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Risks, Rates, and Rays

THE FINANCIAL REALITIES OF BRAZIL’S SOLAR REVOLUTION

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Abstract

The dissertation investigates the financial realities of Brazil's solar energy sector, with a focus on how financing conditions impact the Levelized Cost of Energy (LCOE) for solar photovoltaic (PV) projects. Using a three-tiered methodological approach, it estimates the nominal after-tax Weighted Average Cost of Capital (WACC) for solar PV projects in Brazil, calculates LCOE for projects that won energy auctions from 2014 to 2022, and projects future scenarios for financing conditions from 2024 to 2029. The study highlights how Brazil's macroeconomic environment, including currency volatility, inflation and interest rates, significantly affects financing costs, which in turn drive LCOE.

The analysis shows that, despite technological advancements and falling CAPEX, rising financing costs have limited the potential reduction in LCOE for solar PV projects. These dynamics are particularly significant in emerging markets like Brazil, where country-specific risks such as currency depreciation and political instability play a crucial role. The dissertation emphasizes the importance of macroeconomic stability for the successful scaling of solar energy projects and suggests that targeted financial strategies, such as policy interventions, could mitigate the negative effects of volatile financing conditions on renewable energy development.

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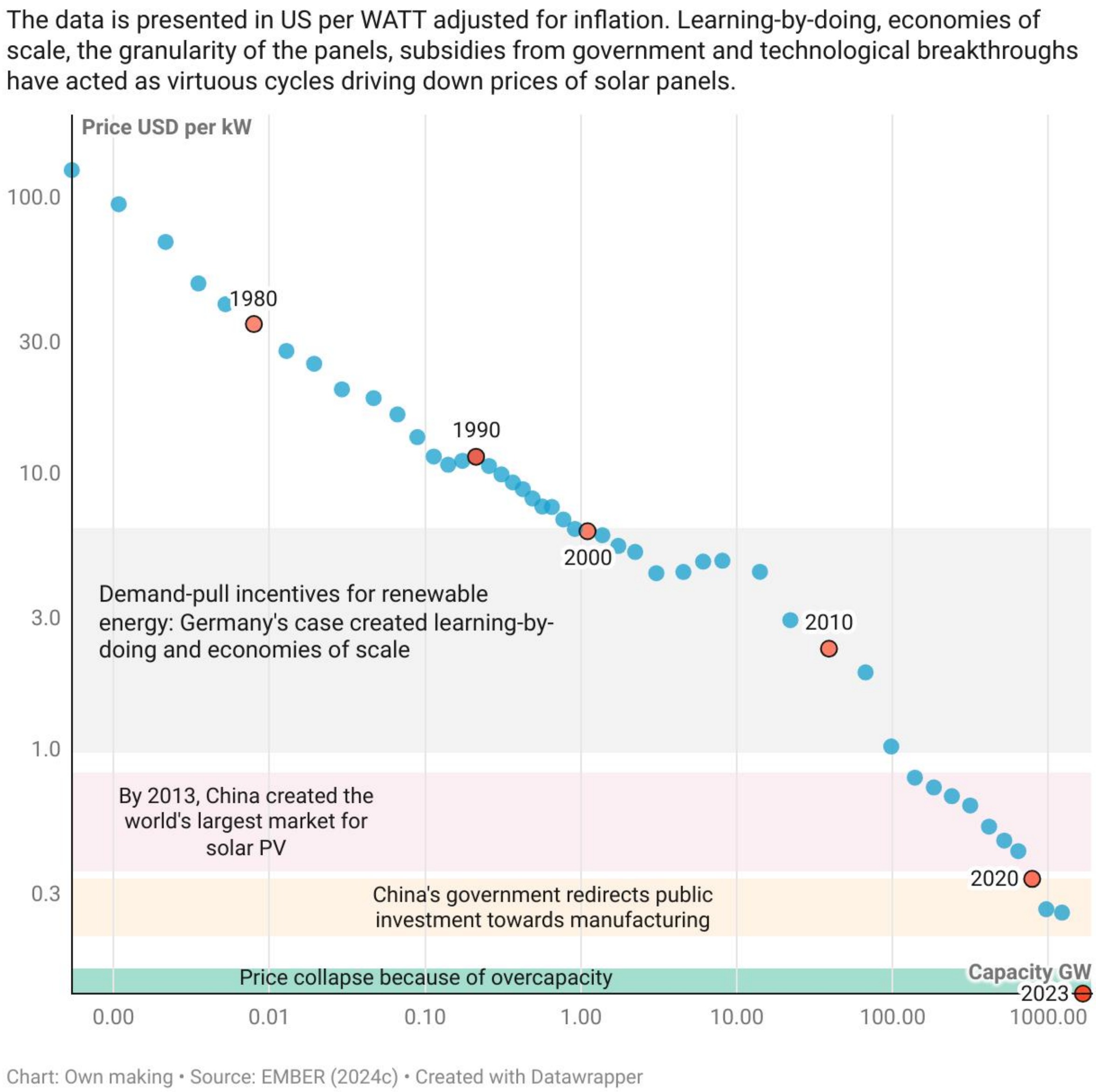
Introduction

