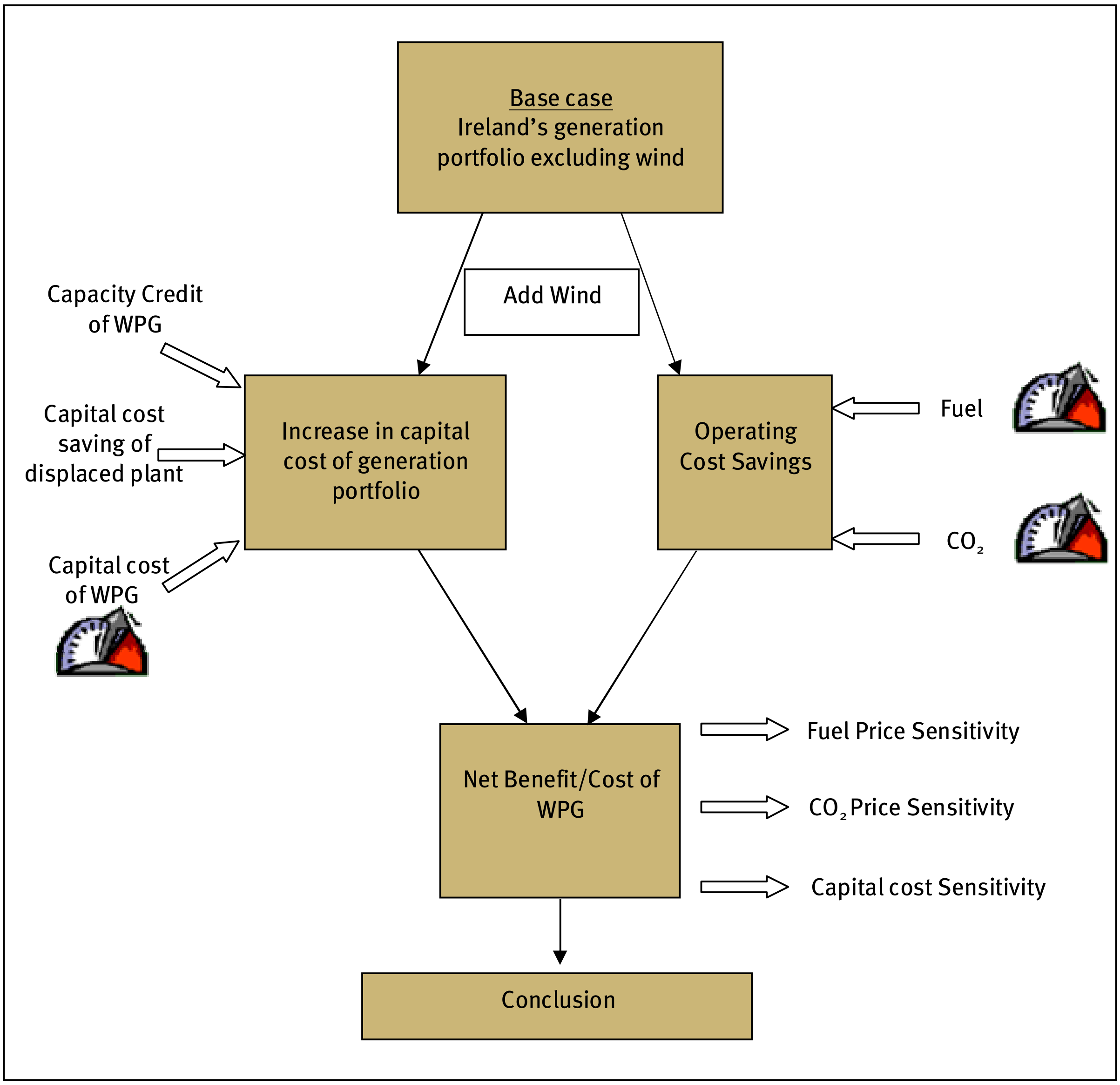


Figure 2 Outline of Methodology

1 MW of conventional plant, a system which includes wind has a greater total installed generation capacity than a system which has no wind, for the same level of security of supply.

This higher level of total installed capacity must, in general, lead to a higher capital cost investment. In turn this higher capital cost will tend to increase the cost of electricity unless the fuel and CO_2 savings achieved through the operation of wind generation are large enough to outweigh it. This additional capital cost can be described as the hurdle which fuel and CO_2 savings must overcome if overall generation cost savings are to be achieved.

WPG produces energy with a variable production cost of close to zero, and zero CO_2 emissions. As more energy is supplied by WPG the overall system variable cost and CO_2 emissions decrease. In order to calculate accurately the fuel and CO_2 saving, a full system simulation is required which takes into account

- Individual generator characteristics;
- how the generators interact as a portfolio; and
- the nature and characteristics of customer demand.

The total quantity of fuel consumed reduces as the penetration of WPG increases. The absolute value of the associated fuel cost saving is directly related to fuel and CO_2 prices. The higher the fuel and CO_2 prices, the greater the cost reduction achieved by not consuming such fuels. The question then arises as to what level of fossil fuel or CO_2 prices allow the additional capital cost hurdle of WPG to be overcome, see Figure 3.

Impact of WPG on Capital Cost of the Portfolio

For the base-line case with no WPG, a total installed capacity of 7363 MW was required to meet the standard security of supply criteria. This translates to a plant margin of 13.3%, as peak demand on the system simulated was 6500 MW.

