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A Real Option Approach to Evaluate Onshore Wind Energy Investments with Government Incentives: The Portuguese Case

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Master in Finance

Supervisor:
PhD, José Carlos Gonçalves Dias, Full Professor,
ISCTE-IUL

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BUSINESS
SCHOOL

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Abstract

In Portugal, wind energy contributes approximately 29% of the total energy production, and investments in wind energy projects, both nationally and globally, have exhibited a consistent upward trajectory in recent years. This phenomenon is primarily attributable to the heightened attractiveness of wind energy as an energy source. Several factors contribute to this trend, including increasing concerns regarding climate change, which are becoming progressively more pronounced. Additionally, the recent increase in electricity prices, driven partly by the Ukraine-Russia conflict, has reinforced the appeal of wind energy investments. Government incentives, particularly Feed-In Tariffs, have also played a pivotal role in fostering this growth.

Considering these dynamics, I propose to depart from the conventional Net Present Value (NPV) framework, which does not account for uncertainties associated with weather conditions and geographical factors. Instead, I aim to employ the Real Options Approach as a more rigorous methodology to identify the most economically viable regions in Portugal for onshore wind energy investments.

Keywords: Real Options Approach; Onshore Wind Energy; Net Present Value (NPV); Feed-In Tariffs.

JEL Classification: D81, G13

Resumo

Em Portugal, a energia eólica contribui com aproximadamente 29% para a produção total de energia, sendo que os investimentos em projetos de energia eólica, tanto a nível nacional como globalmente, têm apresentado uma trajetória consistentemente ascendente nos últimos anos. Este fenómeno é atribuível, maioritariamente, à crescente atratividade da energia eólica como fonte de energia. Vários fatores contribuem para esta tendência, destacando-se as crescentes preocupações com as alterações climáticas, as quais se estão a tornar cada vez mais evidentes. Adicionalmente, o recente aumento dos preços da eletricidade, impulsionados, em parte, pelo conflito Ucrânia-Rússia, têm fortalecido o investimento em energia eólica. Analogamente, os incentivos governamentais, particularmente as *Feed-in Tariffs* têm contribuído favoralmente para o crescimento deste tipo de energia.

Considerando todas estas dinâmicas, proponho afastar-me do cálculo convencional do Valor Presente Líquido, o qual não considera as incertezas associadas às condições meteorológicas e os fatores geográficos e, alternativamente, basear os meus cálculos na teoria das opções reais, uma metodologia mais rigorosa para identificar as regiões economicamente mais viáveis em Portugal para investimentos em energia eólica *onshore*.

Palavras-Chave: Teoria das Opções Reais; Energia Eólica *Onshore*; Valor Presente Líquido; *Feed-In Tariffs*.

Classificação JEL: D81, G13

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Abbreviations

APREN – Associação Portuguesa de Energias Renováveis

ENPV – Expanded Net Present Value

FiT – Feed-in Tariff

GOs- Guarantees of Origin

GW – Gigawatt

GWEC – Global Wind Energy Output

IEA – International Energy Agency

IRENA – International Renewable Energy Agency

KWh – Kilowatt per Hour

MIBEL – Iberian Electricity Market

MW – Megawatts

MWh – Megawatts per hour

NPV – Net Present Value

NUTS – Nomenclatura das Unidades Territoriais para Fins Estatísticos

O&M – Operating and Maintenance Costs

OMIP – Regulated Market Operator

PDF – Probability Density Function

PV – Present Value

RECs – Renewable Energy Certificates

REN – Rede Energética Nacional

RES-e – Renewable Energy Share in Electricity

ROA – Real Options Approach

Notations

S_0 – Underlying Asset Price

K – Exercise Price

T – Maturity Date

σ – Volatility

R_f – Risk-free Interest Rate

$Z(t)$ – Wiener Process

$\varepsilon(t)$ – Random Variable Normally Distributed

$d(Z)$ – Increment of a Wiener Process

μ – Drift Parameter

η – Speed of Reversion

$\bar{S}$ – average mean

$c_{i,j}$ – Call Option

$p_{i,j}$ – Put Option

$N(.)$ – Cumulative Standard Normal Distribution Function

u – Up Movement

d – Down Movement

Δt – Time Interval

p – Risk Neutral Probability

r – Discount Rate

I_0 - Initial Investment Cost

c – Installed capacity

W_m – Expected Mean Load Factor

$g(i)$ – Seasonality in the Load Factor

P_j – Expected Annual Energy Production

REV_j – Revenue Generated from Selling Energy Produced

S_t – Present Value of the Underlying Asset Price

Introduction

Since the 19th century, the consumption of fossil fuels has experienced significant growth, primarily due to the Industrial Era. This surge in fossil fuel usage has had a direct impact on global temperatures, leading to an alarming increase of approximately 0.08ºCelsius per decade (Lindsey & Dahlman, 2022). Recent climate data is disconcerting, with 2021 ranking as the sixth-warmest year on record. Even more concerning, the nine-year period from 2013 to 2021 comprises the ten warmest years ever recorded (Lindsey & Dahlman, 2022). These rising temperatures have coincided with a global surge in natural disasters, including wildfires, hurricanes, droughts, flooding, and powerful winds, adversely affecting populations worldwide.

The energy sector's heavy reliance on fossil fuels remains a primary driver, responsible for three-quarters of greenhouse gas emissions (International Energy Agency, 2014). Given the mounting evidence of escalating climate change, governments in developed nations have become increasingly committed to formulating and implementing policies aimed at global decarbonization. These initiatives aspire to secure a sustainable future for our planet.

The landmark Paris Agreement of 2015 united nations in their quest to limit global temperature increases to 2 degrees Celsius above pre-industrial levels by 2030 (United Nations, n.d.). Additionally, the accord predicts achieving net-zero carbon emissions by 2050, a goal that has gained paramount importance in countries representing two-thirds of the global economy and contributing to 63% of worldwide greenhouse emissions (Murgas et al., 2021). Simultaneously, the Ukraine-Russia conflict has amplified the urgency for countries, particularly in Europe, to expedite energy transitions.

To meet these ambitious goals, countries recognized the imperative to harness renewable energies. Presently, the renewable energy sector has evolved into a well-established and globally significant industry. Investments in renewable power sources soared to an impressive USD 366 billion, with solar and wind energy accounting for over 10% of the world's electricity production. In 2021, the global installed renewable power capacity expanded by 11%, reaching a remarkable 3,146 GW, contributing 28.3% of global electricity generation that year (REN21 Secretariat, 2022). Notably, Portugal exemplifies this global trend, as renewable energy sources now contribute to 29.20% of the country's electricity production (APREN - Associação de Energias Renováveis, 2022). The Portuguese government is committed to decarbonization and expanding green energy production.

Among renewable energy sources, wind power stands out as a pivotal force in expediting the global energy transition. 2020 and 2021 witnessed remarkable growth in the wind power industry, with an astounding addition of approximately 94 GW of Capacity, culminating in a global capacity of 837 GW and a 12% growth rate. Europe played a significant role in this growth, with onshore installations surging by 19% (Lee & Zhao, 2022). Portugal mirrors these global trends, with wind energy constituting a substantial portion of its renewable energy sector.

However, despite the promising prospects, challenges persist. These include the high costs associated with wind energy technology, transmission infrastructure availability, and the inherent variability in energy output (Komor, 2009). To mitigate uncertainties, governments have extended support to investors. Various support mechanisms have emerged recently, including Feed-In Tariffs, Feed-In Premiums, subsidies, and green tradable certificates. In alignment with European practices, the Portuguese government has adopted the Feed-In Tariff regime, recognized by the European Commission as one of the most effective methods for promoting renewable electricity. This scheme guarantees prices above market rates, offering long-term contracts based on the actual generation costs that investors incur.

Nevertheless, the traditional investment analysis approach, namely the standard Net Present Value (NPV), falls short in evaluating these projects because it neglects unpredictable factors and fails to account for the potential value enhancements stemming from flexibility and innovation in these ventures. In contrast, the Real Options Approach (ROA), which factors in timing and investment scale decisions, empowers investors by offering options not only to delay or abandon investments but also to expand or repower their projects.

Considering these complexities, the primary objective of my master's thesis is to determine the most favorable regions in Portugal for investing in onshore wind energy. To accomplish this, ROA will be employed to assess the present value (PV) of wind farm investments and to identify the optimal investment strategy using compound options and Feed-in Tariffs. This analysis will consider inherent uncertainties, like the electricity prices, the wind load factor, and the influence of government support. Combining economic, climatic, and political factors, this research aims to contribute valuable insights to evaluating onshore wind energy projects in Portugal.

CHAPTER 1

Review of Literature

1.1. The Concept of Real Options

1.1.1. Definition

The inadequacy of traditional approaches, such as the Discounted Cash Flow Analysis or the Standard Net Present Value (NPV), in evaluating investment projects has been widely recognized since the late 1960s and early 1970s (Trigeorgis & Mason, 1987). These approaches tend to overvalue projects because they ignore or cannot correctly capture management's flexibility (Kester, 1984).

In this way, when using traditional NPV, we are assuming that the assets held by investors are held passively. So managerial choices are presumed to be limited to the initial decision (accept or reject an initial project) as if project value subsequently unfolds through chance events (like outcome nodes in an event tree) (Dixit & Pindyck, 1994). The value of flexibility or the option premium will be better captured if the value is realized within a decision tree, where flexibility is modeled through decision nodes, allowing future managerial decisions to be made after some uncertainty has been resolved (Trigeorgis & Mason, 1987).