Background and Context

The worldwide power sector is experiencing a seismic shift, propelled by the pressing imperative to combat climate change and swift progress in renewable technologies. This evolution is marked by a transition from fossil fuels to cleaner, sustainable energy sources, notably solar and wind power. Solar photovoltaic (PV) energy has emerged as a cornerstone of this transition, experiencing unprecedented growth and cost reductions over the past decade, it has become the cheapest source of electricity in history (IEA, 2024b). This growth has been nothing short of revolutionary, with global installation rates increasing from one gigawatt per year in 2004 to potentially reaching 520-655 gigawatts in 2024 (The Economist, 2024).

The exponential growth of solar PV is underpinned by a virtuous cycle of increasing production facilitated by demand-pull policies, falling costs derived from economies of sclae and learning-by-doing, and rising demand (Nemet, 2019). Since the 1960s, the levelised cost of solar energy has decreased by a factor of more than 1,000, representing one of the steepest drops in the price of a basic factor of production in economic history. This trend shows no signs of abating, according to the International Energy Agency (2024b), solar energy is poised to be the largest receiver of investment in the world, surpassing USD 500bn in 2024.

Figure 1. Solar Panel Learning Curve



In emerging markets and developing economies, such as Brazil, solar PV holds immense potential to meet rising energy demands while contributing to decarbonisation efforts. Brazil, with its vast landmass and abundant solar resources, is particularly well-positioned to harness solar energy. The country's solar irradiation levels are among the highest globally, with some regions receiving up to 6.5 kWh/m^2/day (Pereira et al., 2017). Despite this potential, Brazil's solar PV capacity has only recently begun to accelerate, growing from negligible levels in the early 2010s to becoming the second largest source of electricity in the country by 2023, accounting for 19% of installed capacity (ANEEL, 2024a).

This rapid growth has been facilitated by a combination of factors, including declining technology costs, supportive policies like energy auctions or financing incentives by the Brazilian Development Bank (BNDES), and the introduction of net metering regulations (Iglesias & Vilaça, 2022). The expansion of solar PV in Brazil is not only crucial for meeting the country's rising electricity demand but also for diversifying its energy mix, which has historically been dominated by hydropower. This diversification is particularly important in light of the vulnerabilities exposed by severe droughts, such as the energy crisis of 2001-2002 (Carstens & Cunha, 2019).

However, the continued expansion of solar PV in Brazil faces several challenges, including grid integration issues, permitting delays, and, crucially, financing constraints (Damasio, 2024). The cost of capital for solar PV projects in Brazil, as in many EMDEs, remains significantly higher than in advanced economies, potentially hindering the sector's growth and competitiveness (IEA, 2024a). This disparity in financing costs is particularly concerning given the recent global shift towards higher interest rates and the end of the 'zero era' for interest rates in many advanced economies (Martin et al., 2024).

Problem Statement

Despite the growing importance of solar PV in Brazil's energy transition and its potential to revolutionise the country's energy landscape, there is a limited understanding of how macroeconomic factors, particularly interest rates, influence the cost of capital for solar PV projects in the country. This knowledge gap is particularly concerning given the recent global shift towards higher interest rates and the end of the 'zero era' for interest rates in many advanced economies (Martin et al., 2024).

The weighted average cost of capital (WACC)[1] is a critical metric for assessing the viability of renewable energy projects, especially for capital-intensive technologies like solar PV (Schmidt et al., 2019). In Brazil, where the cost of capital for clean energy projects can be two to three times higher than in advanced economies, understanding

[1] From now on the WACC and cost of capital concept will be used interchangeably.

the dynamics that drive these costs is crucial for policymakers, investors, and project developers (IEA, 2024a).