Three different levels of WPG were added to the base-line case,

- L1 = 1500 MW
- L2 = 2500 MW
- L3 = 3500 MW

Colour key for later figures:

Green is 1500 MW (L1)
Purple is 2500 MW (L2)
Orange is 3500 (L3)

These cases correspond to wind energy penetration levels of 12%, 20% and 27% respectively. For each level of WPG, the appropriate amount of conventional plant was removed from the system so as to maintain the same level of supply security. The amount of capacity withdrawn in each case is in accordance with the capacity credit of WPG (see Appendix A) and is illustrated in Figure 4. Appendix B (Tables 4 and 6) gives the details of displaced thermal plant.

When 1500 MW of wind was added to base system it was found that 332 MW of conventional plant could be removed while maintaining security of supply. Therefore the

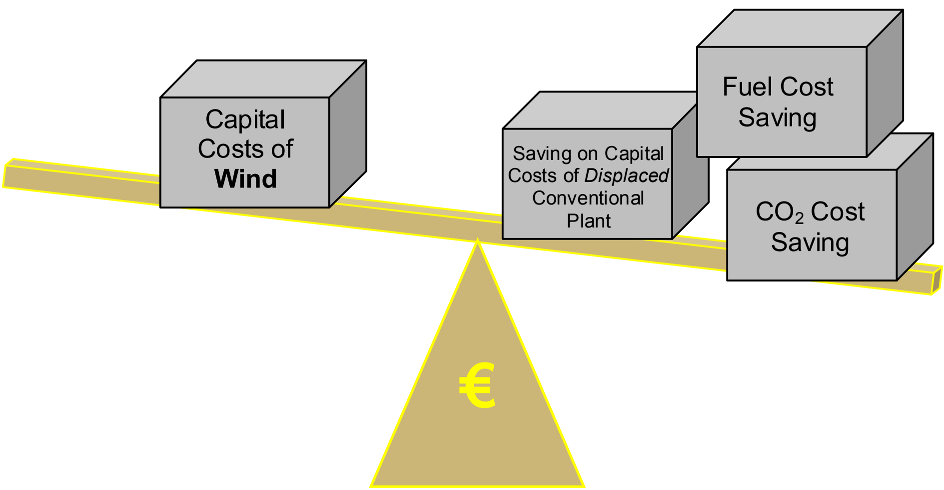


Figure 3 The capital cost hurdle

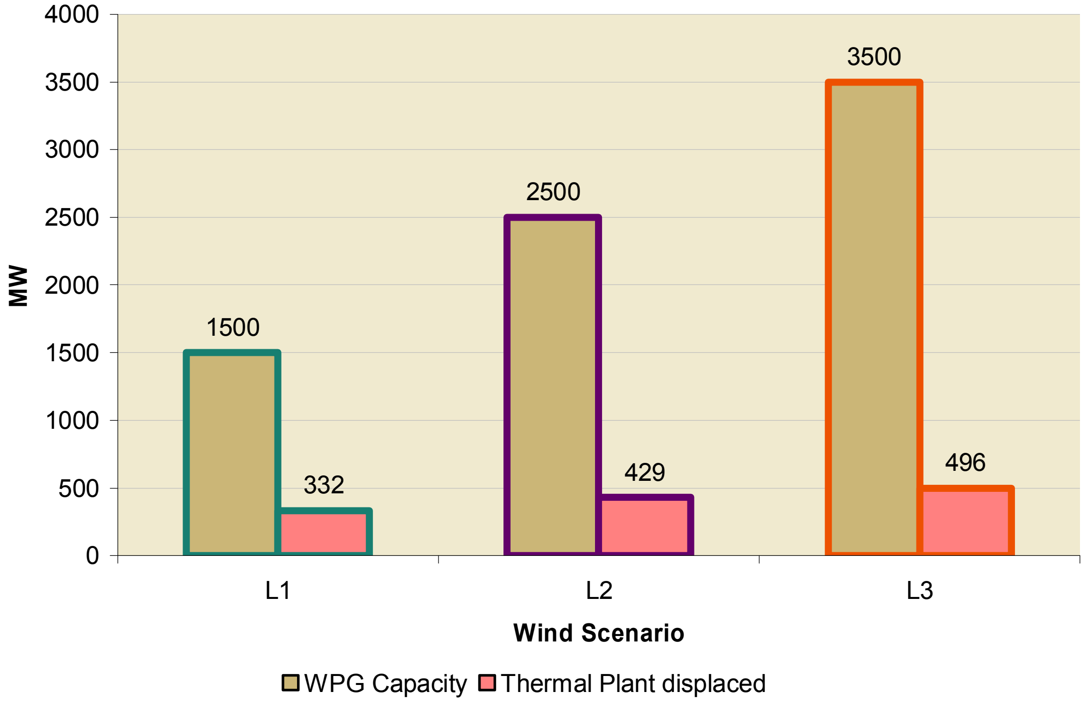


Figure 4 WPG's ability to displace conventional capacity

total installed capacity (conventional + WPG) has grown by 1168 MW (1500 - 332 = 1168 MW) or to a plant margin of 31.2%. As wind penetration increases the required plant margin also increases, such that with 3500 MW of WPG the required plant margin is 59.5%. Table 1 summarises the position for the reference case and all three WPG cases.

Case	WPG capacity (MW)	Conventional capacity (MW)	Plant Margin to meet supply security (%)
Reference	0	7363	13.3
L1	1500	7031	31.2
L2	2500	6934	45.1
L3	3500	6867	59.5

Table 1 Capacity requirement and plant margin

As the total installed capacity increases the amount of money invested in generation assets also increases. The total amount of additional capital investment is calculated by subtracting the cost of the conventional plant displaced from the cost of WPG installed. This was translated into an annualised portfolio capital cost on the basis of a required rate of return and expected asset lifetime. For the purpose of this paper a reasonable set of conventional generation capital costs were assumed (from 0.537 to 0.763 €m/MW). The required rate of return was 7.32%, with a project payback period of 15 years. A full breakdown of both WPG and conventional generation capacity costs is given in Appendix B.

