Energy Policy 38 (2010) 6360–6374

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Small–medium sized nuclear coal and gas power plant: A probabilistic analysis of their financial performances and influence of CO_2 cost

Giorgio Locatelli*, Mauro Mancini[1]

Politecnico di Milano, Dept. Management, Economics and Industrial Engineering, Via Lambruschini 4/b., 20156 Milano, Italy

ARTICLE INFO

Article history:
Received 11 February 2010
Accepted 15 June 2010

Keywords:
LUEC
Small medium plant
Monte Carlo

ABSTRACT

Nations or regions with limited electrical grid and restricted financial resources are a suitable market for small medium power plants with a size of 300–400 MWe. The literature presents several comparisons about the economics of large power plants (of about 1000 MWe); however there are not probabilistic analysis regarding the economics of small medium power plants. This paper fills this gap comparing, with a Monte Carlo evaluation, the economical and financial performances of a nuclear reactor, a coal fired power plant and a combined cycle gas turbine (CCGT) of 335 MWe. The paper aims also to investigate the effect of the carbon tax and electrical energy price on the economics of these plants. The analysis show as, without any carbon tax, the coal plant has the lowest levelised unit electricity cost (LUEC) and the highest net present value (NPV). Introducing the carbon tax the rank changes: depending on its amount the first and the nuclear after becomes the plant with lower LUEC and highest NPV. Therefore, the uncertainty in the carbon tax cost increases the risk of investing in a coal plant above the level of the new small medium reactor.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Most of the studies comparing the economics of power plant presented in the literature concern large plant with an average size of about 1000 MWe. Small medium sized power plants are usually labelled as "not economical" because of the axiom of the economy of scale. However, these plants have many attractive features, as summarised by EMWG (2007), Carelli et al. (2004), Ingersoll (2009) and Kuznetsov (2008, 2009).

- Easier plant-grid matching. Many countries, even in the EU, have smaller grids and old technical infrastructures. These grids are not able to accept the connection of concentrated, large power stations.
- Front end investment. The unit cost of a small plant is a fraction of the cost of a larger plant: this reduction can be "the" critical factor for a utility or country with limited resources.
- Investment scalability. Investments in small plants are modular: due to smaller sizes and shorter construction times, the capacity additions of small plants are more flexible in sizing, timing and sitting than those of large plants. In particular, the plant capacity is more readily adaptable to changing market conditions.
- Co-generation. Besides electricity, other products can be easily obtained by small plant. Part of the heat generated by, for instance, a nuclear reactor can be used for urban heating or desalination process (Tewari and Rao, 2002; Tian, 2001) or for the desalinisation of sea water in the island. A technical requirement is to locate the heat or the desalination plant near the end-user areas that is easier for a small plant than for a large plant.
- Mass production economies. For a certain installed power many more small plants than large plant are required. This aspect allows the small plants to achieve the mass production economies and a more standardised procurement process.
- Modularization. (EMWG, 2007) defines "modularization like" the process of converting the design and construction of a monolithic plant or stick built scope to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies. It is well known that the factory fabrication is cheaper than the site fabrication, but the limit is the possibility of a cheap shipping of the modules built to the site. In general it applies the rule "smaller the size, smaller the components cheaper the shipping".
- Learning economies. It is well known that a Nth-Of-A-Kind (NOAK) plant costs less than a First-Of-A-Kind (FOAK) because of the lessons learned in the construction and deployment of earlier units. The learning curve generally flattens out after 5–7 units. Comparing a small plant and a large plant, the NOAK is reached with less MWe installed for small plants than large plants.

* Corresponding author. Tel.: +39 02 2399 4096; fax: +39 02 2399 4083.
E-mail addresses: giorgio.locatelli@polimi.it (G. Locatelli), mauro.mancini@polimi.it (M. Mancini).
[1] Tel.: +39 02 2399 4057; fax: +39 02 2399 4083.

0301-4215/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2010.06.027

Considering this factors (Carelli et al., 2010) demonstrates as the specific capital cost ($/MWe) of a SMR is similar to an LR. Therefore base load small medium power plants are an attractive option for countries with a limited grid and limited financial resources or islands not connected to the continental grid. Under an investor and decision maker point of view this paper presents the comparison of 3 main plants for the base load: nuclear reactor, coal power plant and CCGT (combined cycle gas turbine).

2. Literature review and scope of the analysis

The literature about the economics of power plants includes two types of studies: deterministic and probabilistic. There are many studies using a deterministic approach and few using a probabilistic approach. The probabilistic approach requires more information (for each data a probability distribution instead of a single value), but represents the best tool for a strategic decision. Therefore this kind of study is the focus of this analysis.

2.1. Probabilistic studies

Regarding base load power plant the most relevant studies using a probabilistic approach are Feretic and Tomsic (2005) and Roques et al. (2006).

Feretic and Tomsic (2005) presents a framework based on the Monte Carlo approach to compare the LUEC of coal plant, CCGT plant and nuclear plant. In this paper there are some areas of improvements addressed in this research:

- input data: three distributions (triangular, flat and five points) without justification from the literature of the values and the shapes of the distributions;
- number of iterations: is fixed at 2000;
- size of the power plant: is not defined.

The results indicate as the LUEC of Nuclear is the lowest (4.2–5.8 US cents/kWh and a most probable value of about 4.8 US cents/kWh), the CCGT is the highest (of 4.5–8 US cents/kWh, with a most probable value of about 5.8 US cents/kWh) and the coal fired is in the middle (are 4.5–6.3 and 5.2 US cents/kWh)

Roques et al. (2006) compares the net present value (NPV) of three base load technology (coal plant, CCGT and nuclear) using a Monte Carlo simulation. The size of these plants is 1000 MWe.

The input data derive from reliable sources such as MIT (2003) and IEA (2005). The uncertainty in the parameters is always modelled as a normal distributed variable with a mean value coming from the analysed literature. The standard deviation is defined using the literature, historical data or expert judgement. The number of iterations used in the simulation is fixed at 100.000. With this methodology the authors investigate the dependence of NPV respect to input values. Then the research focuses on the economic implication of do not produce electrical energy if the selling price is too low.

2.2. Scope of the analysis

As the citied literature our analysis aims to investigate the economic performance of nuclear plant coal fired and CCGT, but differently from the available literature the paper aims to:

- Compare small/medium power plants (335 MWe, the size of IRIS reactor).
- Use as input data the literature (historical values and forecasts) and not experts judgments.
- Define the input distributions with rigorous statistical methodologies.
- Compare the power plant considering: LUEC, NPV to the firm (from free cash flow to the firm or unlevered cash flow), NPV to the shareholders (from free cash flow to the equity or levered cash flow), IRR.
- Use as sampling technique for the probabilistic analysis the Latin hypercube instead of the Monte Carlo (even if the analysis is still called Monte Carlo) because its better performance for this kind of analysis (Saliby, 1997) and assess its convergence.

Table 1 compares our assumptions respect to Feretic and Tomsic (2005) and Roques et al. (2006) whereas in the next section the methodology is deeply presented

3. Methodology

3.1. Data screening and general approach

In a discounted cash flow model the overall evaluation strongly depends by the input data. There are many sources in the literature proving such data, however not all are suitable for an unbiased analysis. Several studies indicate that optimism in the cost estimation in large projects (as power plants) is a common characteristic. In particular Flyvbjerg et al. (2003) shows how the availability and reliability of data on large projects affects the estimation. The author identifies two macro-categories of causes to explain inaccuracy in the cost forecast:

1. inadequacy of the methodologies and
2. strategic data manipulation.

3.1.1. Inadequacy of the methodologies used

Quinet (1998) identifies three sources of errors: methodological problems in the structure of the model estimation, unreliable data used in the analysis, uncertainty about exogenous variables. Trujillo et al. (2002) argues that estimation techniques are the

Table 1
Comparison among the cited studies.

Comparison of this work with the literature			
	Feretic and Tomsic (2005)	Roques et al. (2006)	This paper
Power plant analysed	Nuke, coal, gas	Nuke, coal, gas	Nuke, coal, gas
Plant size (MWe)	Undefined	1000	335
Sampling methodology	Monte Carlo	Monte Carlo	Latin Hypercube
Iterations	2000	100.000	Depending on the case, enough to obtain robust results.
Modelling of uncertainty	Expert judgment	Literature and expert judgment.	Literature
Input curve	Triangular, flat and five points	All Normal	Many, depending on the input data
Indicators	LUEC	NPV	LUEC NPV (firm and shareholders) IRR

main cause of differences between budget and actual values. Flyvbjerg et al. (2003) shows that it is not the model that accounts for most of the differences, but the basic assumptions made by analysts before applying the model; technical explanations are to be excluded because not confirmed by the data (Flyvbjerg et al., 2005, 2005b).

Two reasons support this argument:

- if the inaccuracy depended on technical causes, a normal distribution of error with an average close to zero should be expected, however the actual distribution is not normal with an average error much greater than zero (actual costs are usually over budget).
- it is reasonable to expect an improvement over time of assessment methods due to more sophisticated forecasting models and modern informatics tools. However, over time, the estimations do not improve. Since technical factors do not justify the inaccuracy, authors focus on the second set of reasons.

3.1.2. Strategic data manipulation

Wachs (1990) interviewing government officials, consultants and planners in charge of different projects, noted that estimations were biases. They manipulated forecasts to achieve values, not justified in technical terms, but acceptable for their superiors to implement the project.

Lovallo and Kahneman (2003) show that cognitive biases and organizational pressures push managers to provide optimistic forecasts.

Flyvberg et al. (2003, 2005, 2005b) incorporates the results of previous contributions adding other reasons:

- Opportunism. This reason explains the phenomenon in terms of personal and public interest.
- Optimism bias. The authors indicate that the most common psychological explanation is the presence of a certain "optimism" which induces promoters to consider each assumption positively. The authors point out, however, that such optimism is misleading for the promoters themselves, and not an intentional error.

To cope with these hitches Flyvbjerg (2005, 2005b, 2006), in his main works, proposes a method called "reference class forecast". Flyvbjerg developed this method for infrastructural projects, however can be adapted to power plants. The main goal of this model is to provide the steps for data screening to avoid data manipulation and biased optimism.

