Real options approach for flexible use of green hydrogen in Brazil's renewable energy landscape

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Abstract

Air pollution and global warming pose urgent challenges that require the decarbonization of key sectors of the economy. Brazil, a leader in electricity production from renewable sources, can use part of this energy to produce green hydrogen, offering an innovative solution to environmental problems. This study uses a real option approach to evaluate a hypothetical investment in an electrolyser and an ammonia synthesis plant to exploit the flexibility of hydrogen in being able to be used in different ways by different sectors. In particular, the analysis considers a switch option which gives to the investor the possibility to choose, period by period, when to produce green hydrogen and to which sector to sell it, and when to convert it into green ammonia, with the aim of maximizing the final cash flows. The value of the option is calculated comparing the net present value of the investment with the base case of selling electricity on the free market, subject to high price volatility and therefore high probability of loss. Preliminary results, obtained with a simplified model, indicate that the switch option increases return of the investment, allowing to choose what to produce and sell based on market conditions.

1. Introduction

The world is facing unprecedented challenges related to air pollution, global warming, and the need for energy transitions towards more sustainable energy sources. The widespread use of fossil fuels has significantly contributed to these issues, prompting the international community to seek alternative and more environmentally friendly solutions that could help achieve the 2050 net-zero emissions objective. In this context, Brazil emerges as a virtuous example, especially in generating electricity from renewable sources, with one of the world's largest hydroelectric potentials, accounting for over two-thirds of its total installed capacity. However, while the use of water resources offers numerous advantages, heavy reliance on hydroelectricity leaves the country vulnerable to fluctuations in hydrological conditions: in fact, recent years of intense drought have severely impacted Brazil's primary source of electricity generation, leading to dangerously low reservoir levels and highlighting the urgent need to diversify its electricity generation mix for increase its supply security. For this reason, solar and wind power generation represent two other important sources that the country is exploiting due to its favourable natural conditions in terms of strong winds and average annual solar radiation. Although they still represent a minority in the Brazilian energy landscape, they are rapidly expanding leading to two considerations: first, Brazil's future energy supply looks comfortably stable and second, as renewable's capacity growth shows no sign of slowing down, there will probably be an excess of available renewable supply (counting large reservoirs of hydro as renewable). In such a context, it is possible to forecast that the price of free market energy in the country will drop significantly and, therefore, the possibility of looking beyond conventional sources to embrace innovative solutions becomes attractive. One of these is represented by green hydrogen, a clean and versatile energy carrier produced through water electrolysis using electricity derived from renewable sources. Given its flexibility and environmental neutrality, it offers enormous potential for decarbonising many key sectors: it can be used as a fuel in internal combustion engines and turbines to generate mechanical energy, burned in ovens for heat generation, utilised as a feedstock in various industrial applications that currently rely on hydrogen derived from fossil fuels (such as methane, oil, carbon), or even transformed back into electrical energy through electrochemical processes in fuel cells. Therefore, many countries look at green hydrogen as the solution for future energy management and are increasingly supporting the introduction of hydrogen technologies aimed at a "decarbonised" economy.

However, along with the positive aspects, there are also negative ones: the main obstacle to the introduction of a large-scale application is its production costs, mainly due to the high investment cost for the electrolyser; moreover, there have been discussions about the implications of hydrogen production by water electrolysis in relation to water availability and reserves, considering that a large quantity of water is requested. These challenges often result in a negative NPV for investors who are attracted by the potential of such an innovative product on one hand, but on the other they are discouraged by the huge investment costs, which leads them to adopt more traditional solutions.

Governments are also launching support policies by providing incentives for both the construction of new delivery infrastructures and the production of green hydrogen, but this is not enough. More sophisticated approaches to investment evaluation are needed to consider the uncertainty and flexibility of this kind of investment, which are ignored by classic evaluation methods such as the discounted cash flow. They fail to comprehensively grasp the intricate nature of energy projects, disregarding the stochastic elements inherent in energy investments, their irreversible characteristics, and the managerial flexibility that could allow for the acquisition of further information, potentially mitigating uncertainties and preventing future losses. On the contrary, a Real Option Approach (ROA) emerges as a crucial financial instrument in the evaluation of those kinds of investments characterized by many uncertainties such us future prices, environmental conditions, final demand. Typically used to evaluate tangible assets, ROA provides investors with flexibility in decision-making and highlights uncertainties associated with future cash flows, helping them to make the best choices that can enhance the overall project value e.g. reducing or increasing the investment costs, deferring a decision in a future moment waiting for more pieces of information, switching inputs or outputs or even abandoning the project if the market conditions are not as expected.

In this article, we evaluate the possibility for an entrepreneur, who already owns a photovoltaic system and sell the electricity to the free market, to invest into an electrolyser that uses this electricity to produce green hydrogen through water electrolysis. The decision, which is nothing more than an American option, can be exercised at any time between purchase and expiry of the contract of the option, giving him the flexibility to wait for the best market conditions that is, when electricity prices are very low. After the investment has been made, the entrepreneur could be able to choose period by period whether to sell the electricity directly to the grid or produce and sell green hydrogen to one of the sectors before mentioned. This means that the American option activates a European option since in this case it can only be exercised upon expiry of the contract, i.e. every month the investor will have to choose what to produce and sell based on the price fluctuation of the two outputs. If the decision to produce hydrogen turns out to be profitable, we also evaluate the possibility that a second American option could be exercised: an investment into an ammonia synthesis plant which uses green hydrogen obtained in the first phase to produce green ammonia. Ammonia, in addition to representing a more stable medium for hydrogen storage, also has several advantages in terms of flexibility of use, for example fertilizer production, chemical industry, wastewater treatment, pharmaceutical production to name a few. Being an already widely established product that has demonstrated its economic performance, the infrastructures for its production and distribution have long been established.

