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Feed-in Tariffs: an attractive tool for investing in green hydrogen projects

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Master in Finance

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Resumo

A necessidade de investir em projetos de energias renováveis e, em particular, no hidrogénio verde tem aumentado rapidamente. Sendo esta uma fonte de energia sem emissão de gases com efeito de estufa, tem um potencial substancial para a descarbonização dos sistemas energéticos e contribuição para alcançar emissões nulas até 2050. Notavelmente, algumas políticas governamentais têm surgido, como as *Feed-in Tariffs*, sendo o principal incentivo na Europa para promoção de investimentos no setor das energias renováveis. Assim, a viabilidade de investir num eletrolisador de Membrana de Eletrólito Polimérico para a produção local de hidrogénio verde num parque eólico europeu *onshore* padrão foi avaliada de modo a compreender a sua rentabilidade. Mais concretamente, foi considerada uma opção de investimento com uma maturidade finita, aplicando a Teoria das Opções Reais com o preço de mercado do hidrogénio verde a evoluir estocasticamente ao longo do tempo. O propósito foi compreender o impacto no valor do projeto e no valor da opção sob diversas características do mercado e alterações nos preços *floor* e *cap*. Com base nos resultados, a produção de hidrogénio verde torna-se economicamente viável a preços superiores a 4,59€/kg.

Palavras-Chave: Hidrogénio verde, Turbina Eólica, Eletrolisador de Membrana de Eletrólito Polimérico, Teoria das Opções Reais, *Feed-in Tariffs.*

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Abstract

The need to invest in renewable energy projects has been rapidly increasing, particularly in green hydrogen, due to its absence of greenhouse gas emissions. Accordingly, it has substantial potential to decarbonize energy systems and support the achievement of net-zero emissions by 2050. Notably, a few government policies are in place, with Feed-In Tariff serving as the primary incentive in Europe for promoting new renewable capacity. Therefore, we assess the viability of investing in a Polymer Electrolyte Membrane electrolyser for on-site green hydrogen production at a standard European onshore wind farm. More concretely, the finite-lived option to invest will be considered, by addressing the real options approach, with the market price of green hydrogen evolving stochastically over time. We intend to understand the impact on the project's value and option value under varying market characteristics and changes in floor and cap prices. Based on the results, green hydrogen production becomes economically viable at prices above €4.59/kg.

Keywords: Green hydrogen, Wind turbine, Polymer Electrolyte Membrane (PEM) electrolyser, Real Options Approach, Feed-in Tariffs.

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Glossary

$	Dollar
€	Euro
£	Pound
€[xxx]/kg	Euros per kilogram
$[xxx]/kg	Dollars per kilogram
AC	Alternating Current
AEC	Alkaline Electrolysis
AEM	Anion Exchange Membrane
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CRU	Commodities Research Unit
DC	Direct Current
DCF	Discounted Cash Flow
e.g.	*Exempli gratia*
Eq.	Equation
EU	European Union
EWEA	European Wind Energy Association
FiT	Feed-in Tariff
GBM	Geometric Brownian Motion
GDP	Gross Domestic Product
GHG	Greenhouse Gas
Gt	Gigatonnes
GW	Gigawatt

h	Hours
HER	Hydrogen Evolution Reaction
i.e.	*Id est*
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kg	Kilograms
KOH	Aqueous Potassium Hydroxide
KWh	Kilowatt-hour
KWh/Kg	Kilowatt-hour per Kilogram
LCoE	Levelised Cost of Energy
$LCoH_2$	Levelised Cost of Hydrogen
LHV	Lower Heating Value (of Hydrogen)
m/s	Meters per second
MW	Megawatt
MWh	Megawatt per hour
n.d.	Not Disclosed
NECPs	National Energy and Climate Plans
NFFO	Non-fossil Fuel Obligation
NPV	Net Present Value
ODE	Ordinary Differential Equation
OPEX	Operating Expenses
PEM	Polymer Electrolyte Membrane
PV	Photovoltaic
RE	Renewable Energy

RECs	Renewable Energy Certificates
REN	Renewable Energy Policy Network
RES-e	Renewable Energy Share in Electricity
RO	Real Options
ROA	Real Options Approach
RPS	Renewable Portfolio Standard
SOEC	Solid Oxide Electrolysis
UK	United Kingdom
USA	United States of America
WE	Water Electrolysis

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1 - Introduction

Over the years, the urgency of declining fossil energy resources, environmental pollution, and global warming, have prompted an imperative demand for a sustainable energy supply (Li et al., 2011). Further, governments are developing strategies and establishing targets to decarbonize their energy systems in the pursuit of net-zero emissions by 2050 (Gupta et al., 2023). More concretely, the European Union (EU) has set National Energy and Climate Plans (NECPs), for the years 2021–2030, to achieve the intended goals. Therefore, the necessity of increasingly using renewable energy sources is widely acknowledged.

The renewable energy industry is a well-established and globally important market, which is expected to grow at a Compound Annual Growth Rate (CAGR) of 8.5% between 2024 and 2033, attracting substantial investments totalling USD 1.74 trillion in 2023, according to the International Energy Agency (IEA) (2023a). The latter also projected that by 2050, nearly 90% of global electricity generation will be sourced from renewables, with wind and solar photovoltaic (PV) contributing close to 70% of the total (Bouckaert et al., 2021). Specifically, Europe's installed wind capacity reached 255,615 MW in 2023, with 87% of this capacity attributed to onshore wind, as outlined by the International Renewable Energy Agency (IRENA) (2024a).

Interestingly, green hydrogen (i.e., produced via water electrolysis, using renewable energy as the source) has been identified with significant potential to contribute to accelerating energy transition and enabling a sustainable future, given its complete absence of greenhouse gas emissions (AlZohbi et al., 2023; Rasul et al., 2022). Additionally, it plays a particularly significant role in decarbonizing essential sectors, including transportation and industry. Furthermore, a specific method receiving recognition in green hydrogen production is wind power-electrolysers systems (i.e., employ wind energy generated from onshore wind turbines), due to wind energy being among the fastest-growing sources of renewable power worldwide (Meda et al., 2023).

Conversely, the upfront costs and deployment challenges present obstacles to attracting investors to renewable energy projects, and the following projections highlight that achieving the desired net-zero emissions may be challenging. It will require a 50% increase in Europe's wind and solar capacity to meet green hydrogen demands in the industry and transport sectors, as well as, the green hydrogen production must reach 8 gigatonnes (Gt), covering 15% of energy demand, with an estimated investment of USD 6.8 trillion (Durakovic et al., 2023; Webb et al., 2023).

To mitigate the economic risks of investing in renewable energy, governments often provide support to investors (Abadie & Chamorro, 2014). Consequently, various support mechanisms have been introduced, including green tradable certificates, tax incentives, and Feed-in Tariffs (FiTs). The latter is widely recognised as the most effective, as it has been successful in driving investment in these projects and has become a broadly adopted policy for renewable energy support (e.g., Couture & Gagnon, 2010; Lesser & Su, 2008). Particularly, FiTs with minimum price guarantees ensure that if the market price falls below a predetermined price floor (P_F), producers still receive a fixed payment (i.e., the price floor). Conversely, producers receive the market price if it rises above P_F. They typically involve long-term contracts with renewable energy investors, providing stability and encouraging more significant investment in the sector.

The Real Options Approach (ROA) is generally accepted as an effective method for evaluating such investment opportunities, as it considers the uncertainty and irreversible nature of power generation while allowing for flexible decision-making (Fernandes et al., 2011; Yao et al., 2019). In contrast, traditional methods, such as the standard Net Present Value (NPV) analysis, are limited due to not incorporating these dynamic strategies. This constraint is significant, given that variables like wind velocity and consistency, and fluctuating energy market prices exhibit stochastic behaviour, hindering future cash flow projections. Misinterpreting these variables can result in inaccuracies when assessing the real value of renewable energy projects.

Given these considerations, this study proposes that the Polymer Electrolyte Membrane (PEM) electrolyser for on-site green hydrogen production at a typical European onshore wind farm may be profitable when a Feed-in Tariff is accounted for. Testing this hypothesis also involved ROA's application and employment of concrete data that reflects market conditions. By integrating economic, climatic, and political factors, this research seeks to provide valuable insights that reinforce the notion that green hydrogen has significant potential in the global decarbonization of energy systems. Moreover, while FiT and Collars are often discussed from a theoretical perspective, our project aims to bridge the gap between theory and practical application.

2 - Literature Review

2.1 - Real Options Approach

2.1.1 – Concept and Variables that Influence its Value

Since the late 1960s and early 1970s, there has been widespread recognition of the limitations of traditional methods like the standard NPV or the Discounted Cash Flow (DCF) analysis for evaluating investment projects (Trigeorgis & Mason, 1987). Further, McDonald and Siegel (1986) made evident that the NPV analysis was utterly incorrect.

When only the NPV method is considered for making the investment decision, a project is frequently approved if the computed NPV is positive. However, most of the time, this analysis leads to undervalued investment opportunities. The reason for this evidence is that it does not consider uncertainties and managerial flexibilities that could change the value of a project. An investment decision with a negative NPV may become profitable if the methodology to evaluate that project considers the possibility for the corporate manager to react to the market news or wait to invest when it is favourable. As a result, the literature has become more interested in examining investment and financing decisions in a firm applying ROA (e.g., Mauer & Sarkar, 2005; Sarkar, 2000).

Real Option (RO) was first presented by Myers (1977) and the expression real is used considering that these are not options on financial assets. Instead, it is characterized as the right but not the obligation to perform an investment decision regarding real assets (Ross, 2011).

Nevertheless, let us begin with understanding an option, a security that grants the right to buy (call option) or sell (put option) an asset within a specific timeframe. Additionally, an American option can be exercised at any time until the option's expiration date, whereas a European option can only be exercised at the maturity date (T) (also known as the expiration date) (Black & Scholes, 1973).

Furthermore, the value of call options increases as the underlying asset (S_t) price rises. Conversely, a decline in the S_t price typically enhances the put option's value. Moreover, the exercise price (K) refers to the predetermined price at which the underlying asset can be bought or sold when the option is exercised. This implies that the intrinsic value of an option is determined by the difference between the two previously mentioned values. Also, considering call options, if the exercise price is lower than the underlying asset price, the option is in-the-money and generally more valuable. On the contrary, the exercise price must exceed the underlying asset price for put options to be in-the-money and with greater value (Black & Scholes, 1973; Trigeorgis & Mason, 1987).

In addition to the variables previously considered, there are other factors, as noted by Trigeorgis and Mason (1987), which also influence the option's price. Starting with historical and implied volatility (σ), both measure price variation in the S_t. Considering that higher volatility enhances the potential for substantial price movements and profit opportunities, it is correlated with increases in option prices. Additionally, higher risk-free interest rates (r) lower the present value of the K, leading to higher call option prices and lower put option prices. Furthermore, when a stock loses the right to upcoming dividends, its value drops, affecting the value of related options. Moreover, broader market conditions and investor demand can lead to an increase in options prices, due to increased competition between buyers.

2.1.2 – Option's Valuation

In regards to option pricing, there are common models used, notably: the Monte Carlo Simulation (Metropolis & Ulam, 1949), which generates a wide range of possible outcomes based on random variables; the Black-Scholes-Merton model (Black & Scholes, 1973; Merton, 1976); and the binomial model (Cox et al., 1979). The latter divides the option's lifespan into discrete-time periods and creates a lattice-type structure to represent potential stock price movements, meaning that the price can only go up or down in a specific timeframe. It assumes a constant interest rate, and no transaction costs or taxes.

Fisher Black, Myron Scholes, and Robert Merton, in the early 1970s, developed a formula for valuing options, based on several key assumptions: the underlying stock price follows a continuous Geometric Brownian Motion (GBM), meaning its price variations are random and can happen at any moment (continuous time model), following a specific statistical pattern; there are no taxes or transaction costs; the r is known and constant; the market is efficient; and no arbitrage opportunities exist. This formula is widely utilized as a mathematical model to estimate the theoretical price of European options.

The equation for pricing a European call option is as follows:

$$c_t = S_t * e^{-q\tau} * N(d_1) - K * e^{-r\tau} * N(d_2)\,, \tag{2.1}$$

and for computing a European put option, the given formula is used:

$$p_t = K * e^{-r\tau} * N(-d_2) - S_t * e^{-q\tau} * N(-d_1)\,, \tag{2.2}$$

with

$$d_1 = \frac{ln\left(\frac{S_t}{K}\right)+\left(r-q+\frac{\sigma^2}{2}\right)\tau}{\sigma\sqrt{\tau}}, \; d_2 = d_1 - \sigma\sqrt{\tau}, \; \tau = \mathrm{T} - \mathrm{t},$$

where q is the continuously compounded dividend yield of the underlying asset, τ is the option's time to maturity, N represents the cumulative standard normal distribution function, r denotes the instantaneous riskless interest rate, and σ is the annual volatility of the underlying asset.

2.1.3 – Stochastic Variables and Geometric Brownian Motion

A variable that evolves over time, driven by randomness and unpredictability events is considered stochastic (Dixit & Pindyck, 1994). Its process is determined by a probability law that describes how the variable evolves over a given period, $x(t)$, which enables computing the variable's probability of falling within a specific range at various points in time. Wind speed exemplifies stochastic fluctuations, typically greater in winter and lower in summer. However, high speeds may occasionally and unexpectedly occur in summer, while some winter days may experience almost no wind activity (Islam et al., 2013). Stock prices are no exception, as they fluctuate due to various unpredictable factors.

The GBM, a continuous-time stochastic process, is often used to model uncertainty, randomness, and fluctuations. It accounts for a deterministic drift (μ), meaning that on average, the value tends to grow over time, and ensures that the value cannot hit zero, staying positive.