1. Identification of a relevant reference class of past project.
2. Establish a probability distribution for the selected reference class.
3. Compare the specific project with the reference class distribution, in order to establish the most likely outcome for the specific project.

For the first step we referred to recent data in industrialised countries with legislation and labour cost comparable to USA, for the second we carried out an analysis with a statistical software, for the third we developed a discounted cash flow model.

3.2. The model

The methodology implemented in our study is composed by five steps:

1. Data gathering for the life cost accounts: overnight cost, fuel, operation and maintenance (O&M), decommissioning (only for NPP) and the financial parameters (cost of Equity, cost of debt, etc.).
2. Updating cost account data to 2010 using different cost escalation curves.
3. Distribution assignment. We used the program "Best-Fit" to analyse the data gathered from point one. The distributions found have been assessed with the X2 test (for all the distribution), the Kolmogorov–Smirnov test and the Anderson–Darling test (for the appropriate distribution). If any of these tests does not return a suitable distribution we used a discrete distribution with the data from point 1.
4. Creation of an Excel spreadsheet for the discounting of each cash flow.
5. Fig. 1 summaries the structure of this model and to compute the LUEC (as indicated by GENIV) and the NPV as indicated by Damodaran (2006).
6. Assignment of the distribution found at point 3 to all the not deterministic data by using @risk and running with a number of iteration enough to ensure the robustness of the results.

Application of probabilistic method relieves the difficulties in data prediction because instead of predicting single data values, an uncertainty margin of each data can be predicted with margin width depending upon uncertainty of particular data. However with this methodology it is not possible to manipulate data and use subjective assumptions. Moreover if the uncertainty on an account is relevant the cost data in input will be rather different, therefore the distribution implemented (continuous or discrete) will have a large standard deviations. This will increment the standard deviation in the Monte Carlo simulation. In conclusion, the uncertainty in the result is directly correlated to the uncertainty in the inputs. It worth to remember how discounting distant costs (in particular the fuel) have small influence on the results.

4. The dataset

In order to collect information from different sources the power plants should present similar characteristics. Therefore we decided to define 3 references plants representing the "state of the art" for what concern the production of electrical energy

- Nuclear: the reference plant is a generation III or III+ light water reactor.
- Coal: the reference plant has the systems recommended by the recent environmental laws: NO_x control system, particulate control, mercury removal, fuel gas desulphurization, etc.
- CCGT: the combined cycle gas turbine adopted in the European Union.

4.1. Overnight cost

The overnight cost is the base construction cost plus applicable owner's cost, contingency on the construction and, in case of NPP, the first core costs. This cost is expressed as a constant dollar amount in reference year dollars. The total capital investment cost (from now on capital cost) is the overnight cost plus escalation, fees, interest during construction and contingency on financial costs (EMWG, 2007). The methodology to quantify this cost account is composed by the following steps:

1. Data gathering from the literature of all the estimations and historical data of overnight cost.
2. Actualisation of the former value to 2009 with the escalation indexes. This is required since the estimations are provided for different years.

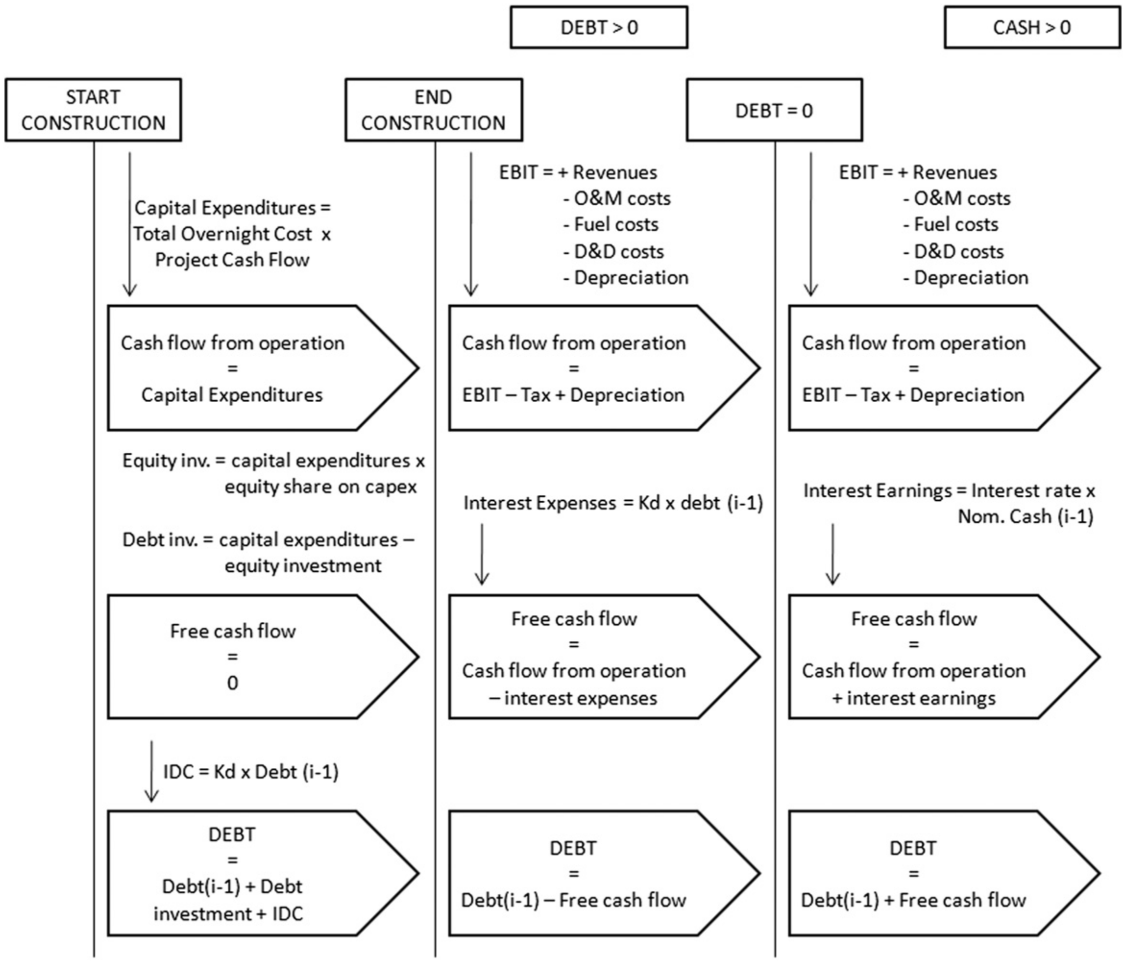


Fig. 1. Framework for the financial analysis.

3. Application of the economy of scale. Since the data are referred to plants with different size with the economy of scale law is possible to scale the various data at 335 MWe. Economies of scale can be quantified (assuming that the two plants are comparable in design and characteristics) using Eq. (1).

$$OC_{small} = OC_{large} \times \left(\frac{S_{small}}{S_{large}}\right)^{\alpha_{ES}} \quad (1)$$

   where OC is the overnight cost ($/kWe), S is the size of the power plant (MWe) and α_{ES} is the economy of scale exponent. If the α_{ES} parameter is smaller than 1, economies of scale exists, the closer the n value is to 0, the stronger the economies of scale. Since α_{ES} depends on the technology a bibliographic analysis of the economy of scale exponent has been included for each type of power plant.
4. Database creation: starting from the data in point 1 we defined a new set of data with the coefficients from point 2 and 3.
5. Distribution assignment.

The next sections present the escalation indexes, then for each technology the data set for the bibliographic references of OC, the economy of scale exponents and the final data fitting.

4.1.1. Escalation indexes

One of the most relevant uncertainty in the estimation of the OC comes from the changing in the design during the time of PP and the commodity cost, as reported by EIA (2008b, 2008c). We chose the 2010 as reference year we updated the estimation from the literature according to three indexes:

1. PCCI (power capital costs index) developed by the DOE and reported by NETL (2008) and FERC (2008) distinguishes two different trends: the first include the NPP, the second is without NPP.
2. CEPCI (chemical engineering plant cost index) (EPRI, 2006) developed since the 1963 from "*Chemical Engineering*" is composed by a weighted average of four cost indexes related to: equipment, labour, construction and engineering.
3. M&S (Marshall & Swift index) (EPRI, 2006) developed since 1926 from "Chemical Engineering" is composed by the weighted average of many indexes from different sectors.

The comparison of these indexes shows as the escalation costs by CEPCI and M&S are quite similar, on the opposite the escalation rate from PCCI is higher. Since we aim to study how the uncertainty influences the LUEC and NPV of different PP all these indexes has been included in the analysis.

4.1.2. Nuclear power plant

4.1.2.1. Data set for the overnight cost. Table 8 (in Appendix) summarises the most recent and reliable estimations for the OC of NPP.

We decided to use the following criteria for the data screening.

The calculation of plant competitiveness based on LUEC has to take into account that power plants that are subject of present studies will enter in operation around 2020 and operate for 30–60 years. Therefore cost data selected for LUEC should expected to be reasonably valid within estimated uncertainty ranges during whole plant operating period.

- data not older of three years. It is clear how the estimations in years 2002–2005 are much more optimistic than the most recent ones. Therefore, being conservative we decided to drop the estimations from MIT (2003) and IEA (2005). We decided also to drop EIA (2008a), since a new data from the same source is available: EIA (2009a) which increases the former value by 50%.
- data referred to USA and comparable country as labour cost and nuclear legislation. Therefore we included USA (10 data), Japan (8 data), South Korea (4 data), France (1 data) and United Arab Emirates (1 data). We included also 12 data coming from studies (e.g. MIT, 2009) referring to USA or comparable country. We dropped estimations regarding reactor under construction or proposed in former URSS country or China.

In our data sampling 11 are GEN III reactors recently connected to the grid (therefore is an actual value), 2 are under construction, 1 is in the bidding phase, 22 are forecast from reliable studies. We tested the cost difference among the 11 actual values against the 22 forecast and there difference is not statistically significant therefore we included all these estimation.

4.1.2.2. Economy of scale exponent. In order to quantify α_{ES} for the entire plant Bowers et al. (1983) summarises 28 studies and Trianni et al. (2009) presents the result other nine more recent relevant studies.

