The costs of nuclear power in the study “The Future of Nuclear Power” (MIT)

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Abstract—Considering the annual growth in electricity consumption, as well as the rising price of fossil fuels, we face the need to develop sources of energy. The production of electricity from fossil fuels is the leading cause of increasing emissions of CO₂.

There are some risks associated to a nuclear power plant construction. It is important to know how to reduce them or transfer them to those who can manage them more efficiently.

This paper re-creates part of the study published by MIT that discusses the costs associated with building a nuclear power plant. So it was developed the economic model similar to that proposed by MIT.

From the model created is interesting to analyze different scenarios and determine the sensitivity of various parameters on the final result.

It was concluded that the debt rates and return to investors are essential for the viability of the project and the final calculation of the price of electricity. Also important is the debt/investment that can lead to a significant reduction in the price of electricity.

Index Terms—nuclear power, investment, risk, cost analysis.

I. INTRODUCTION

It is urgent to develop alternatives for power generation in order to meet the annual growth in electricity consumption and as a mean of reducing dependence on fossil fuels whose price has undergone major changes in the market, and its use is associated with the emission of Carbon Dioxide CO₂.

Currently there are not very many few realistic alternatives to reduce CO₂ emissions in power generation, however in [1] the following solutions to help solve the energy problem are presented:

- increased efficiency in production and consumption of energy power;
- expansion of the use of renewable energy sources like wind, solar, biomass and geothermal;
- capture CO₂ emissions from electricity generation by fossil fuels and permanent carbon sequestration;
- increase the use of nuclear energy.

Currently nuclear energy can not be a cost effective option when compared with other technologies. In the future, when the price of CO₂ emissions reach a high value the nuclear can be vital for the production of electricity. Portugal exceeded by 7%, in 2008, the target set fr 2008-2012 by the Kyoto protocol for the emission of greenhouse gases [2]. Due to this new sources of less polliolet sources of energy should be found.

This paper aims to recreate an economic-mathematical model that calculates the costs of construction and operation of a nuclear power plant, based on a study prepared by the Massachusetts Institute of Technology (MIT) in 2003 [1]. The model allows to analyze and recreate different scenarios, and assess the weight of each party in the cost of a nuclear power plant.

We will start by addressing the issue of nuclear power with special attention to the production of electricity. The risks of investment are studied on Section III. The economic model developed by MIT to calculate the real costs of nuclear power plant are discussed on Section IV. The Section V is about different scenarios, more real, and the Finland solution using the re-created model. The conclusions are discussed in Section VI.

II. THE NUCLEAR

The production of electricity comes from two kind of sources:

- non-renewable or conventional;
- renewable.

By non-renewable energy source we consider all the fossil fuel like oil, coal, gas and uranium used in power plants. The water, wind, sun, tidal, biomass and geothermal are renewable sources used in electricity production. In Portugal, the electricity that reaches the consumer comes from the vast majority of plants installed in our country (oil, coal, gas, water and wind). The remaining energy required is imported from Spain, see Fig. 1. In this import are also associated production costs, from which you may be advantageous to import energy.

![Fig. 1. Electricity sold by type by EDP (2008)](image)

In Portugal the installed production capacity was increased by 50% during the period between 2000 and 2007. This increase is due to the installation of new power plants of natural gas, wind and hydro.

Nuclear power are controlled nuclear reactions to produce energy. There are two ways to convert power into heat: the
Fusion and fission. Fusion comes from the collision of two atoms to form a heavier one, releasing energy in the form of heat. Fission is the breaking of an unstable nucleus in two other lighter, this process occurs with the collision of heavy nucleus with a neutron. Thus releasing a large amount of energy as heat and radiation. Fig 2.

Fig. 2. Illustration of the fission process

Currently, fission is already used not only for electricity generation but also for naval propulsion and weapons. Although uranium is currently almost the only being used, other substances such as plutonium or thorium can also be used in this process. The nuclear fission of uranium is used in many nuclear power plants around the world, especially countries such as France, Japan, United States, Germany, Brazil, Sweden, Spain, China, Russia, North Korea. The main advantage of the energy produced by nuclear fission is the non dependence on fossil fuels.

The biggest problem around the nuclear is safety and environmental risk, however this form of energy production began to be defended by environmentalists due to reduced CO₂ emissions. If the media attention surrounding the nuclear was not so negative, this option would probably be high on the list to tackle global warming. The advantages are several, among which we can highlight:

- generation stability;
- price stability;
- competitive prices;
- no contribution to global warming;
- absence of emission of solid particles and pollutant gases.