For our specific application, it is expressed as:

$$dP = (r - q)Pdt + \sigma PdW, \quad (2.3)$$

where P is the market price of green hydrogen, $(r - q) = \mu$, is a deterministic drift under the risk-neutral measure, and dW the standard Brownian motion process.

In the ROA it is common to assume (for simplicity) that P follows a GBM. Boomsma et al. (2012), and Ritzenhofen and Spinler (2016) have applied this assumption in their renewable energy investment research. Despite GBM being considered analytically handy in the real options world, it might not be the most precise method for modelling spot market prices of commodities (Pindyck, 2001). Mean reversion and jump diffusion processes are suggested as possible alternatives, however, it was shown that the application of GBM in energy projects leads to small errors, considering the long duration of this type of project (Lo & Wang, 1995; Pindyck, 2001).

Thus, until more details concerning hydrogen market developments are revealed (which leads to improved estimations of the price of hydrogen), the assumption described is the most suitable (Biggins et al., 2022). Despite most of the RO models used in energy finance typically consider only a single stochastic variable, interestingly, Himpler and Madlener (2011) accounted for both the revenue and the investment as stochastic.

2.1.4 – Employment of the Real Options Approach in Renewable Energy Projects

Addressing global warming, environmental pollution, and public health issues has become urgent, making producing energy from renewable resources essential. ROA provides a robust framework for valuing projects in the renewable energy (RE) field, especially given the uncertainty in energy market prices, among other variables, and the high capital costs that are inherent in this field (Ceseña et al., 2013). Further, it is attractive to corporate managers and practitioners, considering it accounts for managerial flexibility. Yao et al. (2019) indicated some decisions that can be performed over a project's lifetime, namely: invest, delay, expand, switch, suspend, contract, or abandon.

Therefore, several studies have been done to enhance ROA in various types of RE, for instance: hydropower (e.g., Bøckman et al., 2008; Kjaerland, 2007), wind farms (e.g., Abadie & Chamorro, 2014; Chen & Lu, 2011) and solar energy (e.g., Martinez-Cesena et al., 2013). Besides, Schmitz and Madlener (2015) found that the present values of their case studies improved, by considering the ROA. They evaluated hydrogen production through kite-based wind energy, applying a Monte Carlo simulation for uncertainties (e.g., hydrogen price and storage cost) and a binomial lattice approach to assess options. Moreover, Biggins et al. (2022) used ROA to examine the value of waiting before investing in a PEM electrolyser at a wind farm for the generation of green hydrogen. Nevertheless, studies that specifically address investments in green hydrogen production are still few (Biggins et al., 2022).

2.2 – Green Hydrogen

2.2.1 – Capacity to Decarbonize Energy Sectors

According to a recent report from IRENA (2024b), hydrogen has been receiving increased attention, considering its potential to play a critical role in decarbonizing sectors, for instance, industry, heating, and transportation, which are more difficult to electrify. Furthermore, the growing energy demand, the exhaustion of fossil fuel resources such as oil, coal, and natural gas, and rising temperatures primarily caused by greenhouse gas (GHG) emissions have made the transition to generating energy from renewable sources (i.e., clean/green energy) imperative (Meda et al., 2023).

Conversely, the proportion of green hydrogen (i.e., obtained by renewables), of total hydrogen produced remains low. Therefore, some European countries have set targets for the future, namely for green hydrogen production and electrolysis capacity. To achieve the pretended objectives, fossil fuel prices need to be increased, and production costs decreased (caused by lower renewable energy prices and technological advancements), according to the IEA (2022).

Policymakers should pay close attention to the reality that investing in hydrogen as a transport fuel can offset the losses from diminished diesel demand. Thus, employing clean energy for vehicles can significantly reduce GHG emissions and improve air quality. According to Zainal et al. (2024), green hydrogen is a crucial element of a future energy system known for its safety, cleanliness, and economic viability. Both investors and policymakers need to evaluate its value appropriately.

2.2.2 – Sources and Methods for Hydrogen Production

Hydrogen energy is not naturally available on its own and needs to be extracted from compounds that contain it (Acar & Dincer, 2014). Moreover, it is known that the cost of the sources and the production method used to obtain hydrogen determine if this energy is cost-effective (Ismagilov et al., 2019). Regarding the primary sources that can be applied, it is possible to separate them into two groups: fossil fuels (e.g., natural gas, biogas, coal, and oil), and renewable resources (e.g., biomass, and water).

It is also viable to identify various methods that can be adopted. For instance: steam reforming is an energy-intensive process that involves reacting a hydrocarbon fuel with steam at high temperatures, producing significant amounts of carbon dioxide (CO_2); gasification, in which a limited amount of oxygen is added to the reaction outlined; and electrolysis, which is considered the cleanest process and produces green hydrogen and oxygen gases from water, using electrical energy (Apostolou & Xydis, 2019; Dutta, 2014; Salvi & Subramanian, 2015; Zhang et al., 2020).

Moreover, Mehrenjani et al. (2022) evaluated the hydrogen generation and cost efficiency of a hybrid system combining wind, solar, and ocean thermal energy (particularly viable in tropical regions, the latter takes advantage of the natural temperature gradient in the ocean to generate electricity) for power generation and hydrogen production. The analysis highlights wind speed and solar collector area as critical factors affecting both cost and energy performance (which measures the quality of the energy and its potential to be used efficiently).

Regrettably, IEA (2022) affirmed that the production from hydrocarbons (i.e., primary components of fossil fuels) continues to be the most affordable alternative for hydrogen in industries; more concretely, fossil fuels (less expensive) are used for 96% of the hydrogen supplied globally (Vedyagin et al., 2021). On the contrary, Proost (2020) believed that if it is considered a small production scale, it is feasible for green hydrogen to be competitive against hydrogen produced from fossil fuels. Furthermore, a recent research conducted by Khan et al. (2021) displayed all the specific costs regarding the production of green hydrogen as well as a sensitivity analysis on diverse economic and technical parameters.

Recognizing the potential of green hydrogen, several recent research have been conducted. An interesting study was undertaken by Gupta et al. (2023) and focused on Switzerland, which revealed (under the model's assumptions) that investing in green hydrogen reduces GHG and CO_2 emissions, but also positively impacts Gross Domestic Product (GDP) and employment, compared to diesel. This delivers a crucial policy message to decision-makers of hydrogen strategies, highlighting social, environmental, and socioeconomic renewable energy benefits. In addition, Jiang et al. (2019) optimized the size of on-site hydrogen production at a wind farm to maximize economic returns for varying hydrogen prices. It was discovered that the hydrogen price needs to exceed €4.34/kg for on-site generation to be economically viable.

2.2.3 – Is Blue Hydrogen a Viable Alternative? Exploring the Challenges of Green Hydrogen

Interestingly, blue hydrogen is more attractive than green hydrogen, if energy return on investment (i.e., energy obtained/energy required to produce) is considered. The reasoning is tied to its lower costs, since it is directly generated from fossil fuels, like natural gas, through a chemical reaction that provides greater energy efficiency than green hydrogen. The latter requires two stages of energy transformation, from wind or solar (examples of sources) to electricity, and then from electricity to hydrogen, based on Solena Green Hydrogen (SGH2) Energy (n.d.). Moreover, the research findings of Shen et al. (2024) alerted for the area of land occupied by renewable infrastructures and the amount of water needed to perform the electrolysis method. Nevertheless, the paper of Webb et al. (2023) supported that efforts should persist in advancing green hydrogen knowledge, considering the significant risks associated with blue hydrogen production. In addition, its estimated cost will range from \$1.21 to \$1.93 per kilogram by 2030 and from \$0.70 to \$1.60 per kilogram by 2050, positioning green hydrogen as more competitive than blue hydrogen.

However, certain challenges persist and may continue for at least the next decade. These include the slow development of infrastructure, the high costs associated with producing clean hydrogen that requires substantial capital investment, intermittent supply from renewable sources, market development, and the need for global collaboration. Additionally, hydrogen also presents obstacles in storage, transportation, and distribution. A multidisciplinary approach with cooperation among industry, government, researchers, and organizations will be crucial for achieving the intended goals. Moreover, ongoing research and technological progress are vital for enhancing hydrogen safety across its lifecycle and halting the degradation of the electrolyser stack. By overcoming these challenges, the disclosure of green hydrogen's potential for economic growth, environmental sustainability, and energy security will be more evident (Biggins et al., 2022; Islam et al., 2024; Zainal et al., 2024).

2.3 – Renewable Energy Projects

2.3.1 – Onshore and Offshore Wind Farms

For over 20 years, wind power has been a leading renewable energy source, particularly in countries like Denmark, which has been a pioneer in developing onshore wind turbines (Himpler & Madlener, 2011). However, according to Global Wind Energy Council (GWEC) (2021), at the current wind power installation rate, achieving carbon neutrality by mid-century will not be feasible. To optimize wind power generation, both onshore and offshore wind energy systems require ongoing improvements in areas such as deployment, capacity factor (i.e., measures how efficiently a wind farm produces electricity compared to its maximum possible output), and cost efficiency (Desalegn et al., 2023).

Let us begin by understanding the characteristics of onshore (located on land) and offshore (built on the seabed) wind farms. The latter is gaining recognition for its consistent wind speeds and higher energy production, leading to a higher capacity factor and greater efficiency than onshore wind farms. Since ocean water has a smooth surface without obstacles, it does not cause significant fluctuations in wind flows. However, it requires a stronger bearing structure, more concretely, specialized cables are necessary for transmitting electric power, and unique vessels and equipment are essential for installation and maintenance. As expected, these factors significantly increase the costs of offshore wind power generation, making it considerably more expensive than onshore wind power deployment. On the other hand, onshore wind energy industries face limitations due to land availability, potential urban expansion, and the visual and noise impacts they may cause (Desalegn et al., 2023; Enevoldsen & Valentine, 2016). Interestingly, a recent article conducted by Wang et al. (2024) analysed the characteristics and the layout of hybrid offshore wind farms, consisting of bottom-fixed and floating wind turbines. The latter incurs higher installation and maintenance costs due to the complexity of the floating platforms and the required technology. However, they can operate in deeper waters where fixed turbines cannot be installed.

These renewable energy systems provide three major advantages: they greatly cut CO_2 emissions, lower environmental impact, and offer competitive clean energy prices. Notably, the crucial element for unlocking their full capacity is the aerodynamic design of the turbine blades. Desalegn et al. (2023) computed and analysed the variations in average wind speed and wind power density across onshore and offshore locations, considering seasonality. Both variables are crucial for assessing wind quality, given that wind energy is variable and dependent on weather conditions, directly affecting the amount of energy produced. Also, this energy is typically transmitted via the grid, leading to transmission losses (Islam et al., 2013). Thus, it is implied that the selection of the ideal location and the optimization of the turbine's physical components is impacted by wind quality. Furthermore, the findings of Koragappa and Verdin (2024) corroborated the importance of carefully examining the turbine parameters, considering that both the position of the blades during rotation and the angle of the blades relative to the wind direction, known as the pitch angle, impact the efficiency of the wind turbine.

Moreover, an interesting study carried out by Enevoldsen and Jacobson (2021) proposed an automated method to estimate the area occupied by existing onshore and offshore wind farms worldwide. Their research revealed that the current wind turbines might harness more wind power using less water or land than formerly assumed, considering that large-scale development of onshore wind energy across countries may need substantially less land area than previously projected in other studies. Consequently, development costs (for instance, electrical infrastructure and land acquisition) can be reduced now that it has been established that wind turbines with closer spacing perform as effectively as those with similar wind climates along with other conditions. This implies a greater potential for new wind project development opportunities.

Considering the high market price volatility associated with energy prices, revenue from produced energy carries significant uncertainty, which may hinder further repowering. Therefore, the study carried out by Himpler and Madlener (2011) highlighted the need for enhanced energy support schemes to ensure a larger portion of secure revenue. Furthermore, Abadie and Chamorro (2014) examined the finite-lived option of investing in an operating wind farm, considering diverse energy support policies. They also demonstrated the influence of several factors, included in the investment decision, namely: upfront subsidy, the amount received per megawatt-hour (MWh) produced, the investment option's maturity, and fluctuations in energy prices.

2.3.2 – Water Electrolysis

It is now well established that hydrogen generated from renewable energy sources, usually referred to as green hydrogen, can significantly contribute to the decarbonization of sectors that are challenging to electrify, such as industry and heavy transport (Coninck et al., 2018; Shukla et al., 2022). Also, the European Commission (2020) aims to have 40 gigawatts (GW) and 600 GW of electrolyser capacity by 2030 and 2050, respectively. Therefore, green hydrogen production is anticipated to achieve considerable growth in the coming years, with electrolysis emerging as the primary method for producing green hydrogen (Kirchem & Schill, 2023).

Water electrolysis (WE) is the electrochemical process of splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) by supplying electrical and thermal energy.

The overall chemical reaction for water electrolysis can be expressed as:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \, . \tag{2.4}$$

An electrolyser is an electrochemical device that converts the provided energy into chemical energy, which is then stored within the green hydrogen (Dincer, 2012). During this process, the hydrogen is produced through a process called the hydrogen evolution reaction (HER) at the cathode (i.e., negative electrode); and at the anode (i.e., positive electrode), oxygen is produced through an oxidation reaction (Ursua et al., 2012).

Electrolysis can be carried out using different technologies, such as alkaline electrolysis (AEC), which has been commercially employed for decades and employs an aqueous potassium hydroxide (KOH) solution to split the water components; PEM electrolysis, a more recent technology that offers high power density and dynamic performance and uses a solid polymer electrolyte to conduct protons from the anode to the cathode, needing electricity and water to generate hydrogen; and solid oxide electrolysis (SOEC), which uses a solid oxide electrolyte to convert steam into H_2 and O_2 more efficiently, and operates at high temperatures. Each of these technologies has its advantages and disadvantages concerning performance range, operating temperature and pressure, and durability (Woznicki et al., 2020).

