Simulation theory applied to the LCOE analysis for Offshore Wind Power Plants and other competing technologies

This work deals with the comparative "levelised cost of electricity" (LCOE) for various technologies, in particular for a typical offshore wind power plant compared to ASC coal FGD plant with CCS, and Nuclear EPR 3, onshore wind and gas CCGT plants. This paper proposes a stochastic approach based on Monte-Carlo simulation to account for various uncertainties for the most significant cost components when determining the overall cost of electricity generation: furthermore, by using forecast data, the simulation performed can help estimate the long-term reliability of the costs calculated under uncertainty. In addition, the study explains the components of unit cost calculations and includes a sensitivity analysis of investment and fuel costs, applicable discount rates and carbon emission costs

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Teoria della simulazione applicata ad un'analisi LCOE per l'eolico offshore e tecnologie concorrenti

Il lavoro si occupa del "costo livellato dell'energia elettrica" (LCOE) comparato per varie tecnologie, in particolare per un tipico impianto eolico offshore confrontato con impianti a carbone ASC FGD con CCS, nucleare EPR 3, eolico on-shore e gas a ciclo combinato CCGT.

Viene proposto un approccio stocastico basato sulla simulazione Monte Carlo per tenere conto di varie incertezze per i componenti di costo più rilevanti per la determinazione del costo totale di generazione di energia elettrica: inoltre, utilizzando dati di previsione, la simulazione effettuata può essere utilizzata per stimare la affidabilità a lungo termine dei parametri di costo calcolati in condizioni di incertezza. Inoltre lo studio effettuato spiega le principali componenti del calcolo dei costi unitari e include un'analisi di sensitività sui costi di investimento e di combustibile, sul tasso di sconto applicabile e sui permessi di emissione di carbonio

Offshore Wind Technologies have played an increasingly important role in the recent strong development of RES technologies. Over the past 10 years offshore wind power cumulative capacity in EU has grown more than 1GW per year[28]. This significant growth in all renewable technologies has been strongly affected by measures like incentives scheme, resulting from climate mitigation policies[9].

Policy makers need to be able to compare costs and benefits of different types of power generation plants to make decisions about energy policy. It is crucial to *"compare like with like"* to increase the meaning and usefulness of this kind of work[7] and for this reason, to

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support policy makers, an LCOE analysis is discussed in this paper. The present analysis is based on a DECC (Department of Energy and Climate Change - UK) study (2011), integrated with other works (RAE, 2004 and others).
The Levelised Cost Of Energy (LCOE) is a global standard as an economic measure for energy plants: LCOE is the average price that consumers would have to pay so that the investor/operator for the capital, operation, maintenance and fuel expenses is repaid exactly, with a rate of return equal to the discount rate[17]. Therefore, the levelised cost of energy allows to compare alternative technologies under different scales of operation, different investment and operating time periods, or both. In this paper, an LCOE analysis is supported by Monte Carlo simulations of the main generation cost parameters, subject to high unpredictability.
As always, the hardest part of this work was to get reliable and fairly recent data at the basis of LCOE equation specifications. It is necessary to remark that there are important cost components not captured by this type of approach (e.g., externalities)[3,10,13]: LCOE is only one of the indicators available to evaluate investment options: it can be seen as a sort of "first order assessment of project viability"[5]; the same holds for the simulation methods used in this work, in addition to estimate indications on the robustness of the results under conditions of uncertainty[29].
Initially, the work of analysis is concerned with describing the technologies examined, in particular the major key assumptions on plant costs and their technical performance. Then, a focus of the financial part of the LCOE model is performed and Monte Carlo techniques are shown. The last sessions present the study results and summarize the main conclusions.
In the Appendix, a short list of acronyms and abbreviations used in this work is given.

Technical and economic data

The aim of this work is to evaluate the electricity generation cost from Offshore Wind plants and to know under which conditions these costs could become economically competitive with a representative set of other power plants.