Nuclear power needs public acceptance, but the MIT study polled 1350 adults in the United States of America (USA) on nuclear energy and there were unexpected results:

- Public opinion in the U.S. are formed primarily by perceptions of technology, and not because of politics or demographics such as income, education and gender.
- The U.S. public evaluation of U.S. about nuclear waste, safety and costs is essential for decisions on the future implementation of this technology. Technological improvements that reduce costs and increase security can increase public support of technology.
- In the U.S. people do not associate the concerns about global warming with the production of nuclear which is a source of energy free of carbon emissions.
- Public awareness can help improve understanding about the connection between global warming, the use of fossil fuels, with the need to produce carbon-free.

Safety in a nuclear power plant is possible through plans and regulations for that purpose, minimizing the risk, assuming that this will never cease. In the history of nuclear, there are two big accidents to be recorded, first in 1979 at Three Mile Island (USA) and the second at Chernobyl (Ukraine) in 1986. The Chernobyl accident was the most serious but will not be repeated, since the existing plants use water instead of graphite moderated nuclear. Currently, reactors operate with pressurized water which makes them safer, because the automatic safety system can not be blocked. In the accident at Three Mile Island pressurized water reactors were already being used but it was the beginning of the second generation reactors. Currently, third generation reactors are an improvement of previous reactors. Improvements include an increase of life; improvements in the fuel cycle and thermal efficiency; security systems; and a standardized design to reduce maintenance costs and capital expenditures.

A major problem associated with nuclear is the management of waste in the long term. Since nuclear waste has some danger, is important need to develop standards and programs for waste disposal. Many independent experts agree that the geological repositories are able to isolate the waste safely in the biosphere. However the application of this method is very demanding, in particular it uses a very high number of operational and regulatory resources.

In 2005 it was submitted a proposal to build a nuclear power plant in Portugal. With a private investment amounting to 3500 million of euros, the aim was to install a unit of 1600MW using EPR technology.

III. INVESTMENT

The construction of a nuclear power plant root is a challenge in terms of engineering and economics. The terms of the MIT study is an investment of around 3000 million dollars, 50% of capital to expect return at the end of 40 years, and 50% as a loan. This type of investment is only available to large business groups, where government support will be a great help.

An investment of this size has some risk. This is reflected in the rate of return demanded by investors, that is, the greater the risk of the investment the higher the expected return, assuming no investment without risk. In Fig. it is possible to see the relation between risk.

A. Specific Risks

To the construction of a nuclear power plant are associated with specific risks, such as construction costs, operating performance, regulatory and market risks. Traditionally many of these risks are borne by consumers.
According to the theoretical model of decentralized electricity market, investors bear the risk of uncertainties associated with the construction and permit requirements, risks of construction costs and risks of operating performance [9]. When the law allows, some of the risks affecting investors may be transferred to the distributors and consumers through long-term contracts and/or vertical integration.

According to Dominique and Roques [9], the success of nuclear power in deregulated markets can be reached through cooperation with regulatory authorities and security suppliers and consumers by allocating shares in the risks. Transferring the risk of pre-construction, construction, operation and market to others, the producers will be in a better position to attract investors.

They [9] also argue that there are 4 major types of risks related to the construction of a nuclear power plant:

- regulatory and political risks;
- construction risks;
- operating and performance risks;
- market risks.

Many of these risks are linked and may overlap, but it is important to reduce them or transfer them from the producer/investor for others. Market risks are not unique to nuclear power, but are due to increased construction time, high investment and the lack of correlation between production costs and the costs per hour of electricity.

1) Regulatory and political risks: It is important to consider that such risks are exogenous and are not involved in project management. All the technologies of energy production are subject to the risk of changes on environmental protection, however nuclear projects face specific regulations and political risks. In particular in Germany and the U.S., there was a delay in the completion of a nuclear power plant due to licensing problems, local opposition, source of cooling water, construction requirements, quality control, among others [10].

Delmas and Heiman [11] argue that in many cases, “reopen the nuclear option” requires strong political leadership to reduce risks in the licensing and regulation at different levels:

- safety regulations;
- creating a solution to the problem of waste disposal;
- stability of the legal structure in a limited number of obligations and provision of insurance in case of accident;
- political process to accept the location of the plant construction and waste management.

