A WORLDWIDE REVIEW OF THE COST OF NUCLEAR POWER

M. LECOMTE, N. MARIO, D. VIGNON
NucAdvisor
168/172 boulevard de Verdun, 92408 Courbevoie Cedex - France

ABSTRACT

The “true cost” of nuclear energy is a subject of great controversy, especially when considering capital costs of recent projects which opponents to this technology claim to be out of control.
In order to provide an objective assessment of nuclear competitiveness, a systematic review of nuclear costs as estimated by stakeholders on a worldwide basis (parliamentary commissions, general accounting offices, academics from universities, non-governmental organizations [either promoting nuclear, or non-nuclear energy], utilities and vendors) has been performed. Based on these data, levelized costs of electricity (LCOE) were calculated, for different technologies and different regional areas. A cost breakdown between key factors (pre-construction and owner costs, Capex, Opex, spent fuel management, dismantling and decommissioning) was estimated.
The study generally concludes that nuclear energy remains competitive, although costs of advanced technologies soared compared to Gen II. It also demonstrates the benefit of steady and ongoing nuclear programs compared to construction of single projects from time to time.

1. Introduction

The cost of nuclear projects has significantly increased over the past years, due to more stringent safety and quality requirements, safer designs, and higher construction costs.

To provide an unbiased view of recent nuclear costs, NucAdvisor built up a very large data base of all published and documented data and sorted it out to find, so long as it is possible, the “true costs of nuclear energy”, and compared it to other generation technologies. The main steps of the study, including data collection, data analysis, and its key findings are hereafter summarized.

2. Data collection

A very high number of sources provide inputs on nuclear generation costs. There accuracy; completeness and reliability are quite variable. After eliminating unreliable or redundant information, more than sixty reports were reviewed and qualified according to their reliability. Sources can be categorized as follows:

Generic studies	A large number of generic studies (as opposed to vendor specific information) have been published in recent years, providing overall information of today's nuclear generation costs. Writers were from different categories of organizations: intergovernmental or international (OCDE, NEA, governments or state agencies, parliaments, accounting offices, professional organizations (nuclear industry, but also oil or wind industry, etc.), universities and academics, etc.).
Specific studies	Most large utilities committed to nuclear projects issue publicly tradable shares or bonds. Therefore they have disclosure obligations on their main projects, and long term provisions. From worldwide reports (US, European, and most Asian utilities), it was possible to extract accurate information on on-going projects and decommissioning accruals. Direct information received from clients or vendors were also used for several projects in different countries (China, Vietnam, Turkey, France) encompassing different technologies (EPR, ATMEA1, AP1000, VVER 92, etc.) when NucAdvisor had access to recent information about bids and contracts. Apart from Utilities accrual, a specific survey about spent fuel management and decommissioning costs was performed.

Table 1: Classification of collected Information

In total, more fifty reports and studies issued between 2009 and 2013 were collected and reviewed, covering more than twenty different nuclear projects all over the world. The gathered data include 38 data points, of which 18 stemming from the generic studies and 20 from the analysis of specific studies.

3. Data analysis

In order to perform levelized cost of electricity (LCOE) calculations, data were normalized using $_{2013}$USD with the following breakdown of the coststructure.

- Capital costs (USD/kWe Installed) – *including preparatory works costs*
- Fuel costs (USD/kWh)
- Long term fuel waste management (USD/kWh)
- Operation and maintenance costs (USD/kWh)
- Decommissioning and dismantling costs (USD/kWe decommissioned)

Additional information (unit Power, efficiency, availability, fuel burn-up, discount rate, etc. …) were also considered for LCOE calculation.

Nuclear power costs are directly linked to a specific technology, a country or a nuclear program. A categorisation was established to regroup projects with comparable characteristics. The energy mix strategy and the rhythm of nuclear development have an influence on nuclear power costs; therefore, a split was done between countries (e.g. China) having a multiple units program (on-going or planned) and those where a single unit is under construction (e.g. Finland, or France).

