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Subsidy Schemes and Managerial Flexibility in Solar Power Projects: A Case Study Approach

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September, 2024

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Acknowledgments

I would like to express my gratitude to everyone who has supported me throughout this journey, particularly as I balanced the challenges of completing this dissertation while working full-time. Their encouragement, no matter how small, was invaluable and contributed significantly to this achievement.

I owe a great deal of gratitude to all my professors for their support and valuable insights throughout my master´s program. In particular, I would like to thank Professor Luciana Barbosa for her expert guidance, patience, and insightful feedback.

I am also deeply appreciative of my parents, Rute and Paulo, and my little sister, Leonor. Their love, sacrifice and confidence in my abilities have been a constant source of motivation.

To all my friends, master´s colleagues, and coworkers, I extend a huge thanks for the encouragement, friendship, and collaborative spirit.

To all, thank you sincerely.

Abstract

This dissertation explores the integration of managerial flexibilities within subsidy policies to optimize the financial viability of solar power projects in Portugal. Through a case study approach, it evaluates four subsidy models: fixed-price Feed-in-Tariffs (FiTs), fixed-premium FiT, minimum price guarantees, and investment subsidies. By applying a semi-analytical real options framework, the research calculates the value of the project, the value of the investment opportunity, and the optimal investment threshold for each scheme. This framework assesses how these models influence investment decisions and project outcomes under market uncertainty. The findings suggest that fixed-price FiTs offer strong financial security, ideal for risk-averse investors in stable markets by increasing project value and reducing investment thresholds. However, the result depends on the tariff value. Nevertheless, they have limited adaptability. In contrast, fixed-premium FiTs and minimum price guarantees allow greater flexibility, enabling investors to adjust or delay investments based on market dynamics, making them more suitable in volatile environments. These findings emphasize the necessity of formulating subsidy frameworks that harmonize financial motivations with the requisite adaptability to accommodate evolving market dynamics. Moreover, this investigation provides significant guidance for investors aspiring to enhance returns amidst volatile market conditions, as well as for policymakers striving to devise flexible and efficacious subsidy strategies that stimulate investment in renewable energy. Furthermore, this study is congruent with the United Nations Sustainable Development Goals (SDGs) 7, 9 and 13 through its advocacy for renewable energy initiatives.

Keywords: Renewable Energy, Subsidy Policies, Managerial Flexibilities

JEL Classification: D81, Q48

Resumo

Esta dissertação analisa a integração de flexibilidade de gestão em políticas de subsídios com o objetivo de otimizar a viabilidade financeira dos projetos de energia solar em Portugal. Através de um estudo de caso, são examinados quatro modelos de subsídios: tarifas *feed-in* de preço fixo, tarifas *feed-in* de prémio fixo, garantias de preço mínimo e subsídios ao investimento. É aplicada uma estrutura semi-analítica de opções reais para calcular o valor do projeto, a oportunidade de investimento e o limiar ótimo de investimento para cada tipo de subsídio, com o objetivo de entender como é que estes modelos influenciam as decisões de investimento e os resultados dos projetos em situações de incerteza de mercado. Os resultados demonstram que as tarifas *feed-in* de preço fixo proporcionam uma forte segurança financeira, sendo mais adequadas para investidores avessos ao risco, ao aumentar significativamente o valor do projeto e reduzir os limiares de investimento. No entanto, essa segurança vem acompanhada de uma menor capacidade de adaptação. Por outro lado, as tarifas *feed-in* de prémio fixo e as garantias de preço mínimo oferecem uma maior flexibilidade, permitindo que os investidores ajustem ou adiem os investimentos de acordo com a dinâmica do mercado, sendo mais eficazes em ambientes voláteis. Estas conclusões destacam a necessidade de desenhar subsídios que conciliem incentivos financeiros com a adaptabilidade necessária para responder às condições variáveis do mercado. Adicionalmente, este estudo está ainda alinhado com os Objetivos de Desenvolvimento Sustentável (ODS) 7, 9 e 13 que promovem soluções de energia renovável sustentáveis e adaptáveis.

Palavras-Chave: Energia Renovável, Políticas de Subsídios, Gestão de Flexibilidades

Classificação JEL: D81, Q48

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Glossary of Acronyms

AC - Alternating Current

BOS - Balance of System

BSM - Black-Scholes-Merton Model

DC - Direct Current

EPIA - European Photovoltaic Industry Association

FiT - Feed-in Tariff

GBM - Geometric Brownian Motion

GHI - Global Horizontal Irradiance

IEA - International Energy Agency

IPCC - Intergovernmental Panel on Climate Change

IRENA - International Renewable Energy Agency

JEL - Journal of Economic Literature

kW - Kilowatt

MW - Megawatt

NREL - National Renewable Energy Laboratory

PPPs - Public-Private Partnerships

PV - Photovoltaic

PVGIS – Photovoltaic Geographical Information System

SDGs - Sustainable Development Goals

Wp - Watt peak

Glossary of Symbols

P - Price of electricity

Q - Quantity of energy produced

S - Subsidy level

r - Risk-free rate

μ - Drift rate

σ - Volatility

T - Duration of the contract

I - Initial investment cost

$W(P)$ - Value of the investment option

$V(P)$ - Value of the project

$\Pi(P)$ - Profit flow of the project

β_1 - Root of the characteristic equation (positive root)

β_2 - Root of the characteristic equation (negative root)

A_1, B_2 - Constants used in the solution of the Ordinary Differential Equation

P^* - Investment trigger

dP_t - Differential of the price over time in the GBM model

B_t - Brownian motion term

Introduction

The global energy sector is currently encountering a pivotal juncture as international efforts escalate to alleviate the repercussions of climate change and shift away from fossil fuel dependency. The immediacy of this transition is underscored by the alarming manifestations of climate change, which are evident in the growing frequency of extreme weather phenomena, escalating global temperatures, and the deterioration of natural ecosystems. The Intergovernmental Panel on Climate Change (IPCC) posits that global carbon emissions must be reduced by nearly fifty percent by the year 2030 to avert most devastating consequences of climate change. Within this framework, the advancement and implementation of renewable energy sources are not merely advantageous but fundamentally imperative.

Among the array of renewable energy technologies, solar energy has emerged as one of the most viable solutions. Solar power is characterized by its abundance, scalability, and increasing cost-effectiveness when compared to conventional fossil fuels. The International Energy Agency (IEA) reported that in the year 2022, solar energy constituted the largest proportion of newly installed electricity capacity worldwide, making a significant contribution to the almost 30% of global electricity now derived from renewable resources.

Notwithstanding these progressions, the extensive adoption of solar energy encounters numerous obstacles. The upfront capital expenditures associated with solar initiatives, albeit on a declining trajectory, remain considerable, and the economic viability of these initiatives is frequently susceptible to market fluctuations and alterations in policy. In response, various governments worldwide have instituted a range of subsidy mechanisms to facilitate the proliferation of solar energy. These subsidies, which encompass FiTs, investment grants, and tax incentives, are instrumental in alleviating financial impediments and fostering investment in solar power. For instance, in China, the FiTs mechanism, combined with reduced investment costs, has driven a substantial increase in utility-scale solar PV installations (Zhang et al., 2022). Moreover, in Germany, FIis have effectively promoted rooftop solar panel investments, demonstrating their role in enhancing market participation (Babich et al., 2020). Corrocher and Cappa (2020) also shown that public finance tools, including tax incentives, have been positively correlated with increased private investments in solar energy across OECD countries. However, the efficacy of these subsidies is not homogenous and is heavily contingent upon their design and the specific market contexts in which they are operationalized.

The significance of effective subsidy design is accentuated by the commitments enshrined in international accords such as the Paris Agreement, wherein nations have pledged to restrict global warming to significantly below 2 degrees Celsius above pre-industrial levels. Realizing this objective necessitates a substantial escalation in the deployment of renewable energy technologies, bolstered by policies that effectively stimulate investment and mitigate financial uncertainties. This thesis investigates the pivotal role of subsidy policies within the renewable energy sector, with a particular emphasis on solar power initiatives in Portugal, a nation that has distinguished itself as a frontrunner in the adoption of renewable energy. Portugal's dedication to renewable energy is manifested in its ambitious objectives and comprehensive policy framework. By the year 2020, the nation had already exceeded its renewable energy goals, with renewables constituting over 60% of its electricity consumption, representing one of the highest proportions in Europe (REN, 2024).

The present research is congruent with several pivotal global objectives, particularly those delineated within the United Nations Sustainable Development Goals, notably Goal 7: Affordable and Clean Energy, Goal 9: Industry, Innovation, and Infrastructure, and Goal 13: Climate Action. By examining the potential optimization of disparate subsidy schemes through the integration of managerial flexibilities, this inquiry aspires to augment the overarching endeavour to expedite the transition toward sustainable energy solutions and fulfil international climate commitments.

Motivated by a profound apprehension regarding the prospects of forthcoming generations, the principal aim of this investigation is to scrutinize the implications of various subsidy schemes on the economic viability of solar energy initiatives. Furthermore, the research explores the significance of managerial flexibilities in enhancing these investment decisions, particularly amidst prevailing market uncertainties. The ultimate aspiration is to furnish pragmatic insights and policy recommendations that can inform the formulation and execution of subsidy frameworks, thereby ensuring they are both efficacious in stimulating renewable energy investments and adaptable to the shifting landscape of market dynamics.

In pursuit of these objectives, the study engages with the following critical inquiries: In what manner do diverse subsidy policies affect investment decisions and financial results in solar energy projects? How can policymakers craft subsidy schemes that adeptly reconcile the necessity for financial incentives with the flexibility essential for responding to market volatility? What significance do managerial flexibilities hold in optimizing investment decisions within the context of various subsidy schemes?