Additional security is for the government to be liable for additional costs relating to any unforeseen costs due to regulatory changes.

2) Construction risks: Miller and Lessard [12] showed that, in an analysis of 60 major engine projects valued at 1000 million dollars, the critical factors of poor performance are a large proportion of public ownership due to budget constraints, management issues, and the mere fact of being pioneer. The last two are of great importance in nuclear power projects.

The nuclear, is characterized by a long period of construction and large movements of money compared to an equivalent central combined cycle [9].

The International Energy Agency (IEA) believes that the risks of building a nuclear power plant increases with the investment: a delay in the construction of 24 months increases the cost of nuclear power in 10 % compared with 3 % for gas and 7 % for oil [13].

A possible solution to transfer the construction risk is to realize “turnkey” contracts, transferring them to supplier. Finish The Olkiluoto 3 reactor, the first EPR unit, has the most construction risks assumed by AREVA, a project with total value of 3200 million dollars [9].

3) Operating and performance risks: A technology still untapped, sees the degree of uncertainty changing depending on the use of previous projects, or if they have new projects.

The risk of performance can be attributed to the equipment supplier, for example, providing security during the lifetime. Major suppliers such as General Electric, Siemens and Alstom assume the risks of operation in combined cycle plants. Being a pioneer reactor is unlikely that providers take that risk [9]. However, this risk was assumed by AREVA in the Finnish case.

4) Market risks: Market risks largely depend on the fluctuation of fuel prices, CO₂ and energy. They are not specific to nuclear energy, but the large dimension of the project, exposes investors to greater risks than any other smaller technology production [14].

In the U.S., a large number of producers using Gas Turbine Combined Cycle (CCGT) went bankrupt in 2002-2003 when gas prices soared to three times, because they have to operate at half load. A nuclear power plant is not exposed to the same risk, since the low variable costs mean that is always operating at full load [9].

According to Dominique and Fabien [9] if there are several options for investors to ensure that any investment in electricity markets transfers part of market risk to other parties, they are:

- long-term contracts between new producers and large buyers;
- model of cooperative production;
- combination of organizational structures, vertical and horizontal.

B. Analysis in Portugal

Politically, by the start of the Second Republic, Portugal had 17 constitutional governments [15]. This causes political

![Fig. 3. Relationship between risk and return](image-url)

Fig. 3. Relationship between risk and return

- stability of the legal structure in a limited number of obligations and provision of insurance in case of accident;
instability. The construction of a nuclear power plant in Portugal would very likely run through two, probably of opposing parties, governments. This would increase the risk of the possible problems appearing during, the construction since it would force a compromise between the key players in portuguese plotics.

Market risks do not go unnoticed in Portugal. The fluctuation in fuel prices (which also affects European and American markets, as well as CO₂ emissions, that year after year exceed the limit set by the Kyoto Protocol) may stimulate interest in new technology, and the nuclear has been discussed in relation to this matter.

Prof. Mira Amaral, was an opponent of the nuclear bet in the 80’s, when he was Minister of Industry and Energy, is today one of the advocates of nuclear power as a means of obtaining energy. He also argues that the production of energy from renewable energy sources is not a solution as the only alternative to fossil energy sources. He also shows the fear that delay the output of operation of old plants, because of “political cynicism”, not investing in new, more secure nuclear power plants [16].

IV. THE MIT STUDY

To calculate the cost of construction and operation of a power plant during its economic life we us the MIT study [1], with all figures in U.S. dollars ($).

An important concept to assess the economic competitiveness of the various sources of energy production is the levelized cost. The value of levelized cost is equivalent to the price of electricity that would be needed during the lifetime of the power plant, to cover the operating expenses, interest payments and repayments of debt, taxes and ensure a given value for its investors. Similarly we can define the overnight cost ($C_o$) as the cost of construction of the project if it was not considered interest rates. The total cost ($C_{TOT}$) of the plant is calculated based on the 50% equity at a rate of return $r$ and 50% of debt paid with an interest rate $t$. The parcela $Inv$ is the sum of the annual costs of the power plant during its construction.

$$C_o = \sum \frac{X_n}{(1+i)^n}$$

$$C_{TOT} = \sum \left( \frac{1}{2} \frac{X_n}{(1+r)^n} + \frac{1}{2} \frac{X_n}{(1+t)^n} \right)$$

Construction costs of nuclear power are shown in Tab. I.