Applying the LCOE methodology, a typical Offshore Wind plant has been compared with the major competitors' generation plants, considering the average technical characteristics. We chose the main base-load technologies (like CCGT), the cheapest way of generating electricity, but also "innovative" technology options that can become significant in the future, like as Coal Plants with CCS.
The generation technologies set and the data and specifications, coming from the reference studies[2,5,6,7,8] and other sources[24,25,29], are:

- one "mature" technology: Gas fired Combined Cycle Gas Turbine, CCGT, without CCS to take account of relatively less "advanced" but economically competitive characteristics - gas CCGTs type is in a configuration based on a twin block installation with a gross capacity of 830 MW, comparable with the other plants examined.
- Onshore Wind plant (100 MW), located 10 km from a MV substation.
- Offshore Wind plant of 200 MW, located 25 km from shore in 20 meters of water, using monopole foundations.
- the Nuclear European Power Reactor (EPR), third generation: pressurized water reactors (PWR) of 1600 MW.
- the Advanced Supercritical (ASC) coal plant with Flue Gas Desulphurization (FGD) and with post-combustion Carbon Capture and Storage (CCS) with a plant capacity of 1600 MW.

The selected cost and performance parameters take into account timing (like construction, operational and decommissioning period), technical data (plant heat and power output, efficiency, load factor, and so on), capital costs (like EPC), operational and maintenance costs (like fixed and variable maintenance costs).
Several assumptions for the cost of CO_2 disposal, waste disposal, decommissioning, fuel price projections, and other variables are also considered.
LCOE is calculated for the plant lifetime and given in currency units per megawatt-hour (€/MWh). Each technology has a set of variables and parameters necessary to calculate the LCOE standard expression. Special attention is given to the distinction of characteristics for the first of a kind (FOAK)[1] and the nth of

	m.u.	Wind Offshore	Wind Onshore	Gas - CCGT	ASC Coal with CCS	Nuclear EPR 3
Key Timings						
Construction period	years	1.5-3	2-2.2	2.5-3.2	4.8-6	5-7
Plant operation period	years	21	22	28	36	60
Technical data						
Gross power output	MW	200	100	830	1600	1600
Gross Efficiency	%	100	100	58	35	100
Average Degradation	%	0	0	3,5	2,5	0
Average Load Factor	%	39	28	78	78	90
Capital costs						
EPC cost	€/kW	3000-3850	1450-1900	700-780	2900-3400	3100-4000
Pre-licensing cost, Technical and Design	€/kW	50-72	55-110	31-44	66-130	55-110
Regulatory + licensing + public enquiry	€/kW	50-71.5	38.5-77	27.5-39	66-130	55-110
O&M costs						
O&M fixed fee	'000€/MW/yr	125.4-141.9	34-41.3	22.2-31.6	92.4-134	85.8-106.7
O&M variable fee	€/MWh	0	0	2.4-2.5	14.8-15.8	2-2.75

TABLE 1 Key parameters for the examined technologies[2,8]

a kind (NOAK)[2] plant. The previous distinction is useful to compare mature and innovative technologies[30]: this is very important when considering the capital cost and forward price adjustments of new technologies about this work.

Assumptions about FOAK and NOAK values for all parameters follow the main reference studies[7,8,17].

For the power plant that uses fossil fuels, the variability of the fuel price and the carbon price is very important to establish a realistic value of power generation cost. Fuel prices have been based on DECC's[2] projections until 2030 and they are shown in Table 2.

As shown in Table 2, three different scenarios of projected costs were considered, depending on varying global energy demand levels. It is worth noting that the nuclear fuel price includes uranium enrichment and fabrication of fuel elements[20] (average 3-5 €/GJ). In general, a high fossil fuel price is expected in case of strong climate mitigation policies (so in the case of higher carbon prices).

Scenario	Unit	Gas	Coal
Low	€/GJ	4.3	1.5
Mid	€/GJ	8.1	2.4
High	€/GJ	11.2	4.0

TABLE 2 Average fuel prices in 2015-2030[2, 7, 8]

As mentioned above, there are many other components not captured by levelised costs[3,6], like the externalities, the system factors (e.g., transmission costs), etc. Indeed, it is possible to incorporate some of these factors. In this study we have considered the CO_2 emission cost because, for fossil fuel plants, uncertainty in the damage costs by air pollutants can potentially increase significantly the LCOE in some cases. In the no-externality case, fossil fuel technologies are highly attractive, but as externalities cost increase, their fuel intensity and emissions can raise their LCOEs well above those of RES in general, and Wind Offshore in particular[6]. This work relies on the central hypothesis of the reference study[7] (CO_2 price starts from 14 €/t in 2010 and rises to 18 €/t by 2020 and to 77 €/t in 2030).