However it is also possible to compute α_{ES} more accurately considering the breakdown cost of the NPPs and applying the specific economy of scale exponent (α_{ESi}) to each *i*th account. The algorithm consists of the following four steps:

1. Define the breakdown cost for the large size reactor;
2. Compute the economies of scale for each account using Eq. (1) and the specific α_{ES} exponent. The main reference for the α_{ESi} exponents are Phung (1987) and EMWG (2007);
3. Sum up the accounts' values to compute the total capital cost for the SMR. The SMR is now characterized by a size S_{SMR} and an overnight cost, OC_{SMR} (total overnight cost/size).
4. Compute the general exponent using Eq. (2)

$$\alpha_{ES} = \frac{\ln \frac{OC_{SMR}}{OC_{LR}}}{\ln \frac{S_{SMR}}{S_{LR}}} \tag{2}$$

The result from this "account by account" analysis on the reactor of interest (e.g. the IRIS reactor) leads to an exponent value of α_{ES}=0.619, coherent with the literature values.

The best fitting curve for the data is a logistic with alpha=0.5914 and beta=8.92433 E−02. The tails cut at 0.2 and 1 are in correspondence of the boundary values found in the literature. The mean value of α_{ES} is 0.59.

The economy of scale applies "as is" only if the considered designs are similar, which is not the case here, since an SMR takes advantage of design solutions not accessible to large size reactors. Mycoff et al. (2007) and Carelli et al. (2008, 2010) quantify this advantage as a 17% cost saving. This result is consistent with a study performed by ORNL (Oak Ridge National Laboratory) (Reid, 2003). Therefore all the data in the database (referred to Large reactors) have been multiplied by 0.83. Moreover, since we aim to study a generic NOAK (Nth-of-a-kind) 335 MWe plant all the data referred to FOAK (First-of-a-kind) have been multiplied by 0.8, as suggested by EMWG (2007).

4.1.2.3. OC distribution. The distribution assignment process for the OC indicates as best fit the LogLogistic distribution curve with the following parameters:

Gamma = −3086.5; Beta = 7060.1; Alpha = 10.492.

Such distribution has a mean value of 4080 $/kWe and a standard deviation of 1261.8 $/kWe. The upper and lowest values are: 1333 and 10,647 $/kWe. This distribution is the input for the financial analysis to compute the capital cost.

4.1.3. Coal power plant

The data set for coal power plant is presented in Table 9 (in Appendix). Only power plants able to respect the tight emissions limits foreseen in the EU and USA are considered in the analysis therefore estimations related either to non OECD countries or far east countries are not included in the database since not representative (IEA, 2008).

The most reliable data source of α_{ES} is (Bowers et al., 1983c) providing a list of 25 values. We decided to drop the two extreme values because, with an ex-post analysis, can be considered as outliers. With these remaining 23 values is not possible to assign a continuous distribution; therefore a discrete distribution was used instead.

The distribution assignment process for the OC indicates as best fit the Beta distribution curve with the following parameters:

Alpha1 = 1.4299; Alpha2 = 4.3430; minimum value = 1571.8; maximum value = 4844.3.

Such distribution has a mean value of 2500 $/kWe and a standard deviation of 589.74 $/kWe.

4.1.4. CCGT power plant

Table 10 summarises the references providing estimations of OC of CCGT plants. For what concern α_{ES} for CCGT power plants the literature provides just one value: 0.48 (EMWG, 2007, page 59). However it is possible to determine further value with a regression analysis on the database provided by GTW (2005). The result of this analysis is α_{ES}=0.88. The difference between these two values is remarkable, however the effect of this difference (in case of CCGT power plant) is quite negligible, because:

1. The average size of the power plant in the database (377 MWe) is really close to the size of the reference plant (335 MWe). Closer the size, less the economy of scale effect is relevant.
2. The sensitivity analysis show how shifting α_{ES} from 0.48 to 0.88 increase the capital cost of this plant by 10%. Since the capital cost weight for 13% on the LUEC the maximum error has an order of magnitude of 1–2%.

The OC best fit is the LogLogisitc distribution curve with the following parameters:

Gamma = −204.83; Beta = 1151.9; Alpha = 7.1661.

Such distribution has a mean value of 983.12 $/kWe and a standard deviation of 270.25 $/kWe. The upper and lowest values are: 461.46 and 1990.22 $/kWe.

4.2. Operation and maintenance

Operation and maintenance are the costs for the decisions and actions regarding the control and upkeep of property and equipment. They are inclusive, but not limited to, the following:

(1) actions focused on scheduling, procedures, and work/systems control and optimization; and (2) performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability and safety (Sullivan et al., 2004).

4.2.1. Nuclear power plant

Table 2 summarises the most recent literature for what concern the O&M costs.

For what concern α_{ES} the literature report two values, both included in this analysis:

Bowers et al. (1987)	0.6
Carelli et al. (2008)	0.71

However, as already presented for the capital cost, in case of nuclear power plants, the economy of scale has to be corrected since small medium reap advantages from the smaller size. For example, the reduction of the site can increase the months among the refuelling from 18–24 to 48 (Carelli et al., 2004). This has two impacts:

- A saving in the cost associated to the outage.
- An increment the capacity factor, therefore the specific O&M cost is reduced.

In order to consider these two factors Carelli et al. (2008) suggests to multiply two coefficients:

Outage additional cost:	0.97
Capacity factor improvement:	0.96

Considered few data available on any of continues distribution passed the statistical tests; therefore we assigned a discrete distribution.

Such distribution has a mean value of 90 ($/kWe year) and a standard deviation of 22 ($/kWe year). The upper and lowest values are 160 and 69 ($/kWe year).

4.2.2. Coal and CCGT power plant

Table 9 and Table 10 summarise the dataset available, respectively, for the Coal and CCGT power plants. Since the public literature does not provide any particular value of α_{ES} related to O&M for coal and CCGT we adopted the same values used for NPP.

For coal plant the distribution is continue and presents a mean value of 55 ($/kWe year) and a standard deviation of 22.3 ($/kWe year). The upper and lowest values are 87.5 and 22.3 ($/kWe year).

For CCGT the distribution is continue and presents a mean value of 28 ($/kWe year) and a standard deviation of 9.7 ($/kWe year). The upper and lowest values are 50.40 and 12,34 ($/kWe year).

4.3. Fuel

The international literature can be dived in two main groups.

1. Literature about many different types of fuel. For this group the most recent and reliable documents are EIA (2008b, 2008c) and IEA (2007).
2. Literature about only one particular fuel/technology. Such literature has been analysed in the following specific sections.

4.3.1. Nuclear power plant

For what concern the fuel cost for NPP the worldwide reference is the "red book" (IAEA and NEA, 2008). The fuel cost for a nuclear power plant can be broken down in two main accounts (Ayres et al., 2004)

- Front end: this includes the cost of uranium (26% of the front end cost), enrichment (59%) and fabrication of the fuel elements (15%);
- Back end: this is the cost of transportation of the fuel from the power plant to disposal in a spent fuel facility. It might include the cost of the following treatment.

Since the cost of the raw material (uranium) accounts for only 26% the escalation of this cost, as showed in IAEA and NEA (2008 Fig. 16), as weaker impact than in other technologies. WEC (2007) states that if the uranium cost increases by 500% the fuel cost increases by 20% and the LUEC by 10%. Moreover IAEA and NEA (2008 Fig. 16) refers to the spot price, whereas in nuclear industry long term contracts are more common. Therefore in our analysis we adopt a long term view referring to the literature in Table 3

For what concerns the back end cost, a conservative value from the citied literature is about 0.8 $/MWh. For what concerns the escalation cost there is not a clear indication, however a value 0.5%/year appears to match the analysis by IEA (2006) and MIT (2003).

A discrete distribution of the fuel cost as been assumed.

4.3.2. Coal power plant

Three trends, from EIA (2008b) has been included in the model:

- Base trend: a 5% of global increment from 2006 through 2030 (*Reference case*).
- Low trend: a 24% of global decrement from 2006 through 2030 (*Low coal cost case*).
- High trend: a 63% of global increment from 2006 through 2030 (*High coal cost case*).

4.3.3. CCGT power plant

The fuel price is the most relevant account for a CCGT power plant, therefore this cost has to be modelled really carefully.

The natural gas cost is correlated to the oil price (IEA, 2006 pp. 273) and the most common indexes are the "Henry Hub spot

Table 2
NPP Operation and Maintenance cost.

Source	Plant size (MWe)	O&M costs ($/kWe year)
MIT (2003)	1000	63
IEA (2005)	1450	58
WEC (2007)	1300	47–70
DOE (2008b)	1350	66
Trianni et al. (2009)	1340	71

Table 3
NPP fuel cost.

Source	Year	Fuel cost ($/MWh)
MIT (2003)	2003	4.3
Ayres et al. (2004)	2004	3–4
The University of Chicago (2004)	2004	4.35
IEA (2007)	2007	4–5 (includes back end)
WEC (2007)	2007	3.5–4.5

market" and the "Lower 48 wellhead". Both the indexes foreseen that the natural gas cost will decrease until the 2016 and than increase from 2016 through 2030) provides also four main scenarios analysis for the 2030: high price: 26.27 $/MWh; low price: 18.73 $/MWh; slow oil a natural gas technology: 24.23 $/MWh and rapid technology: 20.81 $/MWh.

Also IEA (2007) provides estimations. However Bolinger et al. (2006) points out that the forecasts by the EIA (Energy Information Administration) in the AEO (Annual Energy Outlook) are usually significantly different from the real values of forward gas price. Bolinger et al. (2003) shows that, with few exceptions, the EIA reference case forecast has generally been higher than most other forecasts generated from 2000 to 2003. Sanchez (2003) found that, as a general rule, the rate of increase in nominal energy prices has been overestimated by EIA in its past AEO forecasts (18 out of 21 forecasts). Bolinger et al. (2006, 2008) also underlines that the EIA "reference case" is not surely the most like scenario and the AEO underestimate the forward gas price.

The most detailed analysis of gas trend cost is the "World Gas Model" (WGM).The WGM developed by Nexant's Global Gas; simulates the global natural gas market covering the next three decades. It included more than 80 countries and covers 95% of global natural gas production and consumption. Huppmann et al. (2009) simulate eight scenarios using the WGM ranging from an annual cost escalation of 2.5% (low scenario) to 3.9% (high scenario) with a base case of 3%. These scenarios have been included in the model. Moreover, as shown in Section 5.1.3 a sensitivity analysis of the natural gas price has been performed to assess the elasticity of this account.