From an assessment of current market prices, and potential future trends, a plausible range of WPG capital costs was determined. For this report the impact of three WPG capital costs were assessed. These were 1.0, 1.2 and 1.4 million euro per MW installed. A world-wide shortage of WPG manufacturing capacity, coupled with strong growth in demand, means that prices are currently at the upper end of this range. Wind-farm developers are hopeful that this supply shortage will reduce over time and that prices will then return to the lower end of this range.

As the capital cost per MW installed varies the overall capital investment required for the three levels of WPG penetration considered also varies as illustrated in Table 2.

Case	Wind Capital Cost 1.0 €m/MW	1.2 €m/MW	1.4 €m/MW
L1 (1500 MW)	164	202	252
L2 (2500 MW)	284	348	431
L3 (3500 MW)	408	498	615

Table 2 Annualised additional portfolio capital cost

For example, if each MW of WPG costs 1.4 €m and there is 2500 MW installed, the annualised capital cost of the complete portfolio increases by 431 €m/year. This figure takes into account the capital cost avoided due to the fact that WPG has displaced some conventional capacity, while maintaining security of supply.

In all cases the addition of WPG increases the annualised capital cost of the portfolio. This increase ranges from 164 to 615 million euro per annum as WPG penetration and capital cost vary.

WPG Capacity Credit – International Comparison

The capacity credit of wind has been the subject of much discussion at home and abroad. A paper entitled ***"Wind Power has a Capacity Credit: A Catalogue of 50+ Supporting Studies"*** by Gregor Giebel, Risoe National Laboratory, summarised studies of the capacity credit of wind. Published in February 2006 it compares results from different countries. A summary graph is shown in **Figure** 5. From this graph it is possible to see that the absolute value of the capacity credit given to wind for this study is one of the highest values within the peer group. This is not unreasonable as Ireland does have one of the best wind regimes in Europe. It also confirms that the methods used by different institutions across Europe to evaluate capacity credit give broadly similar results. The key points of the study include the following:

- Wind does have a capacity credit,
- This capacity credit is relatively low by comparison with conventional plant,
- The capacity credit of WPG declines as wind penetration increases.

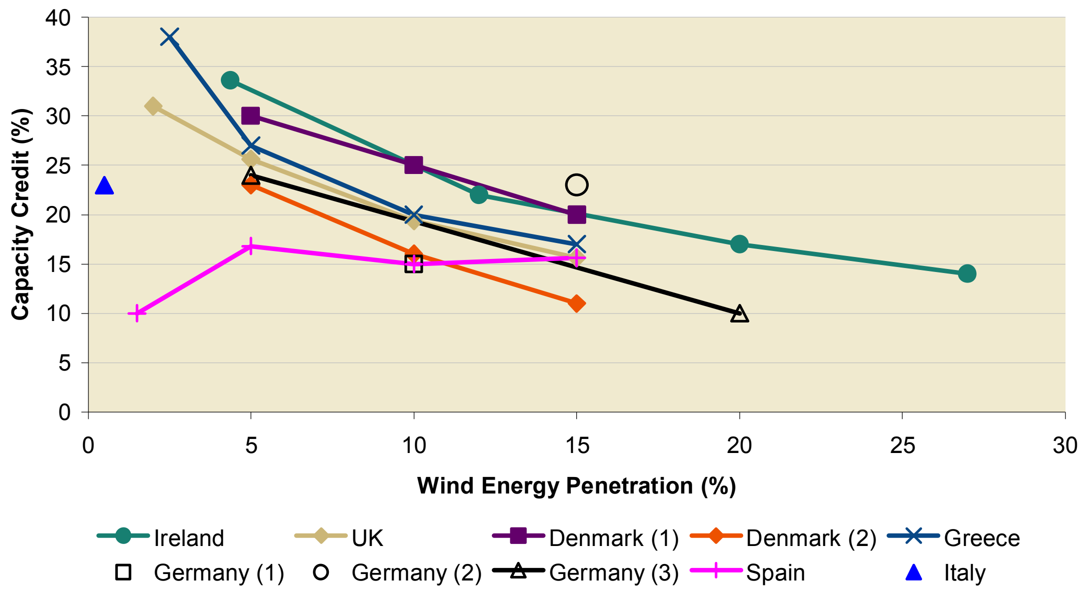


Figure 5 Capacity credit of WPG as a Function of Wind Penetration – international comparison

Operating Cost Savings

The incorporation of WPG into the generation portfolio decreases operating (fuel) cost and CO_2 emissions. As shall be seen in some cases the savings in operating and CO_2 cost were more than sufficient to counterbalance the capital cost premium for WPG, while in other cases it was not.

This section outlines the scale of operating and CO_2 cost savings under a number of fuel and CO_2 price scenarios.

In order to obtain an accurate assessment of how changes in the generation portfolio impact on operating cost and CO_2 emissions, an hourly chronological unit commitment and economic dispatch model was utilised. Such detailed modelling is required if the complex interactions between generation units is to be simulated with sufficient accuracy. While simplified models take into account the primary influencing factors on operating costs, such as generation unit efficiency and fuel prices, they exclude other material factors such as unit minimum load points, ramp rates, minimum up and down times and the link between fuel price and pattern (and volume) of usage. These characteristics influence the amount of fuel cost and CO_2 saving which can be achieved through the introduction of WPG.