Multiple projects	China, Korea, Vietnam, Turkey, Jordan, United Arab Emirates, United Kingdom , United States of America
Single projects	Finland, France

Table 2: project type classification

A second split was done between technologies themselves; the study aimed at considering families of technologies, because of the design gap between Generation II & III/III+ reactors in terms of safety improvements, severe accidents prevention and mitigation requirements, fuel technology improvements.

Gen II	OPR 1000, CPR 1000
Gen III/III+	ABWR, AP 1000, APR 1400, ATMEA1, EPR, VVER – AES 2006

Table 3: technology classification

Calculations of the LCOE was done for these categories, with a breakdown into its main components (Capex, fuel, long term fuel waste management, operation and maintenance and decommissioning and dismantling). When cost breakdown was not fully documented, assumptions had to be made, based on additional investigations specifically performed on preparatory works or decommissioning.

Decommissioning costs were evaluated using a very conservative approach, and discounted with a low discount rate, in order not to minimize their influence on the cost of nuclear generation..

4. Summary of the main results

The main focus of this Results section is to analyse the various factors that govern the cost distribution, based upon observations and subsequent calculations. A brief look at capital cost values from generic and specific studies show the large disparity between projects.

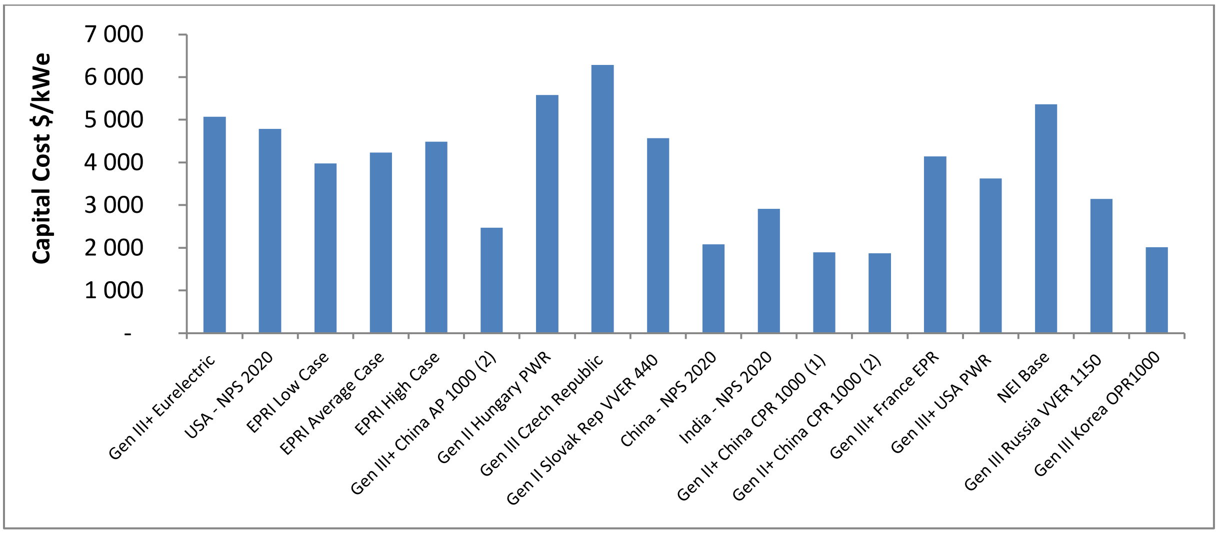

Figure 1: Capital costs overview from generic studies

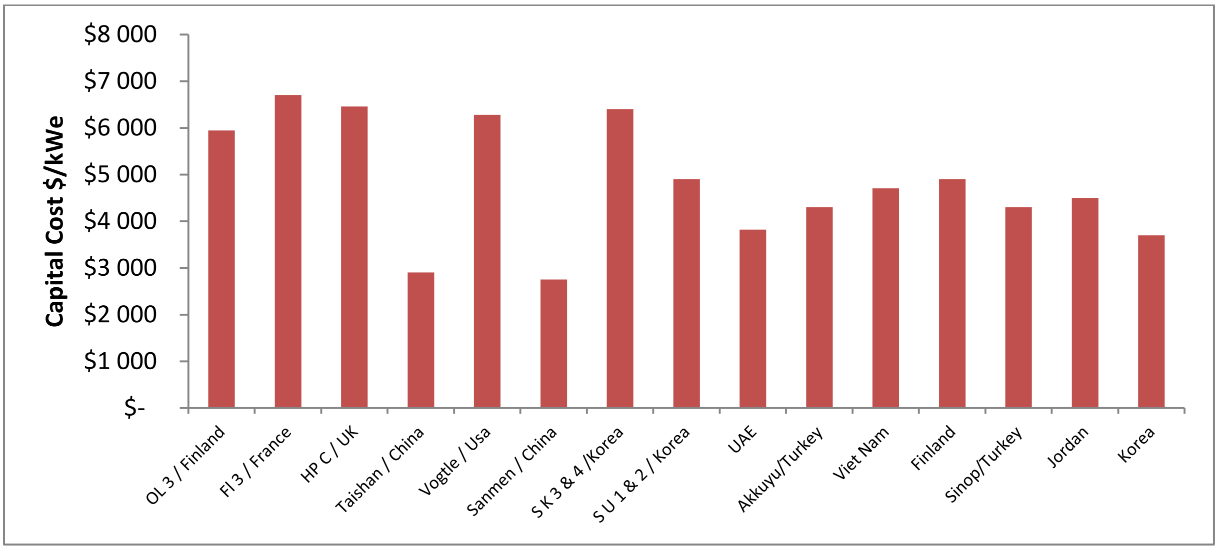

Figure 2: Capital costs overview from specific studies

However, results are pretty close between the two set of data (Generic and Specific studies); especially in the multiple unit project (MUP) category. Some differences on single projects (SP) can be explained due to recent new estimates of some project (EPR Flamanville France, EPR Olkiluoto Finland...). Generic studies do not always take into account recent cost updates, leading to lowest prices in literature studies for SP (Single Projects) and Generation III technologies.