4.4. Decommissioning

This account is relevant only for NPP and includes all the cost necessary to perform "Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility [...]. The actions will need to be such as to ensure the long-term protection of the public and the environment, and typically include reducing the levels of residual radionuclides" (IAEA, 2007).

This cost accounts for few percentages of the life cycle cost (Williams and Miller, 2006; Mackerron et al., 2006) therefore is not necessary to include a curve in the analysis (really speculative considered the uncertainty associated), but it is enough a single value. OECD (2003) provides the results of a survey indicating how the average decommissioning cost of a large reactor is about 500 $/kWe. According to Locatelli and Mancini (2009) it is possible to compute the decommissioning cost of a small medium reactor by multiplying for: 3.09 (because of the economy of scale) and by 0.81. This latter value is the quantification of the technical saving i.e. advantage of adopting the solutions embedded in the small medium reactors. Therefore, the decommissioning cost for a 335 LWR implemented in the model is 1251.45 $/kWe.

4.5. Financial and life cycle values

The weighted average cost of capital (WACC) used in the analysis is computed as Brealey and Meyers (2003)

$$WACC = D \times Kd \times (1-t) + E \times Ke \tag{3}$$

D is the percentage of debt on the total capital, Kd is the cost of debt, t is the marginal corporate tax rate, E is the percentage of equity on the total capital, Ke is the cost of equity and t is the marginal corporate tax rate.

Table 4 summarises the main references to estimate the parameters in Eq. 3. From this table it is possible to derive the average value used in our analysis. Table 5 summarizes the main assumption for the various technologies.

Table 4
Values of the financial parameters to compute the WACC. Tax rate=35%.

Source	Plant	D (%)	Kd (%)	E (%)	Ke (%)
NETL (2007)	Coal/CCGT	45–50	9–11	50–55	12
MIT (2007)	Coal	55	6.5	45	11.5
EPRI (2006)	Coal/CCGT	45	9	55	12
Ayres et al. (2004)	Coal/CCGT/ Nuclear	50	8	50	12
University of Chicago (2004)	Nuclear	50	10	50	15
MIT (2003)	Coal/CCGT	60	8	40	12
MIT (2003)	Nuclear	50	8	50	15
Used in this analysis		50	9	50	12

Table 5
Main assumptions for the various technologies.

	Nuke	Coal	CCGT
Size (MWe)	335	335	335
Construction time (years)	5	4	3
Plant life (years)	(40) 60	40	40
Capacity factor (%)	(85) 95	85	85
Thermal efficiency (%)	33	40	57

As shown in Section 5 we investigated the elasticity of these values on the final results with a sensitivity analysis. For what concern the NPP, considering the new reactor design (EPR, AP1000, ABWR, etc...), is possible to increase the expected plant life from 40 to 60 years (Worral and Gregg, 2007); and the capacity factor from 85% to 95% (Carelli, 2004).

- Electricity price: 80 $/MWh
- Electricity price escalation rate: 2%/year
- O&M cost escalation: 3%/year
- Construction cost escalation: 2%/year
- Depreciation rate: 6%/year
- Interest earnings nominal rate: 3%/year
- LUEC discount rate: 5%/year

5. Results

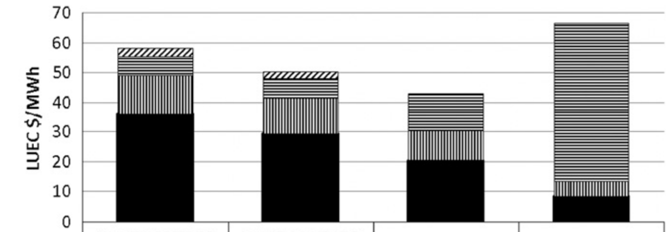
This section presents the results of the Monte Carlo analysis. LUEC and NPV are the financial indicators evaluated for the different technologies and under different scenarios. For each indicator the paper provides first a deterministic analysis made with the mean values of the input distribution and then the Monte Carlo analyis made with the entire dataset presented in the previous section. For this reason even the "deterministic results" are rappresentative of all the information gathered at point 4.

5.1. LUEC

The formula used to compute the levelised unit electricity cost (LUEC) is (IEA, 2005)

$$LUEC = \sum[(I_t + M_t + F_t)(1+r)^{-t}] / \sum[E_t(1+r)^{-t}] \tag{4}$$

I_t is the investment expenditures in the year t, M_t is the operations and maintenance expenditures in the year t, F_t is the fuel expenditures in the year t, E_t is the electricity generation in the year t and r is the discount rate.



	NUKE 40 YEARS 85%	NUKE 60 YEARS 95%	COAL	CCGT
D&D	2.8	2.5	0	0
Fuel	6.5	6.5	12.5	53.1
O&M	13	12	10	5
Capital	36	29.5	20.5	8.5

Fig. 2. LUEC breakdown cost.

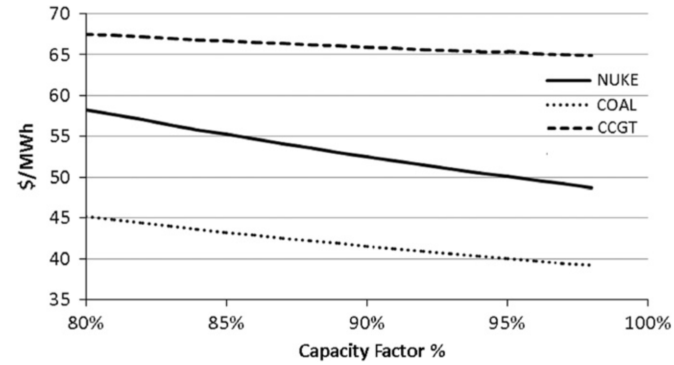


Fig. 4. Capacity factor's influence on LUEC.

Fig. 3. Plant life's influence on LUEC.

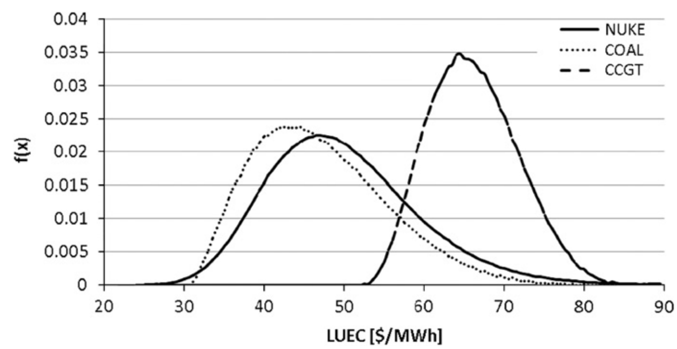


Fig. 5. LUEC's probabilistic distributions for the various technologies.

5.1.1. *Deterministic results*

Fig. 2 presents, for the different technologies, the average values of LUEC and their breakdown. From LUEC value in Fig. 2 to conclude that:

- the coal PP has the lowest LUEC and the CCGT the highest.
- the improved capacity factors and the longer life reduce the SMR LUEC from 59 to 50 $/MWh and becomes competitive with coal.
- Capital cost is the major component for nuclear and coal accounting for more than 50%.
- For what concerns the CCGT the first cost is the fuel cost.

These results are alligned with the cited literature. What is not alligned is the cost for decomissioning in case of NPP (10% wherease the typical values are 3–5%). However, this results were expected because, as showed in Section 4.4, there is a strong economy of scale for this accounts, therefore reducing the size increases the share on the total cost.

5.1.2. *Sensitivity*

We investigated how increasing the plant life and the capacity factors impacts on the various technologies. Figs. 3 and 4 shows as the effect of the plant life and the capacity factor strongly impact on nuclear and coal reducing the cost, whereas for CCGT the cost increase during the life of the plant. The trend in the natural gas cost increments the generation cost with this technology having as main cost the fuel cost. For nuclear and coal the main cost is the capital therefore a longer life reduce the cost. Consequently that is really valuable to extend the life of the plant and to increase its capacity factor. The model assumes for the CCGT a life until it can reap revenues (even if the cost of the EE increases).

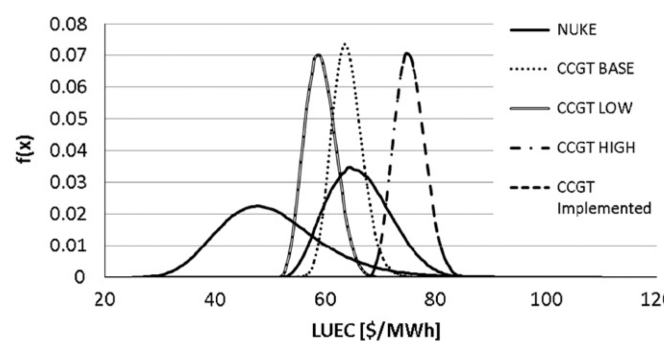


Fig. 6. Effect of the natural gas cost reduction on LUEC.

5.1.3. *Monte Carlo analysis*

Fig. 5 shows how the behaviour of the CCGT technology differs from coal and nuclear because of its low variability and higher price. For what concerns coal vs. nuclear seems that coal technology is slight better than nuclear because of its lower LUEC and lower variability. This result is valid as long as the CO_2 cost is not included. Fig. 6 compares the NPP with the CCGT and demonstrates as the natural gas cost has to drop below the most optimistic scenario to match the LUEC of NPP and CCGT (a reduction of 40% respect to base case it is necessary). On the opposite in the LUEC can increase to 80 $/MWhe

5.2. *NPV*

The NPV is the sum of all the cash flow (inbound and outbound) generated by a firm (in this case a power plant) actualised to a certain time-now. This definition, even if widely used, is too simple for this kind of analysis since does not have a holistic view of the financial sources and the cash flow. In an investment the capital is usually provided by two distinct subjects:

- The shareholders (for what concern the equity)
- The banks (for what concern the debt)

Therefore, the investment has to create a value sufficient enough to assure firstly by its feasibility (to have the support from the banks) and secondly a reasonable remuneration for the shareholders. For this reason we considered 3 types of NPV:

- NPV for LUEC: the sum of the net cash flow used to compute the LUEC and discounted @ 5% (the LUEC discount rate). We use this indicators only in the first analysis, to give an order of magnitude of total cash flow generated, but since is not meaningful for the investors is not included in the following analysis.
- NPV to the firm: the sum of the unlevered cash flows or "the free cash flow to the firm" discounted with the WACC value as indicated by Damodaran (2006). It represents the value generated for all the investors in the plant. If this value is greater than zero the investment generates enough value to pay back the debt and banks might be willing to finance the construction of the plant.
- NPV to the shareholders: the sum of the levered cash flows "discounting free cash flows to equity at the cost of equity will yield the value of equity in a business" (Damodaran, 2006). It is the net value generated for the shareholders after the payment of the debt to the bank. If the value is zero the shareholders receive a remuneration equal to 12% (the value of *Ke* expected value used in the WACC). A negative value indicate a remuneration less than 12% (but can be still positive, for instance 10%) a positive value that the remuneration is greater than 12%.