Despite having the highest production costs compared to other technologies, PEM WE has become particularly notable for its exceptional efficiency and compact design (Sun et al., 2019). Following a study conducted by Woznicki et al. (2020), it was evident that coupling offshore wind farms with WE is economically viable and facilitates large-scale generation of green hydrogen from seawater. Regardless, it is important to consider some potential constraints for better improvements and further research. It has been reported that approximately 9 kilograms (kg) of water is needed to produce 1 kg of H_2 when the electrolysis method is employed (Barghash et al., 2022). Furthermore, the quality of water applied is crucial, as impurities can impact production efficiency (Zainal et al., 2024). Moreover, Islam et al. (2024) emphasized the importance of reducing the energy required to separate H_2O into H_2 and O_2. Interestingly, a possible solution that is currently an active research area, is an anion exchange membrane (AEM) WE. It uses that particular membrane to conduct hydroxide ions, combining the advantages of PEM WE with utilizing affordable and abundant catalyst materials (Henkensmeier et al., 2020).

2.3.3 – Alternative Energy Sources and Methods to Produce Green Hydrogen

Let us now consider other processes and energy sources that have also gained recognition. The research findings of Wei et al. (2022) indicated that a solar PV-electrolyser system offers higher energy efficiency and a lower hydrogen production cost than a wind-powered electrolyser system. Furthermore, Islam et al. (2024) investigated the photoelectrocatalytic panels (i.e., integration of water-splitting catalysts and PV cells), which transform sunlight into H_2 instantly. Focusing on its scalable manufacturing processes will be essential for widespread adoption, considering the higher efficiency and lower costs.

Regardless, wind energy, as an input for the WE, is still gaining a lot of attention considering its lowest GHG emission and cost, compared to other available renewable energy sources (Uyar & Beşikci, 2017). Remarkably, in the most optimistic scenario, the cost of green hydrogen could decrease to approximately $1.5/kg by 2050, as stated by the Commodities Research Unit (CRU) (2023). Considering that green hydrogen issues zero emissions throughout its production process, it is straightforward to argue that research in this field is highly sought (Dincer, 2012).

2.4 – Policy Mechanisms for Renewable Energy Projects

2.4.1 – Overview of Mechanisms to Incentivize Green Energy Investment

Numerous studies have been conducted to examine a variety of policy measures to stimulate investment in RE projects. Furthermore, facilitating the transition to a sustainable energy system while maximizing social welfare is a contemporary challenge for policymakers. As follows, it is crucial to recognize from the different mechanisms that exist, the one that fits better when considering a specific project. It is also known that the main drive for selecting the most suitable renewable support mechanism is not the competitiveness of the market, instead, it is related to the power producers' resistance to price and volume risk (Pineda et al., 2018).

Public support for cleaner energy technologies is typically defended based on climate change, industrial policy, and the security of supply. Moreover, these government policies are essential for accelerating the adoption of these technologies and ensuring they become market-competitive (Abadie & Chamorro, 2014). Interestingly, Fagiani et al. (2013) presented a dilemma: market risk incentivizes the efficient use of resources, thereby reducing societal costs; however, it also discourages investors, potentially leading to reduced renewable energy production and higher prices. Therefore, increased research in this area would certainly be beneficial, especially considering that a 'good support scheme may not be enough to encourage investments (Abadie & Chamorro, 2014).

These policies can be allocated into two main classifications: (i) regulatory price-based mechanisms, in which the government provides fixed payments per kilowatt-hour (kWh) of energy generated to the project owner; and (ii) regulatory quantity-based mechanisms, where the government establishes a desired level of Renewable Energy Share in Electricity (RES-e), and if green generators achieve the predetermined target, are granted with tradable certificates based on their renewable energy production (Abadie & Chamorro, 2014). The latter can be traded on the Renewable Energy Certificates (RECs) market (Kwon, 2018).

Abolhosseini and Heshmati (2014) contrasted three widely employed renewable energy tools, namely: Renewable Portfolio Standards (RPS) or Quota Obligations, Feed-in Tariffs (FiTs), and Tax Incentives. RPS has been put into practice in 49 states and countries worldwide, including 29 of the 50 states in the United States of America (USA) (Boomsma et al., 2012). It functions as a regulatory quantity-based scheme. The FiT program, comparable to the Tendering Policy, is a long-term contract (typically 20 years) with renewable energy producers, in which a bidding process does not occur, meaning that any qualifying renewable energy facility could be considered. More specifically, the investor will be paid per kWh produced, receiving a portion of guaranteed revenue for a set amount of time. It is recognized as one of the most significant strategies for encouraging new renewable energy projects (Couture et al., 2010). Fiscal-produced incentives such as subsidies and tax deductions are considered Tax Incentives.

The research findings indicated that, when investors give preference to lower-risk schemes, fixed-price FiTs are endorsed. Further, Tax incentives are also attractive considering they increase investor liquidity by making cash available. Furthermore, the employment of the RPS policy may result in price competition, leading to more effective energy markets, since this mechanism depends on a private market for utilities to trade certificates.

Following the Renewable Energy Policy Network (REN) (2021), Tendering is considered one of the three most popular renewable energy mechanisms. The latter can be defined as a commitment to buy the output of a qualifying renewable energy facility at a set price for a set amount of time. A competitive bidding process, another energy scheme, consists of a mechanism to set the price and the renewable energy, meaning that investors will have their energy purchased if it is the one selected. Projects that aim to build new renewable generation facilities are submitted and their renewable developers inform which is the price they would accept for their output (i.e., the energy produced). For instance, the non-fossil fuel obligation (NFFO) in the United Kingdom (UK) is one of the most well-known Tendering policies (Wiser et al., 2002). According to the REN 21 Renewables Now (2021), there is evidence of an increasing trend in both FiT and Tendering schemes, whereas there is a downward trend for the RPS tool.

2.4.2 – Feed-in Tariffs

Studies have evaluated how well these various policy instruments work to encourage investments in RE. In fact, Butler and Neuhoff (2008) compared these mechanisms for RE projects in Germany and UK, finding that FiTs in Germany are more successful in encouraging investment than any other policy in the UK. Further, many authors assert that FiTs are indeed the most efficient RE scheme (e.g., Couture & Gagnon, 2010; Lesser & Su, 2008) as well as the most widespread, having more than 70 countries adopting it (Sawin et al., 2013).

FiT policies fall into two categories: market-dependent; and market-independent. The latter, applies a fixed-price policy, since the payment is independent of the electricity market price, whereas market-dependent FiTs use a premium-price mechanism, considering that a premium remuneration is tied to the market price of electricity (Mendonça, 2012). Market-independent FiTs develop a lower-risk investment circumstance that attracts more investors, which leads to wider employment in many countries. The other group of FiTs gives an incentive to produce more energy when demand is high, and since they carry a higher risk for investors, they also yield a slightly higher return (Schallenberg-Rodriguez & Haas, 2012).

FiT with a minimum price guarantee (i.e., a price-floor regime), is also referred to as minimum price policy, minimum payment guarantee, and spot market gap model (Couture et al., 2010). It implies that if the market price is below the price floor, a producer obtains a fixed amount (i.e., the price floor), whereas the market price is received when it is above P_F. This specific design is identified as a variable-premium FiT (Couture & Gagnon, 2010) and may be considered a form of RO.

Mathematically, it is defined as:

$$\Pi(P, P_F) = Max(P, P_F), \tag{2.5}$$

where, P stands for the revenue for one unit of energy, and P_F is the revenue from the guarantee for one unit of energy.

By providing a wide range of FiT schemes that policymakers use, it was concluded that the advantages of both market-dependent and independent policies are combined into variable-premium FiTs, with caps and floors within the FiT framework. More concretely, market-independent FiTs provide investors with assurance and reliability, when the market price is below P_F. Conversely, it might vanish if the price floor is minimal, considering that investors would hardly receive it. Additionally, when the market price is above P_F, the FiT works as an incentive to produce more green energy (contributed by the market-dependent FiTs). Although, the price floor should not be very high, thus, policymakers must establish its value (Barbosa et al., 2018).

Two possible scenarios could be considered: a perpetual guarantee; and a finite guarantee. Regarding the first possibility, a producer receives remuneration for the entire lifetime of the renewable energy investment, but not for all upcoming green initiatives. Considering now the finite guarantee, an investor only receives payments throughout the FiT contract duration (T_F years). More specifically, it may receive P_F for every unit of produced energy, during T_F years, if the market price is below the price floor. In addition, it is known that the perpetual FiT is not employed by any authority and the results that Barbosa et al. (2018) obtained show that it was not viable, being in accordance. This is due to this contract only encouraging investment at prices below P_F if the guarantee's income is greater than the investment's cost. Otherwise, the finite guarantee can induce investment when the revenue is less than the investment cost at prices below the price floor. Also, when the price floor and duration increase, early investment is encouraged.

While numerous studies have concentrated on analysing diverse policies and design options for FiTs, relatively few analytical methodologies are offered to examine the impact of a FiT on RE projects, from an investor's standpoint. Nevertheless, Boomsma et al. (2012) evaluated renewable energy projects under diverse energy incentives (namely FiTs and RECs). More specifically, they applied this context in wind power generation, concluding that while Certificate Trading is more suitable for larger projects, fixed-price FiTs stimulate accelerated investment.

Miera et al. (2008), by studying the wind generation case in Spain, demonstrated that the decrease in the wholesale price of electricity induced by the integration of more RES-e into the grid is greater than the costs for the consumer that arise from the application of RE support policies. Notably, it results in a net reduction in the retail price of electricity, which is beneficial from a consumer's standpoint. This strengthens the support for RES-e and counters one of the common criticisms of renewable support mechanism implementation: the perceived excessive cost to consumers. Lastly, an important study conducted by Barbosa et al. (2018), elaborated the first analytical model of a FiT with a minimum price guarantee, finite duration, and regulatory uncertainty.

2.4.3 – Collar

The analysis of collars adopts a RO formulation (i.e., considering their option-like properties), resembling what has already been identified in the FiT structure. More concretely, a collar option is a strategy to keep an active project's output price within a specific range. This is done by setting a minimum price (price floor, P_F) and a maximum price (price cap, P_C). If the market price drops below the floor, the project will receive P_F, whereas if it surpasses the cap, the project will only receive P_C. This approach ensures that the investors are protected from adverse circumstances, although they will not benefit from sufficiently favourable returns. From the government's perspective, the role of the cap is to mitigate the cost of guaranteeing a floor. As in the case of the FiT, there are also perpetual and finite collars (i.e., confined to a finite duration, T_C), and it is more realistic to consider the latter.

Adkins and Paxson (2019) provided analytical solutions for perpetual collars, floors and ceilings, and partial floors and ceilings, and performed sensitivity analyses on most of the parameter values. Moreover, it was suggested that it is a viable government policy to incentivize energy investment. Adkins et al. (2019) extended the past research on collar-style arrangements by presenting an analytical framework of a finite collar. Additionally, they determined the idle (i.e., pre-investment) and active (i.e., post-investment) values, and the investment triggers for projects with these characteristics. Their results corroborated that finite collars justify earlier investment than perpetual collars. Lastly, Fernandes et al. (2016) proposed a zero-cost collar, in Brazil, to ensure wind power.

3 – Methodology

3.1 – Case Study Data and Definition of Key Variables

AlZohbi et al. (2023) suggested electrolysis with wind power as an environmentally friendly technology and energy source for green hydrogen production. Therefore, the framework of this thesis focused on analysing the viability of investing in a PEM electrolyser for on-site green hydrogen production at a typical European onshore wind farm, by acknowledging ROA and considering the variable-premium FiT contract with a finite guarantee. To concretize the outlined thesis proposal, a case study will be developed and presented, aiming to align with real-world conditions, to the best of our knowledge.

It was established that selecting reliable data, from trustworthy sources and studies, to evaluate renewable energy projects accurately was essential. Furthermore, it was assumed that our model has annualized and base case parameters (i.e., they represent the standard values for the corresponding variable, under normal conditions).

3.1.1 – European Onshore Wind Farm

Although offshore wind power has gained significant attention in recent years and remains at the forefront of technological and research projects, our model will focus on an onshore wind farm due to its lower investment costs, and broader access to information. Accordingly, we chose to employ the onshore wind turbine manufactured by Vestas, that is a Danish company and the world's largest producer of wind energy turbines. It also designs, manufactures, and installs them worldwide. These power plants were selected given their high-tech nature, their significant adaptability to different conditions that influence energy production, and the company's extensive know-how in the energy sector. For the sake of simplicity, the following data will contemplate one of the N wind turbines that constitute the wind farm, regardless, all results could be equally applicable to the N turbines.

The capital costs of wind energy projects are mainly related to wind turbines, grid connections (i.e., needed to integrate the output source into the existing electrical network), foundations (i.e., the structural base that supports wind turbines), control systems, installation cost, and land; meaning these costs also encompass the construction of the wind farm (European Wind Energy Association (EWEA), 2009). It is important to mention that the specified expenditures vary greatly between countries. In line with Vestas' Interim Financial Report in the second quarter (Vestas, 2024a), the average selling price of one of Vestas' onshore wind turbines is €1,210,000/MW and it was considered as the initial investment (I_T) per MW of installed wind-rated power, incorporating all previously mentioned components.