Finally, the study is structured into five distinct chapters. The Introduction provides the research context, highlights the importance of subsidy schemes and managerial flexibilities in the solar power sector, outlines the primary objectives, and explain the key questions that we want to address. Chapter 1 reviews the relevant literature, focusing on subsidy policies, real options theory, and Public-Private Partnerships (PPPs). Chapter 2 describes the research methodology, particularly the semi-analytical real options framework used to assess the financial implications of various subsidy schemes. Chapter 3 presents a case study of a solar power project in Salinas de Rio Maior, and discusses the results by analysing the impact of different subsidy schemes and their interaction with managerial flexibilities. Lastly, the Conclusion summarizes the key findings and offers valuable insights for future research, policy development, and strategic considerations for investors.

Chapter 1: Literature Review

This chapter examines the current literature on subsidy policies, managerial flexibilities through real options theory, and PPPs in the context of renewable energy investments. The objective is to establish the current state of research, identify significant gaps, and provide a foundation for the analysis conducted in this dissertation.

The first section provides an analysis of subsidies with a particular emphasis on the specific types explored in this study and their impact on renewable energy investments. The second part explores the concept of managerial flexibilities, investigating how these strategic options can be integrated into subsidy frameworks to improve project outcomes under conditions of uncertainty. The third one examines the intersection of subsidies, real options theory, and PPPs, illustrating how their combined use can enhance the effectiveness and sustainability of renewable energy projects.

1.1 The Role of Subsidies in Renewable Energy Investments

Subsidies are widely recognized as a pivotal tool for catalysing investments in various sectors, particularly those characterized by high capital intensity, technological uncertainty, and long payback periods. These financial incentives are essential for making investments appealing to private investors, who might otherwise be deterred by the associated risks and costs. Across different industries, subsidies have been effectively employed to stimulate growth. For example, they are widely used in infrastructure projects, including airports (Chow, Tsui, & Wu, 2021) and roads (Shi, An, & Chen, 2020). In PPPs, subsidies often include government financial support, direct contributions, tax incentives, or guaranteed minimum revenues, all designed to make projects financially viable and attractive to private investors (Schwartz & Clements, 1999).

Within the broader framework of renewable energy, subsidies have emerged as a cornerstone policy instrument. Governments worldwide have adopted various subsidy mechanisms to foster the growth of renewable energy technologies. Among these, FiTs stand out as one of the most effective and widely implemented policies. FiTs, particularly in their fixed-price variant, guarantee a stable price for electricity generated from renewable sources over a specified period, thereby providing long-term revenue stability (Couture et al., 2010). This stability is essential for attracting private investment, especially in sectors like wind and solar energy, where the perceived risks are high due to substantial upfront costs and extended payback periods.

The effectiveness of FiTs in driving renewable energy investments has been well documented. De Jager et al. (2011) conducted a comprehensive study across various European countries, illustrating that FiTs were crucial in significantly boosting the deployment of renewable energy technologies, particularly in markets with unfavourable initial conditions. The study highlighted the importance of the assured cost recovery mechanism provided by FiTs, which was instrumental in building investor confidence and facilitating large-scale investments in renewable energy infrastructure.

Despite the successes associated with fixed-price FiTs, Couture and Gagnon (2010) raised concerns about the long-term sustainability of this subsidy model. While FiTs have been highly effective in the short to medium term, particularly in kick-starting renewable energy markets, their continued use as the primary subsidy mechanism may lead to inefficiencies as markets mature. Couture and Gagnon argued that as renewable energy technologies become more competitive and market conditions evolve, a transition to more market-oriented approaches, such as auction-based systems, may be necessary.

Additionally, fixed-premium FiTs represent an innovative variant of the traditional FiT mechanism, offering a unique approach to incentivizing renewable energy investment. Unlike fixed-price FiTs, which guarantee a specific price for electricity generated from renewable sources, fixed-premium FiTs provide an additional payment on top of the prevailing market price. This model balances the need for financial support with market-driven revenue, making it an attractive option for both investors and policymakers. Barbosa et al. (2020) highlighted the effectiveness of fixed-premium FiTs in creating a stable investment environment, particularly in markets where price volatility poses a significant risk.

Supporting this perspective, Rocha Armada et al. (2012) analysed the impact of fixed-premium FiTs on Portugal's wind energy sector. Their research demonstrated that these subsidies effectively reduce financial risks for investors by providing a stable revenue stream that adjusts with market prices. This flexibility allows producers to capitalize on high market prices while still receiving additional support during less favourable periods, thereby fostering sustained investment in renewable energy projects.

Another critical subsidy mechanism is the minimum price guarantee, which offers a baseline price for energy produced, thereby reducing financial uncertainty for investors. This mechanism is particularly effective in volatile markets where price fluctuations can deter investment. Barbosa et al. (2018) discuss how FiTs with minimum price guarantees operate under a price-floor regime, ensuring that investors are compensated if market prices fall below a certain threshold. This approach has been especially effective in promoting investments in sectors characterized by high volatility, such as solar and wind energy.

The implementation of minimum price guarantees in Portugal has been particularly influential in driving the growth of the solar energy sector. Del Río and Mir-Artigues (2014) emphasize that these guarantees created a stable investment environment, which was crucial during the early stages of solar energy development. By reducing financial risks, minimum price guarantees made it feasible for investors to commit capital to solar projects, fostering the sector's early growth and laying the foundation for its subsequent expansion.

Moreover, Marques and Fuinhas (2011) highlight the broader impact of minimum price guarantees on stabilizing Portugal’s renewable energy market. Their study shows that these guarantees played a significant role in making the renewable energy sector more attractive to private investors by reducing uncertainties associated with market volatility. This stability encouraged more consistent and substantial investments in renewable energy infrastructure, contributing to the overall growth of the sector.

Investment subsidies, which directly reduce the upfront capital costs associated with renewable energy projects, are another powerful tool that governments use to stimulate investment. Almeida et al. (2019) conducted an in-depth analysis of investment subsidies in Portugal, illustrating how government contributions significantly lowered the financial hurdles for solar energy projects. Their study showed that these direct financial incentives not only made large-scale solar investments more attainable but also enhanced the overall appeal of renewable energy projects to private investors.

However, the literature also cautions against the potential drawbacks of prolonged reliance on investment subsidies. Schmalensee (2012) argues that continuous government support can lead to dependency, where projects may struggle to be financially viable without ongoing subsidies. This dependency poses a significant risk to the sustainability of the renewable energy sector, particularly as markets mature and technologies become more cost-competitive. To mitigate this risk, Schmalensee suggests that investment subsidies should be designed with a clear exit strategy, gradually reducing support as the market evolves, thereby ensuring a smooth transition to a self-sustaining, competitive market.

Investment subsidies also play a crucial role in other sectors, such as large-scale public infrastructure projects. In the transportation sector, for instance, capital grants and tax credits can significantly lower the financial barriers for private investors, facilitating the construction of essential infrastructure like highways and airports. Rocha Armada et al. (2012) emphasize that well-designed investment subsidies can stimulate early investment by reducing the initial capital requirements, thereby accelerating the start of crucial infrastructure projects, and preventing delays caused by financial constraints.

1.2 Real Options in Renewable Energy

While subsidies play an essential role in reducing financial barriers, renewable energy investments also require strategic tools to manage the inherent uncertainties of these projects. Traditionally, the Net Present Value (NPV) method has been the predominant approach for evaluating the financial viability of projects by calculating the present value of expected future cash flows. However, NPV is inherently static, assuming fixed conditions and a single decision point, which can be a significant limitation in the dynamic and often unpredictable environment of renewable energy investments.

Real options theory offers a more flexible and dynamic approach to investment decision-making. Introduced by Tourinho (1979) cited by Tourinho (2013), real options theory values the flexibility to adapt, defer, expand, or abandon projects as new information becomes available. This flexibility is particularly relevant in sectors like renewable energy, where market conditions, technological advancements, and regulatory frameworks are in constant flux. Real options theory extends the principles of financial options traditionally used in stock markets to real-world investments, providing a robust framework for managing uncertainty and maximizing value.

Dixit and Pindyck (1994) emphasize that real options allow investors to make decisions in stages, rather than requiring a full commitment of resources upfront. This staged approach is crucial in managing the risks associated with renewable energy projects, where uncertainties such as regulatory changes, technological breakthroughs, or shifts in market demand can significantly impact project outcomes. Trigeorgis (1996) elaborates on the various types of real options relevant to investment decisions, including the option to defer investment until conditions are more favourable, the option to expand a project if initial phases are successful, or the option to abandon a project if it becomes unviable.

Empirical studies, such as those conducted by Guo et al. (2020), demonstrate that integrating real options into investment decision-making processes significantly enhances the resilience and financial viability of renewable energy projects. By allowing investors to adjust their strategies in response to evolving market conditions, real options contribute to more robust and adaptable project outcomes. This flexibility is particularly valuable in environments characterized by high volatility and uncertainty, such as those often encountered in renewable energy markets.

Despite the clear advantages of real options, their practical application in renewable energy projects remains limited. Brandao and Saraiva (2008) identify the complexity of the required financial modelling as a significant barrier to the widespread adoption of real options. The sophisticated analysis required to implement real options effectively can be daunting, especially in markets where expertise in financial modelling is limited. Simplifying and standardizing these models would not only facilitate broader adoption but also enhance the strategic decision-making process in renewable energy investments, leading to more resilient and successful projects.

The integration of real options with other policy mechanisms, such as subsidies, represents a particularly promising area of exploration. Rocha Armada et al. (2012) suggest that subsidies can be structured to incorporate managerial flexibilities, thereby enhancing the strategic management of renewable energy projects. For instance, investment subsidies could be designed to include options that allow for project expansion or contraction based on market conditions, aligning financial incentives with strategic flexibility. This integrated approach could lead to more resilient and sustainable renewable energy projects, ensuring that they remain adaptable to changing circumstances while still benefiting from government support.