To embed investment flexibility, it can be used options. An option is a security that gives the right to buy (call option) or sell (put option) an asset within a specific period (Black & Scholes, 1973). An American Option can be exercised at any time. Conversely, an European Option can only be exercised on a specified future date – the maturity date (Black & Scholes, 1973). The price paid for the asset when the option is exercised is the exercise price, and the higher the price of the stock, the greater the value of the option (Black & Scholes, 1973).

There are distinct types of options available for investors to enhance their investment strategies (Trigeorgis & Mason, 1987):

- Option to defer – investors invest capital only under favorable market conditions. Conversely, if market circumstances deteriorate, the project remains uncommitted.
- Option to default during staged construction (time-to-build option) – each construction phase is linked to an option in subsequent stages. These stages can be evaluated parallel to options on options (compound options).

- Option to expand – if market conditions turn out more favorable than anticipated, investors can choose to escalate production in rate or scale, leveraging the flexibility to seize better opportunities.
- Option to contract – if market conditions are weaker than initially projected, investors could operate below total capacity or even curtail operations, conserving a portion of the planned investment outlays.
- Option to shut down and restart operations – when cash revenues fail to cover variable operating costs due to pricing dynamics, a temporary operational pause might be more prudent, especially if switching between operational and idle modes incurs minimal costs. Conversely, if prices rise substantially, operations can be recommended.

1.1.2. Factors That Influence the Value of The Option

Options are financial instruments subject to various factors. Subsequently, as these factors change, the option's price is adapted under the anticipated payoffs. The factors that most affected an option's price are (Trigeorgis & Mason, 1987):

- Underlying asset price (S_0) – for call options, when the underlying asset price rises, the call option's value increases. Conversely, for put options, a drop in the underlying asset price usually boosts the option's value.
- Exercise price (K) –The fixed price at which the underlying asset is eligible for purchase or sale. The difference between the underlying asset price and the exercise price influences the option's intrinsic value. For call options, when the exercise price is lower than the underlying asset price, the option is in-the-money and tends to be more valuable. In opposition, for put options, if the exercise price exceeds the underlying asset price, the option is in-the-money and usually more valuable.
- Maturity date (T) – Over time, the probability of an option finishing in-the-money decreases, leading to a decrease in the option's value. More extended maturity periods introduce more potential for market fluctuations, which can impact the option's potential profitability.
- Volatility (σ) – Reflects the extent and frequency of price fluctuations in the underlying asset. Higher volatility typically results in higher option prices, enhancing the likelihood of significant price swings and potential profit opportunities. Options are influenced by historical and implied volatility.

- Risk-free interest rates (R_f) – Risk-free interest rates influence option pricing by affecting the cost of holding the underlying asset. Higher risk-free interest rates increase the required return, lowering the present value of the exercise price. Consequently, call option prices rise and put option prices fall.
- Dividends – the stock's value often drops when it goes ex-dividend (loses the right of upcoming dividends), impacting the value of options linked to that stock.
- Market sentiment and demand – broader market conditions, investor sentiment, and demand for options can influence their prices. High demand for options can drive prices up due to intensified competition among buyers, independent of other factors.

1.2. Stochastic Price Process

A stochastic price process results in a variable that develops over time, characterized by a blend of randomness and unpredictability (Dixit & Pindyck, 1994). Wind speed, for instance, exemplifies this variability, showing stochastic fluctuations. While it is understood that wind speeds are greater during winter and notably lower during summer, there are instances where wind speeds may unexpectedly be higher on certain summer days and, conversely, where there may be days during winter with little to no wind activity. Formally, a stochastic process is defined by a probability law for the evolution of the variable over a certain period $x(t)$. This law allows us to calculate the probability of the variable falling within a specific range at different points in time.

The stochastic processes can be classified in two ways based on the nature of the time: continuous-time stochastic processes and discrete-time stochastic processes. Continuous-time stochastic processes are characterized by a time index that varies continuously, implying that the associated variable can undergo continuous changes over time. However, we might observe and measure it only at a specific time point. Conversely, discrete-time processes apply to variables that experience changes solely at distinct, separate time points.

1.2.1. Wiener Process

One notable continuous-time stochastic process is the Wiener Process, also known as Brownian Motion. It is a foundation for other stochastic processes, like the Geometric Brownian Motion and the Mean Reverting Process, and is often used to model uncertainty, randomness, and fluctuations. This process encompasses three fundamental properties: it adheres to the Markov process framework, implying that the likelihood distribution of future values solely depends on the current value; it exhibits the property of independent increments, meaning that the probability distribution of changes within a given time interval remains independent of other time intervals and changes within finite intervals of the process adhere to a normal distribution and, additionally, the variance of these changes increases linearly with the length of the time interval.

Formally, a Wiener Process (Z_t) satisfies the conditions (Dixit & Pindyck, 1994):

1. The relationship between $\Delta(\mathrm{z})$ and $\Delta(\mathrm{t})$ is given by:

$$\Delta(\mathrm{z}) = \varepsilon(\mathrm{t}) * \sqrt{\Delta(\mathrm{t})}, \tag{1.1}$$

where $\varepsilon(\mathrm{t})$ is a normally distributed random variable with a mean of zero and a standard deviation (σ) of one.

2. The random variable $\varepsilon(\mathrm{t})$ is serially uncorrelated, that is $\varepsilon[\epsilon_1 \epsilon_s] = 0$ for $\mathrm{t} \neq \mathrm{s}$.
3. The values of $\Delta(\mathrm{z})$ within two distinct time intervals are independent.

1.2.2. The Brownian Motion

The versatility of the Wiener Process extends to more complex models, such as the Brownian Motion with a Drift. This augmentation involves the addition of a constant rate of change, termed the drift, to the underlying random fluctuations.

Mathematically, it is defined as:

$$d(x) = \alpha * d(t) + \sigma * d(z), \tag{1.2}$$

with $d(z)$ being the increment of a Wiener process, α the drift parameter, and σ the variance parameter (the volatility of the random fluctuations). Consequently, the Brownian Motion with a Drift introduces a systemic trend because it includes in the drift parameter models a deterministic component in addition to the random component.

The Geometric Brownian Motion is a particular case of a Brownian Motion with a drift. This form integrates systemic growth (drift) and random fluctuations (volatility), scaling them concerning the current value of the stochastic process. Thus, the Geometric Brownian Motion can be conceptualized as the endpoint of a random walk when both the time interval and step length tend towards zero in a coordinated manner, all while adhering to the equation's conditions. Additionally, alterations in the variable x across a finite time length follow a normal distribution due to the tendency of the binomial distribution to approximate a normal distribution as the number of steps becomes exceedingly large (Dixit & Pindyck, 1994).

1.2.3. Mean Reverting Process

Brownian Motion is notorious for its propensity to deviate significantly from its starting point. This quality is particularly apt for variables that exhibit short-term randomness. However, certain variables, such as electricity prices, exhibit discernible long-term trends. For these scenarios, adopting a mean-reverting process becomes more suitable for accurate modeling.

A mean-reverting process is a stochastic process in which a variable tends to revert in return to a long-term mean or equilibrium value over time (Dixit & Pindyck, 1994). Since its main characteristic is its tendency to move away from the mean and then gradually return towards it, it is often used to model situations where a variable experiences short-term deviation from its mean but eventually returns to it. The process incorporates both a drift towards the mean and random fluctuations around it, and the most straightforward mean-reverting process is mathematically represented as (Dixit & Pindyck, 1994):

$$dx = \eta(\bar{x} - x)dt + \sigma dz, \tag{1.3}$$

where dx represents the change in the variable x over time, η is the speed of reversion, indicating how fast x returns to its average $\bar{x}$, σ represents the volatility of the process, and dz is a random increment, similar to the Wiener Process. The expected change in x depends on the difference between x and $\bar{x}$. If x follows this mean-reverting process and starts at x_0, its expected value at any future time t can be calculated as (Dixit & Pindyck, 1994):

$$\varepsilon[X_t] = \bar{x} + (x_0 - \bar{x})e^{-\eta t}, \tag{1.4}$$

The variance captures the variability in x around its average $\bar{x}$. For this mean-reverting process, the variance of $(x_t - \bar{x})$ is given by (Dixit & Pindyck, 1994):

$$v[x_t - \bar{x}] = \frac{\sigma^2}{2\eta}(1 - e^{-2\eta t}), \tag{1.5}$$

As time progresses, the expected value $\varepsilon[X_t]$ approaches $\bar{x}$, indicating that in the long run, x tends to settle closer and closer to its average value. The variance $\upsilon[x_t - \bar{x}]$ converges to $\frac{\sigma^2}{2\eta}$. In the long run, the variation in x decreases, suggesting that it becomes less volatile, meaning that the variable's fluctuations become less pronounced, and it gravitates towards its average.

1.3. Valuation of Options

1.3.1. Black-Scholes-Merton Model

In the early 1970s, Fisher Black, Myron Scholes, and Robert Merton derived an options valuation formula assuming the market is efficient and following certain assumptions, namely the fact that the underlying stock follows a continuous Geometric Brownian Motion, which means that its price fluctuations are random and follow a specific statistical pattern; there are no transaction costs or taxes; the risk-free rate is constant and known; the market is efficient, and there are no arbitrage opportunities. This formula is widely used as a mathematical model for estimating the theoretical price of European-style options, which can only be exercised at the expiration date.