As with the portfolio capital cost calculations, the annual operating cost and CO_2 emission in the no-wind reference case was compared with the corresponding values in the 1500, 2500 and 3500 MW WPG cases to determine the magnitude of the savings made. The operating (variable) cost of WPG was assumed to be zero. Thus energy from WPG was always used to meet customer demand in the first instance. Conventional plant was used to top-up WPG energy until customer demand was satisfied.

(a) Gas Price variation

It was found that operating cost savings increased as the penetration of WPG increased from 1500 to 3500 MW. The magnitude of this saving is largely dependent on the price of gas as energy produced by WPG reduces the requirement to burn gas for electricity production. As gas prices increase, the magnitude of the associated operating cost saving also increases.

As recent experience has confirmed gas prices can be volatile and difficult to predict. Therefore three different gas prices were utilised for this report, as documented in Table 3.

The selection of the gas price range was guided by a long term fuel price forecast produced by consultancy group, Poyry, for EirGrid in November 2006. Poyry's gas price forecast for power generation in Ireland is illustrated in Figure 6.

Figure 7 presents the variable cost saving for the three different WPG levels and for three different gas prices. It can be seen that the variable cost saving when the gas price is 33 €cent per therm is relatively modest in comparison to the saving at higher gas prices. Therefore at low gas prices the variable cost saving tends to be insufficient to overcome the additional capital cost investment. As gas prices increase to 100 €cent/therm the operating cost savings also increase so that the savings are comparable, or greater, in magnitude than the additional portfolio capital cost.

It should be noted that the introduction of WPG causes greater variability in the output of conventional generation plant. The price per unit of gas delivered tends to increase in response to such intermittent usage patterns as the fixed cost of gas network capacity

Scenario	€cent/therm	Comment
GP_1	33	As used in ESB National Grid's Economics of wind paper 2004, and in line with Poyry's low price scenario (as of Nov 06)
GP_2	75	In line with Poyry's central scenario price (as of Nov 06)
GP_3	100	In line with Poyry's high scenario price (as of Nov 06)

Table 3 Gas price forecasts

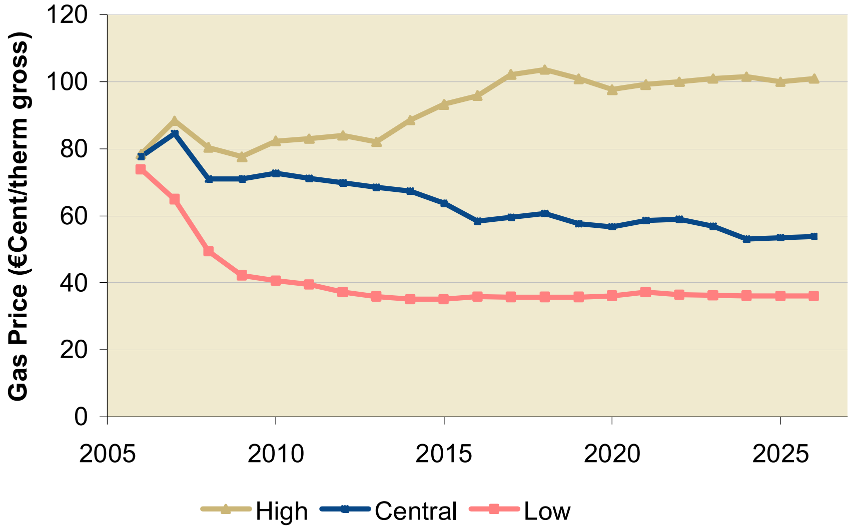


Figure 6 Gas price forecasts

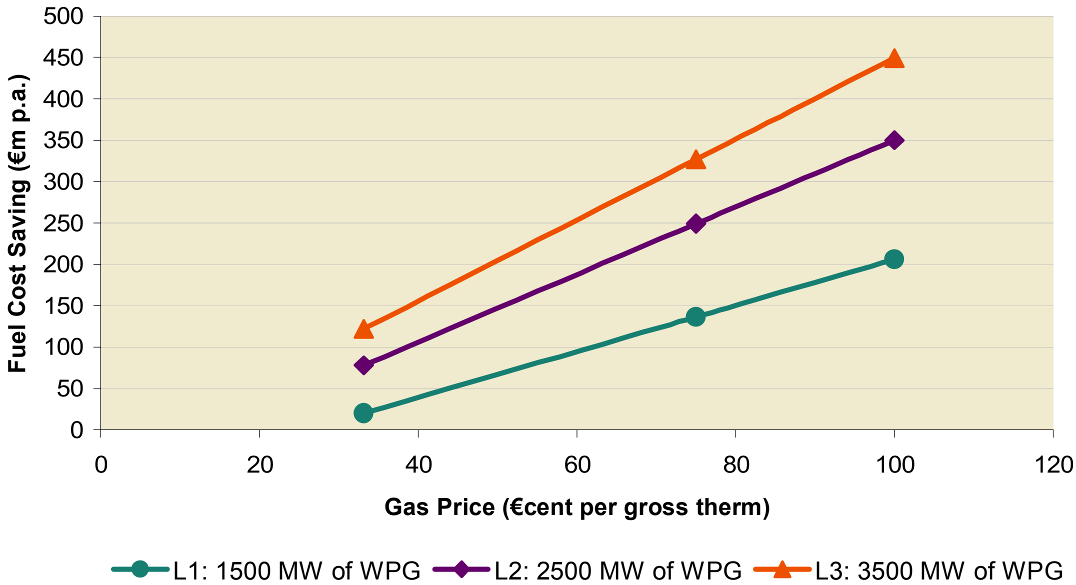


Figure 7 Effect of wind on fuel cost saving

charges is now spread over a smaller volume of overall gas usage. Poyry, international fuel price consultants, provided an estimate of this 'variability' premium. To simulate this effect, a once-off increase in gas prices was introduced in the 1500 MW WPG scenario. However, this gas price increase was not escalated for the higher WPG penetration scenarios. This tends to overestimate the variable cost saving in the 2500 MW and 3500 MW scenarios (relative to the 1500 MW case).