1.3 The Intersection of Subsidies, Real Options, and Public-Private Partnerships

The intersection of subsidies, real options, and public-private partnerships (PPPs) represents a critical and emerging area of study in renewable energy investments. Subsidies provide essential financial incentives, real options offer flexibility to manage uncertainties, and PPPs create a collaborative framework to effectively implement these mechanisms. The synergy between these elements can significantly enhance the effectiveness and sustainability of renewable energy projects.

In the context of PPPs, subsidies are government-provided financial supports designed to encourage private sector investment in public infrastructure and services. These subsidies aim to bridge the gap between the cost of providing a public service and the revenue it generates, ensuring that projects remain financially viable and attractive to private investors. Studies by Barbosa et al. (2018), Grimsey and Lewis (2002), and Engel et al. (2014) highlight the effectiveness of subsidies in promoting private investment in renewable energy.

PPPs leverage the resources and expertise of both the public and private sectors, making them particularly effective for large-scale renewable energy projects. Grimsey and Lewis (2004) argue that PPPs enhance efficiency and innovation, which are essential for the successful deployment of renewable energy technologies. By pooling resources, PPPs mitigate financial risks while capitalizing on private sector expertise in project management and innovation. This is especially valuable in regions with limited public funding, as PPPs help mobilize private capital to fund necessary infrastructure.

Empirical evidence from Fraunhofer ISI (2014) and IRENA (2019) underscores the role of PPPs in mobilizing private capital for renewable energy projects, especially in regions where public resources are scarce. These studies show how PPPs facilitate large-scale deployment of renewable energy technologies by pooling resources and sharing risks. In Europe, and specifically in Portugal, PPPs have been instrumental in scaling solar energy installations, leveraging private investment to meet renewable energy targets.

Incorporating real options into PPP frameworks can further enhance the strategic management of renewable energy projects. Rocha Armada et al. (2012) suggest that structuring subsidies within PPPs to include managerial flexibilities allows both public and private partners to adapt to market conditions, thus improving project outcomes. For instance, an investment subsidy could include options to expand or reduce project scope based on market dynamics, giving both public and private entities the flexibility to optimize project performance. This integration ensures projects remain viable despite unforeseen challenges such as regulatory changes or market volatility.

However, integrating real options and subsidies within PPPs presents certain challenges. Brandao and Saraiva (2008) identify the complexity of real options analysis as a barrier to its broader adoption within PPP frameworks. Additionally, the lack of clear guidelines and standardized models makes it difficult for public and private partners to effectively incorporate these tools into project planning and execution. Developing practical frameworks that integrate real options and subsidies is essential to ensure renewable energy projects remain financially viable and adaptable to changing market conditions.

In summary, the literature clearly demonstrates the critical roles of subsidies, real options, and PPPs play in overcoming financial barriers and managing uncertainties. Subsidies have been instrumental in making renewable energy projects viable and attractive to investors. Real options provide the strategic flexibility needed to navigate the unpredictable market landscape by allowing investors to adapt their decisions as new information becomes available. Meanwhile, PPPs leverage the strengths of both the public and private sectors, enhancing the implementation of these financial and strategic tools. Together, these mechanisms form a comprehensive approach to fostering the growth and sustainability of renewable energy investments.

Chapter 2: Methodology

2.1 Overview of the Research Methodology

This chapter outlines the research methodology used to evaluate investment decisions in large-scale renewable energy infrastructure projects. The methodology combines real options theory with various subsidy schemes to assess financial viability and identify optimal investment strategies. Building on models from previous studies (e.g., Barbosa et al., 2018; Barbosa et al., 2020), this study introduces an investment subsidy, contributing a novel perspective to the existing literature.

The research follows a quantitative approach, utilizing mathematical models to evaluate investment decisions from a single investor's viewpoint with the use of PPPs. Several scenarios are explored, including investments with fixed-price FiT, fixed-premium FiT, minimum price guarantees, and investment subsidies. For each scenario, the optimal investment threshold, the value of the investment option, and the overall project value are calculated to maximize project returns.

2.2 Mathematical Modelling

To account for the uncertainty in energy prices, the price P_t is modelled using a Geometric Brownian Motion (GBM) an assumption from the Black-Scholes-Merton Model (BSM) (Black and Scholes, 1973; Merton, 1973). This is represented by the following stochastic differential equation:

$$dP_t = \mu P_t dt + \sigma P_t dB_t, \tag{1}$$

where μ represents the deterministic drift under the risk-neutral measure of the future market electricity price over time, σ is the volatility, indicating the uncertainty or risk associated with the price movements, and B_t is a Standard Brownian Motion, capturing the random fluctuations in the price.

Considering that $V\ (P)$ is the general value of the project the Ordinary Differential Equation (ODE) will be:

$$\mu P \frac{\partial V(P,S)}{\partial P} + 0.5\sigma^2 P^2 \frac{\partial^2 V(P,S)}{\partial P^2} - rV(P,S) + \Pi(P,S) = 0, \tag{2}$$

where $\Pi(P, S)$ is the profit flow of the renewable energy project with a FiT for one unit of energy. It equals the market price of electricity when it is above the price floor, and equals the price floor when the market price is below it. In this case, S refers to the minimum price guarantee or price floor set in the contract, and r represents the discount rate applied to the project, reflecting the time value of money. Therefore, the general solution to the ODE is:

$$V(P) = \begin{cases} A_1 P^{\beta_1} + \frac{S}{r} & \text{for } P < S \\ B_2 P^{\beta_2} + \frac{P}{r-\mu} & \text{for } P \geqslant S \end{cases}, \tag{3}$$

where β_1 and β_2 are the roots of the characteristic equation associated with the stochastic process of the price P. These roots are given by:

$$\beta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}\right)^{\frac{1}{2}}, \tag{4}$$

and

$$\beta_2 = \frac{1}{2} - \frac{\mu}{\sigma^2} - \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}\right)^{\frac{1}{2}}, \tag{5}$$

here β_1 is the positive root, which typically corresponds to the increasing part of the value function as the price P increases. Additionally, β_2 is the negative root, often associated with the decreasing part of the value function as the price P decreases.

The constants A_1 and B_2 are determined by boundary conditions that ensure the solution behaves realistically at extreme values of P:

As $P \to 0$: The value of the project should converge to the present value of the fixed revenue stream $\frac{S}{r}$.

As $P \to \infty$: The value of the project should behave as $\frac{P}{r-\mu}$, which reflects the value of the project without a price floor.

These constants A_1 and B_2 are calculated as (value matching and smooth-pasting conditions):

$$A_1 = \frac{F^{1-\beta_1}}{\beta_1-\beta_2}\left(\frac{\beta_2}{r} - \frac{\beta_2-1}{r-\mu}\right), \tag{6}$$

and

$$B_2 = \frac{F^{1-\beta_2}}{\beta_1-\beta_2}\left(\frac{\beta_1}{r} - \frac{\beta_1-1}{r-\mu}\right). \tag{7}$$

In the context of real options analysis, the value of the investment option $W(P)$ and the optimal investment threshold P^* are crucial. These are derived based on the general solution for $V(P)$ and the underlying stochastic process.

The value of the investment option $W(P)$ is determined by the difference between the project value and the investment cost, taking into account the optimal timing to invest:

$$W(P) = \begin{cases} (V(P^*) - I)\left(\frac{P}{P^*}\right)^{\beta_1}, & P < P^* \\ V(P) - I, & P \geq P^* \end{cases}, \tag{8}$$

$$(\beta_1 - \beta_2)B_2 {P^*}^{\beta_2} + (\beta_1 - 1)\frac{P^*}{r-\mu} - \beta_1 I = 0, \tag{9}$$

where I is the initial investment cost, β_1 is the positive root of the characteristic equation associated with the stochastic process of the price P, and P^* is the investment threshold, indicating the price level at which it becomes optimal to invest. It is calculated by using the value-matching and smooth-pasting conditions, resulting int the trigger do fixed scheme:

$$P^* = \frac{\beta_1}{\beta_1-1}\frac{r-\mu}{Qe^{-(r-\mu)T}}(I - Present\ Value\ of\ Subsidy\ Benefits). \tag{10}$$

2.3 Investment Decision Models with Subsidies

In this subsection, we present the formulas used to calculate the project value, option value, and investment trigger for each type of subsidy scheme. Each equation is distinguished by the initial letter of the corresponding subsidy model to ensure clarity when analysing the different investment scenarios. For instance, F is used for the fixed-price FiT scheme, P for the fixed-premium FiT scheme, M for the minimum price guarantee scheme, and I for the investment subsidy scheme.