However, for the purpose of this paper, we limit ourselves to the possibility of selling it at the simple free market price, without examining its flexibility of use, which will instead be done for green hydrogen. Even in this second case, the entrepreneur would find himself faced with another European option, this time with the addition of ammonia as a further production option which could help increasing the final profit. It's important to note that while the first American option of investing in an electrolyser is independent, the second American option of investing in an ammonia synthesis plant depends on the first, as it requires the hydrogen produced upstream as an input for the ammonia synthesis.

The question we want to answer is: is the added value given by the flexibility of choosing what to produce in a certain period, given certain market conditions, greater than the additional costs necessary to have this flexibility? In other words, we want to understand if the revenues from the sale of hydrogen or ammonia are greater than the costs necessary to invest and maintain the respective production plants over time. To answer this question, we execute a Monte Carlo simulation to predict the future cash flows over an investment life period of 10 years given a set of stochastic and deterministic inputs regarding a hypothetical plant located in the south-eastern area of Brazil. Consequently, we help the investor to choose period by period the highest cash flow among the following different production options:

1) Base case: Electricity is sold directly to the grid at the current price.
2) Green hydrogen with the flexibility of being able to be sold to different sectors, each one characterised by a different sale price.
3) Ammonia sold at the current price.

The final value of the maximum NPV obtained from the maximum cash flows is then compared with the NPV of the base case to understand if the option’s added value is worth the added investment costs of the electrolyser and the ammonia synthesis plant.

The remainder of this paper is structured as follows: First, we provide an overview of the related literature in Section 2. We then describe our model in Section 3 and apply it in Section 4. Section 5 is dedicated to the presentation of results. Subsequently, we discuss our results in Section 6 and conclude in Section 7.

2. Literature Review

Integrating renewable energy sources (RES) is deemed indispensable for achieving sustainable development in response to critical global challenges such as energy scarcity, global warming, and climate change. In this scenario, RES are pivotal in ensuring universal energy access, fostering new economic opportunities, and mitigating greenhouse gas emissions (Fernandes et al., 2011). Despite their rapid growth, renewables like wind and solar are plagued by inherent intermittency, leading to disparities between energy demand and supply throughout the year, which could result in excess or insufficient energy availability (Al-Ghussain et al., 2022; Kockel et al., 2022). Surplus energy is often deemed wasteful or may be exported under certain geopolitical conditions (Al-Ghussain et al., 2022). Consequently, storage technologies, such as batteries, facilitate optimal energy use derived from RES (Pleßmann et al., 2014). Although batteries represent a competitive storage solution, they are subject to limitations, including a finite number of charge cycles and the requirement of critical raw materials, compounded by recycling challenges (Dehghani-Sanij et al., 2019). In light of these limitations, alternative methods for managing energy surpluses are being explored, with green hydrogen, produced predominantly through water electrolysis, emerging as a viable solution (Al-Ghussain et al., 2022). Hydrogen's versatility, capable of being stored, reconverted into electricity, combusted for heat, or utilised as a fuel or industrial feedstock, underscores its potential as a flexible energy carrier (Squadrito et al., 2023). Despite the significant promise held by investments in renewable energy sources (RES), and energy projects at large, they exhibit distinct characteristics that set them apart from conventional investment avenues (Santos et al., 2014). Notably, such investments are often wholly or partially irreversible, a condition typically arising from the specificity of the invested capital; that is, the capital is tailored to the unique needs of a firm or industry, limiting its applicability elsewhere (Pindyck, 1991). Additionally, these investments are fraught with numerous risks and uncertainties, especially following the deregulation of electricity markets, which introduces volatility in energy prices (Kumbaroğlu et al., 2008). Concurrently, they necessitate higher initial outlays than those required for traditional energy technologies (Muñoz et al., 2009; Santos et al., 2014). Given this context, conventional methods for evaluating investments, such as the simple Net Present Value (NPV) and Discounted Cash Flow (DCF), fall short in their ability to fully capture the complex nature of energy projects. These methodologies often overlook the stochastic elements inherent in energy investments, their irreversible nature, and the managerial flexibility that might, for example, allow an investment to be deferred. Such deferral enables the gathering of additional information, potentially reducing uncertainties and averting future losses (Dixit & Pindyck, 1994).

Real Option Analysis (ROA) is the only asset evaluation method that considers the interaction between the three main characteristics mentioned, defining energy investments: irreversibility, uncertainty, and time flexibility (Dixit & Pindyck, 1994). ROA, mainly used in assessing tangible assets, gives flexibility to investors in making decisions and reveals uncertainties linked with cash flows empowering them to make choices that can increase the ultimate project value (Santos et al., 2014).

Real option valuation is being increasingly applied within the renewable energy field and this tendency is clear when comparing the works of Fernandes et al. (2011) and Koslova (2017): they both offer an extensive review of the application of real options to investments in renewable energy sources but the first consider only eleven articles while the second one hundred one. However, they both emphasize the importance and superiority of a real options approach when dealing with high uncertainty and flexibility, as is the case with renewables (Assereto & Byrne, 2021). It is therefore important to offer to the reader an analysis of the current state of literature to understand how it has evolved over time, which results have been achieved and which ones are yet to be reached, highlighting the gaps in previous studies and suggesting possible future research directions.