(b) CO_2 Price variation

The displacement of energy generated from conventional generation by WPG not alone reduces the fuel related operating costs as outlined above, the cost associated with the emission of CO_2 is also reduced. An accurate forecast of CO_2 emissions avoided is obtained by use of the chronological model which simulates the running regime of each unit on

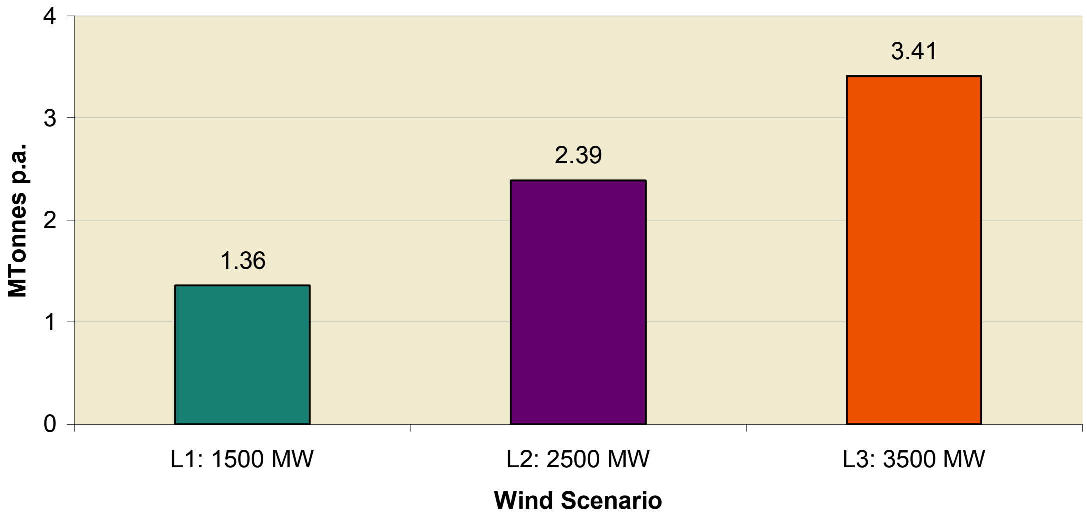


Figure 8 Annual reduction in CO_2 emissions

an hourly basis. Such simulation techniques automatically take into account the interactions within the portfolio. For example the incorporation of WPG tends to result in conventional generation running at lower loads, thereby operating less efficiently and emitting more CO_2 per MWh delivered than if they were operating at higher loads[6]. While this has a secondary effect on emissions compared to the fact that fossil fuel generation has displaced, it does have a material impact on the results.

The impact of WPG on the quantity of CO_2 emitted is calculated by comparing the reference (no-wind) case with the three with-wind cases. The quantity of CO_2 avoided for the different scenarios is illustrated in **Figure** 8.

Once the quantity displaced is known it is translated to a monetary value by using a forecast for the cost of carbon (i.e. the cost of a green house gas emission *Allowance*[7]).

Emission *Allowances* are a commodity whose price is market driven, so there is no 'official' value for them. It is subject to global uncertainties in the same way that fuel prices are. *Allowance* prices for the last 12 months are shown in **Figure** 9. It can be seen that the price can be quite volatile[8].

In May 2007 the price of a 2008 CO_2 allowance (as indicated by the price of *futures* on the European Climate Exchange) is 20 €. Such *futures* have traded at prices up to 30 €/*Allowance*.

For this report we have assessed the monetary benefit that WPG has on the total cost of CO_2 emissions for two different Allowance prices of 30 and 100 €/Allowance. The 30€/Alllowance value represents the current forecast value, while 100 represents the upper limit. This upper limit is based on EU Directive 2003/87/EC, which fixes the excess emissions penalty at 100 €/tonne.

[6] *See paper published by ESB National Grid February 2004, Impact of Wind Powered Generation in Ireland on the Operation of Conventional Plant and the Economic Implications*

[7] *One* **Allowance** *is defined as permission to emit to the atmosphere, one tonne of carbon dioxide equivalent during a specified trading period.*

[8] *The low prices for the second half of 2006 may reflect the fact that the first trading period is due to be completed at the end of 2007, beyond which time these first trading period Allowances will have no value.*