The formula for pricing a European call option is then given by:

$$c_t = S_t * e^{-q\tau} * N(d_1) - K * e^{-r\tau} * N(d_2), \tag{1.6}$$

and for pricing the European put options, the formula is:

$$p_t = K * e^{-r\tau} * N(-d_2) - S_t * e^{-q\tau} * N(-d_1), \tag{1.7}$$

where $d_1 = \frac{ln\left(\frac{S}{K}\right)+\left(r-q+\frac{\sigma^2}{2}\right)\tau}{\sigma\sqrt{\tau}}$, $d_2 = d_1 - \sigma\sqrt{\tau}$, $\tau \coloneqq T - t$ is the option's time to maturity, σ is the annual volatility of the underlying asset, r is the continuously compound short-term risk-free interest rate, q is the continuously compounded dividend yield of the underlying asset, and N represents the cumulative standard normal distribution function.

This formula has been foundational for various real options models, notably the binomial pricing model, the Black-Scholes-Merton Model, and the Monte Carlo Simulation.

1.3.2. Binomial Model

The binomial model, developed by Cox, Ross, and Rubinstein in the 1970s, is a valuation method for options, particularly American-style options that allow exercise before expiration.

The model breaks down an option's life into discrete time intervals and constructs a lattice-like structure of possible stock price movements. By assuming a constant interest rate, no taxes, and no transaction costs, the model discretizes time intervals to model stock price changes.

An European-style option with exercise price K and maturity $T(\geq 1)$ can be valued recursively by denoting $S_{i,j} = S_{0,0} * u^j * d^{i-j}$ the underlying asset price in period i, (with $i = 0,1,\dots,n$) if there exists j (with $j = 0,1,\dots,i$) up moves of the underlying asset. To reflect the potential price scenarios, the up (u) and down (d) movements can be calculated as:

$$u = e^{\sigma\sqrt{\Delta t}}, \quad (1.8)$$

and

$$d = e^{-\sigma\sqrt{\Delta t}}, \quad (1.9)$$

where σ is the volatility of the underlying asset price and the length of the time interval $\Delta t = \frac{T-t}{n}$ years being T the maturity and n the number of periods. The exponential factor accounts for the potential fluctuations in the price.

The binomial model can be extended to multiple periods, creating a flexible lattice structure representing various potential stock price paths. This lattice adapts to different price movements, providing a visual representation of how stock prices evolve and, consequently, how option values fluctuate under different market conditions:

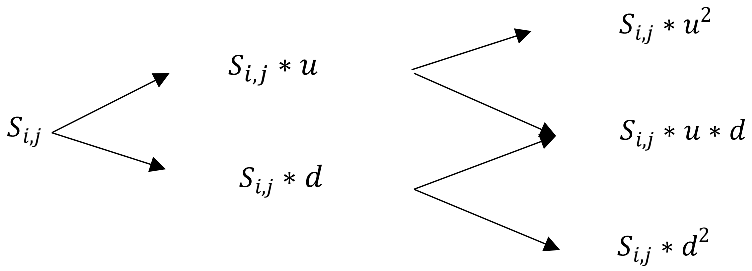

Figure 1. Binomial Tree of the Stock Price

In the real world, investors demand compensation for bearing risk, which affects option prices. However, in the risk-neutral world, probabilities are adjusted so that the expected return on the option matches the risk-free rate. This allows for risk-neutral valuation even in the presence of uncertainty. The risk-neutral probability (p) acts as a bridge between the real world and risk-neutral scenarios, ensuring the expected return on the option matches the risk-free rate (r_f) allowing consistent risk-neutral Valuation. Mathematically, this relationship is expressed as follows:

$$p = \frac{e^{(r_f-q)\Delta t} - d}{u-d}, \quad (1.10)$$

where the r_f represents the risk-free rate and Δt the length of each time step.

At the maturity date $(i = n)$, the option value equals its intrinsic value. For a call option $(c_{i,j})$:

$$c_{i,j} = [S_{i,j} - K], \tag{1.11}$$

and for a put option $(p_{i,j})$:

$$p_{i,j} = [K - S_{i,j}]. \tag{1.12}$$

During the backward progression through the lattice, the model calculates options values at each node by considering the exercise and non-exercise possibilities. Using the risk-neutral probabilities and the expected value of the option in the next time step, at any time before the maturity date $(0 \leq i \leq i - 1)$, the call option value, by backwardation, is equal to

$$c_{i,j} = e^{-r*\Delta t}[p * c_{i+1,j+1} + (1 - p) * c_{i+1,j}]. \tag{1.13}$$

To evaluate an American-style option, it is considering the same payoff as a European-style option, but now, it is necessary to consider the possibility of early exercise. In this way, at any time before the maturity date of the option $(0 \leq i \leq n - 1)$, the call option value is equal to:

$$c_{i,j} = max\left[(S_{i,j} - K); e^{-r\Delta t}\left[q_u * c_{i+1,j+1} + (1 - q_u) * f_{i+1,j}\right]\right]. \tag{1.14}$$

1.4. Renewable Energy Projects

Renewable energy projects, characterized by high capital costs and uncertainty in factors such as electricity prices, mainly benefit from the Real Options Approach (ROA). The ROA gained relevance in this field when it was introduced competitiveness in the electricity market (Dixit & Pindyck, 1994). Currently, the ROA is widely applied to various renewable energy projects, including solar, wind, and hydropower (Murgas et al., 2021), and several studies have provided analytical solutions for uncertainties, with electricity prices being considered the most important, particularly in hydropower projects (Bøckman et al., 2008). Furthermore, models have been developed to simultaneously study the effects of multiple uncertainties, such as wind generation quantity, electricity prices, and subsidies (Abadie & Chamorro, 2014).

1.4.1. Wind Energy Projects and the Weibull Distribution

In the wind power energy field, the volatility of wind speed is a crucial uncertainty (Murgas et al., 2021). Wind speed typically follows a Weibull distribution, allowing the determination of average wind speeds at a specific location. The Weibull distribution is commonly used to model the distribution of a continuous random variable.

Mathematically, the probability density function (PDF) of a Weibull distribution is represented as (Romanuke, 2018):

$$p(s,b,a) = \left(\frac{b}{a}\right) * \left(\frac{s}{a}\right)^{b-1} e^{-\left(\frac{s}{a}\right)^{b}}, \tag{1.15}$$

where s is the random variable (e.g., wind speed), b is the shape parameter (related to the range of wind speed variations), and a is the scale parameter (related to the mean wind speed).

The integral of the probability density functions (PDF)

$$\int_0^{\infty} p(s,b,a)ds = 1, \tag{1.16}$$

gives the cumulative probability up to a specific value of s. The cumulative distribution function is often used to calculate probabilities of events within a specific range.

The Weibull distribution allows us to determine how frequently different wind speeds occur at a location within a specific average wind speed. Thus, it is a tool for analyzing wind energy potential and optimizing wind energy projects.

However, the Weibull distribution might not perfectly match the power curve of a wind turbine - a graph that shows the relationship between the wind speed and the amount of electrical power the turbine can generate – which indicates the turbine's efficiency in converting wind energy into electricity). Wind speed distributions are often thinner than the power curve, meaning that even though wind speeds of various magnitudes are registered, the actual power generated by the wind turbine might not fully utilize the entire range of wind speeds.

The expected power generated by a wind turbine is the average amount of electricity that the turbine is likely to produce under normal wind conditions – considering the statistical distribution of wind speeds at the location is calculated by integrating the product of the power curve $w(s)$ and the Weibull distribution $p(s,b,)$ an over all possible wind speeds:

$$\int_0^{\infty} w(s)p(s,b,a)ds. \tag{1.17}$$

This provides a more accurate estimate of the turbine's average performance under real-world wind conditions, accounting for the variability of wind speeds over time.

1.5. The Role of Public Authorities

The advantages of wind power energy, including lower life cycle greenhouse emissions and minimal environmental impact, have been emphasized (Liu et al., 2021). However, the higher upfront costs compared to operational costs can pose challenges and affect project attractiveness to investors. Governments often intervene by offering support to mitigate price and quantity risks faced by investors, as wind power projects hold significant economic potential (Abadie & Chamorro, 2014). Public support schemes, such as feed-in tariff systems, tax benefits, subsidies, and tradable green certificates, can accelerate renewable energy investments (Barbosa et al., 2020).

These schemes can be broadly classified into two main categories: regulatory price mechanisms and regulatory quantity-based mechanisms. Regulatory price-based mechanisms entail governments establishing a specific price for each unit of energy generated from renewable sources. In the context of wind energy projects, this means that for every kilowatt-hour (KWh) of electricity produced by a wind turbine, the government assures a fixed payment to the project owner. This payment mechanism is commonly called a Feed-in Tariff or Feed-in Premium. In contrast, regulatory quantity-based mechanisms focus on achieving predetermined targets for the proportion of renewable energy within the overall energy mix. The governments set a desired level of renewable energy generation, often termed the Renewable Energy Share in Electricity (RES-e) target. Within this framework, wind energy generators are awarded tradable certificates, often known as Renewable Energy Certificates (RECs) or Guaranteed of Origin (GOs), based on their actual renewable energy production. These certificates are tangible evidence that a specific quantity of electricity has been generated from renewable sources.
The choice between these mechanisms often depends on policy objectives, market conditions, and specific national or regional goals for renewable energy deployment.