### TABLE I

<table>
<thead>
<tr>
<th>year</th>
<th>$$/kWe</th>
<th>-5</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>$Inv$</th>
<th>$C_o$</th>
<th>$C_{TOT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$$/kWe</td>
<td>165</td>
<td>444</td>
<td>566</td>
<td>471</td>
<td>185</td>
<td>1831</td>
<td>2000</td>
<td>2557</td>
<td></td>
</tr>
</tbody>
</table>

The treatment of depreciation is important in the calculation of taxes, since depreciation is a deductible expense. The study used the Modified Accelerated Cost Recovery System (MACRS) to 15 years, which allows to deduct higher amounts during the first years of its operation [17].

The annual costs associated with the operation of nuclear power are treated as the same away that presented in the MIT study [1].

The solution of the model studied is to set the selling price of electricity, so that 15% of the capital invested is returned to investors every year. If the net income is insufficient, the balance is added to the capital as if a investment were made. In the same way, if the net income exceeds the expected return, the investment will have a corresponding reduction in the excess profit.

The MIT study was recreated using a mathematical model that shows similar results. The development of equity in the format re-created, is shown in Fig. 4. The parameters used in the study are shown in Tab. II.

### TABLE II

<table>
<thead>
<tr>
<th>STUDY PARAMETERS</th>
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</thead>
<tbody>
<tr>
<td>inflation rate</td>
</tr>
<tr>
<td>interest rate</td>
</tr>
<tr>
<td>expected return to equity investor</td>
</tr>
<tr>
<td>debt fraction</td>
</tr>
<tr>
<td>tax rate</td>
</tr>
<tr>
<td>debt term</td>
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<tr>
<td>net capacity</td>
</tr>
<tr>
<td>capacity factor</td>
</tr>
<tr>
<td>plant life</td>
</tr>
<tr>
<td>heat rate</td>
</tr>
<tr>
<td>overnight cost</td>
</tr>
<tr>
<td>construction period</td>
</tr>
<tr>
<td>decommissioning costs</td>
</tr>
<tr>
<td>incremental capital costs</td>
</tr>
<tr>
<td>fuel costs</td>
</tr>
<tr>
<td>real fuel escalation</td>
</tr>
<tr>
<td>nuclear waste fee</td>
</tr>
<tr>
<td>fixed O&amp;M</td>
</tr>
<tr>
<td>variable O&amp;M</td>
</tr>
<tr>
<td>O&amp;M real escalation rate</td>
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</tbody>
</table>

Fig. 4. Changes in capital from investors

Using MATLAB® it was recreated a model of the economic study presented by MIT that shows similar results and with a reduced error.

V. CASE STUDY
The MIT study from 2003 needs to be updated. The economic, political and environmental situations have changed and should be updated and analyzed using the created model.

Economically, interest rates have been declining, public investment has collapsed so investors tend to reduce the risk. Environmental concerns about climate change, CO$_2$ emissions, the dependencies on fossil fuels as well as the crisis that existed around the same price, revived interest in nuclear energy.

A. Update debt rate

In the first half of 2008, the markets of the eurozone and the United States saw a rise in interest rates carried out by the increase in credit risk and liquidity constraints in financial markets. However, given the worsening financial situation in the second half, the European Central Bank (ECB) was forced to lower interest rates several times, these measures were also taken by the Federal Reserve of the U.S. [18], as shown by the trend euribor in Fig. 5.

![Fig. 5. Euribor evolution in 2008](image)

Changing only the interest rate to 5%, it is expected that the investment will be recovered in a shorter period of time. Accordingly, the end of 28 years made all the investment is recovered, while the rate of return of 15%, as seen in Fig. 6.

![Fig. 6. Equity changes for the different rates](image)

B. Reducing the price of electricity

While taking advantage of the reduction in interest rates it is important to check the fall of debt rate that has implications for the price of electricity. For the same rate of return it is possible to lower the price of electricity by 2.46%. In the first year of operation the base price of 6.91 cents/kWh will decrease to 6.74 cents/kWh. The changes in capital at $t = 5\%$ and $r = 15\%$ are shown in Fig. 7.

![Fig. 7. Changes in capital for different electricity prices](image)

C. Investment reduction

The rate of return required by investors is, in any case, higher than the interest rate charged by banks. In this sense, increasing the capital invested by the bank, is an option that can be explored with a view to reducing the final price of electricity, see Fig. 8.