Following a chronological order, the first work in this research field is from Vanetsanos et al. (2002) which assesses a wind farm investment in Greece and demonstrates that the real option incorporating managerial flexibility to defer the development of each module of the project and obtain more information yields positive results, unlike the negative outcomes of the traditional NPV. Kjaerland (2007) uses a real options methodology to estimate the value of a potential hydropower investments in Norway; the analysis demonstrates that the volatility of prices has an important impact on the option value therefore, by reducing uncertainty, it is possible to trigger the investments at a lower price. Later, ROA has been applied also to the ethanol with the work of Bastian-Pinto et al., (2009) which investigates the flexibility in the ethanol production from sugarcane using two different price modeling techniques, the Geometric Brownian Motion (GBM) and the Mean Reverting Process (MRP) and demonstrating that even if the GBM is easier to implement, it gives erroneously higher results; furthermore they find that the switching option value increase when the two prices are negative correlated. One year later, Bastian-Pinto et al. (2010) do another similar study with the real option method to analyze the value of the ethanol-gasoline flex fuel option again using both a GBM and MRP for the prices of gasoline and ethanol: depending on the stochastic process used to model the option, the results indicate that the flex option adds significant value to the car owner, and can generate savings in fuel costs of approximately 10% to 15% of total expenditures during the life of the vehicle. Different studies apply the valuation tree to model the price evolution and an example is found in the work of Muñoz et al., (2011) who asses the investment in a wind energy plant: using a trinomial investment option valuation tree, they find the probabilities of invest now, wait or abandon the project and therefore an estimation of the best time to execute the investment and maximize the profit. Di Corato and Moretto (2011), instead, apply a switch option to a biogas plant investment evaluating the possibility to change the production mix depending on the fluctuation of the input prices. The project value increase thanks to a mechanism for hedging against fluctuations in the relative input convenience. Another example of switch option but applied to the output of a process is shown by De Oliveira et al. (2014): their paper analyses the feasibility of an investment in a biomass residue and natural gas cogeneration unit that gives to the owner the flexibility to choose the optimal output from the eucalyptus chips used to generate thermal energy for the plant, namely the production of medium density fiberboard wood panels or surplus energy generation for sale in the short term market when energy price are high, finding that it's possible to increase the value of the plant by R$ 6.9 million after an additional investment of R$ 10 million to interconnect the cogeneration plant to the power grid. Gong & Li (2016) instead, evaluate an investment in renewable power project subject to carbon price uncertainty, adopting a trinomial tree to calculate the NPV of three types of energies, i.e. solar, wind and biomass and the respective ROV, in particular using the option to defer; it draws the conclusion that the fluctuation of carbon price increase the option value but implies that all the three types of projects will postpone the investment decision time. Assereto and Byrne (2021) propose a ROA for a utility scale solar investment in Ireland using the Least Square Monte Carlo method to price the real option and find that the optimal strategy is to defer the investment but without a complete policy support the project is not feasible. Similarly, Zhang et al. (2023) evaluate investment in a utility-scale solar power plant in the USA using a deferring option within the context of the unique subsidy program of solar renewable energy certificates (SRECs). They show how it generates a greater value for the project than the traditional discount cash flow approach, thus concluding that the optimal choice is to postpone the investment in more than 70% of cases.

Focusing more on hydrogen and in particular green hydrogen, the literature is more limited, but it is still possible to find some studies that use a ROA to evaluate these kinds of investments. A first example could be the work of Kroniger and Madlener (2014) who investigate economic viability of hydrogen storage for excess electricity produced in wind power plants. They analyze two scenarios, with and without re-electrification unit, and through a Monte Carlo simulation they find the hourly profits under uncertainty regarding wind speed, spot market electricity prices, and call of minute reserve capacity, concluding that power-to-power operation is highly not recommended under current conditions in Germany, while the power-to-fuel plant can be operated profitably if hydrogen is directly marketed instead of used to store and re-generate electrical energy. Frazena and Madlener (2017) valuate the optimal expansion of a hydrogen wind energy storage system (H2-WESS) using the real option to expand its capacity thanks to a modular design, thus reacting to new project developments. With a Monte Carlo simulation, they reproduce a compound expansion option to invest in a 5, 10, 15 or 20 MW H2-WESS and find a value of about €2 million, compared to the net present value of a 5 MW H-WESS of about €-2.45 million demonstrating the superiority of the ROA over the classic methods. With a compound expansion option, the values of the lower expansion stages of the binomial tree are considered as well so that the investor can at any moment in time, either conduct the expansion to the next stage or keep the option alive and this flexibility allows him to choose the optimal expansion stage depending on the development of the project. Another example of hydrogen-based wind-energy storage systems is found in the article of Xue et al. (2021) which summarizes its advantages through a valuation model based on real options: the results suggest that operators should store energy when the electricity market price is low and discharge it when the electricity market price climbs high. Moreover, the sensitivity analysis shows three others results: first, the less significant the seasonal fluctuation of electricity price, the better the system's economy; second, the lower the unit operating cost is, the more frequent charging and discharging operators perform and third, the subsidy level has an important influence on the value of wind-power storage system. Biggins et al. (2022) investigate the option to wait for a green hydrogen investment using the method of treshold. They consider the future evolution of hydrogen price and of electrolyser CAPEX and analyse how investment time and value is affected by these. The option to wait shows its capability to both improve the expected mean value of the electrolyser investment and reduce the scenarios where the returns are negative. Finally, Zhao et al. (2023) focus on the optimal time to invest in hydrogen-refueling station (HRS) in China considering either independent investment or co-operative investment but demonstrating that, even if growth rate and volatility play important roles in investment timing for both strategies, independent investment is the optimal model for HRS development.