2.3.1 Investments with Fixed-Price

The fixed-price FiT model guarantees, just like the name suggests, a fixed price S per unit of energy produced, regardless of market fluctuations. This model ensures revenue stability, which is crucial for reducing the financial risk associated with energy price volatility. The profit function under a fixed-price FiT is given by:

$$\Pi_F(P) = SQ. \tag{11}$$

The value of the project over a finite duration T is:

$$V_F(P) = \frac{SQ}{r}\left(1 - e^{-rT}\right) + \frac{PQ}{r-\mu} e^{-(r-\mu)T}. \tag{12}$$

The corresponding value of the investment option, using real options analysis, is given by:

$$W_F(P) = \begin{cases} \left(V_F(P_F^*) - I\right)\left(\frac{P}{P_F^*}\right)^{\beta_1}, & P < P_F^* \\ V_F(P) - I, & P \geq P_F^* \end{cases}. \tag{13}$$

Thus, the investment threshold is given by:

$$P_F^* = \frac{\beta_1}{\beta_1 - 1}\frac{r-\mu}{Qe^{-(r-\mu)T}}\left(I - \frac{SQ}{r}\left(1 - e^{-rT}\right)\right). \tag{14}$$

2.3.2 Investments with Fixed-Premium

In a fixed-premium FiT scheme, the producer receives a market price P plus a fixed-premium S for each unit of energy produced. This model adds a layer of financial stability by providing a guaranteed premium over the market price. By following similar steps as in the subsidy scheme already presented, we have that the profit function under this scheme is:

$$\Pi_P(P) = (P + S)Q. \tag{15}$$

The value of the project is calculated as:

$$V_P(P) = \frac{PQ}{r-\mu} + \frac{SQ}{r}\left(1 - e^{-rT}\right). \tag{16}$$

The corresponding value of the investment option is:

$$W_P(P) = \begin{cases} (V_P(P_P^*) - I)\left(\frac{P}{P_P^*}\right)^{\beta_1}, & P < P_P^* \\ V_P(P) - I, & P \geq P_P^* \end{cases}. \quad (17)$$

So, the investment threshold is calculated as:

$$P_P^* = \frac{\beta_1}{\beta_1 - 1}\frac{r-\mu}{Q}\left(I - \frac{SQ}{r}(1 - e^{-rT})\right). \quad (18)$$

2.3.3 Investments with Minimum Price Guarantee

The minimum price guarantee model ensures that the producer receives at least a minimum price S for each unit of energy produced, providing a safety net against low market prices. The profit function is:

$$\Pi_M(P) = max(P, S)\,Q. \quad (19)$$

The value of the project under the minimum price guarantee is calculated as:

$$V_M(P) = \begin{cases} L_1 P^{\beta_1} + \frac{SQ}{r}, & P < S \\ M_2 P^{\beta_2} + \frac{PQ}{r-\mu}, & P \geq S \end{cases}, \quad (20)$$

where L_1 and M_2 are constants derived from boundary conditions, ensuring smooth transitions between different price regimes (value matching and smooth-pasting conditions), β_1 and β_2 and are the roots of the characteristic equation associated with the stochastic process governing the price P.

$$L_1 = \frac{QF^{1-\beta_1}}{\beta_1 - \beta_2}\left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r-\mu}\right), \quad (21)$$

and

$$M_2 = \frac{QF^{1-\beta_2}}{\beta_1 - \beta_2}\left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r-\mu}\right). \quad (22)$$

Then, we can obtain the value of the option to invest:

$$W_M(P) = \begin{cases} (V_M(P_M^*) - I) \left(\frac{P}{P_M^*}\right)^{\beta_1}, & P < P_M^* \\ V_M(P) - I, & P \geq P_M^* \end{cases}. \tag{23}$$

Thus, the investment threshold is given by:

$$P_M^* = \frac{\beta_1}{\beta_1 - 1} \frac{r-\mu}{Qe^{-(r-\mu)T}} \left(I - \frac{SQ}{r}(1 - e^{-rT})\right). \tag{24}$$

2.3.4 Investments with Investment Subsidy

The investment subsidy provides an upfront subsidy S for the initial investment, separate from other FiT schemes.

The profit function for an investment subsidy is simply the market price times the quantity:

$$\Pi_I(P) = PQ. \tag{25}$$

The effective investment cost is adjusted as $I' = I - \frac{S}{r(1-e^{(-rT)})}$, and the value of the project is:

$$V_I(P) = \frac{PQ}{r-\mu}(1 - e^{-rT}). \tag{26}$$

The investment option value is:

$$W_I(P) = \begin{cases} (V_I(P_I^*) - I') \left(\frac{P}{P_I^*}\right)^{\beta_1}, & P < P_I^* \\ V_I(P) - I', & P \geq P_I^* \end{cases}. \tag{27}$$

So, the investment threshold for the subsidy scheme:

$$P_I^* = \frac{\beta_1}{\beta_1 - 1} \frac{r-\mu}{Q}(I - S). \tag{28}$$

Chapter 3: Case study

To provide a comprehensive understanding of this study, it is essential to set the context in which it is conducted. Therefore, we begin by presenting an overview of Salinas de Rio Maior, highlighting its significance in Portugal's renewable energy landscape, particularly in solar energy production.

In this section, we examine the four subsidy schemes explained in Section 2, and our goal is to determine how each of these subsidy models affects the financial viability of the PV project. Additionally, we want to understand how they influence key investment factors such as project value, the value of investment options, and the optimal timing for investment decisions. Through static analyses, we explore how market conditions and uncertainties impact the effectiveness of each subsidy scheme.

3.1. Geographic and Climatic Conditions of Salinas de Rio Maior

Salinas de Rio Maior is in the Santarém district of Portugal, a region characterized by a Mediterranean climate with hot, dry summers and mild winters. The region, historically known for traditional salt extraction, benefits from high solar irradiance, making it ideal for renewable energy projects. According to the Photovoltaic Geographical Information System (PVGIS), Salinas de Rio Maior receives an average Global Horizontal Irradiance (GHI) of approximately 1,750 kWh/m²/year, increasing to around 1,950 kWh/m²/year with optimally tilted PV panels.

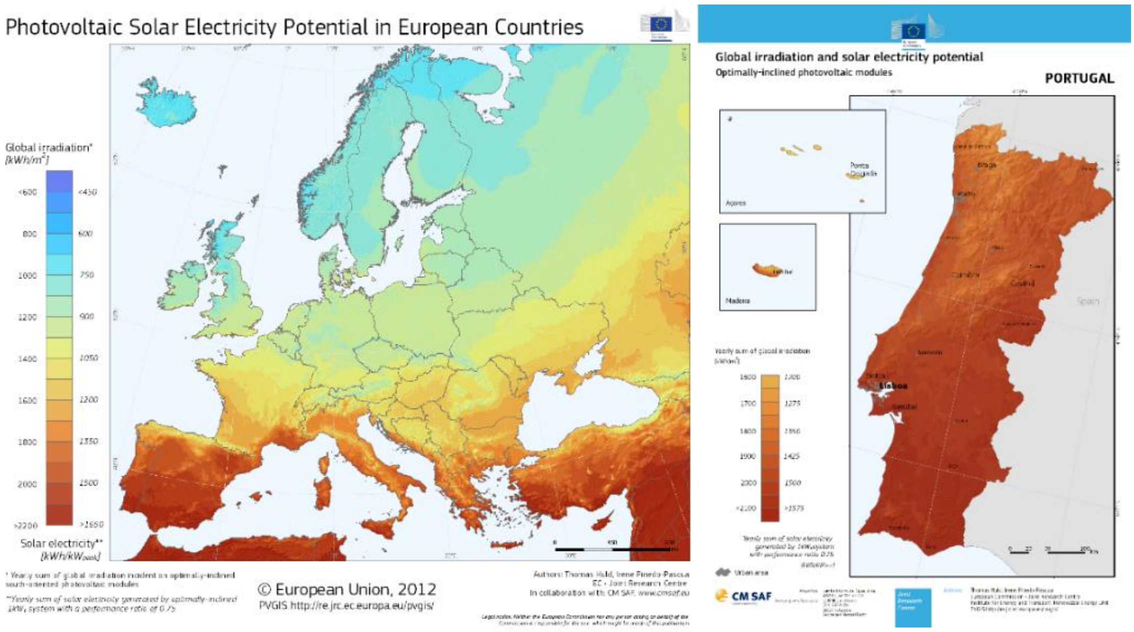

Figure 3.1: Solar irradiance in Europe and Portugal.

Source: Photovoltaic Geographical Information System (PVGIS).


Figure 3.2: Salinas de Rio Maior.

Source: Google Maps.

3.2. Data

The solar irradiance data used in this study was sourced from the PVGIS, a tool that provides high-resolution solar radiation data across Europe, which is crucial for assessing the solar energy potential of Salinas de Rio Maior.

The cost estimates for photovoltaic panels and related equipment were obtained from industry reports by the International Renewable Energy Agency (IRENA, 2020), and the National Renewable Energy Laboratory (NREL, 2018). These sources provide detailed and up-to-date market analyses and benchmarks for PV system costs, including panels, inverters, and balance of system (BOS) components. The data also includes installation labour costs, pivotal for calculating the initial capital expenditure.

Financial data, such as the risk-free rate, volatility, and drift rate were sourced from average yields of Portuguese government bonds as reported by World Government Bonds (2023) and informed by methodologies from Barbosa et al. (2018).

3.3. Photovoltaic Technology: Monocrystalline Silicon Panels

Monocrystalline silicon technology was selected for the proposed PV park due to its superior efficiency and durability. Monocrystalline panels, made from a single continuous crystal structure, offer higher efficiency rates, typically between 20% and 23%, compared to other types of PV panels, such as polycrystalline silicon (Zhang et al., 2017 and Lane, 2021). Moreover, monocrystalline silicon is the most widely used solar cell technology in commercially available solar panels, accounting for more than 85% of global photovoltaic cell market sales in 2011 (Solar Energy Technologies Office, n.d.).

Given the high solar irradiance in the region, monocrystalline panels will convert a significant portion of sunlight into electricity, leading to higher overall energy production. These panels also perform better under low-light conditions and exhibit a lower degradation rate over time, typically around 0.5% per year, ensuring consistent energy production throughout their lifespan (Pereira et al., 2016; Skoczek et al., 2008; Baker et al., 2013). In consideration of the current limitations in cost-effective energy storage technology, the design has been developed without including battery storage. (NREL, 2018). Moreover, the panels' compact design and durability make them well-suited for the Mediterranean climate of Salinas de Rio Maior, where they can operate efficiently even during hot summers and mild winters.