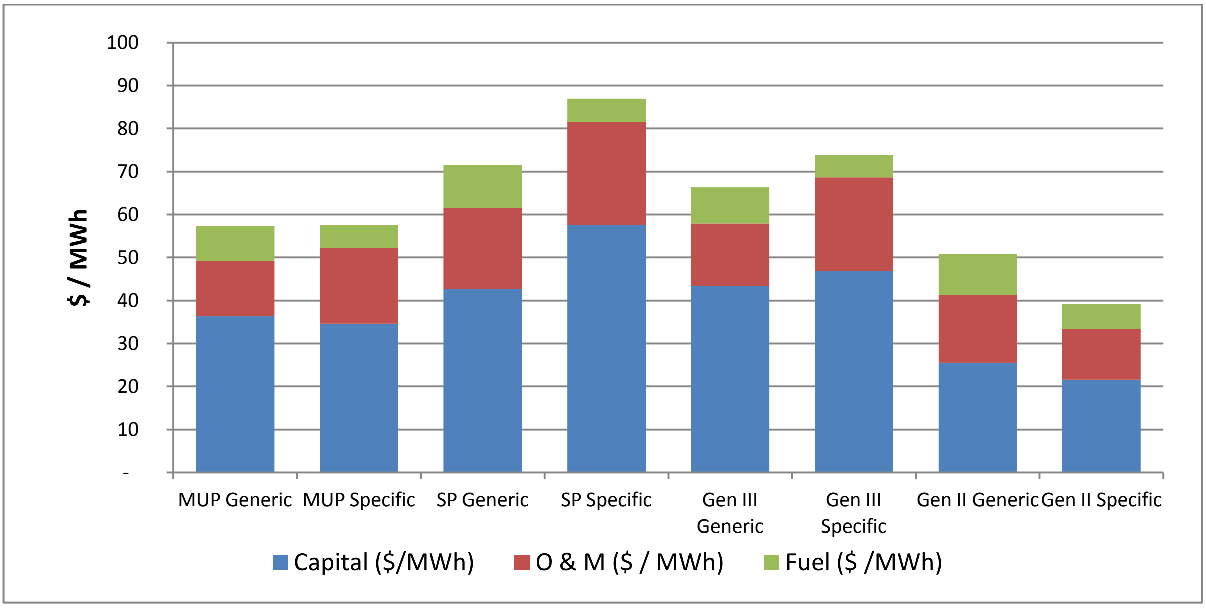

Figure 3: Capital costs, O&M and fuel costs ($/MWh) at 5% Discount Rate Comparison
(Generic Vs Specific studies)

The distribution according to the category previously defined illustrates the cost increase from generation II to generation III/III+ reactors. It underlines the capacity of Gen II reactors to generate electricity at a significantly lower cost than Gen III (LCOE average of 39 $/MWh for Gen II compared to 74$/MWh for Gen III), because of lower requirements in terms of design, safety, etc.…

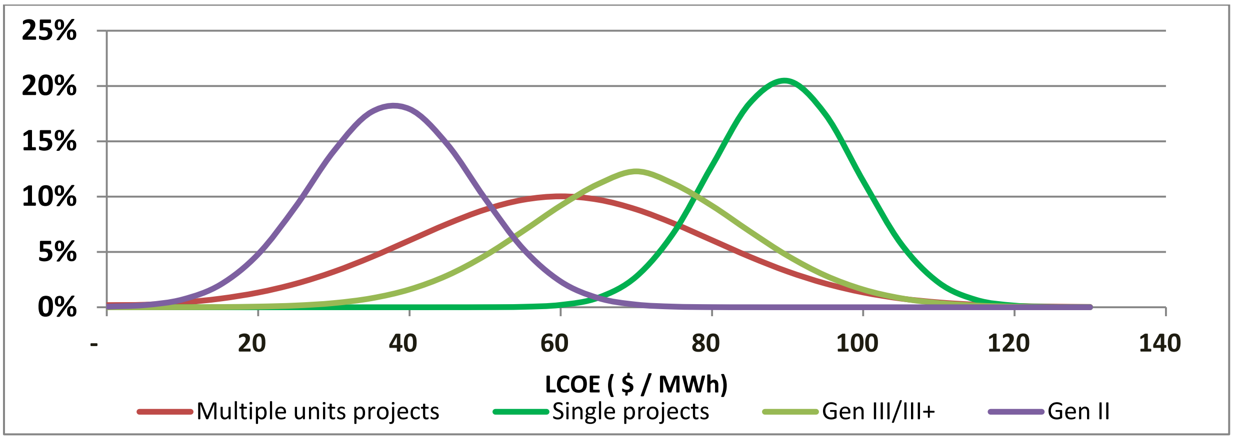

Figure 4: Statistical distribution of LCOE per category (discount rate 5%)

Comparison between single and multiple units NPP projects also illustrates the influence of the serial effect, and the impact of the size of the program on costs. Size of a project has a significant influence on its cost, multiple units projects being far cheaper than single projects.

The distribution of plant costs (figure 4) selected in the study confirms the high influence of this parameter, with lower Capex achieved in countries aiming at a continuing program as opposed to a single unit.

It also underlines the great competitiveness of Chinese CPR 1000 reactors (Gen II).