It's evident how studies utilizing ROA in the assessment of hydrogen investments are relatively scarce and how they predominantly adopt waiting options. However, we previously discussed about hydrogen flexibility in being able to be used in different ways by different sectors and it would be interesting to investigate this aspect further through a real option analysis. For instance, an investor might choose to invest in green hydrogen and decide what to do with it on a case-by-case basis according to the market conditions and price fluctuations: for example, when the electricity price on the free market is very low, it it could be beneficial to invest in its production and then sell it to the sector which, at that precise moment, is willing to pay more than others. If also the price of hydrogen is not high enough to cover the relative costs, perhaps a second investment in an ammonia synthesis plant could be the best solution to increase the final profits. Obviously, each choice involves extra costs which are important to evaluate to understand if they are lower than the benefits that could be obtained. The key is to comprehend when it is preferable to adopt one strategy over another, with the aim of maximizing the option's value and consequently, the investment value. This paper addresses exactly this problem using a ROA and applying it to a Brazilian case study.

3. Model

3.1 Problem description

We consider an investor who owns a photovoltaic plant in the south east area of Brazil, region chosen for our case study. It is characterized by an abundance of renewable energy sources, first of all hydroelectric which represents almost 70% of all electricity produced, but it also has a considerable potential for electricity generation from wind and solar energy which are expected to grow in the next years (Santos et al., 2020). The electricity produced by the plant, at first instance, is sold directly to the free market, subject to high price volatility, which expose him to a high risk of losing money. Consequently, he can choose at any time to use this energy in a different way in order to protect himself against the market fluctuation: a first possibility is to convey the electricity produced by the PV plant into an electrolyser that splits water molecules into hydrogen and oxygen (Dincer, 2011). This first investment represents an American option since it can be exercised at any time between the purchase and the expiration of the contract. Green hydrogen in particular is known for its flexibility and numerous applications which make it a ideal product capable of decarbonising sectors like power production, mobility, and many industrial processes (steel, cement, alumina, fertilizer production) in accordance with the global objectives of reduce CO2 emissions, address climate change and reach net zero emissions by 2050 (Majewski et al., 2023). For these reasons, the final green hydrogen market is characterized by various players that are willing to purchase it and which, for simplicity, could be grouped into three main macro sectors:

- Industrial sector (chemical and material production)
- Transportation sector
- Power and heat generation sector.

However, since it is still an innovative product characterized by high production costs, each of these may have a greater or lesser predisposition to buy it which is then reflected in the final price they are willing to pay. Therefore, we first consider that the investor chooses to sell green hydrogen only to one sector e.g. the industrial sector to see if there is an increase in revenues that at the same time covers the extra cost of the investment in the electrolyser. If this happens, he will consider also the others two: in fact, it's possible that in some periods one sector could prevail over the others in terms of final price (with the same costs of production) and this would give him the possibility to choose the option which maximize the respective cash flow. In this case, he will be faced with an European option since he can only exercise it at expiration, hence at the end of each month (unit period chosen for our analysis). Furthermore, hydrogen would also have the potential to be used in the production of ammonia: this last is considered a good medium for hydrogen storage and has numerous advantages such as high energy efficiency, high safety and stability and low pressure for long term storage (Aziz et al., 2020). Ammonia can be utilized by extracting its stored hydrogen or directly utilized as an agricultural fertilizer, refrigerant gas and in the manufacture of explosives, pesticides and other chemical products. Unlike green hydrogen, ammonia has been widely used for some time and therefore, the infrastructures to produce, store, transport and utilize it have been globally established, leading to its proven economic performance (Fecke et al., 2016). We therefore also evaluate the hypothesis in which the investor also chooses to invest in an ammonia synthesis plant, hence in a second American option (dipendent by the first) with the aim of further maximizing his profits: obviously this choice envolves additional investment and operating costs but at the same time another production option which in some cases could results more profitable. In fact, as for electricity, the free market for ammonia is characterized by moments in which the price rises and others when it falls, so the objective of the model is precisely to understand when it will be worth producing it and when it will be better to produce only hydrogen or even only electricity.

In summary, the final decision is represented by one single European switch option which includes the three possible cases described above:

- Electricity directly to the grid at the free market conditions (base case)
- Green hydrogen (with the possibility of choosing who to sell it among the three macro sectors)
- Ammonia

Figure 1 shows the process of transforming electricity into green hydrogen and ammonia with all their possible end uses:

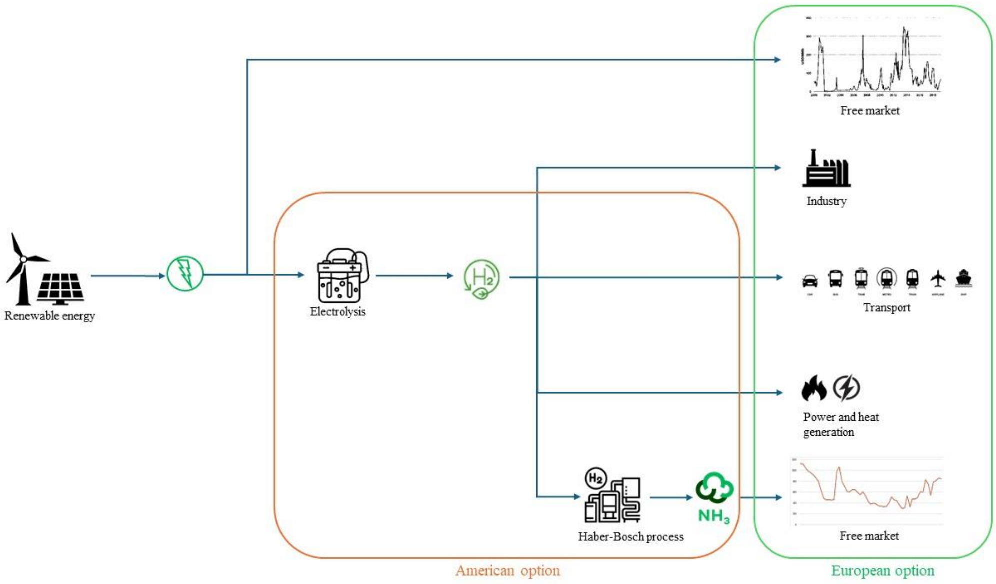


Figure 1: Production process of green hydrogen and ammonia with their possible end uses

This decision will depend on the future selling price of each output and the respective costs necessary for their production. The model, therefore, operates according to a simple but effective logic: at each period t (month) of the total plant lifetime, it calculates the cash flows of all the possible strategies and begins by comparing those relating to the sale of hydrogen and ammonia in pairs, in order to find the maximum value. The latter is then compared with the cash flow deriving from the sale of electricity and precisely this last comparison will determine whether the option will be exercised or not: if the direct sale of electricity is more profitable, the option is not exercised and the plants for the production of hydrogen and ammonia would be inactive. Consequently, although this flexibility may be worthwhile for the investor, it does have costs and it is therefore essential to carefully assess the value of the switch option before deciding to adopt a strategy for maximize the final cash flows. The next section presents the model proposed here to support this decision.

3.2 Mathematical formulation

The model uses the following parametres to asses the value of the switch option:

- T: duration of the investment (e.g. one year), expressed in months
- t: time period (month) in which the investor choose what to produce ($0<t<T$)
- $p_e(t)$= price of electricity at t
- $p_{hi}(t)$= price of hydrogen at t for industry sector
- $p_{ht}(t)$= price of hydrogen at t for transportation sector

- $p_{hp}(t)$= price of hydrogen at t for power and heat generation sector
- $p_a(t)$= price of ammonia at t
- qe(t): quantity of electricity produced in t
- $q_h(t)$: quantity of hydrogen produced in t
- $q_a(t)$: quantity of ammonia produced in t
- CAPEX: total capital expenditures for the whole plant (photovoltaic plant, electrolyzer and the infrastructure for the production of ammonia)
- CAPEX(t): monthly rate of the total CAPEX depreciation period
- OPEX: yearly operating expenditures
- $OPEX_e(t)$: operating expenditures related to the electricity produced in t
- $OPEX_h(t)$: operating expenditures related to the hydrogen produced in t
- $OPEX_a(t)$: operating expenditures related to the ammonia produced in t
- C_{so}: cost of the switch option
- WACC: yearly discount rate
- $WACC_m$: monthly discount rate

We also make the following assumption:

- In order to obtain some initial results, we restrict a first simluation to just two of the twenty years of project lifetime, in which we consider only revenues, operating costs and a 3% tax on revenues (in accordance with the values granted by the Brazilian government for annual revenues lower than 70 million reais).
- An average yearly solar irradiation for the south east region of Brazil is considered.
- The total annual production of electricity, hydrogen and ammonia is equally distributed for each t.
- All amount of electricity, hydrogen or ammonia produced in each t is sold.
- The total cost incurred for the sale of hydrogen does not change based on the sector to which we decide to sell it: the end customer assumes the responsibility of shipping and his willingness to pay the estimated price does not change.

As already mentioned in the previous paragraph, for each month t, the model calculates the cash flows deriving from the possible sale of hydrogen or ammonia and compares them to determine the maximum; the latter is subsequently compared with the cash flow of the base case, i.e. the direct sale of electricity to the grid, therefore:

$CF_e(t)=p_e(t)*q_e(t) - CAPEX(t) - OPEX_e(t)$

$CF_{hi}(t)=p_{hi}(t)*q_h(t) – CAPEX(t) – OPEX_h(t)$

$CF_{ht}(t)=p_{ht}(t)*q_h(t) – CAPEX(t) – OPEX_h(t)$

$CF_{hp}(t)=p_{hp}(t)*q_h(t) – CAPEX(t) – OPEX_h(t)$

$CF_a(t)=p_a(t)*q_a(t) – CAPEX(t) – OPEX_a(t)$

CAPEX and OPEX are two different kind of costs: in particular the firsts refers to the expenses incurred for acquiring or upgrading physical assets with long-term benefits for a company, such as machinery, equipment, or property and these expenses are capitalized and typically amortized over their useful life. In our case, CAPEX is represented by the total capital expenditures necessary for the acquisition and installation of the photovoltaic plant, the electrolyzer and the Infrastructure for the synthesis of ammonia, that we assume to be produced through the Haber Bosch process, which is currently the most used. The CAPEX is the same regardless of what the investor decide to produce and sell, as they are sunk costs that are incurred at the beginning of the investment. On the contrary, the OPEX are the day-to-day expenses necessary to keep a business running, including salaries, utilities, maintenance, and other operational costs, and obviously these change based on what the investor chooses to produce in t. In order to determine the maximum between the cash flows relating to the sale of hydrogen or ammonia, the model performs an iterative pairwise comparison until all values are compared. For this reason, we define the function Max $CF(CF_i;CF_j)$ as follow:

$M_1(t)=Max\ CF(CF_{hi}(t);CF_{ht}(t))$

$M_2(t)=Max\ CF(M_1(t);CF_{hp}(t))$

$M_3(t)=Max\ CF(M_2(t);CF_a(t))$

$M_3(t)$ is then compared with the cash flow derived from the sell of electricity at t: the option will be exercised only if the benefits are greater than the costs, as calculated by (1):

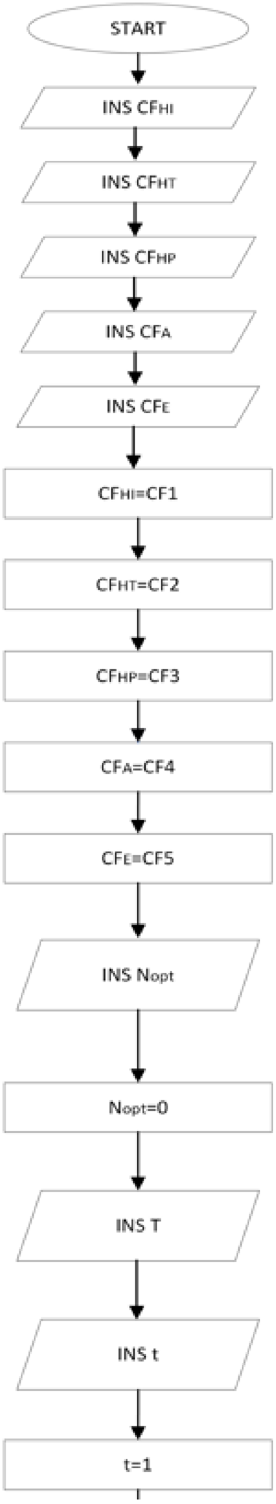
$$\max(M_3(t) - CF_e(t); 0) \tag{1}$$

According with the option payoff estimated by (1), $O_{so} = 1$ if the switch option is exercised, 0 otherwise. The model’s outputs, namely the value of the option V_{so} and the number of times the option is exercised during the life of the investment N_{opt}, are calculated according to Equations (2) and (3), respectively.

$$V_{so}= (\sum_{t=0}^{T} \max(M_3(t) - CF_e(t); 0)\ O_{so}(t)/(1+WACC_m)^t) \tag{2}$$

$$N_{opt}= \sum_{t=0}^{T} O_{so}(t) \tag{3}$$

Figure 2 illustrates the owner’s decision making process when selecting the switch option.


START
INS CF_{HI}
INS CF_{HT}
INS CF_{HP}
INS CF_{A}
INS CF_{E}
CF_{HI}=CF1
CF_{HT}=CF2
CF_{HP}=CF3
CF_{A}=CF4
CF_{E}=CF5
INS N_{opt}
N_{opt}=0
INS T
INS t
t=1