Furthermore, unforeseen damage can occur to the wind turbine, leading to a loss of energy generation. For that reason, it was assumed that preventive maintenance and inspections would take place, leading to fixed operations and maintenance $(O\&M_T)$ costs of $37,800/MW for the project's first year, given the data from IRENA (2023) (a weighted average computation was done for the five European countries that were presented). The latter is equivalent to €34,112/MW, considering the exchange rate from the European Central Bank (2024a) in September of EUR/USD = 1.1081 and by employing the following equation:

$$EUR/USD = \frac{1}{USD/EUR}, \tag{3.1}$$

where EUR/USD can be adjusted for any exchange rate conversion.

Additionally, we adopted the assumption that the referred expenses grow at the inflation rate (π), more concretely at 1.8%, which was withdrawn from the European Central Bank (2024b) in September. Moreover, it should be emphasized that variable costs and any decrease in efficiency are minimal due to regular maintenance and the inherent durability of wind turbines. Therefore, they are considered insignificant for this study.

This concrete model is designed for a broad range of wind and is adapted for different weather and site conditions. This is significant, considering that both the blade size and the wind's velocity will determine the turbine's efficiency, impacting the quantity of energy produced. Its blade is 66.7 meters long, evaluated as substantial and well-suited for generating significant amounts of electricity. Regarding wind characteristics, it needs to be considered that the cut-in wind speed represents the lowest wind speed at which a wind turbine starts producing electricity, that is suitable for use. If this threshold isn't met, the turbine blades won't rotate fast enough to create any power. Conversely, the cut-out wind speed refers to the wind speed at which the turbine's control system is shut down to prevent damage, considering stronger winds can place too much pressure on the turbine's components. The turbine will only restart once the wind speed drops below a safe level, the re-cut-in wind speed.

According to the information obtained on the official website of Vestas company (Vestas, 2024b), the values are 3 meters per second (m/s), 25m/s, and 23m/s, respectively. Therefore, it was considered the estimated annual energy production (AE_P) of 15.0 GWh, associated with a yearly average wind speed (W_S) of 7.25 m/s. Moreover, it was inferred that viability (i.e., the percentage of time the turbine operates annually, as it must be shut down for maintenance) has already been accounted for in the forecasted energy production. Additionally, this turbine has an installed capacity (C_T) of 4.2 MW.

3.1.2 – PEM Electrolyser

For this component of the model, the data applied by Biggins et al. (2022) in their research served as the foundation for our own as well. The initial investment $\left(I_{E_1}\right)$, also referred to as Capital Expenditure (CAPEX), consists essentially of three components: (i) stack (i.e., the core element where the electrochemical process of water splitting takes place to generate hydrogen and oxygen, composed of multiple cells assembled in a stack); (ii) balance of plant (includes water cooling, control system, among others, which are essential for managing the input and output flows, and ensuring the efficient, and continuous operation of the PEM); and (iii) other engineering, procurement, and construction (encompasses equipment installation, project design, in addition to others).

Cells and Undertaking (2018) predicted how the CAPEX would vary in the coming years. Although its breakdown was not disclosed, it was assumed that it was only composed of the stack element, considering the similarity of the values. Hence, the projected amount for 2024 was used. Additionally, as this value is presented in pounds, it was required to utilize EUR/GBP = 0.8448 as the exchange rate, taken from the European Central Bank (2024a) along with Eq. (3.1). For the other components, the decomposition of costs for a PEM electrolyser in Europe was employed, with 2023 as the reference year, established by the European Hydrogen Observatory (2023a). Considering that the base year of our project is 2024, we will need to obtain the respective values for that year. For this purpose, a proportional relation was established between the evolution of the stack's amount from 2023 to 2024 and used as a reference to adjust the remaining values, to reflect the expected cost development. Accordingly, the resulting I_{E_1} is €1,984/KW (in more detail: €829/KW + €433/KW + €722/KW, following the order presented for the components above).

In line with Biggins et al. (2022), its operations and maintenance costs $(O\&M_E)$, commonly referred to as Operating Expenses (OPEX), are projected to be 4% of CAPEX in the first year. Like the corresponding expense category for wind turbines, the latter increases annually at an π of 1.8%. The OPEX includes expenses such as water, which serves as the feedstock for hydrogen production, and costs associated with the degradation and replacement of membranes and electrodes over time, among others. Cells and Undertaking (2018) also predicted the variation of the energy consumption $\left(E_{C_1}\right)$ (i.e., the energy needed to generate 1 kg of hydrogen). Therefore, the estimated value for 2024 is 52 KWh/kg.

On the subject of the PEM's lifetime (T_E), Reduction (2020) identified a range of 50,000 to 80,000 hours (h) for this parameter, and Biggins et al. (2022) used the average of these values, which we also considered. We interpreted this value as representing the number of operating hours the PEM is functional for hydrogen production. Regardless, this does not imply that the PEM operates continuously throughout its entire lifespan, nor does it equate to its total duration. Notably, it is necessary to consider an average utilization rate (U_E), which was contemplated as 74%.

Moreover, its nominal power capacity (C_E) (i.e., the maximum continuous power output it can draw during standard operating conditions) is 1000 kW. In addition, the minimum operating power for this PEM was defined by Biggins et al. (2022) as 2% of the nominal power (20 kW), with the ability to reach up to 200% of nominal power (2000 kW) for up to 10 minutes. These operating limits further validate that 1000 kW is an appropriate nominal value for the electrolyser's typical operations.

3.1.3 – Feed-in Tariff and Collar

Policies are frequently implemented to encourage the development of new renewable energy projects, with the FiT often seen as the most effective mechanism (Abadie & Chamorro, 2014). Hence, the FiT contract with a finite guarantee will be considered, assuming it remains constant over time. Its finite duration (T_F) represents how long the investor will receive financing; however, from the taxpayer's perspective (who ultimately bears this cost), this duration should not necessarily match the length of the project itself. Therefore, it was established for 15 years, as this duration must be shorter than the project's timeframe (i.e., 20 years), which will be further detailed.

Additionally, the price floor (P_F) should ideally be closely tied to the lower half of the forecasted market price range for green hydrogen. However, this is a critical yet complex question without a straightforward answer, especially since this price should factor in the specific characteristics of the technology and energy source studied in our thesis. Regardless, the first European Hydrogen Bank's auction took place this current year and established the range of received funding for hydrogen produced by the winning bidders, more concretely, between €0.37 and €0.48 per Kg/H_2 (European Commission, 2024). Therefore, this led to a P_F which will provide a guaranteed payment to producers of €0.40 for every kg of green hydrogen generated.

Furthermore, it is acknowledged that the market price of green hydrogen at t=0 (P) must comply with being above P_F and below P_C. Based on the value presented in Business AnalytiQ (2024), €4.76/Kg was the value assumed for P.

Moreover, the policy collar will be factored in to provide a more realistic approach. Regarding its finite duration (T_C), the same reasoning mentioned previously was used, setting it at 15 years as well. The price cap (P_C) of the collar was established by considering the referred condition. In this context, P_C ensures that the producer does not receive more than €8.00 per kilogram of green hydrogen generated when the market price surpasses this. Both P_F and P_C serve merely as standard values, considering a sensitivity analysis will be conducted to assess their impact.

3.1.4 – Real Options Approach

Contemplating the investor's perspective, several computations will be carried out to provide further insights, namely the value of the option to invest in this renewable energy project. For that purpose, we will employ the GBM parameters derived from real-world data, based on the work of Ritzenhofen and Spinler (2016). More concretely, a deterministic drift (μ) of 0%, a volatility (σ) of 19%, and a risk-free rate (r) of 5% will be applied. Naturally, this results in a dividend yield (q) of 5%. Regarding the project's lifetime (T), we will consider 20 years, taking into account that a modern wind turbine typically has an operational lifespan of 20 to 25 years (Kaewbumrung et al., 2024). The time to maturity (τ) will correspond to the project's duration, assuming the starting point is year 0.

It is important to note that, for simplicity, we are using parameter values already established in the literature for similar problems, which will be applied in the entire model. Ideally, these values would differ for a more precise approach, particularly given the distinct volatility profiles of wind energy and green hydrogen.

3.2 - Interim Calculations for Core Data Variables

In the upcoming chapters, I will outline how to calculate key variables, essential for evaluating the proposed project's feasibility, using the previously mentioned inputs and sector-specific equations, which are fundamental for comparing different projects in this sector.

3.2.1 – European Onshore Wind Farm

The capacity factor (CF_T) represents the ratio of the average wind power produced by wind turbines to their maximum possible power output (i.e., the installed C_T per power plant) (Desalegn et al., 2023). It is a critical ratio for evaluating the performance of a wind turbine, specifically considering it is primarily impacted by wind resources and the system design of the power plant, both crucial elements in projects in this field (Schmitz & Madlener, 2015). As a result, it is clear the importance of computing this ratio and further comparing the result with projects that combine similar conditions.

The equation for calculating the CF_T (in percentage) is as follows:

$$CF_T = \frac{AE_P}{C_T * Annual\ Operating\ Hours}, \tag{3.2}$$

where Annual Operating Hours are assumed to be 8,760h, representing continuous operation at 24 hours per day, 365 days a year (Tvedt, 2022).

3.2.2 – PEM Electrolyser

Having in mind the T_E and U_E presented below, it is now sensible to consider the PEM's duration (T^*), which represents its lifespan, in years, accounting for both the operating hours and downtime.

The formula used is shown below and resulted in a T^* of approximately 10 years:

$$T^* = \frac{T_E}{U_E * 24 * 365} . \tag{3.3}$$

Moreover, given that T^* is roughly half of T, a second piece of equipment will be required for the other 10 years. Hence, it is worth mentioning that, according to Cells and Undertaking (2018), both CAPEX and consequently OPEX, and E_C are expected to vary throughout the project's lifetime. Specifically, an electrolyser purchased in 2024 is expected to be less efficient and more expensive than one bought in 2028. Further, the estimates from the previously stated source were only available up to 2030, and we needed data from 2034. To implement this in our project, the values for 2022 to 2030, which had been provided, were put in an Excel table, and a linear regression was computed.

This methodology was applied to both CAPEX and E_C, leading to the following linear regressions, respectively:

$$y_{I_{E_2}} = -36.75x + 75{,}096 , \tag{3.4}$$

$$y_{E_{C_2}} = -0.4083x + 878.75 , \tag{3.5}$$

where x represents the year for which we sought to obtain the associated value, which in this case was 2034, $y_{I_{E_2}}$ is the stack's investment for the second PEM electrolyser, and $y_{E_{C_2}}$ represents its energy consumption, equal to 48 KWh/Kg. I_{E_2} was obtained by adding to $y_{I_{E_2}}$ the expected variation for the other cost components, previously mentioned, totalling €982/KW (in more detail: €410/KW + €214/KW + €358/KW, for stack, balance of plant, and other engineering, procurement, and construction components, respectively).

The Vestas' wind turbine, used as a reference for our case study, is equipped with a full-scale converter, which converts the alternating current (AC) power generated by the wind turbines into the required stable direct current (DC) power for the electrolyser. This feature makes the wind turbine well-suited for integration with PEM electrolysers, optimizes power delivery to the electrolyser, and helps minimise energy losses. Additionally, it is important to characterize the efficiency (η_E) parameter, which is mostly impacted by the E_C and the Lower Heating Value (LHV) of Hydrogen (i.e., represents the total energy content in hydrogen that is obtained from a PEM electrolyser, totalling 33.3 KWh/kg) (Abadie & Chamorro, 2023).

The efficiency can be computed using the following formula:

$$\eta_{E_1} = \frac{LHV\ of\ Hydrogen}{E_{C_1}} * 100\ , \tag{3.6}$$

where E_{C_1} can be replaced by E_{C_2} and the value of η_{E_2} is discovered. Note that all other parameters will remain unchanged, as the equipment in question is identical.

It is now appropriate to consider both PEM systems and determine the mass, in Kg, of green hydrogen that is going to be produced (H_P), since it will certainly impact the project's profitability.

The rationale of Biggins et al. (2022) was adopted, thus H_P is determined by:

$$H_P = H_{P_1} + H_{P_2}\ , \tag{3.7}$$

with

$$H_{P_1} = \frac{T_E * C_E}{E_{C_1}}\ , \tag{3.8}$$

where E_{C_1} can be substituted by E_{C_2} and the value of H_{P_2} is computed. Therefore, H_P is equal to 2,596,653 Kg.

Lastly, we needed to confirm if the wind turbine would produce sufficient energy to meet the demand required for green hydrogen production.

For that purpose, $E_{T,E}$, the total effective energy amount that over the lifetime of the two PEMs will go to the electrolysers, in KWh, can be determined as:

$$E_{T,E} = C_E * O_H\ , \tag{3.9}$$

where O_H, represents the total effective operating hours, which are twice T_E, reaching 130,000h.

The following equation allows the computation of the total green energy produced (E_P):

$$E_P = AE_P * \mathrm{T}\ . \tag{3.10}$$

Notably, the verification was successfully conducted, considering $E_P > E_{T,E}$, in particular 300,000,000 KWh > 130,000,000 KWh.

3.3 – Assessment of the Wind Farm’s PEM Electrolyser

In these subsections, we will evaluate the profitability of the proposed renewable energy project from diverse perspectives. The focus will be on the investor's viewpoint, specifically in optimizing the project's value.

3.3.1 – Levelised Cost of Hydrogen

Cost is one of the most critical components in assessing whether onshore and offshore wind power development is feasible. To facilitate a standardized comparison of the cost of energy produced from diverse technologies, energy sources, and locations; the concept of the Levelised Cost of Energy $(LCoE)$ was formalized (Desalegn et al., 2023).