One of the most crucial support schemes is a Feed-in Tariff (FiT), a price-based scheme with long-term contracts whereby an investor receives a fixed or variable remuneration for a lengthy period, usually 15-20 years (Barbosa et al., 2020).

This mechanism gives a sense of assurance and predictability to investors, thereby mitigating the financial risks associated with investments in renewable energy. Feed-in Tariffs can be seen as a form of real options. Theoretical models have illustrated that FiTs can serve as an effective means to stimulate the deployment of renewable energy resources. Nevertheless, the efficacy of FiTs hinges on several factors, including the tariff rate level, the duration of the tariff, and the structural design of the incentive scheme. For instance, if a government establishes a FiT rate of €0.20 per kilowatt-hour (kWh) for wind energy projects, these projects are guaranteed to receive €0.20 for every kWh of electricity they generate over a specified timeframe. Assuming the cost of electricity generation for these projects stands at €0.15/kWh, the project would yield a profit of €0.05/kWh, factoring in the FiT.

The real option value of the FiT can be quantified as the difference between the anticipated profit of a project with the FiT and the expected profit of the same project operating without the FiT. In the hypothetical example provided, the expected profit of the project without the FiT would amount to zero, as the cost of electricity generation exceeds the prevailing market price. Consequently, a positive real option value of the FiT emerges, indicating the economic viability of the renewable energy project.

CHAPTER 2

Methodology

2.1. Data

One key element to performing an accurate evolution of onshore wind energy investment projects and, consequently, knowing the best region in our country to invest in this kind of energy is the utilization of reliable and complete data. In this sense, it is imperative to choose data from trustworthy data sources to use it carefully. Thereby, most of the information will be collected from the database of the Portuguese government to calculate the government benefits. To know what the most used technologies are, the lifetime of the project, and its technical characteristics to make a correct evaluation of the initial and operating costs, I will use IEA (International Energy Agency) and data from IRENA (International Renewable Energy Agency). To make a correct estimation of wind dynamics, I used data from REN (Rede Energetica Nacional). Historical data about electricity prices and energy output will be extracted from OMIP (Regulated Market Operator), belonging to MIBEL (Iberian Electricity Market). Regarding the renewable energy sector and macroeconomic data, some additional reliable statistical websites will be used, such as Pordata, Eurostat, Statista, GWEC (Global Wind Energy Consul), and APREN (Associação Portuguesa de Energias Renováveis). The regions considered in the study will correspond to NUTS III (Nomenclatura das Unidades Territoriais para Fins Estatísticos).

2.2. Parameter Specification

In the upcoming section, I will detail my methodology for modeling the uncertainties of Electricity Price and Wind Load Factor.

2.2.1. Electricity Price

Electricity prices are simulated with the aid of either deterministic fundamental models, predominantly linear optimizing models for the calculation of long-term equilibrium prices, or stochastic processes, such as mean-reversion models for short and mid-term price analysis (Möst & Keles, 2010).

Several scholars have studied the modeling of electricity prices, and one commonly observed aspect of the electricity spot price is its mean-reverting process. Electricity price series are characterized by small random movements around a trend (Scarcioffolo et al., 2018). The presence of peaks can be explained by the physical characteristics of electricity, namely the fact that electricity is an asset that cannot be stored after generation, thus causing the price of electricity to become quite volatile with several peaks over time.

As follows, the price of electricity is inherently unpredictable, following a stochastic process over time. To model this process, I am adopting the approach presented by Scarcioffolo et al. (2018). To capture the behavior of electricity prices, I employ the mean-reverting diffusion process:

$$dS = \eta(\alpha - \ln(S))Sdt + \sigma Sdz. \quad (2.1)$$

In this equation, S represents the stochastic variable (electricity price), $\alpha = \ln(\bar{S})$ represents the long-run equilibrium level, indicating where electricity prices tend to gravitate, η is the reversion speed governing how quickly the price reverts to the long-term mean, σ denotes the volatility of the process, reflecting random fluctuations in price, dz is the standard Weiner Process with a normal distribution where $dz = \varepsilon\sqrt{dt}$ and dt represents the infinitesimal time increment of the process.

To simulate the next value of electricity price, S_t, at time t I utilize the following equation, as proposed by Scarcioffolo et al. (2018):

$$S_t = exp\left\{ln[S_{t-1}]e^{-\eta\Delta t} + \left[\ln(\bar{S}) - \frac{\sigma^2}{2\eta}\right](1 - e^{-\eta\Delta t}) + \sigma\sqrt{\frac{1-e^{-2\eta\Delta t}}{2\eta}}N(0,1)\right\}. \quad (2.2)$$

This equation incorporates both the mean-reverting behavior and random noise. Finally, effective use of this model necessitates the estimation of its parameters (η, σ, α). For that, I employ ordinary least squares (OLS) to estimate these parameters using the formula:

$$ln\left(\frac{S_t}{S_{t-1}}\right) = (1 - e^{-\eta\Delta t})\left(\ln(\bar{S}) - \frac{\sigma^2}{2\eta}\right) + (e^{-\eta\Delta t} - 1)lnS_{t-1}. \quad (2.3)$$

In this context, $a = (1 - e^{-\eta\Delta t})\left(\ln(\bar{S}) - \frac{\sigma^2}{2\eta}\right)$ represents the long-term equilibrium level, which represents the price to which electricity tends to gravitate, and $b - 1 = (e^{-\eta\Delta t} - 1)$. The speed of reversion, volatility, and long-term mean are given by:

$$\eta = -\frac{\ln(b)}{\Delta t}, \quad (2.4)$$

$$\sigma = \sigma_\varepsilon\sqrt{\frac{2\ln(b)}{(b^2-1)\Delta t}}, \quad (2.5)$$

and

$$\bar{S} = exp\left[\frac{\left(a + \frac{\sigma_\varepsilon^2}{(1+b)}\right)}{1-b}\right]. \quad (2.6)$$

2.2.2. Wind Load Factor

The Wind Load Factor represents the ratio of the actual power generation of a wind turbine to its rated or potential capacity. This factor considers the fluctuations in power output due to wind speed variations.

The wind load factor is intimately connected to wind speed. Wind turbines generate electricity by harnessing the kinetic energy of the wind, and this energy production is directly proportional to the cube of the wind speed (Abadie & Chamorro, 2014). As the wind speed changes, the energy output of the turbine also varies accordingly. Therefore, understanding the Wind Load Factor is of paramount importance for accurately estimating the energy production of wind turbines. While wind speed is a fundamental parameter in assessing wind energy potential, the Wind Load Factor offers distinct advantages in the Valuation and comparison of onshore wind energy projects: Unlike using raw wind speed data, the Wind Load Factor takes into consideration the efficiency of the wind turbine and its ability to convert wind energy into electricity, making it a more comprehensive and meaningful metric when evaluating the performance of wind energy projects and provides a more accurate representation of what are the bests regions to generate electricity from wind resources.

The Wind Load Factor is not a constant value but exhibits stochastic (random) behavior. This stochasticity arises from the inherent variability of wind, which can change unpredictability over time. To model this stochastic behavior and capture the fluctuations in the Wind Load Factor, a theoretical model is employed. In this case, I will use the work of Abadie & Chamorro (2014) :

$$W_t = g(t) + W_m + \sigma_W W_m dW_t^W. \tag{2.7}$$

This model incorporates deterministic trends $g(t)$ and W_m and stochastic fluctuations ($\sigma_W W_m dW_t^W$), capturing predictable trends and the inherent randomness associated with wind speed variations. The term $g(t)$ represents the deterministic trends that are predictable and systematic. These trends could arise from seasonal variations, diurnal patterns, or long-term climate cycles. W_m is a constant that represents a baseline or reference value like a predefined performance level. On the contrary, the stochastic fluctuations introduce randomness into the model. It encapsulates the inherent variability and unpredictability associated with wind behavior. In this way, σ_W represents the volatility of the Wind Load Factor. It quantifies how much the factor tends to fluctuate randomly due to changes in wind conditions, and dW_t^W is an increment in a Wiener Process representing the continuous-time stochastic fluctuation, introducing the random element into the equation and reflecting the unpredictable nature of wind speed and its impact on energy generation.

This holistic approach provides a more accurate representation of how wind turbines operate in real-world conditions, granting a more accurate valuation of onshore wind energy projects.

2.3. The Real Options Model for Valuate Onshore Wind Energy Projects

Regarding that the primary goal of this master thesis lies in answering the question, "What are the best zones in Portugal to invest in the construction of wind farms to produce onshore wind energy?" and bearing in mind the complexity of the theme, I will use two scenarios: first, a "Now-or-never perspective" using the Standard Net Present Value (NPV) and, secondly, I will consider that the investor can choose their optimal strategy, this is, I will embed flexibility in the model, and, then, I will focus my study on the evaluation of onshore wind energy investments through the binomial multi-period approach, which is a technique applied to evaluate derivatives considering discrete times, using the approach proposed by Cox et al. (1979).