The problems in getting the data have been overcome, where possible, using data from reference plants or time series from literature, or from institutional data sources[2,5,6,14,17,18,24,28].

For Offshore Wind Plants, special attention was dedicated to key factors affecting the final cost (Figure 1) [11,12,15,16,17,22,24,27,29].

The major problem for the operators of Offshore Wind Farms is to reduce their investment costs; furthermore, to minimize operation and maintenance costs they need to obtain higher reliability. Offshore Wind Technologies and renewables are generally more expensive than conventional generation plants, due to the immaturity of the technology and a still limited diffusion. In addition, fluctuations in the energy source itself may limit the output of generation available from these technologies.

About the future of offshore, since Denmark has a primary role in the European wind industry, some forecasts from Denmark wind players have been used as a benchmark in some sensitivity analysis performed and discussed later: for example, a reasonable target for the above mentioned players is to reduce CAPEX by approximately 40% of current costs[22], an indication used in this work.

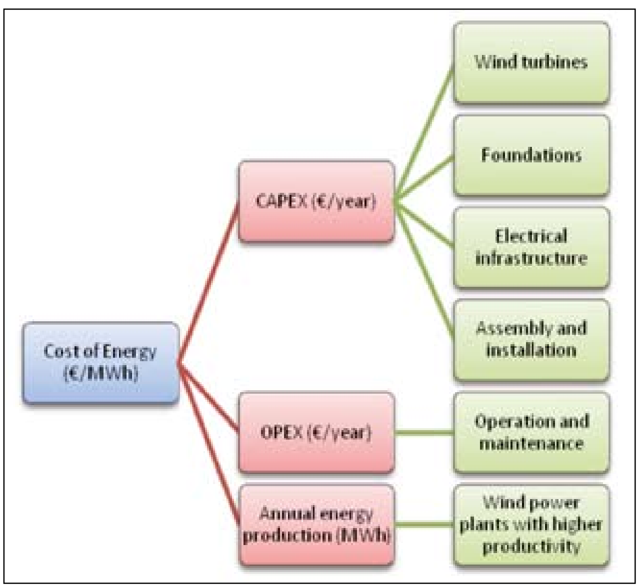

FIGURE 1 LCOE cost structure for Offshore Wind power plants
Source: Rao, Gaeta, 2012

LCOE model and financial analysis

The LCOE approach is adopted to compare the different technologies because it takes into account the various amounts of energy produced over different technical lifetimes[29]. So *the levelised cost of energy (LCOE) allows to compare alternative technologies when there are different scales of operation, different investment and operating time periods, or both. For example, the LCOE could be used to compare the cost of energy generated by a renewable power plant with that of a conventional fossil fuel power plant.*[1]

As always, main components of LCOE are: capital costs, O&M costs, fuel cost, carbon costs; data from plant like lifetime, load factor, and so on; discount rate and others (e.g., shape of the learning curve). For components not captured by LCOE[5], like the externalities, it is possible to incorporate some of these factors by adjusting one or more of the elements described above, so that they act as a proxy for the ‘missing’ elements.

Despite its several limitations, the strength of the LCOE approach is the simplicity and effectiveness of the method: this is reflected in the large number of existing works that use it. However, it is good to be aware that in estimating the LCOE costs components a wide range of ad-hoc assumptions has been used, and each assumption is quite far from being unanimously accepted.

The extended standard equation used in this work is:

$$\mathrm{LCOE} = \frac{\mathrm{INV} + \sum_{n=1}^{N} \frac{O\&M}{(1+\mathrm{DR})^{N}} + \sum_{n=1}^{N} \frac{\mathrm{FC}}{(1+\mathrm{DR})^{N}} + \sum_{n=1}^{N} \frac{\mathrm{CO_2}}{(1+\mathrm{DR})^{N}} - \frac{\mathrm{RV}}{(1+\mathrm{DR})^{N}}}{\sum_{n=1}^{N} \frac{\mathrm{hours} * \sum_{n=1}^{n} (\mathrm{P} * \mathrm{LF})}{(1+\mathrm{DR})^{N}}} \quad 2)$$

where:

INV Investment cost
N Economic Lifetime
O&M Total Operation and maintenance costs, fixed and variable (O&M)
DR Real discount rate
FC Annual fuel cost
CO_2 Annual cost of carbon emissions
RV Residual Value (where available)
P Power (in MW)
LF Load factor

The choice between real or nominal LCOE depends on the purpose of the analysis: this work performs a constant-euro analysis to keep tracks of the real cost trends with more accuracy[1,17]. For the currency unit, the same approach of the reference works has been used[1,8,18]. The model used was developed in an Excel spreadsheet: it performs calculations, comparisons and sensitivity analysis for each examined technology.