To determine the desired value, we can apply the equation below (in €/KWh):

$$LCoE = \frac{CAPEX_T + \sum_{t=1}^{t=20} \frac{OPEX_{T_t}}{(1+r)^t}}{\sum_{t=1}^{t=20} \frac{AEP_t}{(1+r)^t}}, \tag{3.11}$$

with

$$CAPEX_T = I_T * C_T\ , \tag{3.12}$$

and

$$OPEX_{T_t} = O\&M_{t=1} * (1+\pi)^{t-1} * C_T\ . \tag{3.13}$$

Acknowledging that the purpose of this project is the production and subsequent sale of green hydrogen in the market, it is appropriate to consider the Levelised Cost of Hydrogen $(LCoH_2)$, based on the established $LCoE$ (Woznicki et al., 2020). By considering all costs associated with both the wind turbine and PEM electrolyser components, we can provide an accurate and comprehensive understanding of the true cost of the green hydrogen that will be generated. This metric is represented by the discounted sum of expenses, minus the discounted sum of annual revenue of green energy, over the discounted sum of green hydrogen generated throughout the project’s duration (Javanshir et al., 2024; Tvedt, 2022). Straightforwardly, $LCoH_2$ represents the marginal average cost per unit of green hydrogen, typically per €/kg, generated over the lifetime of a PEM electrolyser.

Mathematically, $LCOH_2$ is computed as follows:

$$LCoH_2 = \frac{CAPEX_T + CAPEX_E + \sum_{t=1}^{t=20} \frac{OPEX_{T_t}}{(1+r)^t} + \sum_{t=1}^{t=20} \frac{OPEX_{E_t}}{(1+r)^t} - \sum_{t=1}^{t=20} \frac{ARev_{E_t}}{(1+r)^t}}{\sum_{t=1}^{t=20} \frac{AH_{2_t}}{(1+r)^t}}, \quad (3.14)$$

with

$$CAPEX_E = I_{E_1} * C_E + \frac{(I_{E_2} * C_E)}{(1+r)^{T^*}}, \quad (3.15)$$

and

$$OPEX_{E_t} = \begin{cases} O\&M_{E_{1_{t=1}}} * (1+\pi)^{t-1} * C_E & for\ 1 \leq t \leq 10 \\ O\&M_{E_{2_{t=11}}} * (1+\pi)^{t-11} * C_E & for\ 11 \leq t \leq 20 \end{cases}. \quad (3.16)$$

Note that the second equipment will be purchased 10 years from now, consequently, that cost needs to be discounted to its present value. This rationale is also applicable to the OPEX costs.

As discussed, our wind turbine will generate more green energy than the amount that will be effectively used by the PEM's. Therefore, it is logical to consider selling the surplus energy on the market.

The equation below represents its annual revenue:

$$ARev_{E_t} = \left(\frac{(E_P - E_{T,E}) * Annual\ Sales(\%)}{T}\right) * PRev_E \ , \quad (3.17)$$

where $(E_P - E_{T,E})$ indicates the quantity of unused green energy, Annual Sales (%) expresses the portion that is assumed to be sold (in particular, it is equal to 80%), and $PRev_E$ (i.e., the sale price of the wind energy) will assume the obtained $LCoE$. Considering the variability of wind energy market prices, especially when factoring in location, a conservative position is being taken.

Regarding the annual green hydrogen produced (AH_{2_t}), for the first 10 years, it is calculated as:

$$AH_{P_1} = \frac{H_{P_1}}{10}, \quad (3.18)$$

where H_{P_1} can be replaced by H_{P_2}, reaching for the AH_{P_2} value for the remaining 10 years. Therefore, 125,000 Kg and 134,665 Kg correspond to AH_{P_1}, and AH_{P_2}, respectively.

3.3.2 – Valuation of the Investment in the Absence of Flexibility

The NPV rule is useful for quickly determining whether the project is a good investment. Firstly, the NPV of the project (NPV_{T+E}) will be determined; secondly the NPV for the wind turbine (NPV_T) (i.e., the corresponding value of the wind farm without an electrolyser) will be computed over the same period (i.e., 20 years); and lastly, the additional value from investing in the electrolyser is established (NPV_E).

The following equation allows to calculate NPV_{T+E}:

$$NPV_{T+E} = -(CAPEX_T + CAPEX_E) + \sum_{t=1}^{t=20} \frac{\left(ARev_{E_t} + AH_{2_t}\right) - \left(OPEX_{T_t} + OPEX_{E_t}\right)}{(1+r)^t}, \tag{3.19}$$

with

$$AH_{2_t} = \begin{cases} AH_{P_1} * P \;\; for\; 0 \leq t \leq 10 \\ AH_{P_2} * P \;\; for\; 11 \leq t \leq 20 \end{cases}, \tag{3.20}$$

where $ARev_{E_t}$ employed Eq. (3.17), except for the price it assumed. In this context, $PRev_E$ is replaced by PR_E, which represents the market price of green energy (equals to €66.75/MWh). This value was obtained by considering the average prices for a few European countries in October, given by Nord Pool (2024). This price change derives from adopting a value that is more in line with current market practices, as we were computing a cash flow obtained from wind energy sales (otherwise, we would be significantly harming the project's NPV); whereas in $LCoH_2$ the purpose was to deduct from it the equivalent of the wind energy production cost that would not be used in the PEM (i.e., adopting a conservative approach).

The next mathematical expression permits to compute NPV_T:

$$NPV_T = -CAPEX_T + \sum_{t=1}^{t=20} \frac{AR_{E_t} - OPEX_{T_t}}{(1+r)^t}, \tag{3.21}$$

with

$$AR_{E_t} = \left(\frac{E_P}{T}\right) * PR_E \;\; , \tag{3.22}$$

where annual sales (%) no longer need to be considered, as the producer's focus is now selling green energy (instead of both green energy and green hydrogen). Thus, it will be assumed that is all sold.

Ultimately, a positive value in the equation shown below indicates that an electrolyser adds additional value, while a negative value suggests that the investment is not worthwhile, at first instance:

$$NPV_E = NPV_{T+E} - NPV_T \ . \tag{3.23}$$

3.3.3 – Valuation of the Investment with Flexibility

While NPV analysis is an effective tool for assessing simple projects with predictable cash flows, it proves inadequate for handling uncertainty in revenue. In contrast, ROA offers a more versatile approach by incorporating management flexibility and uncertainty, when evaluating a project in the energy field. This time, the American-style option to invest will be considered, which gives the flexibility to delay the initial investment until market conditions become favourable. Notably, the investment cost (K) will assume the $LCoH_2$ value without considering the effect of the potential sale in the market for the wind energy that will not be used by the PEM, totalling €6.61/Kg. Moreover, floors and caps will be accounted for, since they can be interpreted as a series of options on continuous flows.

3.3.3.1 – Feed-in Tariff

To put into practice the purpose of our thesis, we will apply the analytical model of a FiT with a minimum price guarantee, considering the finite scenario that Barbosa et al. (2018) presented in their research, which was built on the work done by Shackleton & Wojakowski (2007). Since it is a more realistic approach, it will serve as our baseline. The following framework will mainly focus on straightforward and conclusive equations.

It is accepted that the green hydrogen market price (P) follows a GBM, as the Eq. (2.3) demonstrated. It is the chosen stochastic variable of our model, meaning it has an associated uncertainty that will directly influence our project's revenue.

To gain deeper insights into the formula used to compute the project’s value, briefly examining the perpetual maturity scenario is useful.

By using Itô’s Lemma, it leads to the Ordinary Differential Equation (ODE) (Dixit & Pindyck, 1994):

$$\mu * P * \frac{\partial V(P,P_F)}{\partial P} + 0.5\sigma^2 * P^2 * \frac{\partial^2 V(P,P_F)}{\partial P^2} - r * V(P,P_F) \ + \ \Pi(P,P_F) = 0 \ , \tag{3.24}$$

where $V(P, P_F)$ symbolises the value of the project, and $\Pi(P, P_F)$ represents the guarantee provided to the investor by ensuring a cash flow equivalent to the price floor for each unit of green hydrogen produced, if the market price (P) falls below the floor (P_F). Conversely, if P exceeds P_F, the investor receives P.

The ODE's general solution is:

$$V(P, P_F) = \begin{cases} A_1 * P^{\beta_1} + A_2 * \ P^{\beta_2} + \dfrac{P_F}{r} & for\ P < P_F \\ B_1 * P^{\beta_1} + B_2 * P^{\beta_2} + \dfrac{P}{r-\mu} & for\ P \geq P_F \end{cases}, \tag{3.25}$$

where A_1, A_2, B_1, and B_2 are constants that the next three economic boundaries will establish, β_1 > 1, and β_2 < 0 the solutions for the quadratic equation:

$$\tfrac{1}{2} * \sigma^2 * \beta * (\beta - 1) + \beta * \mu - r = 0\ . \tag{3.26}$$

Regarding the economic boundaries: (i) the project's value is supposed to converge to $\frac{P_F}{r}$ as $P \rightarrow 0$, concerning the region where $P < P_F$, since β_2 < 0, A_2 must be zero; (ii) for $P > P_F$, when $P \rightarrow \infty$, the value of the project is expected to converge to $\frac{P}{r-\mu}$, therefore β_1 should be zero; (iii) the two regions below meet (i.e., $P = P_F$).

Notably, the simplified solution to the ODE is given by:

$$V(P, P_F) = \begin{cases} A_1 * P^{\beta_1} + \dfrac{P_F}{r} & for\ P < P_F \\ B_2 * P^{\beta_2} + \dfrac{P}{r-\mu} & for\ P \geq P_F \end{cases}, \tag{3.27}$$

with

$$A_1 = \frac{P_F^{(1-\beta_1)}}{\beta_1 - \beta_2} * \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu}\right), \tag{3.28}$$

$$B_2 = \frac{P_F^{(1-\beta_2)}}{\beta_1 - \beta_2} * \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \mu}\right), \tag{3.29}$$

$$\beta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2}\right)^2 + \frac{2 * r}{\sigma^2}\right)^{\frac{1}{2}}, \tag{3.30}$$

and

$$\beta_2 = \frac{1}{2} - \frac{\mu}{\sigma^2} - \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2}\right)^2 + \frac{2*r}{\sigma^2}\right)^{\frac{1}{2}}. \tag{3.31}$$

Remarkably, the value of the PEM's electrolyser in a European onshore wind farm, until T_F (i.e., the period during which the producer takes advantage of the FiT with a finite maturity) is given by:

$$V_T(P, P_F) = \begin{cases} A_1 * P^{\beta_1} * N(d_{\beta_1}) + \dfrac{P_F}{r} * \left(1 - e^{-r*T_F} * \left(1 - N(d_0)\right)\right) \\ -B_2 * P^{\beta_2} * N(d_{\beta_2}) - \dfrac{P}{r-\mu} * e^{-(r-\mu)*T_F} * N(d_1), \qquad for\ P < P_F \\ -A_1 * P^{\beta_1} * \left(1 - N(d_{\beta_1})\right) - \dfrac{P_F}{r} * e^{-r*T_F} * \left(1 - N(d_0)\right) + B_2 * P^{\beta_2} * \\ \left(1 - N(d_{\beta_2})\right) + \dfrac{P}{r-\mu} * \left(1 - e^{-(r-\mu)*T_F} * N(d_1)\right), \qquad for\ P \geq P_F \end{cases}, \tag{3.32}$$

with

$$d_\beta = \frac{\ln\frac{P}{P_F} + \left(\mu + \sigma^2 * \left(\beta - \frac{1}{2}\right)\right) * T_F}{\sigma\sqrt{T_F}}, \tag{3.33}$$

where $N(.)$ is the cumulative normal integral, and β_1, β_2, 0, and 1 can replace β in the parameter d.

Moreover, the project's value until T (i.e., includes the period with the FiT contract and subsequently the period beyond it) is determined by the equation below:

$$V_F(P, P_F) = V_T(P, P_F) + \frac{P}{r-\mu} * e^{-(r-\mu)*T_F}, \tag{3.34}$$

where $\frac{P}{r-\mu} * e^{-(r-\mu)*T_F}$ reflects the cash flow earned by the investor, from the sale of green hydrogen to the market, throughout the remaining operational lifespan of the project.

Regarding the option's value, if we disregard the perpetual profit flow of Eq. (3.24), it results in the desired value, which is provided by:

$$F_F(P, P_F) = D_1 * P^{\beta_1} + D_2 * P^{\beta_2}, \tag{3.35}$$

where we are aware that $F(0) = 0$, when $P \to 0$, and considering $\beta_2 < 0$, $F(0)$ is only zero if $D_2 = 0$.

Therefore, the simplified solution for the value of the American-style option to invest in the project demonstrated is given by:

$$F_F(P, P_F) = \begin{cases} (V_F(P^*, P_F) - K) * \left(\frac{P}{P^*}\right)^{\beta_1} & for\ P < P^* \\ V_F(P, P_F) - K & for\ P \geq P^* \end{cases}, \tag{3.36}$$

where P^* is the optimal investment point, also known as the investment threshold (i.e., represents the optimal hydrogen market price from which it becomes profitable to invest, accounting for the producer's perspective), and K the investment cost.