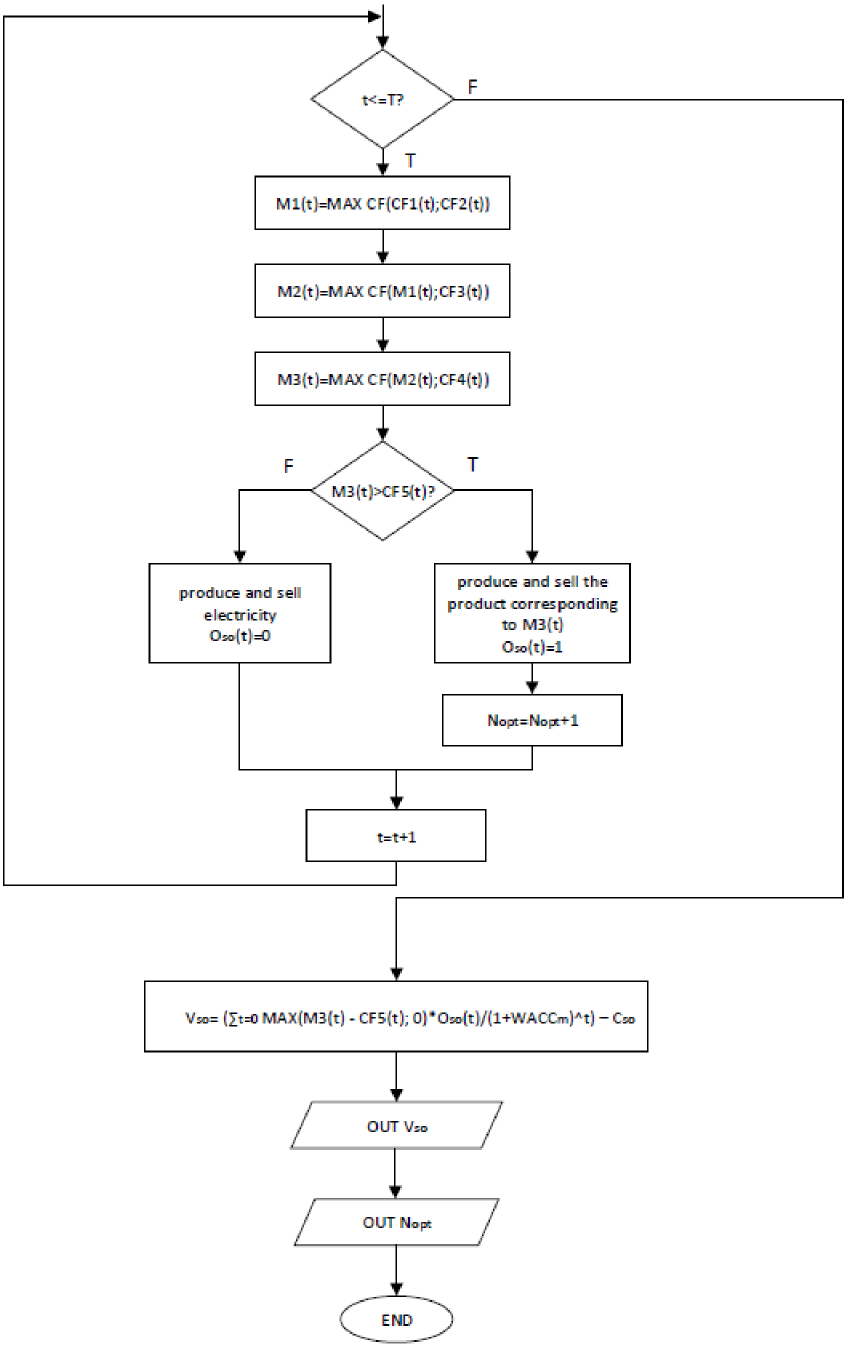


Figure 2: decision process for the excercise of the switch option

Through DADM, a software using Monte carlo simulation for MS Excel, we take into account the uncertainty around the input variables in the model. The output V_{so} and N_{opt} are, therefore, probability distributions and not single values.

4. Application

In this section we apply our model to an hypothetical scenario that take place in the south east region of Brazil: an investor who already owns a PV plant that produce electricity and wants to understand if he should invest or not in a electrolyser and an ammonia production synthesis plant, basing on the expected cash flows. The simulation of future cash flows strongly depends on the conditional probability distributions of future trajectories hence, in the next sections, we explain how we chose and applied the best stochastic process to model the dynamics of the underlying asset prices

4.1 Modelling electricity (PLD) price

We started from the collection of the historical electricity prices in Brazil (with a focus on the south-east region) which were extrapolated from the official website of the "Câmara de Comercialização de Energia Elétrica" (CCEE). These prices, monthly collected from January 2001 until October 2023, were subsequently converted into USD/MWh and deflated through the American Consumer Price Index (CPI) to remove any influence of inflation on the stochastic behaviour. These are shown in figure 3.

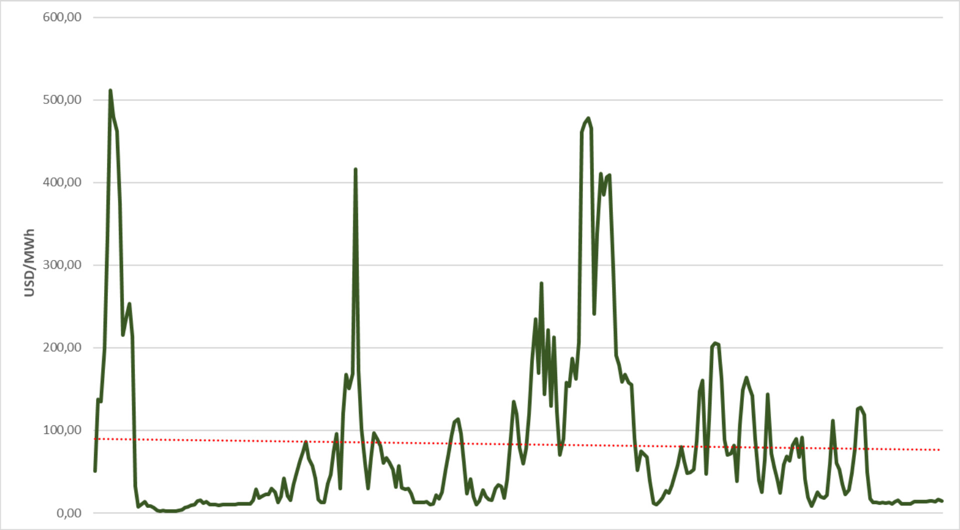


Figure 3: PLD electricity spot prices for the southeast region of Brazil from Jan/2001 to Oct/2023. Source: CCEE

In order to determine the most appropriate stochastic process to model PLD series, an Augmented Dickey-Fuller (ADF) test (Dickey and Fuller, 1981) was run. It is a statistical test used to determine whether a time series is stationary or not. Stationarity is an important assumption in many time series models, as it ensures that the statistical properties of the series do not change over time. The ADF test evaluates the null hypothesis that a unit root is present in a time series sample: if the test statistic is less than the critical value at a certain confidence level, the null hypothesis is rejected, indicating that the series is stationary and the presence of a mean reversion; on the contrary, if the test statistic is greater than the critical value, the null hypothesis cannot be rejected, suggesting that the series is non-stationary leading to the evidence of a Geometric Brownian Motion (GBM) component. The critical values are standardized and can be divided in two groups, basing on the assumption of a trend or not. These are shown in table 1.