Figure 9 Historical emission allowance prices

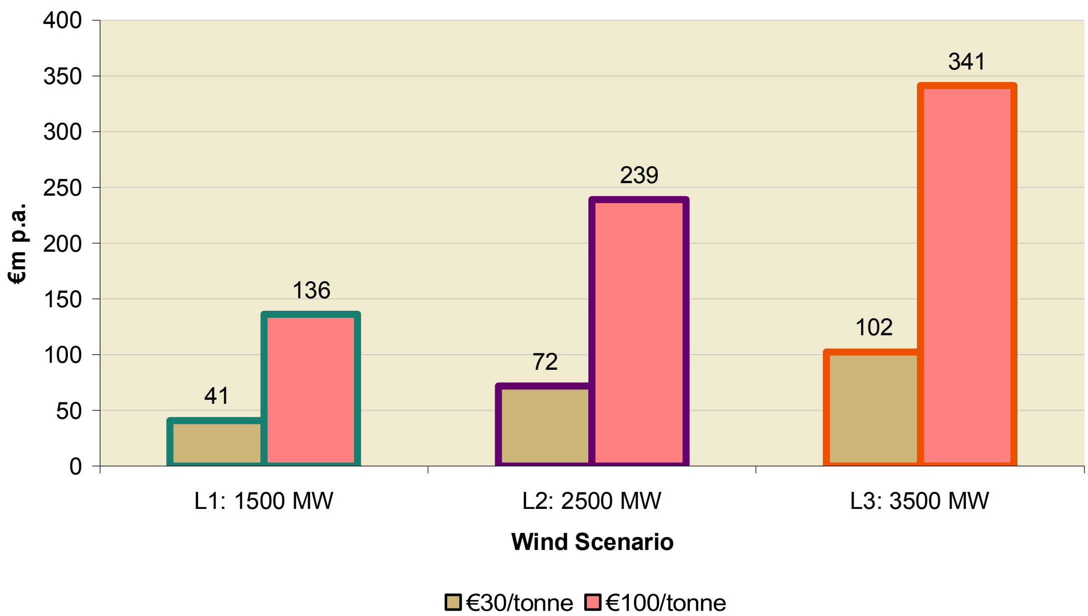


Figure 10 Annual reduction in CO_2 emission cost

Net Benefit/Cost of WPG

Having established, through simulation studies, the annual portfolio capital cost increase and related fuel/CO_2 saving for a number of different scenarios, the net impact of WPG on generation costs can be calculated. The following factors are allowed to vary:

1. WPG penetration levels
2. WPG capital costs
3. Gas prices

Initially, results are presented for CO_2 allowance prices of 30 euro (with the impact of a higher Allowance price studied later). As can be seen from the results in Figure 11, WPG can have a significant impact on generation costs. This impact ranges from significant cost penalties of up to 391 €m/year, through a neutral range, to material cost benefits of up to 143 €m/year.

As would be expected, the most advantageous case for WPG (the greatest generation cost benefit) is driven by the lowest WPG capital costs and highest gas prices. The converse is also true; the lowest gas price combined with the highest WPG capital costs leads to the largest WPG cost penalty. The magnitude of these extreme and intermediate cost penalties/benefits depends on the combination of gas price, and the level of WPG installed as illustrated in Figure 11. These results are also tabulated in Appendix B.

The enhanced economic benefits of WPG, under the scenario where CO_2 prices rise to the Emissions Trading Scheme penalty price of 100€ (as established under EU directive 2003/87/EC), were also examined, and are illustrated separately in Figure 12. This shows how the economics of the 2500 MW WPG scenario improves when a high penalty is placed on CO_2 emission. At this CO_2 allowance price it can be seen that WPG provides a generation cost benefit under the majority of scenarios and the economic case for wind is much less dependent on high gas prices.

Conclusions

While the cost implications presented in Figures 11 and 12 vary widely according to the particular scenario, some general conclusions can also be drawn from these graphs. From an investment risk perspective it can be seen that the 1500 MW WPG case represents a low-risk low-reward scenario. If low gas prices emerge then the cost penalty is limited, but consequently, so also are the rewards should gas prices rise to the higher end of the range.

On the other hand the 3500 MW WPG scenario represents a high-risk high-reward investment decision. If gas prices are high the rewards are higher but the penalties are significantly larger should low gas prices emerge. Comparing the 1500 and 3500 MW cases illustrates that the potential downside (cost penalty) is growing more rapidly than the upside (cost saving) as WPG penetration increases. Therefore the relative risk is also increasing as WPG penetration increases.

The 2500 MW scenario represents a hedged investment decision, where most if not all of the economic upsides of WPG can be realised if gas prices are high, but exposure to the downside associated with low gas prices is limited. With 2500 MW of WPG the maximum potential benefit achieved is 138 €m/annum, just 5 €m/annum less than the 3500 MW WPG case[9]. However the maximum potential cost penalty in the 2500 MW case, is 109 €m/annum less than the equivalent 3500 MW case.

The analytical framework laid out in this paper allows the economic trade off between potential risks and rewards to be quantified as the level of WPG increases.

[9] Independent of the gas price, as WPG penetration increases, total generation cost savings can actually decrease due to saturating capacity credit combined with high wind capital costs (e.g. WPG > 1€m/MW)/. Under this scenario there is no economic case for higher WPG penetration.