The wind speed, which varies depending on the geographical location, is one of the variables that most affect the wind turbine's performance. Hence, prior to initiating the project's Valuation, it is imperative to scrutinize the wind turbine's performance within their specific geographic context. This entails an initial assessment of environmental elements, encompassing meteorological and technical factors. Subsequently, a comprehensive economic and financial analysis is conducted to evaluate the wind energy investment prospects while quantifying associated uncertainties.

2.3.1. The Value of the Investment Without Flexibility

To realize the investment, the economic rule that must be applied is to calculate the present value of all future revenue streams generated by the wind energy project and discount them back to their current value using the discount rate. I denote I_0 as the initial investment that investors can amortize over time and, by O&M, the annual costs essential for maintaining the wind turbines. The installed capacity is denoted by c.

I will base my calculation on the model used by Abadie & Chamorro, (2014). I will start by calculating the wind generation for a given period, t, based on the expected mean load factor over the year (W_m), the capacity factor (c), the number of hours in a day (24), and the number of days x_i in a month i (with $i = 1, \dots, 12$). The variable $g(i)$ represents the seasonality in the load factor over the $i - th\ month$.

Accordingly, the expected annual energy production (P_j) from the wind farm amounts to

$$P_j = \sum_{i=1}^{i=12} c * 24 * x_i * W_m * g(i), \tag{2.8}$$

being $j = 1, \dots, 20$, the number of years of the project.

Secondly, I consider that every year, a wind turbine is expected to lose 1.6% of its efficiency (Lee & Zhao, 2022) and, then I subtract this value from the annual energy production. By multiplying these values by the spot electricity market price (P). I calculate the revenue generated from selling the energy produced by the wind:

$$Rev_j = (P_j * (1 - rate\ of\ efficiency\ loss)) * P. \tag{2.9}$$

By subtracting the O&M costs, I determine the annual cash flows.

On the other side, using the discount factor for each year, I compute the present value of the revenues (PV_{Rev}):

$$PV_{Rev} = Rev_j * \frac{1}{(1+r)^j}. \tag{2.10}$$

Finally, the Net Present Value (NPV) of the project is calculated as follows:

$$NPV = \sum_{i=1}^{j} \frac{Rev_j - O\&M_j}{(1+r)^j} - I_0, \tag{2.11}$$

where r is the discount rate that considers the riskiness of wind farm investment, and I_0 is the initial investment cost.

2.3.2. Valuation of the Investment with Flexibility

Although the NPV analysis is a valuable tool for evaluating straightforward projects with deterministic cash flows, it falls short when dealing with complex, uncertain, and strategic projects. The real options provide a more comprehensive and flexible approach to project valuation, allowing decision-makers to adapt and make more informed decisions in the face of uncertainty and changing conditions.

Primarily, I will focus my study on the Valuation of onshore wind energy investments by applying the binomial multi-period approach developed by Cox et al. (1979). In the field of quantitative finance, the binomial lattice model serves as a powerful tool for assessing derivatives within a discrete time framework. For the calculation of the underlying asset value lattice, I consider the underlying asset of a real option to be represented by the present value of the investment, denoted as S_t. To apply the binomial lattice model, I divide the investment's maturity period, denoted as T, into n equal time intervals, each of length $\Delta t = \frac{T}{n}$. The investor decides at the end of each node:

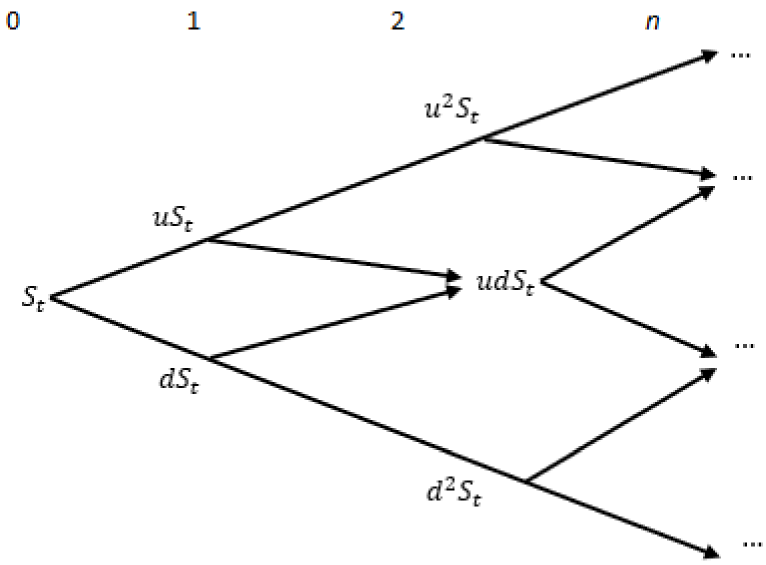

Figure 2. Binomial Tree of the Underlying Asset

The asset's value evolves as a binary random walk with two movements: an upward movement with a risk-neutral probability p and a downward movement with a probability $(1-p)$. The parameters u and d are used to represent the upward and downward movements, with certain conditions to avoid arbitrage: $d < 1 + r_f < u$ with $u > p + 1, d < 1$.

To create the option valuation lattice, I will start with calculating the risk-neutral probability p, essential in option pricing to account for risk, applying equation (1.10).

Thus, the value of the option is established through backward induction, meaning starting from the end of the investment horizon, and payoffs at terminal values are the option's intrinsic value:

$$c_{i,j} = max[S_{i,j} - K, 0], \tag{2.12}$$

for a call option and,

$$p_{i,j} = max[K - S_{i,j}, 0], \tag{2.13}$$

for a put option.

The potential payoff for each scenario is determined by comparing the future potential gains, adjusted to their present value, with the initial investment cost, also adjusted to their present value. This comparison involves assessing whether the potential gains, when discounted, exceed the initial investment cost. If they do, the payoff is positive, demonstrating that exercising the option is financially advantageous.

Conversely, suppose the potential gains, after discounting, are less than the initial investment cost. In that case, the resulting payoff is negative, indicating that continuing with the project would result in a financial loss. In such circumstances, the investor may decide not to proceed with the investment and may opt to exercise the option to abandon it for a salvage value.

The project value with flexibility is then equal to the present value of the investment plus the value of the option, and the total expanded net present value then will be:

$$Expanded\ NPV = Standard\ NPV + Option\ value. \tag{2.14}$$

2.3.3. Valuation Using a Feed-in Tariff

As Merton (1973) showed, the exercise of an option before the maturity is not optimal under the zero dividends scenario because, by waiting until maturity, we might gain more value from the option. However, if we consider government support, namely a feed-in tariff, the scenario can change, and the investor can decide to exercise the option before maturity. To understand the impact of feed-in tariffs (FiTs) on the valuation of onshore wind energy projects, it can be used the model presented by Barbosa et al. (2018).

In this way, assuming that the electricity market price P follows a Geometric Brownian Motion (GBM):

$$dP = \mu P dt + \sigma P dW, \tag{2.15}$$

where μ is a deterministic drift under the risk-neutral measure of the future market electricity price, σ is the volatility, and dW is the standard Brownian motion process.

Considering that $V(P,F)$ is the value of the project and applying Itô's Lemma, it will be the Ordinary Differential Equation (ODE):

$$\mu * P * \frac{\partial V(P,F)}{\partial P} + 0.5\sigma^2 * P^2 * \frac{\partial^2 * V(P,F)}{\partial * P^2} - r * V(P,F) + \Pi(P,F) = 0, \quad (2.16)$$

where $\Pi(P,F)$ is the profit flow of the renewable energy project with a FiT for one unit of energy, and it is equal to the market price of electricity if the market price is above the price floor and equal to the price floor if the market price is below the price floor.

The general solution to the ODE is:

$$V(P,F) = \begin{cases} A_1 * P^{\beta_1} + A_2 * P^{\beta_2} + \frac{F}{r} & for\ P < F \\ B_1 * P^{\beta_1} + B_2 * P^{\beta_2} + \frac{P}{r-\mu} & for\ P \geq F \end{cases}, \quad (2.17)$$

where A_1, A_2, B_1, and B_2 are constants determined by the following boundary conditions:

i) For the region where the market price is below the price floor $(P < F)$, the value of the project should converge to $\frac{F}{r}$ when $P \rightarrow 0$. To this happen, $A_2 = 0$ because $\beta_2 < 0$.

ii) In the region where the market price is above the price floor $(P > F)$, the value of the project should converge to $\frac{P}{r-\mu}$ when P goes to infinity. B_1 should be zero, and the value of the project should be:

$$V(P,F) = \begin{cases} A_1 * P^{\beta_1} + \frac{F}{r} & for\ P < F \\ B_2 * P^{\beta_2} + \frac{P}{r-\mu} & for\ P \geq F \end{cases}, \quad (2.18)$$

iii) The two regions above meet $(P = F)$.