Significance level	**Without trend**	**With linear trend**
1%	-3.43	-3.96
2.5%	-3.12	-3.66
5%	-2.87	-3.41
10%	-2.57	-3.12

The t-Statistic obtained is − 14.55, which rejects the presence of a unit root even at a 1% level for this number of samples. Therefore, there is a strong indication that the series is mean reverting and, in particular, we chosed to model it with the simplest between the several distinct approaches for the modeling of mean reverting processes, that is to say the Arithmetic Ornstein Uhlenbeck (O-U) model (Dixit and Pindick, 1994) shown in Eq.(1).

$$dx = \eta(\bar{x} - x)dt + \sigma dz \quad (1)$$

where x is the asset price; $\bar{x}$ is the equilibrium level to which the process reverts in the long run; η is the reversion speed parameter, σ is the volatility parameter, and dz is the standard Wiener increment. Expected value, variance, discretization, and simulation equations, as well as parameter estimation for the O-U process have been calculated according to the formulas founded in the appendix A of a study regarding the selection of the appropriate stochastic process for real options applications (Bastian-Pinto et al., 2021). Considering that the use of the Ornstein-Uhlenbeck model for simulating future price paths may result in negative values, we considered that the logarithm of prices, rather than the prices themselves, follow such a process, which implies that prices, therefore, follow a geometric MRM that can be represented by Eq. (2).

$$dS = \eta[\ln \bar{S} - \ln S]Sdt + \sigma S dz \quad (2)$$

where S is the price to be modeled and $\bar{S}$ is the long-term equilibrium level in the same unit as S.

4.2 Modeling ammonia price

As it was not possible to find a single monthly time series long enough, ammonia prices have been collected from the US department of agriculture on a yearly basis (1960 - 2014) and from Bloomberg.com on a monthly basis (july 2016 - june 2023) both in USD per material short ton. Then, they have been deflated according to the CPI index. Figures 4 and 5 show respectively the yearly and the monthly time series.

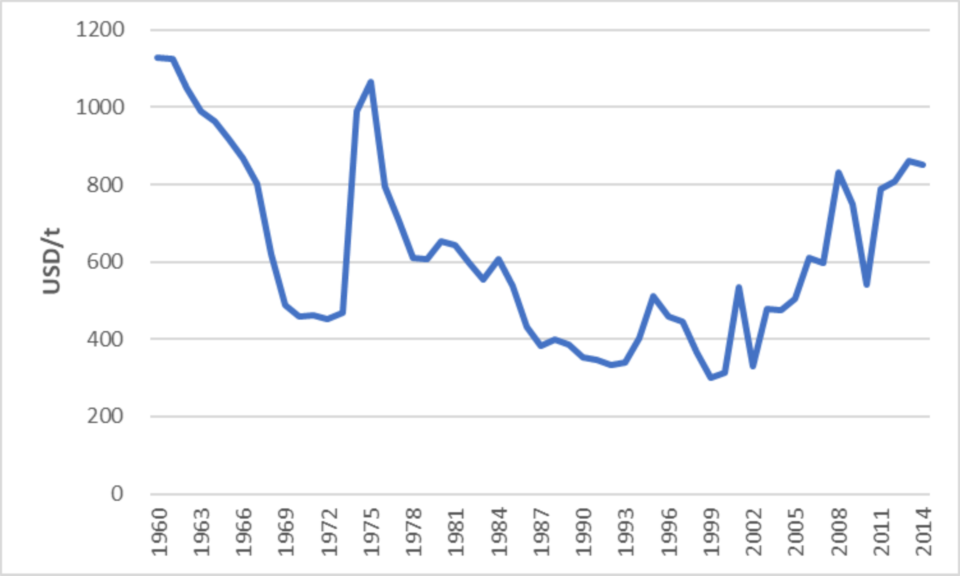


Figura 4: Ammonia spot prices from 1960 to 2014. Source:US Department of Agricolture

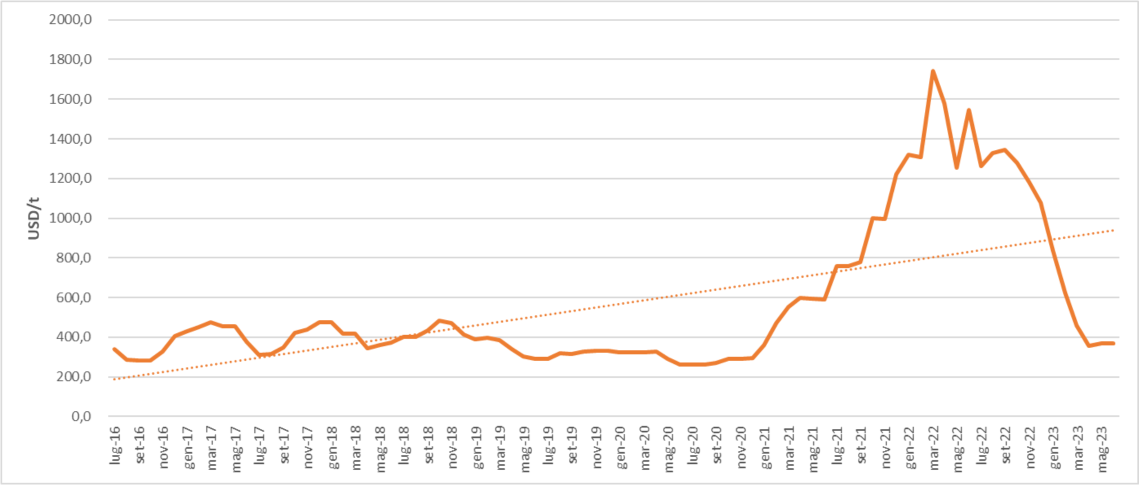


Figura 1: Ammonia spot price from Jul/2016 to Jun/2023. Source: Bloomberg.com

5. Results

6. Discussion

7. Conclusion

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