5.2.1. Deterministic results

For coal and NPP the LUEC and NPV to the firm is greater than for CCGT (Fig. 7). This is due to the lower LUEC and, for nuclear power plants, the more energy produced (because of the longer life and higher capacity factors). However for what concern the shareholders' NPV the value dramatically drops especially for NPP and coal. The nuclear reactor has a high capital employed and a long payback time, on the opposite the CCGT plant has a lower capital employed and the shorter payback time (as shown in Figs. 8 and 9) and obtains a minor reduction for the NPV. These aspects dramatically influence the present value of the cash flows: because of a discount rate of 12% cash flows postponed account much less than cash flows in the early years, therefore the final net effect penalises the nuclear reactor and advantages the CCGT. The coal technology is in the middle. The negative value for the nuclear technology indicates that remuneration of the shareholders is not 12% as expected but lower (11%).

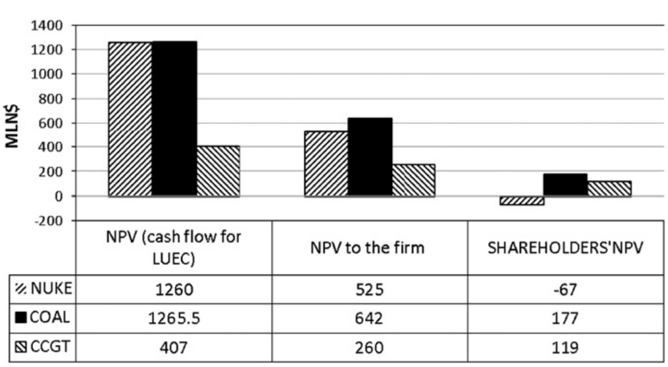


Fig. 7. NPV for the different technologies.

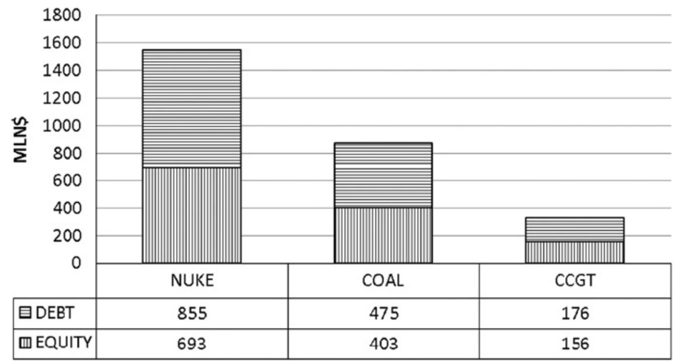


Fig. 8. Equity and debt required for each plant.

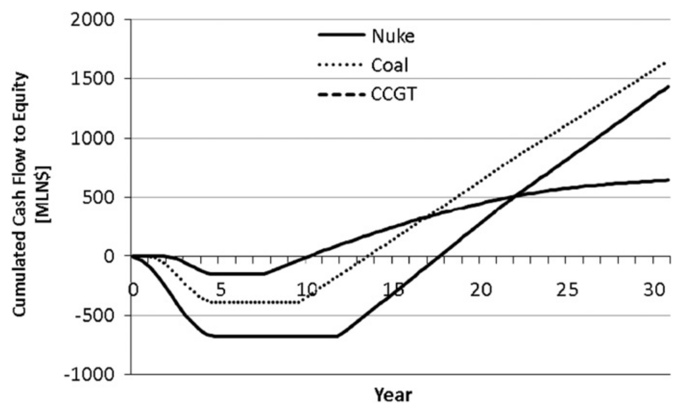


Fig. 9. Equity cash flow for the various plants (not discounted value).

5.2.2. Sensitivity and IRR for the shareholders

As showed in the previous section the cost of equity (*Ke*) strongly impacts on the profitability of a PP. Fig. 10, dealing with this aspect, shows a strong elasticity for the nuclear technology, whereas the CCGT is more rigid. This figure points out other two important results:

1. Others things being equal the nuclear and coal technologies take a great advantage from the reduction of the *Ke*. If *Ke* is less than 10.5% the NPV to the shareholders of nuclear is greater than CCGT, if it is lower than 7.5% the NPP has the greatest NPV.
2. The internal rates of return (IRR) for the shareholders are: 18% in case of CCGT, 14% for coal and 11% for nuclear. The higher value of IRR, the lower capital employed and the lower variability seems to justify the choice of investors toward CCGT plant as happened in the 80s and 90s in Europe and USA. However, the following analysis updated with the most recent data and scenarios confute the universality of this paradigm.

Figs. 11 and 12 show the effect in changing the electricity price. As expected to increase the electricity price increases the NPV to the firm, however the three technologies increase with a

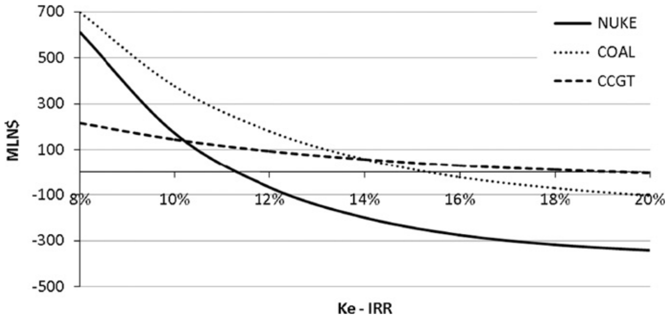


Fig. 10. NPV to the shareholders respect to the cost of equity (*Ke*).

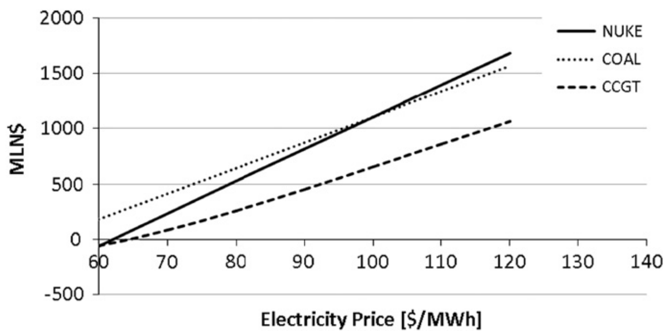


Fig. 11. Electricity price's influence on the NPV to the firm.

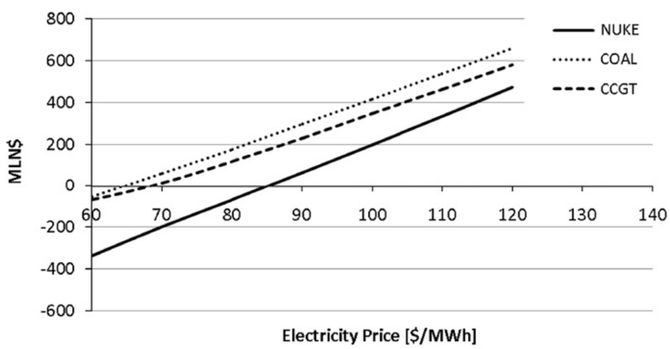


Fig. 12. Electricity price's influence on the NPV to the shareholders.

different rate. The nuclear technology takes a greater advantage from increasing the price since it reduces the payback time and therefore increases the value of the cash flow for the investors. Moreover, due to the lower marginal cost and higher capacity factor, the NPP increases the revenue more than other technologies.

5.2.3. Monte Carlo analysis

Fig. 13 reports the probability distribution of the NPV to the firm for the 3 technologies. The coal plant is the most attractive choice because of the higher mean value (643 M$) and a probability of negative value almost zero. CCGT has the lowest mean value (261 M$) but also the lowest variability and a probability of negative value almost zero. The NPP has a high mean value (525 M$), but a huge variability with a 10% of probability of value below zero.

For what concerns the NPV to the shareholders (Fig. 14) it is clear as the NPP is not attractive because, in more than 50% of the case, the investment do not provide the expected remuneration

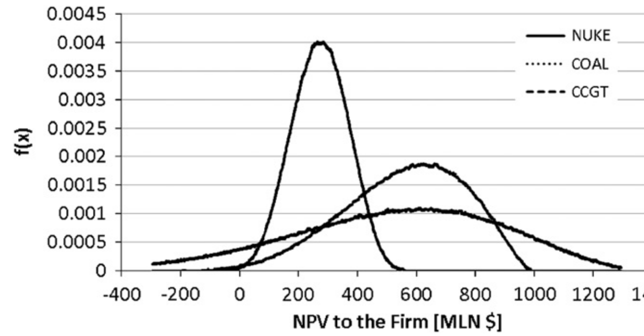


Fig. 13. NPV to the firm probabilistic distribution.

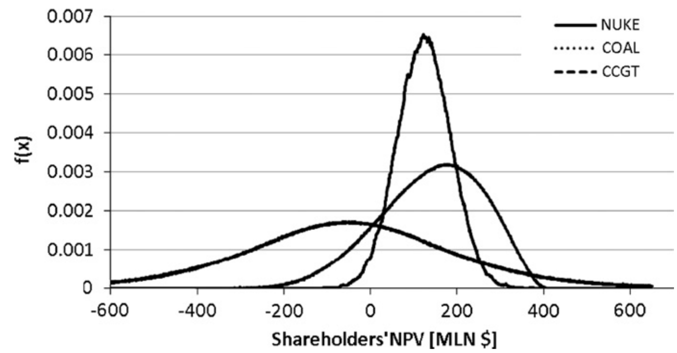


Fig. 14. NPV to the shareholders probabilistic distribution.