Financial analysis and discount rate

The LCOE methodology discounts time series of cost components to their present values in a specified base year by applying a discount rate (DR) value; as expected, the capital-intensive technologies are very sensitive to discount rates, and some technologies should be associated with higher discount rates because they are perceived to be riskier: DR should incorporate or reflect in some way the risk profile associated to the riskier technologies, but this is very difficult using the LCOE approach[5]. According to the IEA (International Energy Agency), different ways to finance projects (i.e., debt versus equity) reflect the indirect assumption that *"equity is riskier than debt"*, so high risk technologies should require higher discount rates.

This work uses a classical discount rate model from the CAPM theory, considering a low randomness of the equation parameters (like β) to get a compromise solution about one of the LCOE approach limitations: different DRs should be applied to the various components of cost (typical case is O&M costs vs. fuel costs). The chosen DR model is consistent with those of other reference works[18].

DR was fixed at 10% per annum (sensitivity analysis ranges from about 2.5% to 12.5% per annum)[5,6,8,17]. Discounting is applied over the economic life of power plants, which is assumed to be somewhat longer than the typical financing terms. A fixed discount rate and a model based DR have been used.

The DR Model

The WACC[3] formulation is given by the rate that a company is expected to pay on average to all its security holders to finance its assets. The equation is:

$$WACC = w_d * k_d\,(1 - t) + w_s * k_s \qquad 3)$$

where:

w_d	weight of debt proportion to total capital
w_s	weight of equity proportion to total capital
k_d	cost of debt
k_s	cost of equity
t	corporate tax rate

Projects can be financed by both debt and equity; specifically, the after-tax weighted average cost of capital is the discount rate used in evaluating investment opportunities.

K_d is equivalent to the interest-rate paid by the company (the so-called risk-free rate[4]): it is assumed exogenous.

Capital Asset Pricing Model (CAPM) provides methods to compute the cost of equity[5], which is an implied investor's opportunity cost that reflects the specific risk of the investment.

The model for such a cost is:

$$k_{st} = k_{RFt} + (EMRP * \beta_{equity}) \qquad 4)$$

where

k_{st}	cost of equity at year t
k_{RFt}	risk-free rate at year t
EMRP	expected market risk premium (constant)
B_{equity}	equity beta (constant)

The assumptions about the main DR model variables are based on an elaboration of hypothesis from current literature.

Simulation

The Monte Carlo technique is a non-parametric statistical method, based on the use of random numbers and probability to get solutions for mathematical problems which have many variables not easily solved, simulating different probability distributions of the main parameters. Simulation methods made uncertainty analysis through "the substitution of a probability distribution for any factor that has a huge uncertainty" [32].

This work implements the so-called "raw" Monte Carlo (MC): this choice relies on various considerations: there are problems in establishing the boundary delimiting the domain of integration; there are no peaks concentrated in restricted regions for variables to be integrated and, finally, raw MC allows to get an acceptable trade-off between accuracy and simplicity.

The probability distribution model used is continuously Uniform: this choice was made for two main reasons. The first relates to the lack of suitable data to define evenly patterns of specific probabilities for all the simulated variables. The second reason is that this choice corresponds to a compromise between the need to standardize methods and calculations between different technologies and various cost components and the aim of characterizing them as close as possible to the true value. The number of simulations for the random variables considered is 10000: the results are rounded to the nearest full euro.

Results

In this paragraph some results are presented in various graphics. They show LCOE comparison among the five technologies mentioned above.
The average cost of a megawatt hour generated by Offshore Wind plants is centered around 175 €/MWh, a value significantly higher than all the other competing technologies (Figure 2).