The value-matching condition (i.e., the ideal investment point at which holding the option or implementing the project is irrelevant, from the investor's point of view), and the smooth-pasting condition (i.e., the option's value must be tangent to the project's value at the ideal investment point) are derived as, respectively:

$$D_1 * P^{*\beta_1} = V_F(P^*, P_F) - K\ , \tag{3.37}$$

and

$$\beta_1 * D_1 * P^{*\beta_1 - 1} = \frac{\partial V_F(P^*, P_F)}{\partial P^*}\ , \tag{3.38}$$

Both conditions are transformed into the following nonlinear equation, which requires numerical solutions to determine P^*:

$$\begin{cases} -(\beta_1 - \beta_2) * B_2 * P^{*\beta_2} * N(d_{\beta_2}) - (\beta_1 - 1) * \frac{P^*}{r - \mu} * e^{-(r-\mu)*T_F} * (N(d_1) - 1) \\ \quad + \beta_1 * \left(\frac{P_F}{r} * \left(1 - e^{-r*T_F} * \left(1 - N(d_0)\right)\right) - K\right) = 0 \qquad for\ \ P^* < P_F \\ (\beta_1 - \beta_2) * B_2 * P^{*\beta_2} * \left(1 - N(d_{\beta_2})\right) + (\beta_1 - 1) * \left(\begin{array}{c} \frac{P^*}{r - \mu} * \left(1 - e^{-(r-\mu)*T_F} * N(d_1)\right) \\ + \frac{P^*}{r - \mu} * e^{-(r-\mu)*T_F} \end{array}\right) \\ \quad -\beta_1 * \left(\frac{P_F}{r} * e^{-r*T_F} * \left(1 - N(d_0)\right) + K\right) = 0 \qquad for\ \ P^* \geq P_F \end{cases} \tag{3.39}$$

Additionally, P^* is replaced by P_F in the second branch of Eq. (3.39) to determine the value of P_F at which both branches have the same solution. Following, $d_\beta(P^* = P_F)$ is computed from Eq. (3.33), and the second condition of Eq. (3.39) is adjusted.

In these terms, it is possible to obtain the arranged equation for the calculation of P_F:

$$\left(\left(\frac{\beta_1}{r}-\frac{\beta_1-1}{r-\mu}\right)*\left(1-N\left(d_{\beta_2(P^*=P_F)}\right)\right)+\frac{(\beta_1-1)}{r-\mu} \right.$$
$$*\left(1-e^{-(r-\mu)*T_F}*N\left(d_{1(P^*=P_F)}\right)+e^{-(r-\mu)*T_F}\right)-\frac{\beta_1*e^{-r*T_F}}{r} \tag{3.40}$$
$$\left. *\left(1-N\left(d_{0(P^*=P_F)}\right)\right)\right)*P_F-\beta_1*K=0$$

Furthermore, the above equation can be rewritten in terms of K and P_F, which will allow the determination of K^* and P_F^*, (i.e., the optimal price floor). From the producer's perspective, the latter is an interesting value, considering they represent the indicators from which it would be profitable to invest.

Moreover, to establish which branch of Eq. (3.39) to use when aiming to obtain P^*, the next conditions must be verified:

$$K^* > \mathrm{K} \rightarrow \ P^* < P_F \ \ => 1^{st}\ branch\,, \tag{3.41}$$

and

$$K^* < \mathrm{K} \rightarrow \ P^* > P_F \ \ => 2^{nd}\ branch \tag{3.42}$$

Lastly, K_{check} permits to understand a critical value, if $K_{check} > \mathrm{K}$, it means that it will be optimal to invest (from the producer’s perspective), regardless of P:

$$K_{check} = \frac{P_F*\left(1-e^{-(r*T_F)}\right)}{r} \tag{3.43}$$

3.3.3.2 – Collar

The collar corresponds to a portfolio consisting of a floor and a cap. In this chapter, we will explore the cap component in greater detail. Like in the FiT scenario, this collar has a finite lifespan, and the framework presented below is based on Adkins et al. (2019).

The following mathematical expression demonstrates the instantaneous flow rate that is generated by this government policy (Dias et al., 2024):

$$\Pi(P) = \ min\{max(P_F, P), P_C\} \tag{3.44}$$

The project's value with a finite-lived collar can be expressed as:

$$V_c(P,T_C) = V_P(P) - S(P,T_C) + \frac{P}{\delta} * e^{-\delta * T_C} \ , \tag{3.45}$$

with

$$V_P(P) = \begin{cases} A_{11} * P^{\beta_1} + \dfrac{P_F}{r} & for\ P < P_F \\ A_{21} * P^{\beta_1} + A_{22} * P^{\beta_2} + \dfrac{P}{\delta} & for\ P_F \le P < P_C \\ A_{32} * P^{\beta_2} + \dfrac{P_C}{r} & for\ P \ge P_C \end{cases} \ , \tag{3.46}$$

$$A_{11} = \frac{\left(P_C^{1-\beta_1} - P_F^{1-\beta_1}\right)}{\beta_1 - \beta_2} * \left(\frac{\beta_2 - 1}{\delta} - \frac{\beta_2}{r}\right) \ , \tag{3.47}$$

$$A_{21} = \frac{P_C^{1-\beta_1}}{\beta_1 - \beta_2} * \left(\frac{\beta_2 - 1}{\delta} - \frac{\beta_2}{r}\right) \ , \tag{3.48}$$

$$A_{22} = -\frac{P_F^{1-\beta_2}}{\beta_1 - \beta_2} * \left(\frac{\beta_1 - 1}{\delta} - \frac{\beta_1}{r}\right) \ , \tag{3.49}$$

$$A_{32} = \frac{\left(P_C^{1-\beta_2} - P_F^{1-\beta_2}\right)}{\beta_1 - \beta_2} * \left(\frac{\beta_1 - 1}{\delta} - \frac{\beta_1}{r}\right) \ , \tag{3.50}$$

and

$$\begin{aligned} S(P,T_C) = A_{11} * P^{\beta_1} * N\left(-d_{\beta_1}(P,P_F)\right) + \tfrac{P_F}{r} * e^{-r*T_C} * N\left(-d_0(P,P_F)\right) + \\ A_{21} * P^{\beta_1} * \left(N\left(d_{\beta_1}(P,P_F)\right) - N\left(d_{\beta_1} * (P,P_C)\right)\right) + A_{22} * P^{\beta_2} * \\ \left(N\left(d_{\beta_2}(P,P_F)\right) - N\left(d_{\beta_2} * (P,P_C)\right)\right) + \tfrac{P}{\delta} * e^{-\delta*T_C} * \left(N\left(d_1(P,P_F)\right) - \right. \\ \left. N\left(d_1 * (P,P_C)\right)\right) + A_{32} * P^{\beta_2} * N\left(d_{\beta_2}(P,P_C)\right) + \tfrac{P_C}{r} * e^{-r*T_C} * N\left(d_0(P,P_C)\right) \ , \end{aligned} \tag{3.51}$$

where $V_P(P)$ represents the value of a project with a perpetual collar, $S(P,T_C)$ illustrates the present value of a forward-start perpetual collar, set to begin at a future time T_C, P (the market price of green hydrogen at t=0), is bounded by P_F and P_C, δ denotes the return shortfall, and the constants A_{11}, A_{21}, A_{22}, and A_{32} are determined by ensuring that $V_P(P)$ is both continuous and continuously differentiable concerning P.

Moreover, the value of the option to invest is given by:

$$F_C(P) = \begin{cases} (V_C(P_C^*, T_C) - K) * \left(\frac{P}{P_C^*}\right)^{\beta_1} & for\ P < P_C^* \\ V_C(P, T_C) - K & for\ P \geq P_C^* \end{cases} \tag{3.52}$$

Lastly, Appendix M provides further details on the calculations of P_C^*.

3.4 – Sensitivity analysis

Sensitivity analyses were performed given that some key parameters that impact the project exhibit stochastic behaviour, to validate the reliability of our methodology, and evaluate some of the underlying assumptions. Double-entry tables were created in Excel, and the "What-If Analysis -> Data Table" function was used to facilitate this process.

Specifically, we analysed the following: (i) varying PR_E (€/MWh) and E_P (MWh) in the NPV_T (€); (ii) altering parameters $ARev_{E_t}$ (€) and P (€/Kg) in NPV_{T+E} (€); (iii) varying P_F and P_C in $V_c(P, T_C)$; and (iv) altering the same parameters in $F_C(P)$. Note that the units for the parameters in the last two analyses are in €/Kg.

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4 – Results and Discussion

In Chapter 3, we explored the case study data and methodology necessary to compute and assess the decision of whether to invest in a PEM electrolyser for on-site green hydrogen production at a typical European onshore wind farm and if so, when, from the viewpoint of a private developer. The following section provides the empirical results and a detailed discussion of the findings.

4.1 – Findings from Interim Calculations

It is evident that wind speed and availability show stochastic fluctuations throughout the year, and this volatility represents a key uncertainty in renewable energy projects (Murgas et al., 2021). This thesis assumed Vestas' estimate for the annual energy production parameter, therefore it is worthwhile to analyse the capacity factor obtained to see if it falls within the range of similar projects, thereby validating the mentioned variable.

Accordingly, the capacity factor of the wind turbine (CF_T), considering Eq. (3.2) amounted to:

$$CF_T = \frac{15{,}000}{4.2 * 24 * 365} = 41\ \% \ . \tag{4.1}$$

This value does not imply that the wind turbine operates always at 41% of its total capacity. Instead, it generates 41% of its maximum possible energy output over the year (i.e., the energy it would produce if it ran at full capacity 100% of the time), which accounts for variations in wind speed and availability.

According to IRENA (2023), the global average capacity factor for onshore wind in 2023 was 41%. Wind Europe (2024) reported in October that this figure reached 37.2% in Portugal. Additionally, IRENA (2019) projects that onshore wind plants will achieve an average capacity factor of 42.5% by 2030. Moreover, higher values are linked to capturing the better performance of newer wind farms compared to older ones, driven by increased investment and enhanced capacity. This trend is expected to be further evidenced by the continued growth in the coming years (Abadie & Chamorro, 2023). Thus, the value we obtained is reasonable, considering it falls within the described ranges.

Regarding the PEM's efficiency, η_{E_1} and η_{E_2} were approximately 64% and 69%, sequentially. This aligns with what was expected, as the second equipment has lower energy consumption, which increases its efficiency.

4.2 – Assessment of the European Onshore Wind Farm

The Levelised Cost of Energy $(LCoE)$ was developed to assess and estimate the cost-effectiveness of the European onshore wind farm component, included in our renewable energy project (i.e., it is characterised exactly as described, however without the PEM electrolyser).

Therefore, concerning Eq. (3.11), $LCoE$ was equal to:

$$LCoE = \frac{5{,}082{,}000+2{,}066{,}344}{\sum_{t=1}^{t=20}\frac{15{,}000}{(1+0.05)^t}} = €0.038/\text{KWh}\ , \tag{4.2}$$

meaning that generating 1 KWh of wind energy costs €0.038KWh. In 2023, based on IRENA (2023), the global weighted average $LCoE$ of newly constructed onshore wind projects was $0.033/KWh, approximately equivalent to €0.030/KWh, and is anticipated to continue declining over the next few decades, falling between €0.018/KWh and €0.027/KWh. This leads to positioning as an already competitive and among the most affordable energy generation sources.

A possible reason for this is the evident focus on reducing the discounted total amount of expenses coupled with increasing the quantity of energy generated, by optimizing technology, expanding research and development, better expertise to reduce energy losses during operation, and greater competition among service providers (Tvedt, 2022). Moreover, it is anticipated that the overall installed costs as well as the $0\&M$ costs for onshore wind will continue to decline.

Furthermore, we focused on the NPV analysis, recognizing it as an expected value. This is due to its reliance on forecasts of future uncertain cash flows, and its inability to account for flexibility. By applying Eq. (3.21), we derived a value of €5,329,444 for this parameter, demonstrating that, since the NPV is positive, the anticipated discounted revenues (€12,477,788) are greater than the initial investment cost, plus the discounted fixed instalments of O&M (€7,148,344), throughout the lifespan of the project.

The next mathematical expression demonstrates (i.e., by applying Eq. (3.22)), in more detail, the annual cash flows, inferring that the total amount of green energy generated is sold on the market at the average market price for this current year, 2024, across various European countries:

$$AR_{E_t} = \left(\frac{300{,}000}{20}\right) * 66.75 = €1{,}001{,}250. \tag{4.3}$$

As a final point, the way that NPV_T responded to fluctuations in PR_E and E_P was analysed, as the following table demonstrates:

5329444	25.56	38.24	51.24	66.75	80.12	91.23
220000	-3644469	-1906225	-124144	2002034	3834851	5357858
250000	-3166668	-1191391	833701	3249812	5332559	7063249
270000	-2848134	-714834	1472265	4081665	6331032	8200176
300000	-2370333	0	2430111	5329444	7828740	9905567
325000	-1972165	595695	3228315	6369260	9076830	11326727
350000	-1892532	714834	3387956	6577223	9326449	11610959

Table 1. – Sensitivity analysis of NPV_T (€) by varying PR_E (€/MWh) and E_P (MWh)

Interestingly, the investment in this onshore wind farm might become more attractive to investors if higher green energy market prices were factored into the revenue projections from energy sales, even when less quantity is sold. Conversely, when the market price drops, increasing production to boost the quantity sold would not be sufficient to make the project profitable. Notably, NPV_T reaches zero when the trading price equals the production cost per unit (i.e., $LCoE$ = €38.24/MWh) and the total produced quantity is sold (i.e., E_P = 300,000 MWh). It aligns with a breakeven point scenario, where costs match revenues.

4.3 – Assessment of the Wind Farm's PEM Electrolyser

Beginning with the result of the Levelised Cost of Hydrogen ($LCoH_2$), which is exhibited above by employing Eq. (3.14):

$$LCoH_2 = \frac{5{,}082{,}000+2{,}586{,}263+2{,}066{,}344+860{,}806-3{,}240{,}583}{1{,}603{,}595} = €4.59/Kg, \tag{4.4}$$

indicating that it costs €4.59 to generate 1 Kg of green hydrogen, and its market price should exceed this value to ensure profitability. This price is strongly dependent on the technology used to produce hydrogen and the input energy chosen. It is noted that the present value of all costs of the wind turbine seems to be the primary factor influencing the total cost of hydrogen, instead it is moderately offset by the sale of surplus wind energy that is not utilized in the electrolysis process. If this revenue stream was not accounted for, $LCoH_2$ would equate to €6.61/Kg.