(i.e. 12%), on the opposite the shareholders might be willing of invest in the coal technology, because of its better performance.

5.3. Impact of CO_2

5.3.1. The CO_2 cost

Coal and CCGT plants produce CO_2 during the operative life. Likely in the near future there will be a cost associated to this production. The cost can be due to the carbon sequestration or the emission with the "carbon tax". In our analysis we included a new cost account related to the production of the CO_2 as $/ton regardless if it is due to sequestration or carbon tax (it is always a cost associated to the tons of CO_2 produced), however for simplification we always refer to carbon tax. This cost is always zero for NPP because they do not produce any CO_2 and it is greater for coal than CCGT because coal plants have a lower efficiency than the CCGT, therefore emits more CO_2 to produce the same amount of EE.

There is a huge uncertainty for this cost account. According to EIA (2009b) a reasonable value for the carbon tax is 15 $/ton, for IEA (2005) is 20 €/ton and for Ayres et al. (2004) is 15 $/ton. EIA (2008a, 2008b, 2008c) and MIT (2007) report curves correlating the emission cost to the years according to different scenarios.

Aydin et al. (2010) summarises the literature about storage of CO_2. The cost range from 1–2 to 50 $/ton. However considering the "cap and trade" market the cost CO_2 cost can increases. According to Durand-Lasserve et al. (2010) the CO2 cost is $47/ton for the soft cap (550 ppm scenario) and $105/ton (450 ppm) for the hard cap (in the 2030). These values are significantly lower than those proposed by IEA (2008): 90 €/ton (soft cap) and $180 €/ton (hard cap).

This bibliographic review points out the great uncertainty in the CO_2 cost. To assign a distribution curve to this cost is really

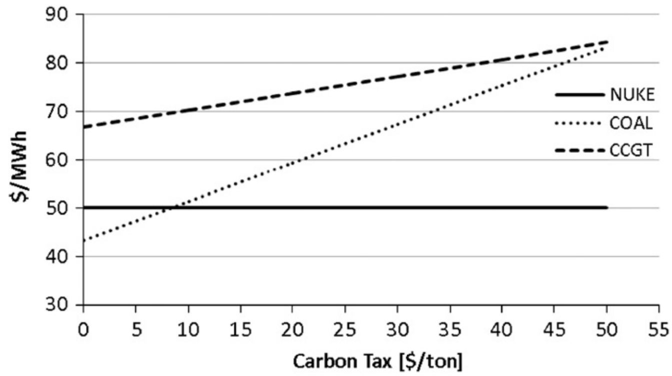


Fig. 15. Impact of carbon tax on LUEC.

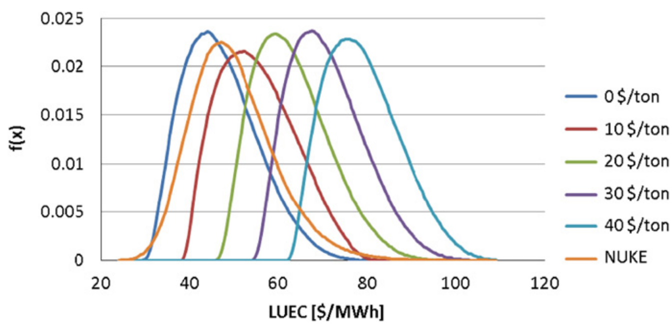


Fig. 16. Impact of carbon tax cost on coal plant.

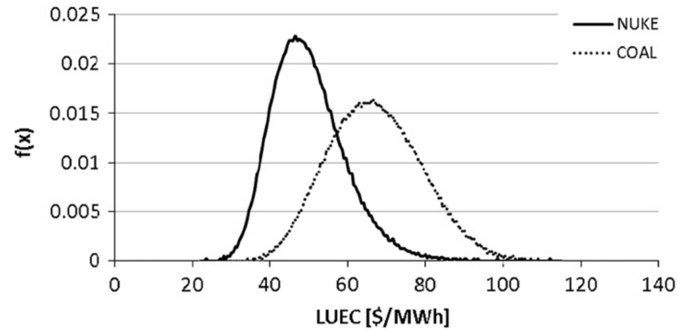


Fig. 17. Uncertainty introduced by the carbon tax on the coal plant's LUEC.

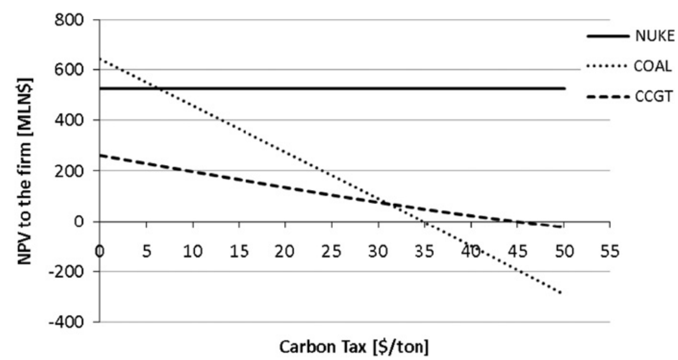


Fig. 18. Impact of carbon tax on the NPV to the firm.

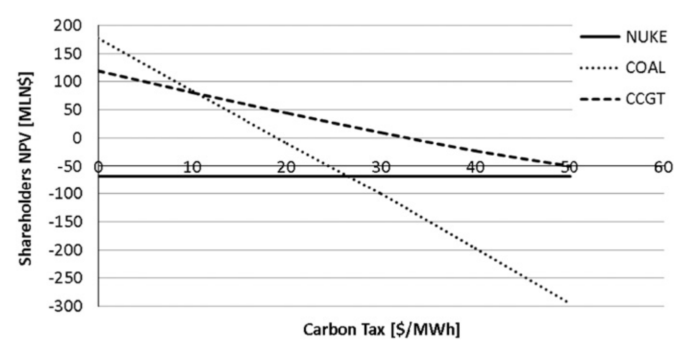


Fig. 19. Impact of carbon tax on the NPV to the shareholders.

speculative; therefore we decided to perform a sensitivity analysis showing the economic attractiveness of each technology respect to the CO_2 cost. The goal is to find the CO_2 cost level shifting the choice of a technology to another.

Because of the increasing the production cost could increase the EE price we investigate in the next sections also how the correlation of CO_2 cost and EE price can influence the profitability of the different plants.

5.3.2. CO_2 on LUEC

From Fig. 15 is clear how the carbon tax dramatically increases the LUEC for the coal plant: from 10 $/kWe the NPP becomes the cheapest technology. Fig. 16 focuses on this aspect showing as the carbon tax moves to the right (i.e. increase the LUEC) of about 8 $/MWh for each 10 $/ton. Fig. 17 quantifies the effect of the uncertainty on the carbon tax on the investment. Under the hypothesis of a carbon tax described by a triangular distribution among 0 and 40 $/ton and a mean value of 20 $/ton is it clear as the nuclear technology has the lower LEUC but also the lower uncertainty. The bottom line is therefore that the carbon tax (relevant and uncertain cost) deep impacts on the coal plant increasing both his LUEC and variability above the nuclear plant. The carbon tax increases also the LUEC of the CCGT, which was already the higher.

5.3.3. CO_2 on NPV

Regarding the NPV to the firm (Fig. 18), the results are comparable with LUEC: from 8 $/KWh the NPP has the higher NPV.

The shareholders' NPV (Fig. 19) is quite different: with a lower carbon tax (0–15 $/ton) the coal is the best plant, then a medium carbon tax (15–35 $/ton) the CCGT, thanks to the better efficiency is the best plant, above 35 $/ton the NPP is the best plant. However above 25 $/ton any of the technology present a Shareholders' NPV greater than zero.

It is reasonable to assume that the introduction of the carbon tax will increase the EE price, therefore we investigate the combined effect of electricity price and carbon tax on the various tecnologies. We used a Monte Carlo approach to include the variability of the results, in fact the next tables report the best technology for each combination of EE price/carbon tax and the result between the round bracket indicate that the overlappig of the curve with another technology (the second choice) is more than 90%.

Table 6, refferred to the NPV to the firm, shows as the coal plant is the best plant only if both the carbon tax and the electricity price are low. If at least one of them increases, the NPP is the best choice.

For what concern the NPV to the shareholders (Table 7) the results are different: the carbon tax impacts the most on the choice, shifting the ranking from coal (low cost), CCGT (medium cost) and nuclear (high cost). The electricity price "anticipate" the

Table 6
Plants with the highest NPV to the firm respect to the carbon tax and electricity price.

Electricity Price [$/Mwh]							
130	Nuke	Nuke	Nuke	Nuke	Nuke	Nuke	Nuke
120	Nuke (coal)	Nuke	Nuke	Nuke	Nuke	Nuke	Nuke
110	Nuke (coal)	Nuke	Nuke	Nuke	Nuke	Nuke	Nuke
100	Nuke (coal)	Nuke	Nuke	Nuke	Nuke	Nuke	Nuke
90	Nuke (coal)	Nuke	Nuke	Nuke	Nuke	Nuke	Nuke
80	Coal (nuke)	Nuke	Nuke	Nuke	Nuke	Nuke	Nuke
70	Coal	Coal (nuke)	Nuke	Nuke	Nuke	Nuke	Nuke
Carbon tax ($/ton)	0	5	10	15	20	25	30

Table 7
Plants with the highest NPV to the shareholders respect to the carbon tax and Electricity price.

Electricity Price [$/Mwh]									
130	Coal	Coal (ccgt)	CCGT (coal)	CCGT (nuke)	CCGT (nuke)	Nuke (ccgt)	Nuke (ccgt)	Nuke (ccgt)	Nuke
120	Coal	Coal (ccgt)	CCGT (coal)	CCGT	CCGT (nuke)	CCGT (nuke)	Nuke (ccgt)	Nuke (ccgt)	Nuke
110	Coal	Coal (ccgt)	CCGT (coal)	CCGT	CCGT	CCGT (nuke)	CCGT (nuke)	Nuke (ccgt)	Nuke
100	Coal	Coal (ccgt)	CCGT	CCGT	CCGT	CCGT	CCGT	CCGT (nuke)	Nuke (ccgt)
90	Coal	CCGT (coal)	CCGT	CCGT	CCGT	CCGT	CCGT	CCGT	CCGT (nuke)
80	Coal	CCGT (coal)	CCGT	CCGT	CCGT	CCGT	CCGT	–	–
70	Coal	CCGT	–	–	–	–	–	–	–
Carbon tax ($/ton)	0	5	10	15	20	25	30	35	40

Table 8
Nuclear power plant construction cost.