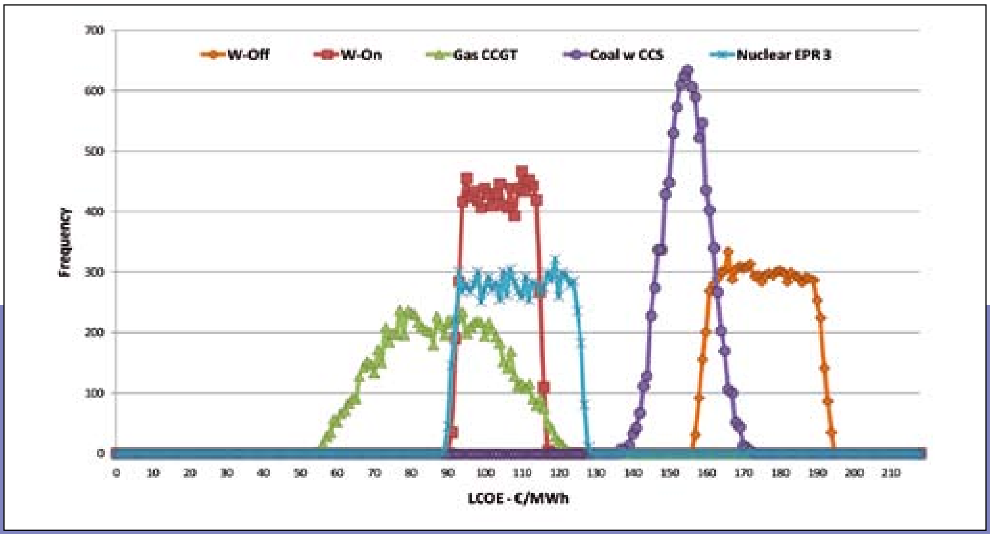

FIGURE 2 Probability distribution for LCOE (discounted rate: 10%)
Source: Rao, Gaeta, 2012

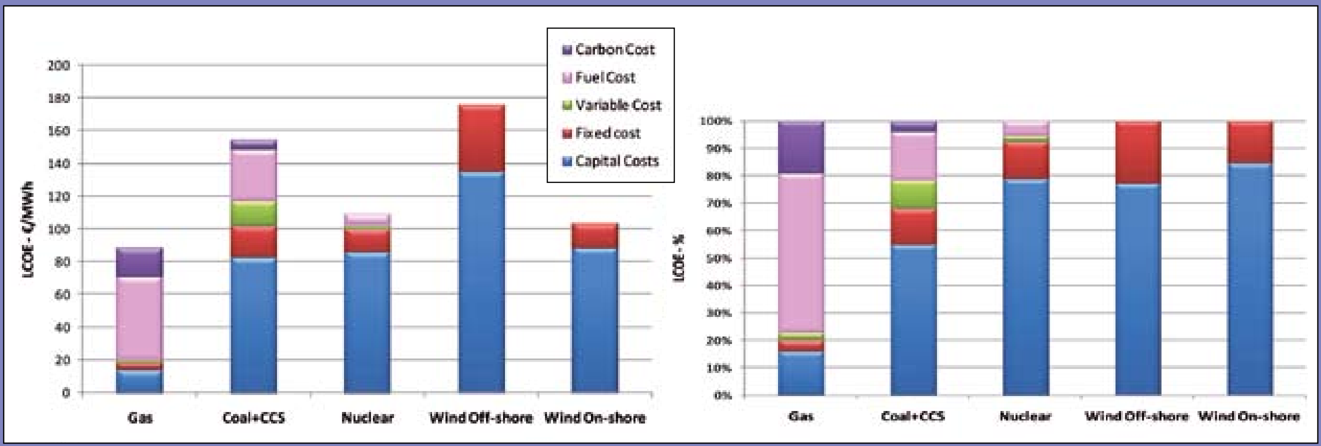

FIGURE 3 PMain components of average LCOE for the examined power plants
Source: Rao, Gaeta, 2012

The Gas fired CCGT is the one able to achieve the lowest cost of generation (89 €/MWh) under the assumptions made (e.g., in particular about the adopted GHG and gas prices dynamics).
Offshore wind energy cost itself proves not competitive without incentives for electricity production with technologies such as CCGT, but the first reachable target could be (in a similar order of the required investments) the FGD with CCS coal plant, or maybe the nuclear EPR 3. The investment costs, changes in financing conditions, especially in greenhouse gas emissions costs, can impact deeply to get the future target.
Figure 3 shows the average LCOE, total and main components. Future competitiveness of offshore wind plants, in the baseline scenario, relies mainly on the investment costs. The complete independence of wind