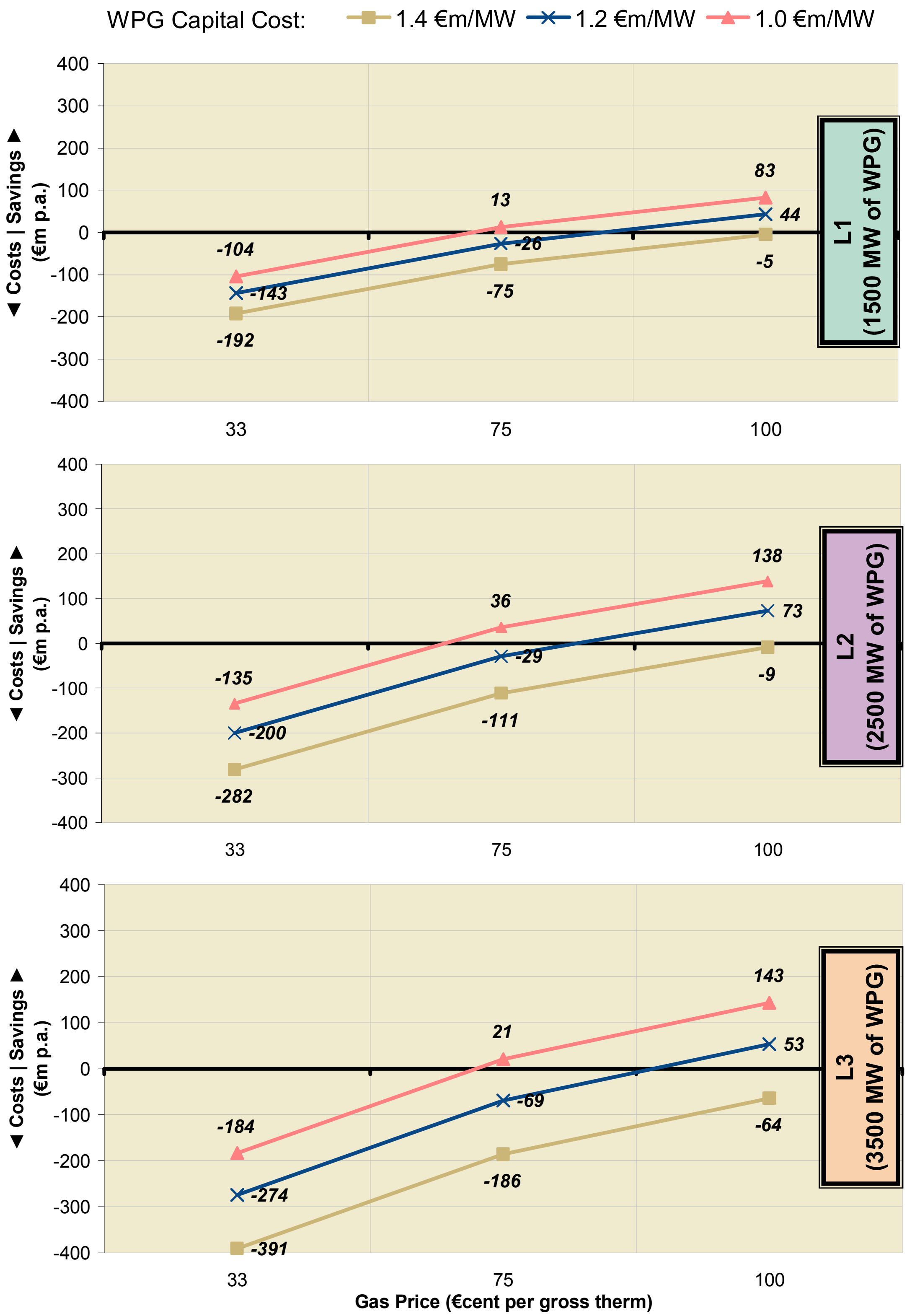


Figure 11 Generation cost implications for three levels of WPG, with CO_2 at €30/tonne

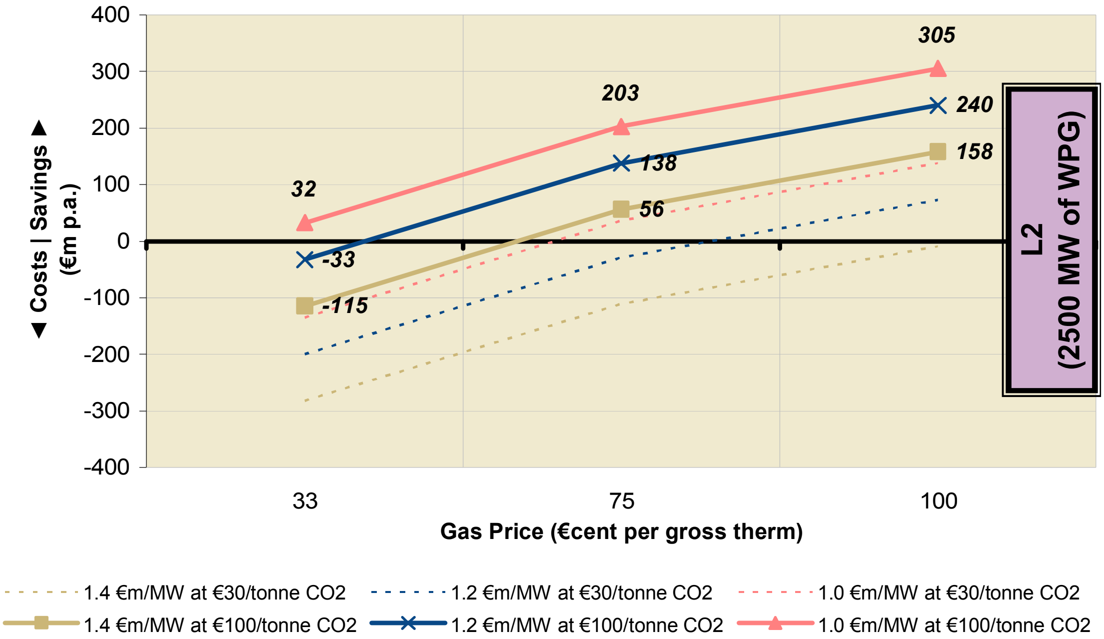


Figure 12 Net Benefit with 2500 MW of WPG, and CO_2 at €100/tonne (with CO_2 at €30/tonne as thinner lines)

It is worth stressing that this study has investigated the purely economic argument. There may be issues related to the real time operation of the power system which are not captured in this analysis, such the ability to control system frequency with high levels of WPG. On the other hand there are many, non-economic benefits that may accrue from increasing levels of WPG penetration. These include

- sustainability,
- diversity of fuel source, and hence security of supply,
- exploitation of our own natural resource
- development of expertise in the growing wind market
- fulfilment of our international obligations under the Kyoto Agreement
- positive impact on climate change.