![Fig. 8. Changes in capital for different margins of debt and investment](image)

The reduction in investment allows the profitability of the project at the end of 19 years, which allows a scope to reduce the price of electricity.
D. The Finnish case

In May 2002 the Finnish parliament approved the construction of a new nuclear power plant, the fifth, with 2009 as start operation date. The criterion for the construction of the plant was the low cost of $kWh$, the low sensitivity to changes in fuel prices, safety and the environment.

The Finnish solution provides a turnkey solution for construction, which is to set a final price for the electricity and all the extra costs are attributed to third parties. The new Finnish power plant has as its assumptions of $91\%$ capacity factor, $5\%$ interest rate, $5\%$ return and $40$ years of life [19]. The comparison of the evolution of capital in this solution and in the MIT proposal is shown in Fig. 9.

![Fig. 9. Changes in equity for the solution of MIT and Finnish](image)

E. Delay in the start of operation

The great Finnish investment is already a controversial topic since it is delayed by more than two years and with a budget above predicted [20]. A delay in the start of operating results in increased costs, although in effect without the entry of new capital entry, because the money is invested without any return during the delay time. A delay in the start-up of 2 years corresponds to a construction period of 7 years in which, for simplicity, in the last two investment is zero. The cost of building the plant are represented in Tab. III.

![Table III: Costs of central in $/kWe](image)

<table>
<thead>
<tr>
<th>year</th>
<th>-7</th>
<th>-6</th>
<th>-5</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>C_ROE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 years</td>
<td>-</td>
<td>-</td>
<td>165</td>
<td>444</td>
<td>566</td>
<td>471</td>
<td>185</td>
<td>2557</td>
</tr>
<tr>
<td>7 years</td>
<td>165</td>
<td>444</td>
<td>566</td>
<td>471</td>
<td>185</td>
<td>0</td>
<td>0</td>
<td>3201</td>
</tr>
</tbody>
</table>

This delay of 2 years adds about 25% to the total cost of construction of a nuclear power.

With a delay of 2 years the changes in capital for the MIT study are in Fig. [10] The growing trend of capital, in delay time of 2 years, of entry into operation is a sign of the economic inviability of the project without an adjustment in the final price of electricity.

The price of electricity that can handle the delay, and thus make possible the investment is around 8.27$\text{cents/kWh}$ compared with the initial 6.91$\text{cents/kWh}$. For the Finnish situation, delay in operation, would involve an increase in the cost of electricity of 3.25$\text{cents/kWh}$ to 3.40$\text{cents/kWh}$.

VI. Conclusion

It is necessary to create environmentally friendly alternatives, to ensure the functionality and stability of power system in Portugal. The economic and environmental concerns are real and immediate action is needed. In Portugal the thermal power plants have been replaced by gas gas power plants which have fewer emissions of particles that cause the greenhouse effect and do not emit sulfur dioxide, but even this may not be enough. One possible alternative is to increase the use of nuclear energy.

The interest rates on debt and returns to investors and affect the investment are directly related to the final price of electricity. The variations between them are not linear since the MIT study is done with different rates of $8\%$ and $15\%$ respectively.

A reduction of 3 percentage points in interest rate allows a reduction of $2.46\%$ in the final price of energy. Similarly, a reduction of 7 percentage points in rate of return allow a $37\%$ reduction in the final price of energy produced. So it is easy to observe that the final price of electricity is more sensitive to the rate of return for investors while it is higher than the rate paid to banks.

Another alternative for reducing the final price of energy is the reduction in investment compared to debt. As discussed in Section 5, for a ratio of $60\%/40\%$ debt and investment respectively, could result in a return of investment in half the initial time, i.e after 20 years. This type of solution may no be accessible to the investment by private companies or less market power. In any case you will need the support from government entities, as collateral to obtain the loan from the bank.

In this work makes sense study two of stakeholders: investors and consumers.

For the investor it is, above all, a project of 40 years, and it is expected a fixed return on any investment. The risk exists and can be minimized and transferred to third parties, outlining
the most critical part of the entry into operation. If the target for electricity power is energy market, it is appropriate that the investor is a producer in order to avoid middlemen in the process and to be able to enjoy a higher profit margin. For an end user, a nuclear power plant is a new source of energy that can compete in the market. Because it is an energy without greenhouse gas emissions, it is an alternative to the dependence on the production from fossil fuels. The producer price is relatively low and risks are associated somehow to be the consumer.

REFERENCES