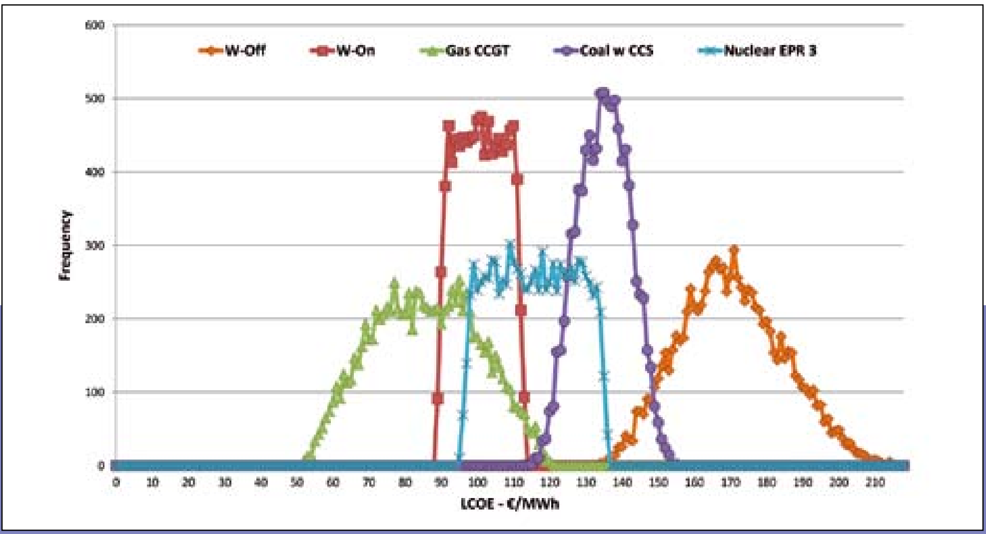

FIGURE 4 Probability distribution for LCOE (using the discounted rate model)
Source: Rao, Gaeta, 2012

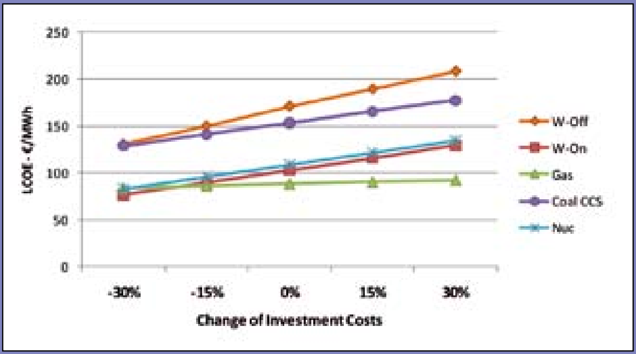

FIGURE 5 Effects of the change of the investment cost
Source: Rao, Gaeta, 2012

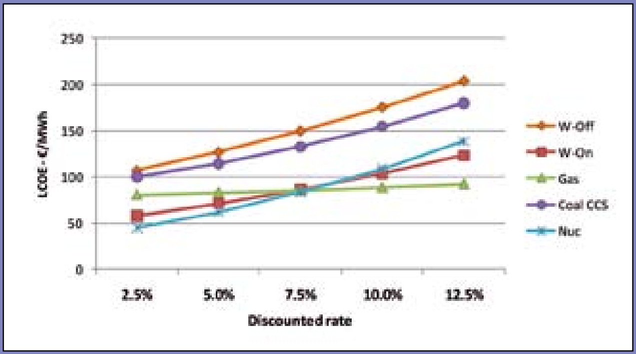

FIGURE 6 Sensitivity of levelised costs to discount rate variation
Source: Rao, Gaeta, 2012

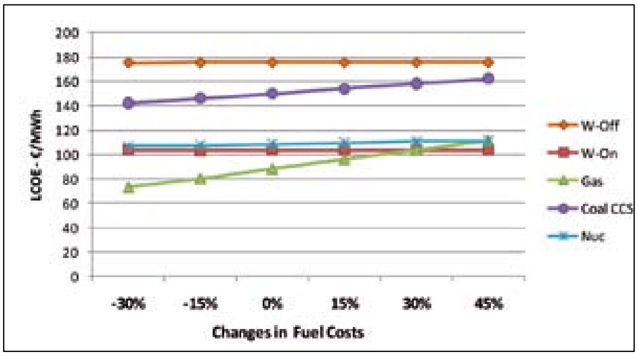

FIGURE 7 Sensitivity of levelised costs to fuel price variation
Source: Rao, Gaeta, 2012