Figure 2.3: Monocrystalline silicon panels at a solar park.

Source: Coopérnico PME Magazine (2021).

3.4. System Design, Land Requirements, and Grid Connection

The land area required for these panels is a crucial consideration. Each monocrystalline panel occupies approximately 2.5 square meters, including the necessary space for maintenance and to minimize shading between rows of panels. The total land area required for the 4,000 panels is approximately 10,000 square meters (1 hectare). This modest land requirement underscores the efficiency of monocrystalline technology in maximizing energy output per unit of land.

The feasibility of the project is further enhanced by the existing electrical infrastructure in Salinas de Rio Maior. The proximity of the PV park to the national grid is crucial for minimizing transmission losses and reducing the costs associated with grid connection. The estimated distance from the site to the nearest grid connection point is within a few kilometres, which reduces the need for extensive transmission lines. This proximity lowers the initial capital expenditure and ensures efficient integration of the generated energy into the national grid with minimal losses.

An assessment of the local grid's capacity indicates that the existing infrastructure can handle the additional load from the PV park. This is important because, in regions where the grid is not sufficiently robust, significant upgrades would be required to accommodate new power generation, potentially adding to the project's cost and complexity. However, in Salinas de Rio Maior, the grid's readiness ensures that the generated electricity can be distributed efficiently, contributing to the stability and reliability of the local and national energy supply.

3.5. Composition and Cost Analysis of Utility-Scale Photovoltaic Systems

The estimation of the initial cost for the proposed utility-scale PV system in Salinas de Rio Maior includes a detailed breakdown of the key components: solar panels, inverters, BOS components, and installation and labour costs. This section outlines the methodology and assumptions employed to calculate the total initial investment required for the project.

3.5.1 Solar Panels

A utility-scale photovoltaic system is a large-scale solar power installation designed to generate electricity for the grid, rather than for individual consumption. Unlike domestic systems, which are typically installed on residential rooftops with capacities ranging from a few kilowatts (kW) to tens of kW, and commercial systems, which are installed on business premises with capacities from tens to hundreds of kW, utility-scale PV systems are much larger. These systems often have capacities ranging from several megawatts (MW) to hundreds of MW, and are installed on large, open land areas.

Photovoltaic systems convert sunlight into electricity through the photovoltaic effect, where solar panels generate direct current (DC) electricity, later converted to alternating current (AC) for grid use.

The proposed PV system will utilize 4,000 SunPower Maxeon 3 monocrystalline silicon panels, each with a power output of 400 Wp. Monocrystalline technology is selected due to its high efficiency, reaching up to 22.6%, which is critical in maximizing energy output per unit of land. The total installed capacity of the system is 1.66 MW.

Based on reports from IRENA (2020), the cost of high-efficiency solar panels such as the SunPower Maxeon 3 is estimated at €0.72 per watt. Therefore, the total cost for the solar panels is calculated as follows:

$$Cost\ of\ Solar\ Panels\ = 1.66\,MW \times 1000\,kW/MW \times 1000\,W/kW \times €0.72/W = €1{,}195{,}200. \tag{29}$$

3.5.2 Inverters

The system requires approximately 11 to 12 SMA Sunny Highpower PEAK3 inverters, which are designed specifically for utility-scale solar power plants. Each inverter is capable of handling around 150 kW, ensuring minimal energy loss during the conversion of DC to AC power with an efficiency of up to 99%.

The cost of inverters is estimated between €0.10 and €0.20 per watt, as indicated by NREL. For this analysis, the midpoint cost of €0.15 per watt is applied:

$$Cost\ of\ Inverters\ = 1.66\,MW \times 1000\,kW/MW \times 1000\,W/kW \times €0.15/W = €249{,}000. \tag{30}$$

3.5.3 Balance of System Components

BOS components, including wiring, mounting structures, and other electrical systems, are essential for the installation and operation of the PV system. According to studies by the Fraunhofer Institute for Solar Energy Systems ISE, the cost of these components is estimated between €0.20 and €0.30 per watt. A midpoint value of €0.25 per watt is used for this calculation:

$$Cost\ of\ BOS\ Components = 1.66MW \times 1000kW/MW \times 1000W/kW \times €0.25/W = €415{,}000. \tag{31}$$

3.5.4 Installation and Labour Costs

Installation and labour costs are a significant part of the initial investment and are typically estimated to constitute 5% to 10% of the total project cost. This estimation is supported by data from IRENA and the European Photovoltaic Industry Association (EPIA). For this analysis, a midpoint of 7.5% of the total equipment cost is assumed:

First, the total cost of the equipment (panels, inverters, and BOS components) is calculated:

$$Total\ Equipment\ Cost\ = €1{,}195{,}200 + €249{,}000 + €415{,}000 = €1{,}859{,}200. \quad (32)$$

Then, the installation and labour costs are determined as:

$$Installation\ and\ Labor\ Costs = 7.5\%\ \times\ €1{,}859{,}200 = €139{,}440. \quad (33)$$

3.5.5 Total Initial Cost

The total initial cost of the utility-scale PV system, incorporating the costs of solar panels, inverters, BOS components, and installation and labour, is summarized as follows:

$$Total\ Initial\ Cost\ = €1{,}859{,}200 + €139{,}440 = €1{,}998{,}640. \quad (34)$$

This estimated cost of approximately €1.998 million provides a comprehensive overview of the financial requirements for establishing the proposed PV park in Salinas de Rio Maior. Moreover, it is assumed that the owner of the PV project already possesses the land.

3.6. Solving the Case Study

This section puts the methodology into action by applying it to the real-world scenario of Salinas de Rio Maior. First, I present the base case results, and then I conduct a sensitivity analysis on the primary factors influencing the model.

Therefore, the financial and economic evaluation of study is structured around key parameters that are essential for assessing its feasibility. The project is planned for a 25-year lifespan, aligning with the typical durability of PV panels and standard practice in Portugal (Frondel et al., 2010).

To determine the appropriate discount rate, a risk-free rate of 3.34% was used. This rate was derived from the average yields of Portuguese government bonds with 20-year and 30-year maturities, which are currently around 3.24% and 3.44%, respectively, providing a realistic basis for the 25-year FiT (World Government Bonds, 2023).

The deterministic drift rate is set at 0%, following the approach by Barbosa et al. (2018), simplifying the model by excluding long-term electricity price trends. Volatility is estimated at 12%, with the methodology informed by Bloomberg New Energy Finance (2020), which reports that volatility for this type of projects typically falls within the 10-15% range. The current market price of electricity is set at 0.07 EUR/kWh, based on recent averages in Portugal (Eurostat, 2020). Next, we calculate the project value, option value, and investment trigger for each subsidy scheme under consideration. Therefore, the project value reflects the total expected revenue generated by the solar system, taking into account factors such as the market price of electricity, the system's efficiency, its capacity, and the specific subsidy scheme in place. A higher project value indicates a more profitable investment, making it an attractive opportunity for investors given the current market conditions.

The option value, on the other hand, represents the flexibility to delay the investment. This flexibility can be particularly valuable in volatile or uncertain market conditions. A high option value suggests that postponing the investment could lead to better returns, especially if future market conditions are expected to improve or if changes in policy are anticipated. In essence, the option value provides investors with the ability to wait and make a more informed decision when the circumstances are more favourable.

The investment trigger marks the point at which it becomes optimal to proceed with the investment. When the investment trigger is low, it indicates that the conditions are advantageous for investment, encouraging immediate action. However, when the investment trigger is high, it suggests that better conditions, such as increased subsidies, reduced costs, or more stable market prices, are needed to justify moving forward with the investment.

With this understanding, we can simplify the numerical analysis by calculating the investment threshold for a single solar system using the given specifications. These results can then be easily scaled up for larger solar farms or commercial installations. As with other studies on renewable energy investments, all parameters are assumed to be annualized. For instance, under a fixed-price subsidy FiT regime, an annual revenue of €230,048.11 is generated (i.e., 22.6% × 1.66 MWh × €0.07/kWh × 24 hours/day × 365 days/year).

Table 3.1: summarizes the key parameters used in the design of the PV park.

Table 3.1: The base case parameters.

Parameters	Value
Risk-free rate (r)	3.34%
Drift rate (μ)	0%
Volatility (σ)	12%
Duration of the contract (T)	25 years
Current market price (P)	0.07 EUR/kWh
Initial investment cost (I)	1,998,640 EUR

3.6.1 Comparative statics

In this section, we analyse the main factors driving our model by comparing how different parameters influence the optimal investment triggers in the four subsidy policies. We base our numerical analysis on the parameters outlined in the case study.