From these boundaries conditions A_1 and B_2 are derive as follows:

$$A_1 = \frac{F^{1-\beta_1}}{\beta_1 - \beta_2} * \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r-\mu}\right), \quad (2.19)$$

$$B_2 = \frac{F^{1-\beta_2}}{\beta_1 - \beta_2} * \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r-\mu}\right). \quad (2.20)$$

β_1 and β_2 are calculated as follows:

$$\beta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2}\right)^2 + \frac{2*r}{\sigma^2}\right)^{\frac{1}{2}}, \tag{2.21}$$

$$\beta_2 = \frac{1}{2} - \frac{\mu}{\sigma^2} - \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2}\right)^2 + \frac{2*r}{\sigma^2}\right)^{\frac{1}{2}}. \tag{2.22}$$

Accordingly, with a finite duration of the FiT contract ($T\ years$), which is the case, the investor has the opportunity to earn F (price floor) for every unit of energy produced if the market price P is below the price floor. In this way, the value of the project until T, whereby the producer benefits from the finite guarantee of the FiT contract, is:

$$V_T(P,F) = \begin{cases} A_1 * P^{\beta_1} * N\left(d_{\beta_1}\right) + \frac{F}{r} * \left(1 - e^{-r*T} * \left(1 - N(d_0)\right)\right) - \\ -B_2 * P^{\beta_2} * N\left(d_{\beta_2}\right) - \frac{P}{r-\mu} * e^{-(r-\mu)*T} * N(d_1) \quad for\ P < F \\ -A_1 * P^{\beta_1} * \left(1 - N\left(d_{\beta_1}\right)\right) - \frac{F}{r} * e^{-r*T} * (1 - N(d_0)) \\ +B_2 * P^{\beta_2} * \left(1 - N\left(d_{\beta_2}\right)\right) + \frac{P}{r-\mu} * (1 - e^{-(r-\mu)*T} * N(d_1))\ for\ P \geq F \end{cases}, \tag{2.23}$$

where $N(.)$ is the cumulative normal integral and

$$d_\beta = \frac{ln\left(\frac{P}{F}\right) + \left(\mu + \sigma^2\left(\beta - \frac{1}{2}\right)\right) * T}{\sigma\sqrt{T}}, \tag{2.24}$$

where β_1, β_2, 0, and 1 can substitute β.

After the end date of the scheme, the producer receives a cash flow with a present value equal to $\frac{P}{r-\mu} * e^{-(r-\mu)*T}$, which corresponds to selling energy to the market for the remaining lifetime of the project.

Thus, the value of the project, which includes the period with the FiT contract and therefore, is given by the following equation:

$$V_F(P,F) = V_T(P,F) + \frac{P}{r-\mu} * e^{-(r-\mu)*T}. \tag{2.25}$$

CHAPTER 3

Case Study

3.1. Parameters Estimation

3.1.1. Electricity Price

To estimate the electricity price, I use 31,271 prices of Portuguese Electricity Futures extracted from the OMIP webpage. The sample period goes from 2 January 2017 to 30 December 2022. The futures prices correspond to the settlement prices, fixed by OMIP daily. I only consider the MIBEL PTEL Base Load Futures Contracts with monthly and yearly delivery. The MIBEL PTEL Base Load Futures are futures contracts that allow participants to buy or sell electricity at a predetermined price for a specific future delivery period and are related to the electricity market for Portugal. These have maturities of up to 10 years (120 months), thus representing long-term future prices, distinct from short-term forward prices or immediate day-ahead prices. Observed electricity prices are a comprehensive reflection of the complex interplay of factors influencing the electricity market. It implies that market participants, such as power plant operators, investors, and consumers, are making decisions based on these prices, as they incorporate all the relevant market information available at the time (such as fuel prices).

I estimate the parameters underlying the mean reversion model using daily futures prices. Since my data is daily, my time increment (Δt) would be one day. Firstly, I calculate the logarithmic returns for the electricity price data to assess the percentage change in electricity prices over time.

Independent variables $(a, b - 1)$ for an ordinary least squares (OLS) regression model are prepared, and the dependent variable for the OLS regression model corresponds to the Logarithmic Returns of the electricity price. Furthermore, I calculate the parameters representing the speed of reversion (η), the volatility (σ), and the long-term mean $(\bar{S})$ based on the regression results and statistical properties of the data.

The $R^2 = 90\%$ indicates that the model explains a substantial variation in the dependent variable. The low *p-values* and the higher *F-statistic* indicate that the model is statistically significant. The speed of reversion (η) is 0.00098 and represents how quickly a stochastic variable returns to its long-term mean, suggesting a slow reversion rate. The volatility $(\sigma) = 17\%$ measures how much the price of electricity varies over time, suggesting a moderate level of volatility. The long-term mean $(\bar{S}) = 4.5145e - 07$ represents the equilibrium level that the electricity price tends to revert over time, and this value suggests that the long-term mean is very close to zero. Overall, these results indicate that the electricity price tends to revert to a very long-term mean with a slow reversion speed and moderate volatility.

Lastly, I estimate the spot electricity price for t_0 from the futures contracts with the nearest maturity using a log-normal model and assuming that the logarithm of the spot price follows a normal distribution:

$$S_t = F_t * e^{-\eta \Delta t}, \tag{3.1}$$

with

$$F_t = e^{\ln(S_{t-1}) - \eta \Delta t) + (\ln(\bar{S}) - \frac{\sigma^2}{2\eta})(1 - e^{-\eta \Delta t}) + \sigma \sqrt{\frac{1 - e^{-2\eta \Delta t}}{2\eta}} * \varepsilon}. \tag{3.2}$$

The spot price at t_0 (S_t) equals the implied futures price at $t_0 (F_t)$ multiplied by a factor that decays exponentially over time $(e^{-\eta \Delta t})$. The implied futures price is equal to the observed futures price at $t - 1$ (S_{t-1}) plus a correction term that accounts for the speed of reversion (η), the long-term mean $(\bar{S})$, the volatility (σ), and a random variable (ε) with a normal distribution. According to the model and the information available from future contracts with the nearest maturity, it is expected that the spot price for electricity at t_0 is 157.33€.

3.1.2. Wind Load Factor

To determine how the Wind Load Factor at a future time point is influenced by both deterministic factors $g(t)$ and (W_m) and random fluctuations, I use the model based on Abadie & Chamorro (2014):

$$W_{t+\Delta t} = g(t) + W_m + \sigma_W \sqrt{\Delta t} W_m \varepsilon_t^W. \tag{3.3}$$

The sample comprises the monthly ratios between output electricity and installed capacity for each region (NUTS III) of Portugal from 2010 until 2022, and this is 156 observations for each region.

Based on Abadie & Chamorro (2014), firstly, I take out the seasonal component of the original series, proceeding with the estimation on the deseasonalized series.

The estimated average value $(\widehat{W}_m)$ and the standard deviation (σ_W) for the different regions are present in Table 1:

	$\widehat{W}_m$	σ_W
Alto Minho	29%	10%
Cavado	0%	0%
Ave	25%	9%
Alto Tâmega	28%	9%
Área Metropolitana do Porto	28%	12%
Tâmega e Sousa	28%	10%
Douro	26%	8%
Terras de trás os montes	33%	8%
Algarve	31%	5%
Oeste	29%	3%
Região de Aveiro	16%	6%
Região de Coimbra	29%	6%
Região de Leiria	30%	5%
Viseu Dão Lafões	25%	9%
Beira Baixa	28%	7%
Beiras e Serra da Estrela	29%	7%
Área Metropolitana de Lisboa	29%	5%
Alentejo Litoral	22%	5%
Baixo Alentejo	28%	4%
Lezíria do Tejo	37%	6%
Alto Alentejo	25%	5%
Alentejo Central	0%	0%
Médio Tejo	31%	4%

Table 1. Estimate Wind Load Average and Standard Deviation for the Regions

3.2. Analysis of Geographical and Technical Conditions

Considering that there is a strong relationship between energy production and the Wind Load Factor, I consider this latter factor to examine the advantage of installing a wind farm in a particular region. From the data above, the average load factor for the "Médio Tejo" region is one of the highest. Thus, I consider an assumption that, based on this factor, the "Médio Tejo" region is generally favorable to investing in wind farms, so I will start by analyzing this region and then replicate the model for other regions.

3.2.1. Determination of Costs

Currently, the initial cost to install and operate a wind farm includes mainly turbine costs, foundations, electrical installation, connections to the electrical grid, consultancy fees, land costs, financing, security, road construction, and operating and maintenance costs (European Environment Agency, 2009). As the costs depend on various factors, they tend to vary between regions. However, I will consider the onshore wind weighted average costs to Portugal and assume that this initial cost will be equal for all regions.

According to IEA (International Energy Agency), at the end of 2022, the cumulative installed Capacity in Portugal was 5,671 MW distributed over 267 wind parks, representing 2,836 wind turbines (International Energy Agency, 2021). Considering this, I will consider, for the calculations, an onshore wind farm with an installed capacity of $c = 21MW$. Additionally, I will consider a useful lifetime of 20 years.

To compute the total cost, I consider that the fixed annual operating and maintenance costs (O&M) grow at a riskless rate of return of 2%/year. The rate of return considered will be the preliminary rate of return before taxes set by ERSE and will be 4.3% (*Reuters: EDP.LS Bloomberg: EDP PL*, n.d.). I consider the official exchange rate from the European Central Bank in December 2022 (*Euro Foreign Exchange Reference Rates*, n.d.): €1=$1.0666, $1=0.9387€.

Accordingly, for a wind farm with a capacity of 21MW, I have the following summarized costs:

		Costs		
	Size	**Overnight total costs**	**Variable Costs**	**Fixed O&M**
Initial Data($/Kw)	1	1,718	0	27.57
Total (Kw)	21000	36,078,000		578,970
Case Study Data ($MW)	21	36,078,000	0	578,970
Case Study Data (€MW)	21	33,866,418	0	543,479

Table 2. Wind Farm's Costs

3.3. Valuation in a Now-or-Never Perspective

Considering all the data above, I calculated the expected annual energy production from a wind farm in "Médio Tejo".