Nuclear power plants						
Reference	Location	Design	Size (Mwe)	Cost year	Cost ($/Kwe)	Note
WNA—The Economics of Nuclear Power (WNA, 2010)	Francia	EPR	1643	2009	3400	Under construction
	Sud Corea	APR-1400	1350	2009	1850	Under construction
	Florida USA	AP1000	1100	2009	3582	Forecast
	Florida USA	AP1000	1105	2009	3462	Forecast
	Texas USA	ABWR	1350	2009	2900	Forecast
	United Arab Emirates	APR-1400	1400	2009	3643	Bidding
	Georgia USA	AP1000	1100	Mid 2008	4363	Forecast
		ESBWR	Large	Mid 2008	3000	Forecast
		ABWR	Large		3000	Forecast
		AP1000	Large		3000	Forecast
Update on the cost of nuclear power—(Du and Parsons, 2009)	Japan	BWR	825	2007	4336	In operation
	Japan	PWR	1180	2007	5072	In operation
	Japan	PWR	1180	2007	4118	In operation
	Japan	ABWR	1356	2007	3636	In operation
	Japan	ABWR	1356	2007	3222	In operation
	South Korea	PWR	2000	2007	3600	In operation
	Japan	ABWR	1325	2007	2759	In operation
	Japan	BWR	1067	2007	3351	In operation
	Japan	ABWR	1304	2007	2357	In operation
	South Korea	OPR	995	2007	2257	In operation
	South Korea	OPR	994	2007	2942	In operation
	USA	ABWR	1371	2007	2930	Forecast
	Florida USA	ESBWR	3040	2007	3530	Forecast
	USA	AP1000	2212	2007	4206	Forecast
	USA	AP1000	2234	2007	3787	Forecast
	USA	AP1000	2200	2007	4745	Forecast
	Texas USA	ABWR	2700	2007	3480	Forecast
MIT (2009)		LWR	Large	2007	4000	Forecast
Vaillancourt et al. (2008)		LWR	Large	2007	3381	Forecast Capital Cost
EIA (2009a)		LWR	1350	2008	3308	Forecast
Keystone Center (2007)		AP1000	1130	2006	2950	Forecast
Moody's Investor Services (Schlissel and Biewald 2008)		LWR	1300	2006	5000	Forecast
Florida Power and Light (Schlissel and Biewald 2008)		AP1000	1117	2006	3824	Forecast
Shaw (Schlissel and Biewald 2008)		AP1000	1117	2007	4387	Forecast
IEA (2008)		LWR	1300	2007	4250	Forecast
World Nuclear News (2009)		AP1000	1117	2008	3441	Forecast

effect shifting again from coal (low price), CCGT (medium price) and nuclear (high price).

6. Conclusions and future developments

Many reports and papers dealing with the economics of power plants have been published. However, they usually refer to large power plants (with a size of about 1000 MWe) and are based on deterministic analysis. Few of them are based on probabilistic analysis and no one is referred to small medium power plant, therefore the main goal of this paper was to fill this gap. Improving the method presented by Feretic and Tomsic (2005) this paper shows the financial strengths and weaknesses of three base load power plants: combined cycle gas turbine, coal power plant and nuclear power plant.

The main result is the fundamental role played by the carbon tax (or the sequestration cost). Without this cost is clear how coal

Table 9
Coal power plant construction cost.

Coal power plants					
Source	Reference (year)	Country	Size (MWe)	Overnight cost ($(ref. Year)/KWe)	O&M costs ($(/KWe year)
IEA (1998)	1996	Belgium	400	1386	72.99
		Portugal	315	1999	81.69
		Portugal	411	1902	80.7
		USA	300		36.61
		Finland	500		63.06
		Oland	600	1254	56.6
		Spain	500	1326	43.4
		Oland	600	1450	58.3
		Denmark	400	1329	47.94
		France	572	1346	70.4
		Korea	500		58.06
IEA (2005)	2003	Denmark	400	1294	39.15
		USA	600		46.1
		France	600	1270	48.38
		Finland	500	1233	46.28
		Canada	450	1320	47.05
Kaplan (2008)	2008	USA	600	2083	
		USA	960	3073	
		USA	689	2467	
		USA	649	2857	
		USA	580	2433	
		USA	900	2440	
Parsons and Shelton (2002)	2002	USA	397		73.37

Table 10
CCGT power plant construction cost.

CCGT power plants					
Source	Reference (year)	Country	Size (MWe)	Overnight cost ($(ref. Year)/KWe)	O&M costs ($/KWe year)
IEA (1998)	1996	Belgium	350	761	45.32
		Denmark	337	809	27.8
		Denmark	400	885	37.05
		Hungary	389	595	21.17
		Portugal	326	790	16.1
		Spain	315	663	31.37
		Oland	350	664	23.71
		USA	350	419	17.42
		Korea	450	583	21.8
		Oland	250	725	24.59
		Portugal	459	697	15.04
		USA	250	422	18.09
EPRI (2000)	1999	USA	398.9	859	25.2
		USA	384.4	420	17.1
Parsons e Shelton (2002)	2002	USA	379.1	339.2	26.83
IEA (2005)	2003	USA	400	609	26
		Belgium	400	958	28.6
		Greece	377.7	549	17.16
		Italy	384	667	30.24
		Switzerland	400	584	35.96
		Canada	580	589	19.21
		Oland	500	1030	34.32
		Switzerland	250	631	41.23

and CCGT are, for a 335 MWe power plant, more attractive than nuclear. Coal has the lowest LUEC, and the highest NPV, CCGT the higher IRR. NPP does not seem an attractive option because of the low NPV to the shareholders and the high uncertainty in the results. The literature usually reports the lowest value of LUEC for NPP, however because of their strong economy of scale, the size reduction implies a cost increasing greater for NPP than for coal and CCGT.

On the other hand is fundamental to point out as the construction of a power plant is a long-term investment, with a life of decades. Therefore is necessary to plan the investment considering long-term scenarios. The literature foresees, even for the near future, a cost associated to the emission of CO_2, and an increasing in the EE price, therefore an investment evaluation must deal with these aspects. Considering these elements the results change because of the NPP does not produce CO_2 and the coal PP produce more CO_2 than CCGT for the same amount of EE produced. According to different levels of carbon tax the nuclear power plant has the lowest LUEC and most of the times even the better financial performance. The carbon tax dramatically increase the production cost of a coal and CCGT and, being uncertain, increase the overall uncertainty of the investment even above the NPP.

Since small medium power plants are a suitable choice for countries with a limited electricity grid, modest financial resources or isolated locations is important to choose the power plant according to the policy of the investors. So far the paradigm for private investors was to chose CCGT because of the low capital required and the attractive IRR, whereas public investors was willing to invest in COAL because of the lower LUEC. The introduction of the carbon tax can indicate as a wise choice, both for private and public investors, the construction of a NPP.

The results presented in this paper are the basis for further development of this research about the economics of small medium power plants. There are at least three main areas for developments:

- The electricity market model. This paper assumes a fix price for the EE (increased by 2%/year). Even if, for base load power plant, the assumption is realistic in many markets, considered the long term of the investment, the price of EE can be better modelled by a periodical function with a Brownian component.
- The paper compares one plant vs. another plant; however an investor can consider the construction of more than one plant. This implies a reduction in the construction cost (because of fix cost shared, learning, etc…) and the management of a new degree of freedom: the construction schedule. In the cited literature there are algorithms to compute the "multiple units saving" and the real option approach can be a valuable tool to decide the construction schedule in a liberalised market.
- In order to minimize the risks and increase the revenues an investor could build power plants of different technologies, creating a portfolio able to balance the escalation costs and achieve a higher degree of flexibility. The literature reports studies about the portfolio of power plant, but no one is referred to small medium power plants.

Appendix

See Tables 8–10.

References

Aydin, G., Karakurt, I., Aydiner, K., 2010. Evaluation of geologic storage options of CO_2: applicability, cost, storage capacity and safety. Energy Policy. doi:10.1016/j.enpol.2010.04.035.

Ayres, M., Macrae, M., Stogran, M., 2004. Levelised Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario. Canadian Energy Research Institute.

Bolinger, M., Wiser, R., Golove, W., 2006. Accounting for fuel price risk when comparing renewable to gas-fired generation: the role of forward natural gas prices. Energy Policy 34 (2006), 706–720.

Bolinger, M., Wiser, R., 2008. Comparison of AEO 2008 Natural Gas Price Forecasts to NYMEX Futures Prices. Berkeley Lab (LBNL).

Bolinger, M., Wiser, R., Golove, W., 2003. Accounting for fuel price risk, Using Forward Natural Gas Prices Instead of Gas Price Forecasts to Compare Renewable to Gas-Fired Generation – LBNL-53587. Lawrence Berkeley National Laboratory, Berkeley, CA.

Bowers, H.I., Fuller, L.C., Myers, M.L., 1987. Cost estimating relationships for nuclear power plant operation and maintenance. ORNL/TM-10563. Oak Ridge National Laboratory, TN, United States.

Bowers, H.I., Fuller, L.C., Myers, M.L., 1983. Trends in Nuclear Power Plant Capital Investment Cost Estimates 1976 to 1982. ORNL/TM-8898. Oak Ridge National Laboratory, TN, United States.

Brealey, R.A., Meyers, S.C., 2003. Principles of Corporate Finance seventh ed. McGraw Hill Higher Education, pp. 522-552.

Carelli, M.D., Garrone, P., Locatelli, G., Mancini, M., Mycoff, C., Trucco, P., Ricotti, M.E., 2010. Economic features of integral, modular, small-to-medium size reactors. Progress in Nuclear Energy 52, 403–414.

Carelli, M.D., Mycoff, C.W., Garrone, P., Locatelli, G., Mancini, M., Ricotti, M.E., Trianni, A., Trucco, P. 2008. Competitiveness of small–medium, new generation reactors: a comparative study on capital and O&M costs. In: Proceedings of the 16th International Conference on Nuclear Engineering. May 11–15, 2008, Orlando, Florida, USA. Paper 48931.