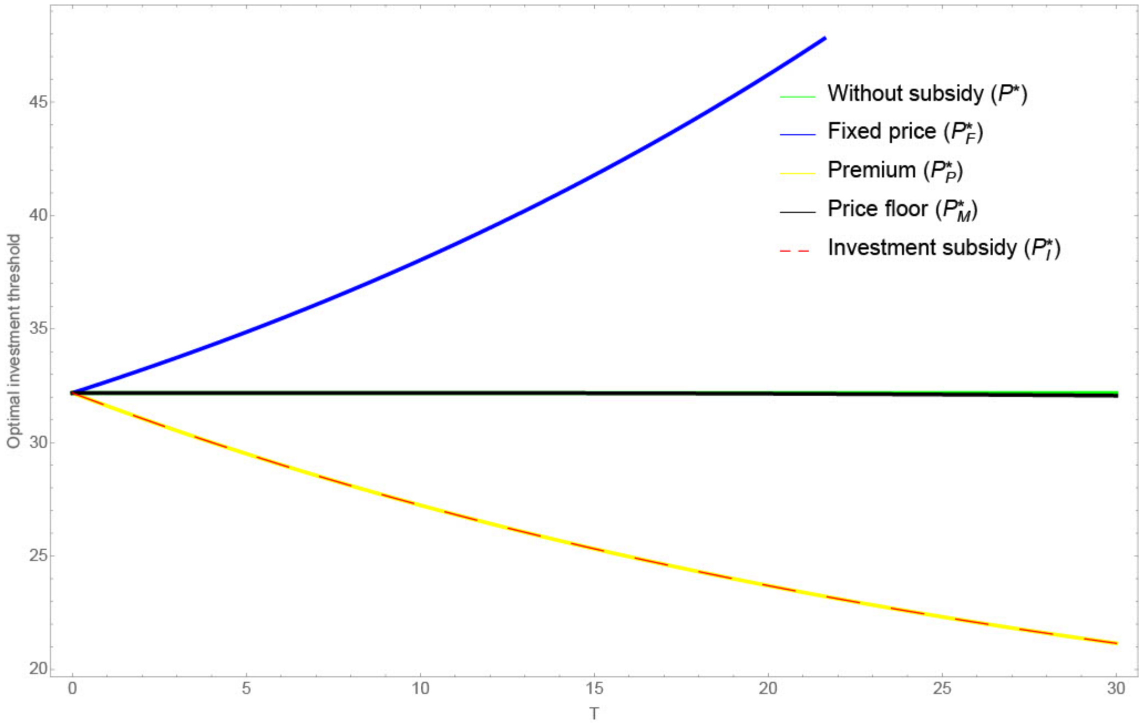

Figure 3.4: Triggers as a function of the duration of the contract T.

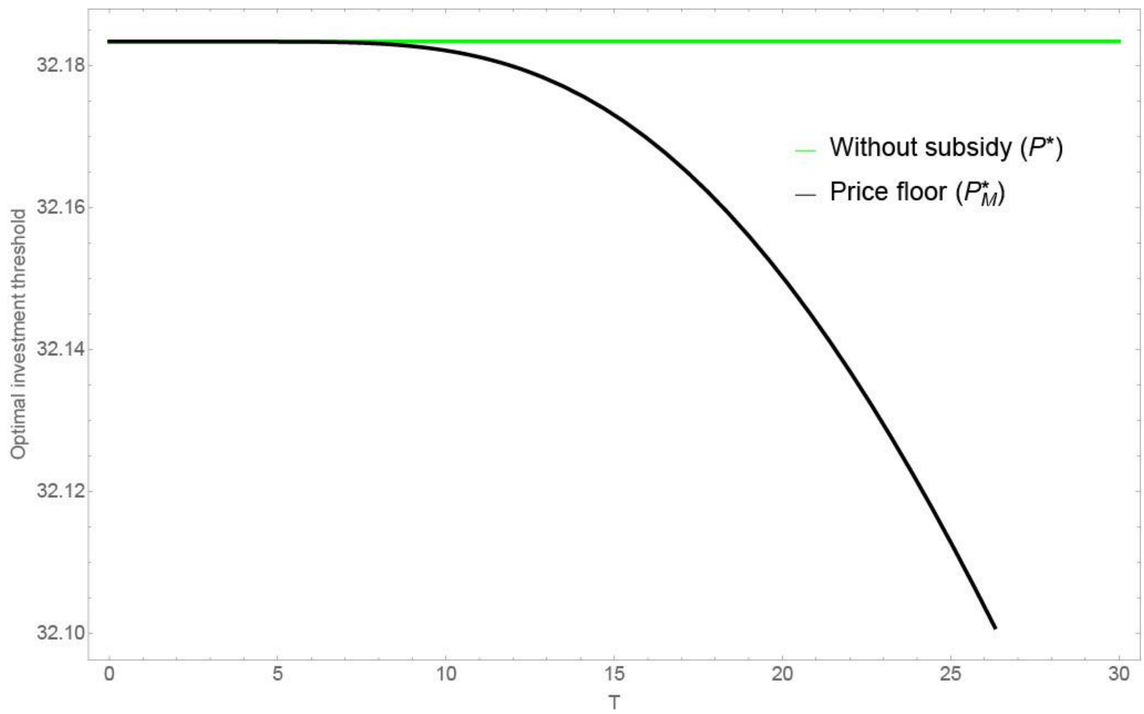

Figure 3.5: Triggers as a function of the duration of the contract T.

Figure 3.4 presents the value of the investment thresholds as a function of the duration of the contract T across five different scenarios of schemes. The fixed-price scenario, represented by the blue line, shows an increasing investment threshold over time. This suggests that the fixed price offered is potentially lower than market prices, as indicated in Barbosa (2020). As such, this type of scheme may deter investors from delaying their investment, pushing them to either invest early or risk facing higher thresholds later. This scheme could therefore ensure that only projects with very strong fundamentals proceed, as investors may be hesitant to wait too long under these conditions.

As observed, in **Figure 3.4** the without subsidy scenario remains perfectly flat, indicating that the investment threshold is constant over time due to the absence of a contract or subsidy. This constancy suggests that the duration of the contract does not influence investment timing when subsidies are not a factor. As such, investors face a stable cost structure, allowing them to defer investment indefinitely until market conditions are deemed favourable, without the pressure of contractual durations or changing investment thresholds.

In contrast, the price floor scenario shows a slight but noticeable decline in the investment threshold as time progresses. This decrease is gradual and becomes more pronounced as the contract duration extends, particularly after $T = 15$, as shown in more detail in **Figure 3.5**, which is an amplified version of **Figure 3.4** to improve the interpretation of the values. The price floor provides a minimum revenue guarantee that slightly reduces the threshold over time, making the investment marginally more attractive as the contract continues. This reduction suggests that the price floor adds value by lowering the required conditions for investment, especially in the later stages of the contract, though the difference remains relatively small compared to the without subsidy scenario.

Both the investment subsidy and premium FiT scenarios exhibit similar impacts on the investment thresholds due to their financial equivalence in present value terms. This results in both scenarios showing a sharp decline in the investment threshold over time, strongly incentivizing immediate investment. The observed pattern of declining thresholds over time is nearly identical between the two, reflecting their equivalent effectiveness in promoting early investment. This consistency underscores the effectiveness of both schemes in reducing investment barriers and highlights the flexibility in subsidy design that allows for different forms of financial support to achieve the same outcome.

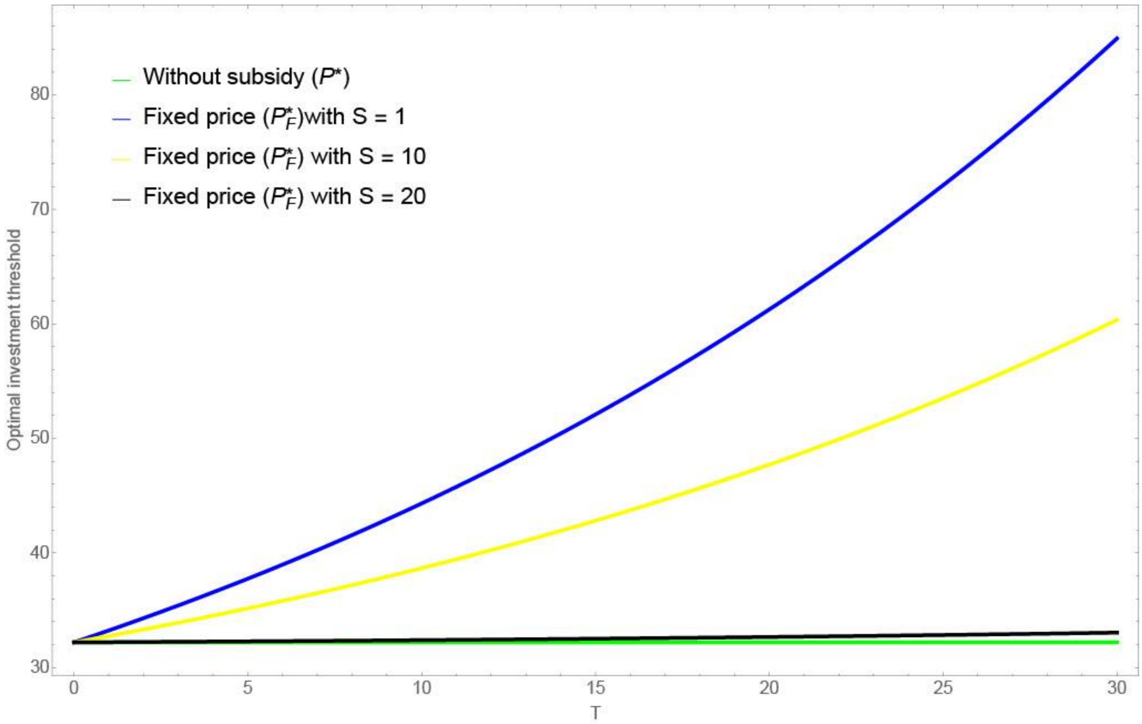

Figure 3.6: Triggers as a function of the contract duration T under different subsidy levels S.

Figure 3.6 presents the optimal investment thresholds of a fixed-price subsidy as a function of the contract duration T under different subsidy levels (S = 1, S = 10, and S = 20). The analysis of these scenarios provides insight into how varying levels of subsidies within the same scheme influence the investment threshold over time.

Lower subsidy levels (e.g., S = 1) result in a rapidly increasing threshold, potentially discouraging investments as the conditions become progressively less attractive. Higher subsidy levels (e.g., S = 10 and S = 20) slow this increase, offering a more favourable investment environment over time but still not eliminating the upward trend entirely.

From a policy perspective, this analysis suggests that while fixed-price schemes with low subsidies may not be sufficient to encourage investment over time, increasing the subsidy level can partially counteract this effect. However, even with higher subsidies, the investment threshold still increases, indicating that fixed-price schemes might not be the most effective tool for encouraging long-term investments, especially as the contract duration extends.