I start by calculating the monthly expected energy production considering the equation (2.8):

$$33{,}866{,}418 * 0.3061 * 0.3125 * 31 * 24 = 1{,}494.80MW, \quad (3.4)$$

being this the expected energy production for January.

By replicating the calculation for all months, it is expected that the region of “Médio Tejo” has an annual energy production equal to 17,233MW in year 0. Appendix A shows the annual energy production for all regions.

After, I subtract the rate of loss for each year to calculate the revenues and the annual cash flows.

Table 3 summarizes the calculations of the annual cash flows for this region:

Médio Tejo				
Years	**Production**	**Revenues**	**Maintenance costs**	**Cash Flows**
0	17,233			
1	16,958	2,667,947	543,479	2,124,468
2	16,686	2,625,260	554,349	2,070,912
3	16,419	2,583,256	565,436	2,017,820
4	16,157	2,541,924	576,744	1,965,180
5	15,898	2,501,253	588,279	1,912,974
6	15,644	2,461,233	600,045	1,861,188
7	15,393	2,421,853	612,046	1,809,808
8	15,147	2,383,104	624,287	1,758,817
9	14,905	2,344,974	636,772	1,708,202
10	14,666	2,307,455	649,508	1,657,947
11	14,432	2,270,535	662,498	1,608,037
12	14,201	2,234,207	675,748	1,558,459
13	13,974	2,198,459	689,263	1,509,196
14	13,750	2,163,284	703,048	1,460,236
15	13,530	2,128,671	717,109	1,411,562
16	13,313	2,094,613	731,451	1,363,161
17	13,100	2,061,099	746,080	1,315,019
18	12,891	2,028,121	761,002	1,267,119
19	12,685	1,995,671	776,222	1,219,449
20	12,482	1,963,741	791,746	1,171,994

Table 3. Calculations of the Annual Cash Flows for the Region of “Médio Tejo”

Lastly, I calculated the NPV for this region:

$$NPV = \sum_{i=1}^{20} \frac{Rev_i - O\&M_i}{(1+r)^i} - I_0 = -10{,}772{,}981, \quad (3.5)$$

with $I_0 = 33{,}866{,}418€$ being the total initial investment cost for a wind farm with 21MW. According to the standard NPV analysis, this region is not attractive to investors, and consequently, they should not invest in wind farm projects.

However, it is essential to note that the NPV approach relies on specific assumptions about an "expected scenario.” It does not consider factors such as the value of managerial flexibility or the possibility of postponing the investment to wait for more favorable conditions, among others.

3.4. Valuation of Onshore Wind Energy Projects Using ROA

Applying real options analysis enhances investment decisions in onshore wind energy projects, potentially leading to alterations in investor choices regarding project realization. In this case, following the work of Loncar et al. (2017), I will consider in my analysis a multi-phased compound option framework encompassing expansion, repowering, contracting, and abandonment options.

The expansion option (European call option) will be evaluated in year 5, providing favorable outcomes in the initial years of operation. This approach allows the investor to potentially extend the wind farm’s capacity by 50% at a reduced technology cost, representing a 35% reduction compared to the initial investment, considering that over the years, it is expected that these costs will decrease (Renewable Energy Agency, 2022). Subsequently, in year 10, the repowering option (European call option) and the contracting option (European put option) will be considered. The repowering option accounts for replacing aging wind turbines, utilizing an investment cost reduced by 65% compared to the initial investment. Simultaneously, the contracting option grants the investor the choice to decrease capacity by 30% at an exercise price representing the saved value.

Further, throughout the project’s lifetime, an abandonment option (American put option) will be accounted for, enabling the investor to abandon the project and recoup the salvage value, which is anticipated to diminish over time. In this way, considering all the costs inherent to a wind farm, 85% of the total investment corresponds to the cost of the wind turbines. Over the years, the material will be depreciated at a depreciation rate corresponding to 25%/year. The investor can recoup this investment by selling the technology.

The region of “Médio Tejo" will continue to serve as the focus, with the present value of revenues (PV_{Rev}) from energy production acting as the underlying asset value. For this region, this is equal to €18,608,986. The volatility of this investment is directly linked to the volatility of the electricity price (17.03%), and I use a riskless rate of return equal to the risk-free rate: $R_f = 0.0403 = 4.03\%$. The useful lifetime of the project is assumed to be $T = 20$ years, and I assume that the real option can be exercised at the end of each year, so $n = 20$. Consequently, $\Delta t = 1$. The up and down probabilities are:

$$u = e^{\sigma\sqrt{\Delta t}} \approx 1.185660496, \tag{3.6}$$

$$d = e^{-\sigma\sqrt{\Delta t}} \approx 0.843411755. \tag{3.7}$$

Table 4 shows the resume of the initial parameters that will be considered in my analysis:

	Values	**Measures**
Time to Expiration Option (T)	20	years
Strike price (K)	33,866,418	Euros (for 21 MW of Capacity)
Volatility(σ)	17.03%	percentage
Risk-free rate (R_f)	4.03%	percentage
Exchange Rate (USD/EUR)	0.9387	
Number of Steps (n)	20.00	
Δt	1.00	
Up Factor (u)	1.185660496	
Down Factor (d)	0.843411755	
Rate of loss	1.60%	
Risk neutral probability (p)	0.577683	
Electricity price market	157.33	

Table 4. Initial Parameters for the Case Study

I create an underlying asset value lattice using the binomial multi-period model. In real option valuation, I construct an option valuation lattice, applying a backward induction approach. Initially, I generated a binomial tree to evaluate the option to abandon. At each final node, the option’s value corresponds to its intrinsic value, determined by the maximum asset value at the 20th period or the salvage value.

Under American exercise rules, investors choose to exercise the option if the exercise value exceeds the salvage value at each decision node.

Subsequently, I constructed a second binomial tree to evaluate the options for repowering and contracting in year 10. At each node, the investors select the option with the highest value. The Valuation of the option to repower is calculated by subtracting the cost of repowering and the wind farm's value in year 10. Similarly, the option to contract is computed by considering the wind farm's value at year 10, accounting for the contract rate and the scrap value.

Lastly, a third decision tree is developed to assess the option to expand in year 5, incorporating calculations involving the wind farm's value at year 5, the capacity rate, and expansion cost. The resulting value of the option, V^{RO}, for the evaluation of an onshore wind energy project in the "Médio Tejo" region will be the value in the third decision tree, which incorporate all previous option in one value and amounts to €55,002,938. Consequently, the Expanded Net Present Value (ENPV) is computed as the sum of the Net Present Value (NPV) and the value of the option, V^{RO}, resulting in €44,229,956. Considering these findings, the optimal investment strategy for this region involves refraining from exercising any options or repowering in year 10 if the conditions are the best or contracting under less favorable market conditions.

Moreover, by considering only the option to abandon, which has a value of €31,738,712, resulting in an ENPV equal to €20,965,730, I deduce that enhancing project flexibility leads to an increase in ENPV. Appendix B shows the results for every region of Portugal, and Appendix C shows the optimal strategy that can be used for the best market conditions scenario, the neutral scenario, and the worst market condition scenario.

3.4.1. Valuation of an Option with Feed-in-Tariff

In conjunction with the compound option analysis, I evaluate the investment's value for each region, incorporating the assumption of a government incentive, specifically a feed-in tariff (FiT) contract that serves as a finite guarantee. Under this framework, I consider a FiT established by the Portuguese government, set as 95€/MWh. (Jimeno, 2019).

Implementing the model outlined by Barbosa et al. (2018), I compute the total value of the project with a FiT using the following inputs:

Electricity market price (P)	157.33	€/MWh
Feed-in Tariff (F)	95	€/MWh
Drift (μ)	0.00098	
Volatility (σ)	17.03%	
Duração FiT (T)	15	Years

Table 5. Inputs for the Valuation of an Investment with FiT

Consequently, the value of the project $V_T(P, F)$ is determined to be 2,239€/MW over the initial 15 years of the project. For the subsequent years, I determined the cash flows at the project's conclusion as follows:

$$\frac{P}{r-\mu} * e^{-(r-\mu)*T} = 3{,}904€/MW, \qquad (3.8)$$

To determine the total value of a wind farm, I multiply this value by the average annual production. For the "Médio Tejo" region, this equates to €90,522,426. Then, I replicated the calculations for all regions across Portugal. Appendix D shows the results for all regions. Upon comparing the results, I deduce that the project value increases with enhanced investment flexibility through options. The prospects of government assistance significantly augment the project's value, providing several regions economically viable.

Conclusion:

In recent years, the energy sector has undergone significant transformations. The year 2022, the last year considered in my master thesis, proved notably challenging not only for consumers but also for energy producers and suppliers. The Ukraine-Russia conflict led to a surge in fuel prices, consequently inflating electricity prices. Against this backdrop of macroeconomic shifts globally and in Portugal, my research sought to provide comprehensive insights into the Valuation of onshore wind energy investments. My analysis extended across various regions in Portugal, enabling the identification of the most financially viable locations for potential wind energy projects.