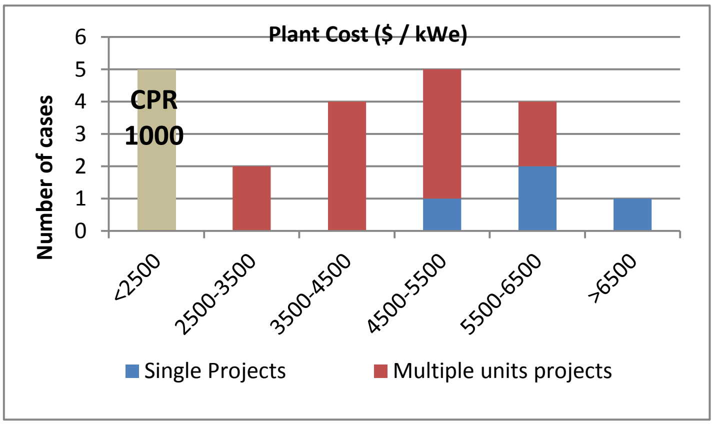

Figure 5: Distribution of plant cost

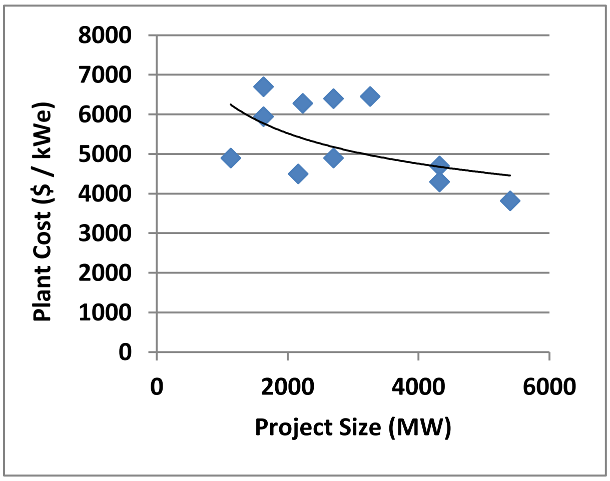

Figure 6: plant cost as a function of project size

When excluding Chinese Gen II projects from the sample, the analysis shows a cost reduction of 20 to 30 % when the project size is above 4 000 MW. This trend is confirmed by NucAdvisor experience of recent quotations that would indicate cost savings for multiple unit orders. The increase of Project Size by building several units at the same site provides opportunities for capital cost reduction, in areas such as siting, licensing costs, construction efficiency, common facilities, etc

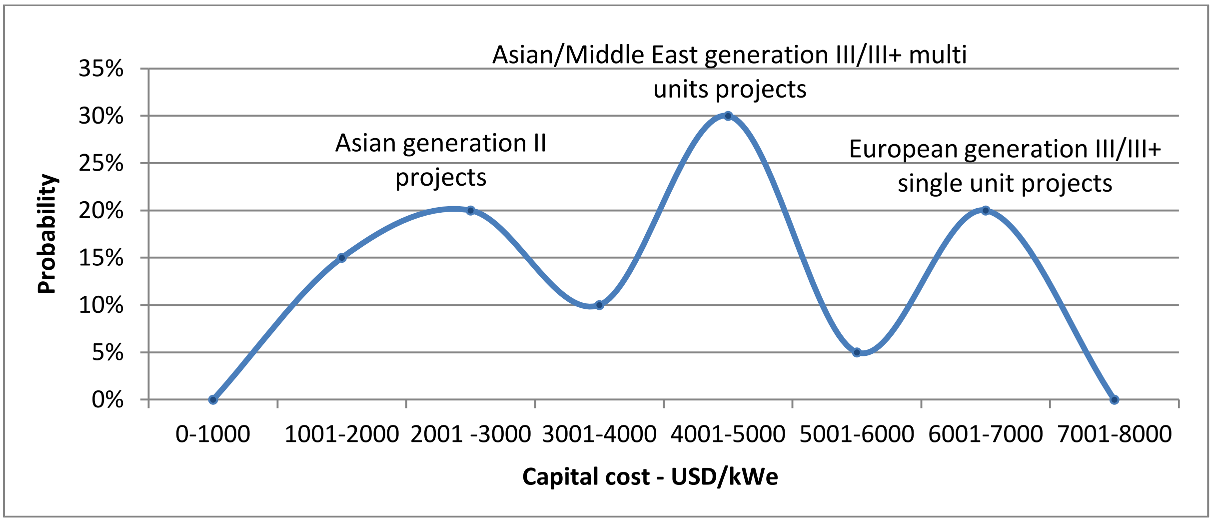

Figure 7: Capital Cost Distribution for all reviewed projects

The distribution of capital cost for all projects considered in the study quantifies the influence of project environment over nuclear costs. Even if each nuclear project has several unique characteristics which drive costs (Technology, Nuclear Program, Safety requirements…), three main categories of projects appear:

Asian Generation II Nuclear Projects
These projects have the lowest costs (Capital Cost lower than 2100 USD/kWe, LCOE < 30 USD/MWh), all reactors have Generation II technology (CPR 1000). The combination of CPR 1000 technology and China localization leads to very low costs projects. However CPR 1000 are no longer being licensed for new projects.

Asian Generation III/III+ Nuclear Projects and Middle East with Multi Unit Program
These projects have higher costs (capital cost between 3000 and 5000 USD/kWe) explained by improved technology, but the increase is to some extent offset by the serial effect, and localization benefits in part of the world where labor costs are low.

Europe and USA Generation III/III+ Nuclear Projects with Single Unit Program
The highest costs are associated to single unit program (OL3 Finland, FL3 France) after long periods of construction freeze; these new projects are based on Generation III or III+ technology, leading to high costs being not balanced by localization or serial effect.

The consolidation of all Generation III/III+ projects provides the results shown in table 4 (at a 5% discount rate). Generation II projects were not considered because the technology is no longer licensed.

USD 2013		**Average**	**Standard deviation**
LCOE	**$/MWh**	$ 73,8	$ 16,0
Decommissioning		$ 4,7	$ 1,3
O & M		$ 17,2	$ 2,8
Spent Fuel		$ 1,3	$ 0,4
Fuel		$ 3,9	$ 0,2
Capital		$ 46,8	$ 12,7
Capital	**$/kWe**	$ 4 917,8	$ 1 289,2

Table 4: average LCOE and Capital cost breakdown for all generation III/III+ projects studied

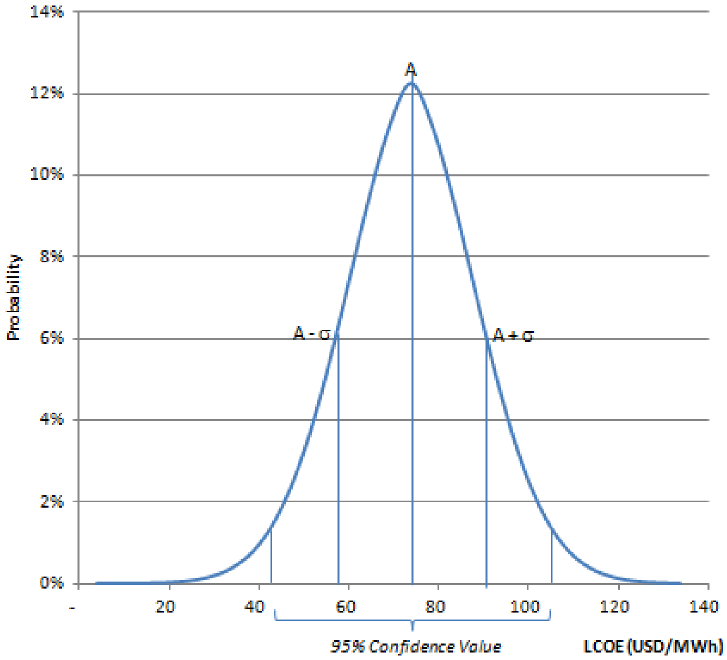

Figure 8: Distribution of LCOE for Gen III/III+ projects selected

The overall review of all Generation III/III+ projects shows that the expected levelized cost of nuclear power for projects having a 60 years lifetime is about 73,8 USD/MWh. There is a 95% probability that the LCOE will be between 42 and 105 USD/MWh. This relatively large standard deviation results from the fact that different countries and technologies were considered.