In conclusion, the graph demonstrates that while subsidies can mitigate the disadvantages of a fixed-price subsidy, they do not fully neutralize the increasing investment thresholds over time. Therefore, for encouraging long-term investments, policymakers may need to consider higher subsidy levels or alternative subsidy mechanisms that more effectively stabilize or reduce the investment threshold as time progresses.

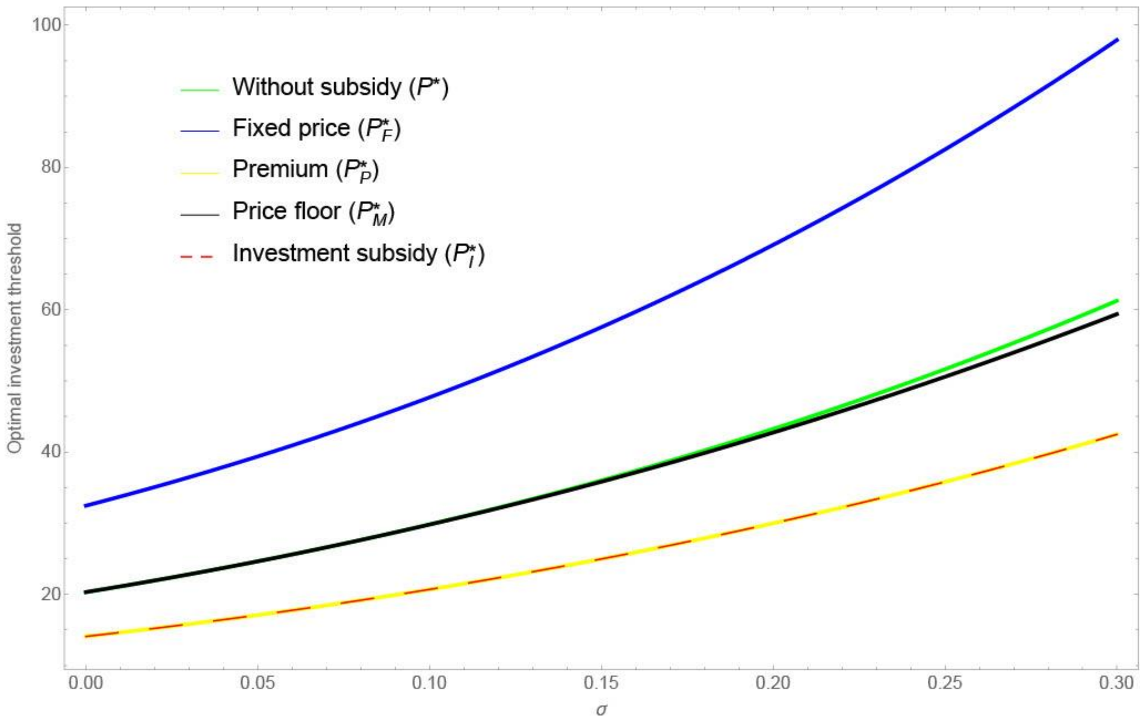

Figure 3.7: Triggers as a function of the volatility σ.

Figure 3.7 presents the graph of the investment thresholds for different values of the volatility σ. The outcomes align with the principles of real options theory, wherein higher volatilities increase the thresholds, consequently deferring the investment decision. Overall, this analysis highlights the varying degrees of sensitivity to risk among different subsidy schemes. The fixed-price policy's high sensitivity to volatility suggests that it may be less suitable in highly uncertain environments, potentially leading to significant delays in investment.

On the other hand, both the premium FiT and the investment subsidy schemes demonstrate a consistent and similar resilience to increasing volatility, offering lower and more stable investment thresholds. This behaviour reflects their financial equivalence, meaning that any differences in investor response should be minimal and driven by factors other than the subsidy structure itself. The price floor and no subsidy scenarios offer moderate risk mitigation, but they do not provide as strong an incentive for investment as the premium or investment subsidy schemes. Critically, while the premium and investment subsidy are effective at lowering barriers and encouraging investment, policymakers should be cautious of the potential market distortions they could introduce, ensuring that these subsidies are applied judiciously to avoid unsustainable investments and maintain market integrity.

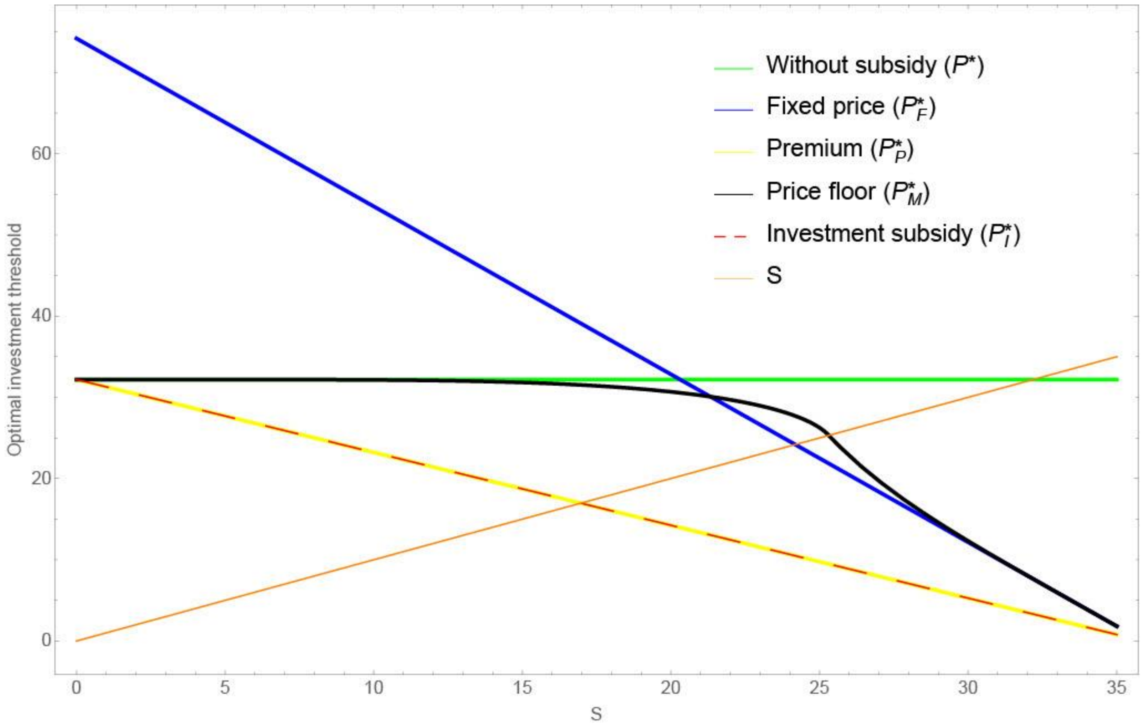

Figure 3.8: Triggers as a function of the subsidy levels S.

Figure 3.8 illustrates the optimal investment threshold as a function of varying subsidy levels S across different scenarios. As subsidies increase, each scheme shows distinct patterns in how it influences investment thresholds, revealing the strengths and weaknesses of each approach.

As the subsidy level increases, its impact on the fixed-price policy becomes progressively more pronounced. Initially, at lower levels of S, the subsidy does not provide enough financial support to meaningfully reduce the investment threshold, which results in the threshold being higher or comparable to the no-subsidy scenario. This limited impact occurs because the subsidy at these levels is insufficient to adequately mitigate the risks or costs associated with the investment.

However, as S continues to increase and reaches a critical point (around S = 22), the subsidy starts to have a more substantial effect. At this level, the financial support provided by the subsidy is finally strong enough to lower the investment threshold below the no-subsidy threshold. This reduction in the threshold makes investments more attractive by decreasing the required conditions for a viable investment, thereby encouraging earlier investment decisions. The increase in S thus transforms the fixed-price policy from being ineffective at lower levels to becoming a powerful tool for promoting investment as the subsidy level rises sufficiently.

The price floor scheme initially shows minimal impact on the investment threshold at lower subsidy levels. However, as S increases beyond S = 15 to S = 20, the price floor becomes more effective, with a sharper decline in the threshold. This improvement suggests that higher subsidies make the guaranteed minimum return more attractive, thereby enhancing the investment environment. Despite this, the price floor still lags behind the premium and investment subsidy schemes in overall effectiveness, especially at higher subsidies, where those schemes continue to provide greater reductions in the threshold.

Additionally, the premium and investment subsidy schemes consistently lower the investment threshold as subsidies increase, making them the most effective across a wide range of S values. These schemes are particularly advantageous when substantial subsidies are needed to drive investment. This similarity suggests that the decision between these two schemes would depend on investor preference for upfront financial support versus ongoing premiums, rather than on differences in financial effectiveness. The consistency in their impact across varying subsidy levels reaffirms that both are highly effective in driving investment when substantial subsidies are required."

The without subsidy scenario remains flat across all levels of S, indicating that it serves as a baseline with no impact from subsidies. This scenario is useful for comparison but does not provide any additional incentive for investment.

In summary, while the fixed-price scheme is effective at both low and high subsidy levels, it becomes less favourable at mid-range subsidies, where no subsidy might be a better option. The price floor scheme, though less effective at lower subsidies, becomes more attractive as subsidies increase but still falls short compared to the premium and investment subsidy schemes. These latter schemes consistently lower the investment threshold but require careful calibration to avoid market distortions. The effectiveness of each subsidy scheme is closely tied to the value of S, underscoring the importance of precise subsidy calibration to optimize investment outcomes and ensure cost-effectiveness.