Appendix A - Calculating Capacity Credit of WPG in Ireland

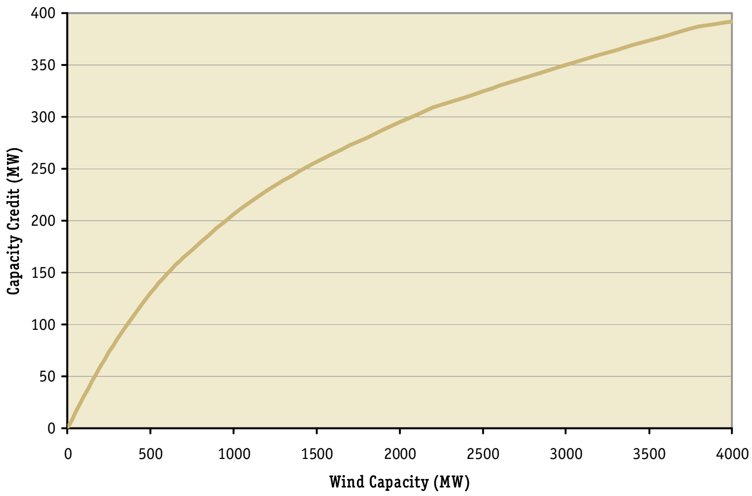
The capacity credit of a generation unit is a measure of its contribution towards generation adequacy (i.e. maintaining the demand supply balance). For example, a unit which has a name plate rating (full output capability) of 200 MW may provide a capacity credit of only 150 MW. Normally this capacity credit is measured relative to the "perfect unit's" capacity credit. The perfect unit, from a generation adequacy perspective, is one which is always available to meet customer demand. Such a unit would not require maintenance and would not be subject to unplanned failure. As the perfect plant contributes in every hour, by the full extent of its rating, to keeping supply greater than or equal to demand, a 200 MW perfect unit provides 200 MW of capacity credit.

Real units provide less than 'perfect plant' capacity credit. There are a number of possible reasons for this

1. The generation unit is unavailable for a number of hours due to planned maintenance or mechanical failure.
2. The primary energy source (e.g. fossil fuel, wind) is not available
3. The generator cannot run at full output due to energy storage limits (e.g. pumped storage, hydro)
4. The output from the generation unit cannot be delivered to the customer due to network constraints

WPG provides a limited capacity credit for two principal reasons. Firstly, the annual energy provided by WPG is limited by actual wind conditions to approximately 35% of that which might be expected under perfect wind conditions. In addition wind conditions provide a link between all WPG in the country. Therefore wind farms which are geographically and electrically separate from each other may still tend to act in unison when common wind conditions exist across the country. Analysis of historical total power output from WPG over a number of years, would suggest that there will be hours and even days over the course of a year when the output from all WPG will be simultaneously very low due to either very high or low wind speeds. This characteristic of simultaneously low output causes the capacity credit to saturate. Therefore at high levels of WPG penetration the incremental generation adequacy benefit of additional wind capacity approaches zero.

By using the historical performance (electrical power output) of WPG, and projecting it to higher levels of installed capacity it is possible to calculate the impact WPG would have on the probability of demand exceeding supply. From this the capacity credit of wind can be calculated relative to the capacity credit of perfect unit. From such calculations it was found for example, that the first 1500 MW of wind is worth the same in capacity credit terms as 250 MW of perfect plant (or 322 MW of real plant).



From this it can be seen that 1 MW of WPG displaces much less than 1 MW of perfect plant. Similar analysis was used to determine how much generation with 'real' availability performance could be displaced by WPG.

Appendix B

Plant	Capital Cost (€m/MW)	Capital Cost (€m/[MW x year])	Fixed O & M (€m/[MW x year])	Capital + F.O & M (€m/[MW x year])	Cost/MWh (Based on 34.5% capacity factor)
WPG	1.0	0.1120	0.0170	0.1290	42.7
	1.2	0.1344	0.0204	0.1548	51.3
	1.4	0.1568	0.0313	0.1882	62.3
235 MW CCGT	0.694	0.0779	0.0131	0.0909	
67.3 MW OCGT	0.537	0.0609	0.0192	0.0802	
29.9 MW OCGT	0.763	0.0870	0.0209	0.1079	

Table 4 Generation annualised capacity costs, based on 7.32% rate of return, and 15 year lifetime.

CO_2 price (€/tonne)	WPG Capacity (MW)	Wind Capital Costs (€m/MW)	Gas Price (€cent per therm)		
			33	75	100
30	1500	1.0	-104	13	83
		1.2	-143	-26	44
		1.4	-192	-75	-5
	2500	1.0	-135	36	138
		1.2	-200	-29	73
		1.4	-282	-111	-9
	3500	1.0	-184	21	143
		1.2	-274	-69	53
		1.4	-391	-186	-64
100	2500	1.0	32	203	305
		1.2	-33	138	240
		1.4	-115	56	158

Table 5 Generation cost benefits (in black) and penalties (in red) for CO_2, WPG capital cost and gas price scenarios.

Wind (MW)	Displaced Thermal Plant			
	235 MW CCGT	67.3 MW OCGT	29.9 MW OCGT	Total MW
1500	1	1	1	332
2500	1	2	2	429
3500	1	3	2	496

Table 6 Number of Thermal Plant units displaced by Wind.