Considering the European Hydrogen Observatory (2023b), the average expense of producing hydrogen through electrolysis, using a direct connection to a renewable energy source, was €6.61/Kg across all countries. Additionally, following Abadie and Chamorro (2023) study (which evaluates a wind farm that provides energy to an electrolyser to produce hydrogen, i.e., the same approach used in our thesis), revealed that the manufacturing of green hydrogen begins to turn a profit above €3.00/Kg.

Alternatively, Jiang et al. (2019) showed that for the on-site generation to be profitable, the price of hydrogen must be higher than €4.34/kg, by optimising the scale of on-site hydrogen generation at a wind farm and maximising economic returns for fluctuating hydrogen prices.

The tendency is for this cost to decrease as capital, operational, and maintenance expenses are expected to diminish, along with an increase in the capacity factors of the employed technologies, which directly contribute to a rise in the quantities produced (Desalegn et al., 2023).

Regarding NPV_{T+E}, Eq. (3.19) was applied and €2,702,173 was the obtained value, making the project profitable (total costs amounted to €10,595,413, and total revenues €13,297,586). Regardless, it is essential to recognize that this figure was calculated based on a few assumptions: (i) the hydrogen production can be directly marketed (i.e., it can be sold or supplied straight to customers or markets without intermediaries or additional processing steps, such as storage and transportation); (ii) it is presumed that the entire amount of hydrogen produced can be sold; (iii) the hydrogen retail price will remain constant, at €4.76/Kg; (iv) all turbine expenses were included, as the wind turbine is indispensable for hydrogen production; and (v) not all surplus wind energy will be offered for sale, as the investor's primary focus is to ensure that all green hydrogen will be traded, regardless, the presented market price will be assumed (i.e., €66.75/MWh).

Moving on to a more detailed review of the revenue, the following expressions will illustrate the annual cash flows from the sale of green energy and green hydrogen, respectively (by employing Eq. (3.17) and Eq. (3.20)):

$$ARev_{E_t} = \left(\frac{(300{,}000-130{,}000)*0.8}{20}\right)*66.75 = €453{,}900\,, \tag{4.5}$$

and

$$AH_{2_t} = \begin{cases} 125{,}000*4.76 = €595{,}614 \;\; for\; 0 \le t \le 10 \\ 134{,}665*4.76 = €641{,}669 \;\; for\; 11 \le t \le 20 \end{cases}. \tag{4.6}$$

It is noted that the green hydrogen market price is a key variable in the model and serves as the only stochastic parameter. Given that the green hydrogen market is still emerging, there is limited available data, making hydrogen price projections only approximate at best (Biggins et al., 2022). Following IRENA (2020, December), hydrogen market prices are estimated to fall within £1.92 to £4.96, per kilogram (using the GBP/EUR exchange rate, the referred values are approximately €2.27/Kg to €5.87/Kg).

Accordingly, a sensitivity analysis was carried out to explore the effects on NPV_{T+E} due to different annual sales (%) and wind energy market prices (which impact the annual revenue generated from wind energy sales), and diverse green hydrogen trading values (all critical points worthy of analysis: P_{F}, lower bound of the referred range, intermediate price, P, upper bound of the indicated interval, and P_{C}, respectively):

2702173	0.4	2.27	3.65	4.76	5.87	6
195024	-7523545	-4524823	-2311862	-523994	1248118	1456585
260033	-6713389	-3714667	-1501706	286162	2058274	2266741
340425	-5711527	-2712805	-499844	1288024	3060136	3268603
453900	-4297378	-1298656	914305	2702173	4474285	4682752
567375	-2883228	115494	2328454	4116323	5888434	6096902
681020	-1466960	1531762	3744722	5532591	7304702	7513170

Table 2. - Sensitivity analysis of NPV_{T+E} by varying the annual revenue of wind energy and P

This assessment reveals that NPV_{T+E} is extremely volatile regarding the market price of green hydrogen, impacting the economic feasibility of the project. More concretely, independent of the revenues of green energy, P_{F} is never sufficient for this project to become a viable project, considering the investor perspective. Another point worth mentioning is when the annual cash flow arising from the sale of green energy is equal to €260,033, given that this value represents the conservative conditions associated with the calculation of the $LCoH_2$, i.e., it was assumed that only 80% of the green energy produced is sold, which adapted to the new context, equates to 80% of the surplus green energy, with the selling price set at €38.24/MWh. Once again, the profitability of the PEM's electrolyser in a European onshore wind farm will be highly affected by the market price throughout the project's lifespan.

Lastly, the next mathematical expression allowed the computation of NPV_E (by applying Eq. (3.23):

$$NPV_E = 2{,}702{,}173 - 5{,}329{,}444 = €(2{,}627{,}271). \qquad (4.7)$$

The presented result illustrates that it is not worth investing in a PEM electrolyser, considering it does not bring additional value to the onshore wind turbine. Nevertheless, when NPV_{T+E} equates €5,532,591 (i.e., the case in which all surplus green energy is sold at €80.12/MWh, with P = €4.76/Kg), NPV_E is considerably less adverse, supporting our understanding that energy market conditions significantly impact the evaluation of our project. A possible reason for this is that the costs of green hydrogen remain very high, making it crucial to invest in research and development to drive these costs down.

4.4 – Assessment of the Wind Farm's PEM Electrolyser with Flexibility

NPV is often inadequate since it does not account for the flexibility inherent in many investments, particularly in renewable energy projects, characterised by substantial CAPEX and cash flows that are challenging to predict. Additionally, it assumes the project must be executed immediately, disregarding management's ability to adapt to market changes. Conversely, ROA incorporates a dynamic strategy that adds option value (Dixit & Pindyck, 1994) (Trigeorgis, 1996).

Firstly, the value of the PEM's electrolyser in a European onshore wind farm (given by Eq. (3.32)), until 15 years, which corresponds to the period that the producer benefits from the FiT, was equal to approximately €50.28/Kg. Additionally, the following equation permits to compute $V_F(P, P_F)$, which corresponds to the project's value until maturity:

$$V_F(P, P_F) = 50.28 + \frac{4.76}{0.05-0} * e^{-(0.05-0)*15} = €95.30/\text{Kg}. \tag{4.8}$$

As expected, $V_F(P, P_F) > V_T(P, P_F)$ is accomplished.

The investment threshold was calculated, totalling €0.52/Kg, meaning that if the market price of green hydrogen is equal to or higher than this value, it is optimal to invest, considering the producer perspective. Conversely, if the green hydrogen market price is below this value and P_F = €0.40/Kg, it is never optimal to invest in the project. It is important to note that, to maximise the value of the option to invest in an onshore PEM, it should be exercised at the optimal time, hence, this value holds significant importance. For this computation, Eq. (3.39) was used, more concretely, the second branch of that mathematical expression, since Eq. (3.42) was accomplished (i.e., €5.95/Kg < €6.61/Kg → €0.52/Kg > €0.40/Kg).

Furthermore, since P^*= €0.52/Kg is greater than P_F^* = €0.44/Kg (i.e., indicates the optimal price floor), it implies that there is a greater chance that the project will receive revenue from the market price rather than from the guarantee during its lifetime. Accordingly, $V_T(P^*, P_F)$ amounts to €5.89/Kg, and $V_F(P^*, P_F)$ equals €10.80/Kg.

Regarding K_{check}, considering it resulted in €4.22/Kg, which is lower than k = €6.61/Kg, only further contributed to understanding the relance of P on the project's value, as it means that for the project to be optimal, it is depended on P.

Furthermore, the option value to invest in this irreversible project under revenues as the one uncertain factor was given by the above mathematical expression:

$$F_F(P, P_F) = 50.28 - 6.61 = €43.68/Kg, \tag{4.9}$$

where the second branch of Eq. (3.36) was employed, considering $P \geq P^*$.

We will now explore the cap component in greater detail, specifically focusing on how the presence of a price cap will constrain the project's value and the American-style option to invest in the PEM's electrolyser on the onshore wind farm. Respectively, the mentioned values are €92.88/Kg and €86.27/Kg.

Lastly, we analysed the behaviour of the project's value and the value of the option to invest, both considering the collar as the government incentive, as we changed the price floor and the price cap. The following tables will illustrate this analysis:

92.88	0.25	0.31	0.40	0.90	1.55	2.10
5.20	87.97	87.97	87.97	87.98	88.09	88.41
6.00	90.13	90.13	90.13	90.14	90.25	90.57
6.70	91.39	91.39	91.39	91.40	91.51	91.84
7.40	92.30	92.30	92.30	92.31	92.42	92.74
8.50	93.25	93.25	93.25	93.26	93.38	93.70
9.10	93.62	93.62	93.62	93.63	93.74	94.06

Table 3. - Sensitivity analysis of $V_C(P, T_C)$ by varying the P_F and P_C. Please note that all values have €/Kg as units.

86.27	0.25	0.31	0.40	0.90	1.55	2.10
5.20	81.36	81.36	81.36	81.37	81.48	81.80
6.00	83.52	83.52	83.52	83.53	83.64	83.96
6.70	84.79	84.79	84.79	84.80	84.91	85.23
7.40	85.69	85.69	85.69	85.70	85.81	86.13
8.50	86.65	86.65	86.65	86.66	86.77	87.09
9.10	87.01	87.01	87.01	87.02	87.13	87.45

Table 4. - Sensitivity analysis of $F_C(P)$ by varying the P_F and P_C. Please note that all values have €/Kg as units.

In the appendix sections, more detailed results can be seen.

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Conclusion

With the global imperative for countries to develop green projects to reduce environmental pollution and combat climate change, and green hydrogen increasingly recognized as a key component in the transition to clean energy, this study explored the economic viability of integrating hydrogen production with wind farms.

Our findings highlighted the economic resilience and strategic benefits of this particular investment, demonstrating that this combination can significantly improve green hydrogen profitability, making it a valuable opportunity. On the other hand, when evaluating this project through NPV, the results revealed that although the green hydrogen component reduces the standalone value of the onshore wind farm, it does not lead to the overall investment being unprofitable. However, given the volatility of the green hydrogen market prices, the project's feasibility remains highly sensitive to these price fluctuations.

Furthermore, green hydrogen production starts to become economically viable above €4.59/kg. Also, it was visible that the amount of energy produced by the wind turbine along with its traded price, directly influences the cost of hydrogen production. Moreover, when considering the ROA, it was observed that since the optimal threshold for the green hydrogen market price (when the FiT is employed) is below the market price at t=0, an immediate investment is prompted.

In conclusion, the outlook for green hydrogen energy is highly promising. With continued research and technological advancements, hydrogen is poised to secure a substantial share of the energy infrastructure and will diminish the impact of transportation and storage challenges.

Throughout our analysis, it was encountered a few limitations: (i) the initial price at t=0 was determined based on an external source, however, establishing a well-supported basis for this value is challenging, as it is an emerging market; (ii) a Mean Reverting Process could have been employed as an alternative to GBM since it is often better suited for modelling assets with historical or natural price boundaries, such as stock prices; (iii) the strike price assumed $LCoH_2$ value (excluding revenues generated by wind turbine), meaning O&M costs throughout the project duration were considered by discounting to t=0, otherwise, each equation would require a different and more complex framework; and (iv) in this context, the perpetual case cannot be considered, as $K < K_P^0$ (€8/Kg), which made not possible to find a positive solution for P_P^* (i.e., optimal green hydrogen market price in the perpetual scenario), therefore this value was assumed as close as possible to what would be the root of the equation to minimise impacts on $F_C(P)$. To address these limitations, extensive efforts were undertaken to cross-verify information from diverse reliable sources, including leading companies, government publications, and key data information in the energy market.

For additional research, it would be worth considering two stochastic variables, the hydrogen market price and the Wind Load Factor. The latter offers a more accurate representation of the wind turbine performance under real-world conditions by accounting for turbine efficiency and capacity to convert wind energy into electricity, enabling a more precise valuation of onshore wind energy projects. Moreover, supplementary studies may offer deeper insights into the energy sector. For instance, our model could be adapted to encompass offshore wind farms and Alkaline electrolysers, providing a comparison to determine the most profitable approach for green hydrogen production. Also, the methodology for the most suitable location for the onshore wind farm could be analysed, by applying extensive wind data and optimization of the wind plant to maximize project efficiency.

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Appendixes

Appendix A: Real Options and Wind Turbine Data.