The research carried out in this thesis has not only evaluated the effectiveness of various subsidy schemes in solar power investments but also brought attention to the critical importance of managerial flexibility that is the ability for investors to adapt to changing market conditions. This flexibility, particularly in the context of volatile markets, is a key factor in optimizing financial outcomes and ensuring the long-term viability of projects. Through the comparative analysis of different subsidy mechanisms, the findings suggest that fixed-price FiTs, fixe- premium FiTs, and minimum price guarantees offer distinct advantages and trade-offs depending on the market context and the investor's need for adaptability.

The research demonstrates that fixed price-FiTs offer the most immediate financial certainty. However, this certainty comes at a cost: rigidity. Once the investment decision is made, the fixed nature of the returns provides no room for adaptability. Investors in such a scheme are unable to capitalize on favourable market shifts or mitigate losses during downturns, which limits the overall strategic flexibility they can exercise throughout the project's life cycle.

In contrast, both fixed-premium FiTs, minimum price guarantees, and investment subsidies offer a different kind of value by balancing financial support with managerial flexibility. These subsidy schemes allow investors to adjust their strategies based on evolving market conditions. Under a fixed-premium FiT, for example, investors receive a premium over the prevailing market price, which enables them to benefit from favourable price fluctuations while still maintaining a level of financial protection during periods of lower market prices. Similarly, the minimum price guarantee provides a price floor that assures investors of a minimum return, but also allows for potential gains when market prices exceed the guaranteed minimum. Thus, effectively mitigates the financial risk associated with price volatility, allowing investors to commit capital with confidence. These schemes, though less immediately certain than fixed-price FiTs, are particularly valuable in volatile markets, where flexibility is essential for optimizing long-term returns.

The findings highlight that managerial flexibility is a critical component in investment decision-making, especially under conditions of uncertainty. Fixed-premium FiTs and minimum price guarantees allow investors to exercise dynamic options such as delaying, expanding, or abandoning projects based on real-time market signals. This ability to adapt is crucial in volatile markets where energy prices can fluctuate significantly. Investors are not locked into a rigid pricing structure, as they are with fixed-price FiTs, and can therefore mitigate risks or capitalize on opportunities as they arise.

The static analysis performed in this study supports this conclusion by illustrating how schemes that incorporate managerial flexibility maintain lower investment thresholds in volatile environments. This encourages investors to engage more readily, knowing that they can adjust their positions as market conditions change. While fixed-price FiTs offer immediate certainty and are ideal for stable markets, their lack of flexibility can be a disadvantage in less predictable environments. Conversely, the flexibility inherent in fixed-premium FiTs, minimum price guarantees, and investment subsidies positions makes these schemes superior in managing uncertainty and optimizing financial outcomes over time.

In terms of investors, those operating in stable markets should prioritize fixed-price FiTs, which provide guaranteed returns and reduce exposure to energy price volatility. These schemes are particularly suited for risk-averse investors who seek predictable, long-term cash flows without needing to adjust to changing market conditions. On the other hand, in volatile markets, investors should consider fixed-premium FiTs, minimum price guarantees or investment subsidies. These schemes offer the critical flexibility needed to navigate market fluctuations, allowing investors to delay investments, expand them when conditions are favourable, or reduce their involvement during less favourable periods. In such markets, investors should focus on maintaining strategic adaptability, utilizing real options theory to assess the optimal timing for investment decisions.

For policymakers, in stable markets, it is essential to maintain or introduce fixed-price FiTs. These tariffs provide the financial security needed to encourage large-scale investments quickly, thus accelerating the deployment of solar energy infrastructure. However, in volatile markets, the focus should shift towards fixed-premium FiTs and minimum price guarantees, which balance risk protection with flexibility. These schemes allow investors to make market-responsive decisions, thereby sustaining investment momentum even during periods of uncertainty. Over time, as markets mature, policymakers should gradually transition from fixed-price schemes to more market-oriented approaches, such as premium-based models or auction systems. This shift would help avoid the pitfalls of over-reliance on government subsidies, fostering a self-sustaining renewable energy market.

Conclusion

This dissertation undertook a thorough investigation into the effects of diverse subsidy policies on investment choices and financial outcomes within the solar power domain, with a specific emphasis on the Portuguese market. By employing the theoretical framework of real options, the study scrutinized the way various subsidy frameworks influence the timing, valuation, and general feasibility of solar energy initiatives. Moreover, the research explored the significant impact of managerial adaptability in refining these investment choices, particularly in the context of market volatility.

The results derived from both the case study and static analysis are congruent, indicating that in stable market conditions, fixed-price FiTs are the most efficacious in alleviating investment obstacles. These frameworks provide assured, consistent returns, which markedly diminish the investment trigger threshold and mitigate the financial risks linked to market fluctuations. Investors operating in stable environments are drawn to fixed-price FiTs due to their predictability and long-term reliability. Nevertheless, the investigation also underscored a fundamental limitation: once the investment has been executed, these frameworks afford no opportunity for adjustment, thereby constraining investors from capitalizing on advantageous market changes and consequently diminishing strategic adaptability.

Conversely, the research uncovered that in volatile market conditions, fixed-premium FiTs, and minimum price guarantees exhibit superior performance by facilitating enhanced flexibility. These frameworks permit investors to modify their strategies in a responsive manner to fluctuating market conditions, thus optimizing returns while concurrently minimizing risks. Both the case study and static analysis reinforced the notion that such adaptability is essential when confronted with uncertainty. Investors possess the ability to defer or escalate their commitments in accordance with market dynamics, which aids in mitigating financial exposure while leveraging potential advantages. This level of adaptability renders these frameworks more appropriate for erratic market conditions.

The efficacy of investment subsidies was somewhat less pronounced than initially anticipated. While they effectively diminish initial capital constraints, rendering projects more viable, they do not substantially augment overall project value or stimulate prompt investment. Both the case study and static analysis illustrated that these subsidies do not offer the same degree of sustained financial backing as FiTs. They fundamentally facilitate feasibility but are inadequate by themselves to uphold significant investment momentum, particularly in volatile markets. However, the static analysis indicated that investment subsidies could expedite investment over time by alleviating upfront expenditures, particularly as project costs diminish. Nevertheless, in the absence of supplementary financial instruments, their capacity to propel immediate large-scale investments remains constrained.

This study emphasizes the significance of contextually aware subsidy frameworks. For policymakers, fixed-price FiTs are advocated in consistent and low-volatility markets as they yield financial assurance, diminish risks, and foster initial investments in solar infrastructure. Conversely, in markets characterized by volatility, it is imperative to employ more adaptable subsidy frameworks such as fixed-premium FiTs and minimum price guarantees, which facilitate flexibility, risk mitigation, and the potential for enhanced returns. These subsidy mechanisms enable dynamic investment approaches, thereby supporting ongoing investment even amidst uncertain circumstances. PPPs are also recommended as efficacious for the distribution of risks in extensive renewable energy initiatives, thereby ensuring financial sustainability in both stable and volatile contexts. For investors, the selection of subsidy types is contingent upon market stability. Fixed-price FiTs are deemed appropriate for stable markets, providing long-term, predictable returns. In contrast, in volatile markets, fixed-premium FiTs and minimum price guarantees are favoured as they afford the flexibility necessary to manage risk and adapt investment strategies, thereby optimizing returns while alleviating potential losses.

While antecedent studies have evidenced the efficacy of fixed-price FiTs in diminishing investment risk within stable markets, this research extends the discourse by elucidating how flexible subsidy mechanisms, such as fixed-premium FiTs and minimum price guarantees, empower investors to navigate uncertain conditions. These revelations underscore the necessity for adaptable subsidy policies in the context of evolving energy markets, where inflexible models frequently prove inadequate in addressing fluctuations.

Moreover, the incorporation of real options theory yielded significant insights regarding how investors can enhance their decision-making processes by dynamically adjusting investments in response to shifting market conditions. Furthermore, the study highlighted the limitations associated with the solitary use of investment subsidies, thereby reinforcing the imperative to synthesize them with ongoing financial mechanisms, such as FiTs, to maximize their efficacy.

Although this research provides meaningful insights, its concentration on the Portuguese market may curtail its broader applicability to regions with disparate regulatory frameworks. Additionally, broadening research to encompass cross-country comparisons could yield a more holistic understanding of the operational dynamics of subsidy schemes in varied contexts. Furthermore, the focus of this study predominantly revolved around financial outcomes, with comparatively less emphasis on environmental and social considerations. The inclusion of these factors in forthcoming studies would yield a more comprehensive evaluation of renewable energy policies. Lastly, investigating how investment subsidies can be more effectively integrated with other financial mechanisms will be crucial for propelling both immediate and prolonged investments as the renewable energy sector continues to evolve.

In reflecting upon this research endeavour, it becomes evident that the trajectory of renewable energy is contingent upon our capacity to devise policies that are as dynamic and responsive as the markets they are intended to support. As we progress, it is my aspiration that the insights derived from this study will contribute to the overarching efforts aimed at establishing a resilient and sustainable energy future. The challenges are considerable, yet so too is the potential for innovation and advancement. By aligning our policies with the realities of market conditions and the needs of investors, we can hasten the global transition to renewable energy and ensure that our endeavours are both effective and enduring.

Overall, the research underscores the enhanced efficacy of fixed-price FiTs within stable market environments, the pivotal importance of managerial adaptability in maximizing investments amidst volatile conditions, and the imperative for meticulously designed subsidy frameworks that correspond with particular market dynamics. The static analysis provides direct corroboration for these conclusions by quantifying the influence of critical market variables such as volatility, subsidy magnitude, and contract length on investment triggers, thereby elucidating how varying subsidy structures affect financial performance and investment choices. These integrated insights are crucial for effectively navigating the intricacies of global transitions to renewable energy while advancing sustainable development objectives.

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