During my analysis, I encountered limitations primarily stemming from the scarcity of detailed information on wind technologies and associated costs, necessitating the utilization of average assumptions. Additionally, reliance on data concerning market electricity prices, volatility, and discount rates posed an added challenge, given the potential inaccuracies in the forecasts. The limited data availability on the subject further complicated the calibration of the real options model. Moreover, recent shifts in the Portuguese government's renewable energy policies introduced uncertainty, rendering the accurate assessment of onshore wind energy projects using the real options approach challenging. To mitigate these limitations, extensive efforts were made to cross-verify information from various reliable sources, including leading companies, government publications, and major players within the electricity market.

Regarding the theoretical model, my analysis initially focused on valuation using the Standard Net Present Value (NPV). Subsequently, I introduce flexibility by incorporating an option to abandon, providing additional flexibility for decision-making. Then, I applied compound options, which entailed adding options to contract, expand, and repower the wind farm over the project's lifetime, thereby expanding the decision space available to investors. Furthermore, I evaluate projects considering investing when the government incentivizes investors, specifically through a FiT.

The results revealed that relying solely on the initial Valuation with the NPV, only the "Leziria do Tejo" region appeared attractive for investing in onshore wind energy projects. However, when considering the Valuation with real options, which included the possibility of abandoning the investment for a salvage value over the project's entire lifetime, the results indicated that nearly all regions of Portugal experienced a significant increase in their value, rendering them attractive for investment. Exceptions to this included the "Aveiro," "Viseu Dão Lafões," "Alentejo Litoral," "Alto Alentejo," "Alentejo Central," "Cavado," "Ave" and "Douro" regions. By adding compound Options, the value of the investment increased significantly, with only the “Aveiro," "Alentejo Central," and "Cavado" regions remaining unattractive for investors in this phase. The most attractive regions for investment were "Leziria do Tejo” and “Terras de Trás os Montes ."Considering government incentives, all regions experienced increased values, resulting in positive Expanded Net Present Value (ENPV), making me conclude that even when the market price exceeds the potential incentives provided by the government, such incentives can significantly enhance the investment’s value.

Throughout the project’s lifetime, the investor can make various decisions, adapting to more or less favorable market conditions. Overall, the results indicate that the expand option would not be exercised. In most regions, the repowering option could be exercised under the best market conditions. If not, the option to contract was recommended, followed by continued wind farm operations until the project’s end. The option to abandon could be exercised in regions with the lowest NPV after year 5 and after contracting operations in year 10, regardless of market conditions. Specifically, in the “Tâmega e Sousa” region, it was recommended not to exercise any option but to continue production in the wind farm under all market conditions.

In conclusion, my focus on the application of the real options approach and the consideration of the impact of government incentives aimed to make a meaningful contribution to research in the renewable energy sector, specifically within the context of onshore wind energy ventures. Further research could involve altering the inputs used to evaluate the options, potentially leading to more accurate decisions. Overall, the results for all regions aligned with the initial assumptions. One plausible explanation could be the use of uniform costs across all regions. In future research, a beneficial input could involve estimating costs for each region separately. In light of the work conducted in this master thesis, I am confident that all goals were achieved, making a positive contribution to research.

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Appendix

Appendix A

Regions	Annual Production
Alto Tâmega	14,077
Área Metropolitana do Porto	14,784
Oeste	15,406
Região de Aveiro	4,892
Região de Coimbra	15,072
Região de Leiria	15,504
Viseu Dão Lafões	11,246
Beira Baixa	14,989
Beiras e Serra da Estrela	15,443
Área Metropolitana de Lisboa	15,497
Alentejo Litoral	8,967
Baixo Alentejo	14,327
Lezíria do Tejo	25,603
Alto Alentejo	11,098
Alentejo Central	0
Médio Tejo	17,233
Cavado	0
Ave	11,715
Douro	12,174
Terras de Trás os Montes	20,483
Algarve	17,916
Alto Minho	14,984
Tâmega e Sousa	14,602

Table 6. Annual Energy Production per Region

Appendix B

Final Results					
Region	**NPV**	**Only the option to abandon**	**ENPV**	**Compound option**	**ENPV**
Alto Tâmega	-16,600,499	21,799,540	5,199,041	46,204,571	29,604,071
Área Metropolitana do Porto	-15,294,436	24,027,109	8,732,673	48,153,208	32,858,772
Oeste	-14,147,198	25,983,790	11,836,592	49,864,878	35,717,681
Região de Aveiro	-33,556,413	4,995,224	-28,561,189	27,539,843	-6,016,570
Região de Coimbra	-14,762,457	24,934,429	10,171,971	48,946,915	34,184,458
Região de Leiria	-13,965,684	26,293,372	12,327,688	50,135,695	36,170,012
Viseu Dão Lafões	-21,826,742	12,885,878	-8,940,864	38,449,786	16,623,043
Beira Baixa	-14,915,726	24,673,019	9,757,293	48,718,239	33,802,513
Beiras e Serra da Estrela	-14,078,700	26,100,616	12,021,915	49,967,075	35,888,375
Área Metropolitana de Lisboa	-13,979,097	26,270,495	12,291,398	50,115,683	36,136,585
Alentejo Litoral	-26,032,900	5,869,933	-20,162,967	32,216,493	6,183,592
Baixo Alentejo	-16,137,952	22,588,441	6,450,489	46,894,687	30,756,735
Lezíria do Tejo	4,677,753	58,090,841	62,768,594	80,338,736	85,016,489
Alto Alentejo	-22,099,112	12,421,336	-9,677,776	38,046,149	15,947,037
Alentejo Central	-42,587,082	4,995,224	-37,591,858	27,539,843	-15,047,239
Médio Tejo	-10,772,982	31,738,712	20,965,730	55,002,938	44,229,956
Cavado	-42,587,082	4,995,224	-37,591,858	27,539,843	-15,047,239
Ave	-20,960,149	14,363,903	-6,596,246	39,734,029	18,773,880
Douro	-20,113,728	15,807,525	-4,306,203	40,988,379	20,874,651
Terras de Trás os Montes	-4,774,654	41,969,209	37,194,554	64,413,956	59,639,301
Algarve	-9,513,581	33,886,693	24,373,112	56,946,978	47,433,397
Alto Minho	-14,926,298	24,654,988	9,728,690	48,702,466	33,776,168
Tâmega e Sousa	-15,631,343	23,452,494	7,821,151	47,650,545	32,019,203

Table 7. Real Options Valuation - Final Results

APPENDIX C

Regions	Best decision in case of more favorable conditions			Best decision in neutral market conditions			Best decision in case of less favorable market conditions		
	In year 5	In year 10	Rest of the years	In year 5	In year 10	Rest of the years	In year 5	In year 10	Rest of the year
Alto Tâmega	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Área Metropolitana do Porto	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Oeste	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Região de Aveiro	Keep it run the project	Contract	Abandon	Keep it run the project	Contract	Abandon	Keep it run the project	Contract	Abandon
Região de Coimbra	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Região de Leiria	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Viseu Dão Lafões	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Beira Baixa	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Beiras e Serra da Estrela	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Área Metropolitana de Lisboa	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Alentejo Litoral	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Baixo Alentejo	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Lezíria do Tejo	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Alto Alentejo	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Alentejo Central	Keep it run the project	Contract	Abandon	Keep it run the project	Contract	Abandon	Keep it run the project	Contract	Abandon
Médio Tejo	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Cavado	Keep it run the project	Contract	Abandon	Keep it run the project	Contract	Abandon	Keep it run the project	Contract	Abandon
Ave	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Douro	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Terras de Trás os Montes	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Algarve	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Alto Minho	Keep it run the project	Repower	Keep it run the project	Keep it run the project	Contract	Keep it run the project	Keep it run the project	Contract	Keep it run the pr
Tâmega e Sousa	Keep it run the project	Keep it run the project	Keep it run the project	Keep it run the project	Keep it run the project	Keep it run the project	Keep it run the project	Keep it run the project	Keep it run the pr

Table 8. Optimal Investment Strategy

Appendix D

Region	NPV	Total value of the project with the FiT
Alto Tâmega	-16,600,499	73,941,066
Área Metropolitana do Porto	-15,294,436	77,657,282
Oeste	-14,147,198	80,921,582
Região de Aveiro	-33,556,413	25,695,464
Região de Coimbra	-14,762,457	79,170,949
Região de Leiria	-13,965,684	81,438,053
Viseu Dão Lafões	-21,826,742	59,070,546
Beira Baixa	-14,915,726	78,734,844
Beiras e Serra da Estrela	-14,078,700	81,116,480
Área Metropolitana de Lisboa	-13,979,097	81,399,887
Alentejo Litoral	-26,032,900	47,102,532
Baixo Alentejo	-16,137,952	75,257,177
Lezíria do Tejo	4,677,753	134,485,258
Alto Alentejo	-22,099,112	58,295,558
Alentejo Central	-42,587,082	0
Médio Tejo	-10,772,982	90,522,426
Cavado	-42,587,082	0
Ave	-20,960,149	61,536,312
Douro	-20,113,728	63,944,683
Terras de Trás os Montes	-4,774,654	107,589,799
Algarve	-9,513,581	94,105,868
Alto Minho	-14,926,298	78,704,764
Tâmega e Sousa	-15,631,343	76,698,662

Table 9. Total Value of the Project with the FiT