Parameters	Notations	Values	Units
Real Options			
Duration of the Project	Ͳ	20	years
Present Time	t	0	years
Time to Maturity	τ	20	years
Volatility of the Green Hydrogen Market Price	σ	0.19	(19%)
Risk-free Interest Rate	r	0.05	(5%)
Rate of Return Shortfall (Dividend Yield)	$q = \delta$	0.05	(5%)
Risk-neutral Drift	$\mu = \alpha$	0	(0%)
Wind Turbine			
Initial Investment	I_T	1210000	€/MW
Capacity	C_T	4.2	MW
Length of the Blade	L_B	66.7	m
Cut-in Wind Speed	-	3.00	m/s
Cut-out Wind Speed	-	25.00	m/s
Re-cut-in Wind Speed	-	23.00	m/s
Yearly Average Wind Speed	W_S	7.25	m/s
Annual Energy Production	AE_P	15000	MWh
Capacity Factor	CF_T	0.41	(41%)
EUR/USD	-	1.1081	-
USD/EUR	-	0.9024	-
Annual Operations and Maintenance	$O\&M_T$	34112	€/MW
Inflation Rate	π	0.018	(1.8%)
Annual Operations and Maintenance t=1	-	34112	€/MW
Annual Operations and Maintenance t=2	-	34726	€/MW
Annual Operations and Maintenance t=3	-	35352	€/MW
Annual Operations and Maintenance t=4	-	35988	€/MW
Annual Operations and Maintenance t=5	-	36636	€/MW
Annual Operations and Maintenance t=6	-	37295	€/MW
Annual Operations and Maintenance t=7	-	37966	€/MW
Annual Operations and Maintenance t=8	-	38650	€/MW
Annual Operations and Maintenance t=9	-	39346	€/MW
Annual Operations and Maintenance t=10	-	40054	€/MW
Annual Operations and Maintenance t=11	-	40775	€/MW
Annual Operations and Maintenance t=12	-	41509	€/MW
Annual Operations and Maintenance t=13	-	42256	€/MW
Annual Operations and Maintenance t=14	-	43016	€/MW
Annual Operations and Maintenance t=15	-	43791	€/MW
Annual Operations and Maintenance t=16	-	44579	€/MW
Annual Operations and Maintenance t=17	-	45381	€/MW
Annual Operations and Maintenance t=18	-	46198	€/MW
Annual Operations and Maintenance t=19	-	47030	€/MW
Annual Operations and Maintenance t=20	-	47876	€/MW

Appendix B: PEM Electrolyser Data.

Parameters	Notations	Values	Units
PEM Electrolyser			
For both PEM's			
Lifetime	T_E	65000	hours
Average Utilization Rate	U_E	0.74	(74%)
PEM's Duration	T^*	10	anos
Cost Factor Lifespan	*	2	-
EUR/GBP	-	0.8448	-
GBP/EUR	-	1.1838	-
Nominal Power Capacity	C_E	1000	KW
Minimal Operating Power	-	20	KW
Maximum Operating Power	-	2000	KW
Lower Heating Value of Hydrogen	LHV_{H_2}	33.3	KWh/Kg
PEM_1			
Initial Investment (t=0)	I_{E_1}	1984	€/KW
Annual Operations and Maintenance (t=0)	$O\&M_{E_1}$	79	€/KW
Annual Operations and Maintenance t=1	-	79	€/KW
Annual Operations and Maintenance t=2	-	81	€/KW
Annual Operations and Maintenance t=3	-	82	€/KW
Annual Operations and Maintenance t=4	-	84	€/KW
Annual Operations and Maintenance t=5	-	85	€/KW
Annual Operations and Maintenance t=6	-	87	€/KW
Annual Operations and Maintenance t=7	-	88	€/KW
Annual Operations and Maintenance t=8	-	90	€/KW
Annual Operations and Maintenance t=9	-	92	€/KW
Annual Operations and Maintenance t=10	-	93	€/KW
Energy Consumption	E_{C_1}	52	KWh/kg
Efficiency	η_{E_1}	64	%
PEM_2			
Initial Investment (t=10.0)	I_{E_2}	982	€/KW
Annual Operations and Maintenance (t=10.0)	$O\&M_{E_2}$	39	€/KW
Annual Operations and Maintenance t=11	-	39	€/KW
Annual Operations and Maintenance t=12	-	40	€/KW
Annual Operations and Maintenance t=13	-	41	€/KW
Annual Operations and Maintenance t=14	-	41	€/KW
Annual Operations and Maintenance t=15	-	42	€/KW
Annual Operations and Maintenance t=16	-	43	€/KW
Annual Operations and Maintenance t=17	-	44	€/KW
Annual Operations and Maintenance t=18	-	45	€/KW
Annual Operations and Maintenance t=19	-	45	€/KW
Annual Operations and Maintenance t=20	-	46	€/KW
Energy Consumption	E_{C_2}	48	KWh/kg
Efficiency	η_{E_2}	69	%

Appendix C: PEM Electrolyser Interim Calculations.

Parameters	Notations	Values	Units
$PEM_1 + PEM_2$			
Green Hydrogen Produced PEM_1	H_{P_1}	1250000	kg
Green Hydrogen Produced PEM_2	H_{P_2}	1346653	kg
Total Green Hydrogen Produced	H_P	2596653	kg
Total Effective Operating Hours	O_H	130000	hours
Total Effective Energy	$E_{T,E}$	130000000	KWh
Total Green Energy Produced	E_P	300000000	KWh

Appendix D: FiT and Collar Data.

Parameters	Notations	Values	Units
Feed-In Tariff			
Finite Duration	T_F	15	years
Price Floor	P_F	0.40	€/Kg
Collar			
Finite Duration	T_C	15	years
Price Cap	P_C	8.00	€/Kg

Appendix E: LCoE, LCoH2, and P Computations.

Parameters	Notations	Values	Units
Wind Turbine			
CAPEX	$CAPEX_T$	5082000	€
Discounted OPEX	-	2066344	€
Total Costs	I_T	7148344	€
Annual Energy Production	AE_P	15000	MWh
$LCoE$ Denominator	-	186933	MWh
Levelised Cost of Energy	$LCoE$	38.24	€/MWh
Levelised Cost of Energy	$LCoE$	0.038	€/KWh
PEM Electrolyser			
CAPEX	$CAPEX_E$	2586263	€
Discounted OPEX	-	860806	€
Total Costs	I_E	3447068	€
Total Costs (Wind Turbine + PEM Electrolyser)	I	10595413	€
Annual Green Hydrogen Produced PEM_1	AH_{P_1}	125000	kg
Annual Green Hydrogen Produced PEM_2	AH_{P_2}	134665	kg
$LCoH_2$ Denominator	-	1603595	kg
Levelised Cost of Green Hydrogen	$LCoH_2$	6.61	€/Kg
Wind Energy Left	$E_P - E_{T,E}$	170000	MWh
Sale Price for Wind Energy (in the hydrogen context)	$PRev_E$	38.24	€/MWh
% Annual Sales	-	0.80	(80%)
Annual Revenue - Sale of Wind Energy	$ARev_{E_t}$	260033	€
Discounted Sale of Wind Energy	-	3240583	€
Levelised Cost of Green Hydrogen with Sale of Wind Energy	$LCoH_2$	4.59	€/Kg
Stochastic Variable			
Green Hydrogen Market Price	P	4.76	€/Kg

Appendix F: NPV Computations.

Parameters	Notations	Values	Units
Wind Turbine			
CAPEX	$CAPEX_E$	5082000	€
Discounted OPEX	-	2066344	€
Total Wind Energy Produced	E_P	300000	MWh
Sale Price for Wind Energy	PR_E	66.75	€/MWh
Annual Revenue - Sale of Wind Energy	AR_{E_t}	1001250	€
Discounted Revenue of Wind Energy	-	12477788	€
Net Present Value	NPV_T	5329444	€
Wind Turbine + PEM Electrolyser			
Total Costs (Wind Turbine + PEM Electrolyser)	I	10595413	€
Discounted Revenue of Green Hydrogen	-	7640989	€
Annual Revenue - Sale of Wind Energy	$ARev_{E_t}$	453900	€
Discounted Revenue of Wind Energy	-	5656597	€
Net Present Value	NPV_{T+E}	2702173	€
Net Present Value of PEM Electrolyser	NPV_E	-2627271	€

Appendix G: Elasticity Parameter β_1 and β_2.

Parameters	Notations	Values	
Elasticity Parameter β1	β1	2.2378	>1
Elasticity Parameter β2	β2	-1.2378	<0

Appendix H: A1 and B2 Constants.

Parameters	Notations	Values	
Constant Associated with the Region $P < P_F$	A1	17.89	-
Constant Associated with the Region $P \geq P_F$	B2	0.74	-

Appendix I: Feed-In Tariff Computations.

Parameters	Notations	Values	Units
Parameter d for the Elasticity Parameter β	dβ	4.6457	-
		1.2788	-
		1.6358	-
		2.0881	-
		-1.2788	-
		-0.9219	-
		2.9989	-
		-0.3679	-
		-0.0110	-
		3.7348	-
		0.3679	-
		0.7249	-
Cumulative Normal Distribution for the Parameter β	N(dβ)	1.0000	-
		0.8995	-
		0.9491	-
		0.9816	-
		0.1005	-
		0.1783	-
		0.9986	-
		0.3565	-
		0.4956	-
		0.9999	-
		0.6435	-
		0.7657	-
Value of the Project with FiT Contract Until T_F	$V_T(P, P_F)$	50.28	€/Kg
Value of the Project with FiT Contract and Thereafter	$V_F(P, P_F)$	95.30	€/Kg
-	K^*	5.95	€/Kg
Optimal Price Floor	P_F^*	0.44	€/Kg
Solving Equation	-	0.00	-
Check K	K_{Check}	4.22	€/Kg
Optimal Green Hydrogen Market Price	P^*	0.52	€/Kg
Solving Equation	-	0.00	-
Value of the Project with FiT Contract Until T_F with P^*	$V_T(P^*, P_F)$	5.89	€/Kg
Value of the Project with FiT Contract and Thereafter with P^*	$V_F(P^*, P_F)$	10.80	€/Kg
Value of the Option to Invest	$F_F(P, P_F)$	43.68	€/Kg

Appendix J: Collar Constants.

Parameters		Notations	Values	
Constant Associated with the Region	$P < P_F$	A_{11}	17.4499	>0
Constant Associated with the Region	$P_C > P \geq P_F$	A_{21}	-0.4386	<0
Constant Associated with the Region	$P_C > P \geq P_F$	A_{22}	0.7404	>0
Constant Associated with the Region	$P \geq P_C$	A_{32}	-603.1529	<0

Appendix K: Collar Parameters.

Parameters	Notations	Values							
		$d_\beta(P,P_F)$	$d_\beta(P,P_C)$	$d_\beta(P_F,P_F)$	$d_\beta(P_F,P_C)$	$d_\beta(P_C,P_F)$	$d_\beta(P_C,P_C)$	$d_\beta(P^*,P_F)$	$d_\beta(P^*,P_C)$
		2.9989	-1.0721	-0.3679	-4.4390	3.7031	-0.3679	-1.0114	-5.0824
Parameter d for the Elasticity Parameter β	d_β	3.7348	-0.3362	0.3679	-3.7031	4.4390	0.3679	-0.2755	-4.3465
		4.6457	0.5747	1.2788	-2.7922	5.3498	1.2788	0.6354	-3.4357
		2.0881	-1.9830	-1.2788	-5.3498	2.7922	-1.2788	-1.9223	-5.9933
		0.9986	0.1418	0.3565	0.0000	0.9999	0.3565	0.1559	0.0000
		0.9999	0.3684	0.6435	0.0001	1.0000	0.6435	0.3915	0.0000
	$N_{(d_\beta)}$	1.0000	0.7172	0.8995	0.0026	1.0000	0.8995	0.7374	0.0003
Cumulative Normal Distribution		0.9816	0.0237	0.1005	0.0000	0.9974	0.1005	0.0273	0.0000
		0.0014	0.8582	0.6435	1.0000	0.0001	0.6435	0.8441	1.0000
	$N_{(-d_\beta)}$	0.0001	0.6316	0.3565	0.9999	0.0000	0.3565	0.6085	1.0000
		0.0000	0.2828	0.1005	0.9974	0.0000	0.1005	0.2626	0.9997

Appendix L: Collar Computations.

Parameters	Notations	Values	
Forward-Start Perpetual Collar	$S(P,T_C)$	33.11	€/Kg
Value of the Project	$V_C(P,T_C)$	92.88	€/Kg
	$Z(P)$	-52.36	-
	$Z(P_F)$	-9.26	-
	$Z(P_C)$	-77.76	-
-			
	K^0	4.22	€/Kg
	K^F	5.95	€/Kg
	K^C	95.65	€/Kg
-	$Z(P_C^*)$	-8.67	-
-	-	0.00	-
Investment Trigger	P_C^*	0.25	€/Kg
Forward-Start Perpetual Collar with $P = P^*$	$S(P^*,T_C)$	4.41	€/Kg
Value of the Project with $P = P^*$	$V_C(P^*,T_C)$	8.19	€/Kg
Value of the Option to Invest	$F_C(P)$	86.27	€/Kg

Appendix M: Mathematical Expressions that Must be Solved to Find the Investment Trigger P_C^*:

$$\begin{aligned} Z(P) &= \beta_1 S(P, T_c) - S'(P)P \\ &= -(\beta_1 - \beta_2)\Big[A_{22}P^{\beta 2}\Big(N\Big(d_{\beta_2}(P, P_F)\Big) - N\Big(d_{\beta 2}(P, P_C)\Big)\Big) \\ &\quad + A_{32}P^{\beta 2}N\Big(d_{\beta 2}(P, P_C)\Big)\Big] \\ &\quad - (\beta_1 - 1)\frac{P}{\delta}e^{-\delta T_c}\Big(N\big(d_1(P, P_F)\big) - N\big(d_1(P, P_C)\big)\Big) \\ &\quad - \beta_1\left[\frac{P_F}{r}e^{-rT_c}N\big(-d_0(P, P_F)\big) + \frac{P_C}{r}e^{-rT_c}N\big(d_0(P, P_C)\big)\right] \end{aligned} \tag{1}$$

$$K^0 = \frac{P_F}{r}(1 - e^{-rT_c}) \tag{2}$$

$$K^F = \frac{1}{\beta_1}\left(Z(P_F) + (\beta_1 - 1)\frac{P_F}{\delta}e^{-\delta T_C} + \beta_1\frac{P_F}{r}\right) \tag{3}$$

$$K^C = \frac{1}{\beta_1}\left(Z(P_C) + \left(\beta_1 - \beta_2\right)A_{32}{P_C}^{\beta_2} + \left(\beta_1 - 1\right)\frac{P_C}{\delta}e^{-\delta T_C} + \beta_1\frac{P_C}{r}\right) \tag{4}$$