Carelli, M.D., Conway, L.E., Oriani, L., Petrović, B., Lombardi, C.V., Ricotti, M.E., Barroso, A.C.O., Collado, J.M., Cinotti, L., Todreas, N.E., Grgić, D., Moraes, M.M., Boroughs, R.D., Ninokata, H., Ingersoll, D.T., Oriolo, F., 2004. The design and safety features of the IRIS reactor. Nuclear Engineering and Design 230, 151–167.

Damodaran, A., 2006. Damodaran on Valuation: Security Analysis for Investment and Corporate Finance, second ed., Wiley Finance Series, Hoboken, New Jersey, pp. 15.1–15.45.

Du, Y., Parsons E.J., 2009. Update on the cost of nuclear power—CEEPR , Center for Energy and Environmental Policy Research.

Durand-Lasserve, O., Pierru, A., Smeers Y., 2010. Uncertain long-run emissionstargets, CO_2 price and global energy transition: A general equilibrium approach. Energy Policy, doi:10.1016/j.enpol.2010.04.041.

EIA, 2008a. Electricity Market Module. DOE/EIA-0554.

EIA, 2008b. Annual Energy Outlook 2008. DOE/EIA-0383.

EIA, 2008c. International Energy Outlook 2008. DOE/EIA-0484.

EIA, 2009a. Electricity Market Module. DOE/EIA-0554.

EIA, 2009b Annual Energy Outlook 2009. DOE/EIA-0383.

EMWG, 2007. Cost Estimating guidelines for generation IV nuclear energy systems Revision 4.2, Economic Modeling Working Group available at 〈www.gen-4.org/Technology/horizontal/EMWG_Guidelines.pd〉.

EPRI, 2000. Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal. Interim Report 1000316. Electric Power Research Institute.

EPRI, 2006. Updated Cost and Performance Estimates for Clean Coal Technologies Including CO_2 Capture. Report 1013355. Electric Power Research Institute.

FERC, 2008. Increasing Costs in Electric Markets. Department of Energy-Federal Energy Regulatory Commission. Available at 〈www.ferc.gov/legal/staff-reports/06-19-08-cost-electric.pdf〉.

Feretic, D., Tomsic, Z., 2005. Probabilistic analysis of electrical energy costs comparing: production costs for gas, coal and nuclear power plants. Energy Policy 33, 5–13.

Flyvbjerg, B., 2006. From Nobel prize to project management: getting risks right. Project Management Journal, 1–5.

Flyvbjerg, B., 2005. Policy and planning for large infrastructure projects: problems, causes, cures. World banck policy research paper 3781, December 2005.

Flyvbjerg, B., Bruzelius, N., Rothengatter, W., 2003. Megaprojects and risk: An anatomy of ambition Cambridge. Cambridge University Press.

Flyvbjerg, B., Holm, M.K.S., Buhl, S.L., 2005b. How (in)accurate are demand forecasts in public works projects? The case of transportation. Journal of the American Planning Association 71, 131–146.

GTW, 2005. Gas Turbine World Handbook 2004/2005. Pequot publishing.

Huppmann, D., Egging, R., Holz, F., Ruester, S., von Hirschhausen, C., Gabriel, S.A., 2009. The World Gas Market in 2030 – Development Scenarios Using the World Gas Model. German Institute for Economic Research.

IAEA, N.E.A., 2008. Uranium 2007: Resources, Production and Demand. OECD, Paris, France.

IAEA, 2007. Safety Glossary—Terminology used in Nuclear Safety and Radiation Protection 2007 edition International atomic energy agency, Vienna, Austria.

IEA, 1998. Projected Cost of Generating Electricity. International Energy Agency/Nuclear Energy Agency, Paris, France.

IEA, 2005. Projected Cost of Generating Electricity. International Energy Agency/Nuclear Energy Agency, Paris, France.

IEA, 2006. World Energy Outlook 2006. International Energy Agency, Paris, France.

IEA, 2007. World Energy Outlook 2007. International Energy Agency, Paris, France.

IEA, 2008. World Energy Outlook 2008. International Energy Agency, Paris, France.

Ingersoll, D.T., 2009. Deliberately small reactors and second nuclear era. Progress in Nuclear Energy 51, 589–603.

Kaplan, S., 2008. CRS Report for Congress. Power Plants: Characteristics and Costs. Congressional Research Service.

Keystone Center, 2007. Nuclear Power Joint Fact-Finding (Keystone, Colorado: Keystone Center, June 2007). 〈http://www.ne.doe.gov/pdfFiles/rpt_KeystoneReportNuclearPowerJointFactFinding_2007.pdf〉.
Kuznetsov, V., 2008. Options for small and medium sized reactors (SMRs) to overcome loss of economies of scale and incorporate increased proliferation resistance and energy security. Progress in Nuclear Energy 50, 242–250.
Kuznetsov, V., 2009. Design and technology development status and design considerations for innovative small and medium sized reactors. Journal of Engineering for Gas Turbines and Power 131, 1–9.
Locatelli, M., Mancini, M., 2009. Competitiveness of small-medium new generation reactors: a comparative study on decommissioning. In: Proceedings of the 17th International Conference on Nuclear Engineering, July 12-16, Brussels, Belgium. Paper 75254.
Lovallo, D., Kahneman, D., 2003. Delusions of success: How optimism undermines executives' decisions'. Harvard Business Review 81, 56–63.
Mackerron, G., Colenutt, D., Spackman, M., Robinson, A., Linton, E., 2006. Paper 4: The economics of nuclear power, report for the Sustainable Development Commission by Science & Technology Policy Research. SPRU and NERA Economic Consulting.
MIT, 2003. The Future of Nuclear Power: An Interdisciplinary Study. Massachussets Institute of Technology, Cambridge, MA, United States.
MIT, 2007. The Future of Coal: An Interdisciplinary Study. Massachussets Institute of Technology, Cambridge, MA, United States.
MIT, 2009. Update of the MIT 2003 Future of Nuclear Power Study. Massachussets Institute of Technology, Cambridge, MA, United States.
Mycoff, C.W., Carelli, M.D., Petrovic, D., Miller, K., 2007. Paper for IAEA TECDOC Strategies to Demonstrate Competitiveness of SMRs in World Markets. Section IV.1. Methodologies and decision criteria for demonstrating competitiveness of SMRs. 〈http://www.iaea.org/NuclearPower/Downloads/SMR/CRPI25001/2007_new/Mycoff.doc〉.
NETL, 2007. Cost and performance baseline for fossil energy plants. Bituminous Coal and Natural Gas to Electricity. DOE/NETL-2007/1281, volume 1. Department of Energy, National Energy Technology Laboratory.
NETL, 2008. Impact of Cost Escalation on Power System R&D Goals. DOE/NETL - 2008/1308. Department of Energy, National Energy Technology Laboratory.
OECD, 2003. Decommissioning Nuclear Power Plants: Policies, Strategies and Costs. Nuclear energy agency/Organisation for economic co-operation and development, France, Paris.
Parsons, E.L., Shelton, W.W., 2002. Advanced Fossil Power Systems Comparison Study. National Energy Technology Laboratory.
Phung, D.L., 1987. Theory and Evidence for Using the Economy-of-Scale Law in Power Plant Economic. Oak Ridge National Laboratory, TN, United States.
Quinet, E., 1998. Economic Principles of Transport. Economica, Paris.
Reid, L., 2003. Modelling Modularity Impacts on Nuclear Power Plant Costs. Oak Ridge National Laboratory, TN, United States.
Roques, F., Nuttall, W., Newbery, D., 2006. Using probabilistic analysis to value power generation investments under uncertainty. EPRG Working Paper 065. University of Cambridge, England.
Saliby, E., 1997. Descriptive sampling: an improvement over latin hypercube sampling. In: Proceedings of the 1997 Winter Simulation Conference.
Sanchez, E., 2003. Annual Energy Outlook Forecast Evaluation – Accessed January 26, 2004 from 〈www.eia.doe.gov/oiaf/analysispaper/forecast_eval.html〉.
Schlissel, D. Biewald, B., 2008. Nuclear Power Plant Construction Costs – Available at 〈http://www.synapse-energy.com/Downloads/SynapsePaper.2008-07.0.Nuclear-Plant-Construction-Costs.A0022.pdf〉.
Sullivan, G.P., Pugh, R., Melendez, A.P., Hunt W.D., 2004. Operations and Maintenance Best Practices Guide release 2.0, Federal Energy Management Program, pp. 2.1.
Tewari,l, P.K., Rao, I.S., 2002. LTE desalination utilizing waste heat from a nuclear research reactor. Desalination 150, 45–49.
Tian, J., 2001. Economic feasibility of heat supply from simple and safe nuclear plants. Annals of Nuclear Energy 28, 1145–1150.
Trianni, A., Locatelli, G., Trucco, P., 2009. Competitiveness of Small-Medium Reactors: a probabilistic study on the economy of scale factor. In: Proceedings of ICAPP 09, May 10–14, Tokyo, Japan.
Trujillo, L., Quinet, E., Estache, A., 2002. Dealing with demand forecasting games in transport privatization. Transport Policy 9, 325–334.
University of Chicago, 2004. The economic future of nuclear power.
Vaillancourt, K., Labriet, R., Loulou, R., Waaub, J.P., 2008. The role of nuclear energy in long-term climate scenarios: An analysis with World-TIMES model. Energy Policy 36, 2296–2307.
Wachs, M., 1990. Ethics and advocacy in forecasting for public policy. Business and Professional Ethics Journal 9, 141–157.
WEC, 2007. The Role of Nuclear Power in Europe. World Energy Coucil, London, United Kingdom.
Williams, K.A., Miller, K., 2006. A User's Manual for G4 – ECONS: a Generic EXCEL-based Model for Computation of the Projected Levelized Unit Electricity Cost (LUEC) from Generation IV Reactor Systems., Economic Modeling Working Group. Commissioned by the Generation IV International Forum.
WNA, 2010. The Economics of Nuclear Power. Information Paper. World Nuclear Association.
World Nuclear News, 2009. 〈http://www.world–nuclear-news.org/〉 (contract to build new nuclear at Levy).
Worrall, A., Gregg, R., 2007. Scenario analyses of future UK fuel cycle options. Journal of Nuclear Science and Technology 44, 249–256.