5. Comparison with other power generation sources

The cost of nuclear energy alone was compared to alternative supplies, using LCOE as a metrics. Indeed, this method has its shortcomings, like the selection of an adequate discount rate, or the uncertainty of the discount rate over the lifetime of a nuclear project; however, it has the merits of being simple to implement, and widely used. No penalization was added to renewable energies (solar and wind) versus dispatchable energies.

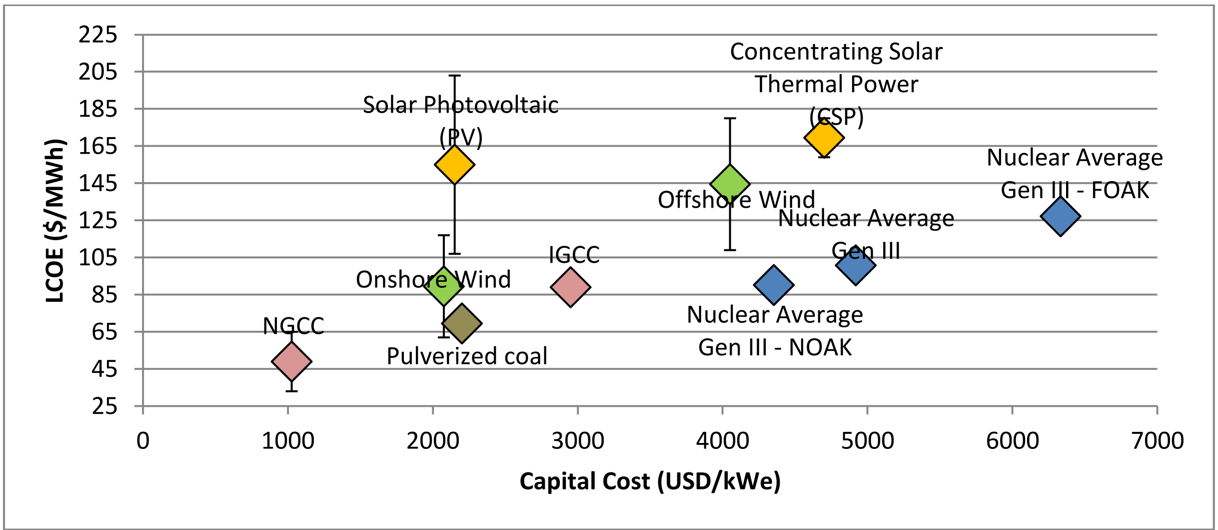

Figure 9: LCOE Vs Capital costs

Figure 9 - Data for energy sources other than nuclear are issued from the EPRI report “Program on Technology Innovation: Integrated Generation Technology Options 2012”.

When comparing nuclear energy, to gas, coal or renewables, nuclear keeps an edge (especially if Carbon sequestration would be required, or if CO_2 emissions were penalised).

6. Conclusion

The scope of the paper is a short summary of a very large literature survey; its main conclusions lay in the casted amount of data, showing the diversity of nuclear projects over the world, and their consequential costs. The study enabled to quantify different factors explaining this wide range of data.

The cost of Nuclear is deeply linked with each country Development Plan; selecting state of the art nuclear technology implies to be faced with higher costs, that can be offset through different parameters; some being intrinsically linked to a country (labor cost, capacity to manufacture components…), others depending on the project itself (number of units, …).
However, the study shows that even advanced technologies built in developed countries can compete against other generation technologies.

7. References

NucAdvisor used more than sixty reports to perform this study; it is not possible to provide here the exhaustive reference list. Full reference list can be asked at contact@nucadvisor.com. Figure 9 is based on NucAdvisor results for nuclear projects, and the EPRI report referenced below.

[1.] Program on Technology Innovation: Integrated Generation Technology Options 2012. EPRI, Palo Alto, CA: 2013. 1026656