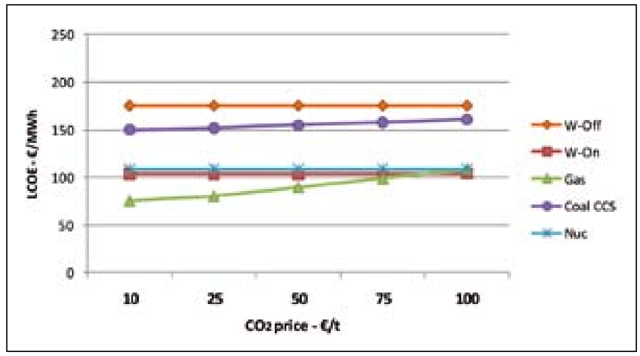

FIGURE 8 Sensitivity of levelised costs to CO_2 price variation
Source: Rao, Gaeta, 2012

technologies from the carbon cost and fuel cost also clarifies that, in a scenario of capital costs abatement, even technologies as CCGT, now unattainable, could become a realistic target. Capital cost component is dominating in nuclear and wind generation costs (~80%). The emission trading systems gives an electricity generation cost growth of 18 €/MWh for CCGT and 6 €/MWh for coal-based plants. Minor increase in the coal plants is due to the presence of carbon capture and storage technology.
In addition, the study includes a sensitivity analysis, as relevant, for various discounted rates, investment and fuels costs, and carbon emission costs[20].
The sensitivity analysis has been carried out by setting all the parameters in the respective average values and simulating it one by one in a predetermined realistic range.
Using the discounted rate model early described, the nuclear, onshore and offshore cost curves are moved forward by 10 €/MWh circa, (these are the most capital intensive technologies): offshore distribution becomes very similar to normal distribution, with a remarkable change of skewness and range of variation (155-195 to 135-205 €/MWh).
The analysis has incorporated the best perspective for investment and fixed cost abatement (Figure 5).
A capital cost reduction for offshore wind plants of 30% compared to the average results, leads to a decrease of 40 €/MWh in power generation cost. As shown in Figure 5, even just a reduction of 15% of the investment cost allows offshore wind plants to become competitive with Coal CCS plant.

Discount rate changes on LCOE are shown in Figure 6. The interval chosen for DR is from 2.5% to 12.5%[26]. As expected, the impact of changes in DR is greater for capital intensive plants as wind, nuclear and CCS (note that nuclear and offshore curves have the highest slope).
About sensitivity to fuel price changes, the technologies naturally more vulnerable are the CCGT and the CCS (Figure 7). If fuel price increases by 30%, nuclear generation cost increases by 2%, coal CCS cost by 5%; gas-based plant by 18%.
With regard to CO_2 costs, nuclear technology is essentially neutral to the simulated changes; the emission trading improves competitiveness of carbon free power production compared to fossil fuel power plants[20] (Figure 8).

Main conclusions

The results obtained demonstrate that currently offshore wind technologies are not yet really competitive without an incentive scheme. The power generation cost for an offshore wind plant could seem relatively high: 175 €/MWh, almost totally due to the high capital cost. The fossil fuel based plants still appear as an appealing investment: however, the sensitivity analysis performed shows that, with a conceivable future capital cost abatement, Offshore Wind plants could become competitive with some conventional plants, like coal with CCS. Furthermore, Offshore Wind plants are not affected by fuel price volatility and carbon price market fluctuations, and could become a plausible option in future power generation.

Appendix: Acronyms list

Capex Capital expenditure
CCGT combined-cycle gas turbine
CCS Carbon Capture and Storage
DECC Department of Energy and Climate Change
EIA Energy Information Administration
EPC engineer, procure and construction
EPR European Pressurised water Reactor
FGD Flue Gas Desulphurisation
IGCC Integrated Gasification Combined Cycle
O&M Operation and Maintenance

notes

1. If a project activity is "first-of-its-kind", this means that the implementation of this specific technology is not "common practice" yet [31].
2. The definition of the (NOAK) plant is arbitrary, (often, NOAK means the fifth or higher plant).
3. Weighted Average Cost of Capital.
4. The rate of interest with no risk, typically based on public bond plus a risk component which itself incorporates a default risk.
5. The return that a firm theoretically pays to its equity investors to compensate for the risk they undertake by investing their capital.

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