The lack of available, context-specific data and analysis on the relationship between macroeconomic factors and the cost of capital for solar PV projects in Brazil hinders the development of effective policies and incentives to support the sector's growth. This information gap may lead to suboptimal investment decisions, inefficient allocation of resources, and missed opportunities in accelerating Brazil's energy transition.

Research Objectives

This dissertation aims to address the knowledge gap by investigating the impact of interest rates on the cost of capital for solar PV projects in Brazil. The primary objective is to analyse the historical trends in interest rates and their correlation with the cost of capital for solar PV projects in Brazil from 2014 to 2024. This period encompasses significant changes in Brazil's macroeconomic environment, including the economic recession of 2015-2016, the COVID-19 pandemic, and the subsequent monetary tightening cycle, providing a rich dataset for analysis.

Building on this historical analysis, the research seeks to develop a model that quantifies the relationship between interest rates and the WACC for solar PV projects in Brazil. This model will consider other relevant macroeconomic and sector-specific factors, such as inflation rates, currency fluctuations, and policy changes in the solar energy sector. By incorporating these variables, the study aims to provide a more nuanced understanding of the drivers of financing costs for solar PV projects in Brazil.

Furthermore, this study will assess the implications of different interest rate scenarios on the future cost of capital and competitiveness of solar PV projects in Brazil. This forward-looking analysis will consider various potential macroeconomic trajectories and their impact on the solar PV sector, providing valuable insights for long-term planning and investment decisions.

By achieving these objectives, this research aims to provide actionable insights and recommendations for policymakers and investors to mitigate the impact of interest rate fluctuations on solar PV financing in Brazil. These recommendations will be grounded in empirical evidence and tailored to the specific context of Brazil's energy sector and macroeconomic environment.

Ultimately, this dissertation seeks to contribute to a more nuanced understanding of the financing challenges faced by the solar PV sector in Brazil and to inform strategies for accelerating the country's clean energy transition. By shedding light on the relationship between macroeconomic factors and renewable energy financing, this research aims to bridge the gap between economic policy and energy policy, facilitating more integrated and effective approaches to sustainable development.

Dissertation Structure

This dissertation consists of an introduction, five chapters, and a conclusion, each section contributing to a comprehensive examination of the relationship between interest rates and the cost of capital for solar PV projects in Brazil. The introduction provides the background, context, problem statement, research objectives, and structure of the dissertation. It sets the stage by highlighting global trends in solar PV adoption, specific challenges and opportunities in Brazil, and the critical role of financing costs in shaping the sector's growth.

The first chapter offers an overview of Brazil's macroeconomic landscape, fiscal and monetary dynamics, and solar PV sector development. It explores how factors such as inflation, exchange rates, and fiscal policies have influenced the investment climate for renewable energy, and examines Brazil's solar PV market, including policy frameworks, market structure, and key stakeholders.

The literature review in the second chapter examines existing research on the WACC, its significance in renewable energy investment, and methodologies for estimating financing costs. It critically assesses various approaches to calculating and analysing the cost of capital in renewable energy projects, with a focus on emerging markets, and identifies key debates and research gaps.

The third chapter details the three-tiered methodological approach used to analyse the relationship between interest rates and the cost of capital for solar PV projects in Brazil. It explains the data sources, analytical techniques, and modelling approaches employed, while discussing limitations and steps taken to ensure robustness and reliability.

The fourth chapter presents the findings of the analysis and discusses their implications for the solar PV sector in Brazil. It examines historical trends in financing costs, results of quantitative modelling, and outcomes of scenario analysis, interpreting these findings in the context of Brazil's broader energy transition goals.

The conclusion summarises key findings, discusses broader implications, and suggests areas for future research. This chapter will synthesize the insights gained from the study and reflect on their significance for both academic understanding and practical policymaking. It will also identify remaining knowledge gaps and propose directions for further research to advance understanding of renewable energy financing in emerging markets.

Through this structure, the dissertation aims to provide a rigorous examination of the complex interplay between macroeconomic factors and solar PV financing in Brazil, contributing to both academic discourse and policy considerations in renewable energy finance.

Brazilian Context

Macroeconomic landscape

Brazil, Latin America’s largest economy and the world’s ninth largest, has experienced significant economic fluctuations over the past two decades. This period has been characterized by dramatic swings between robust growth and severe recessions, shaped by both domestic policies and global economic trends. Understanding this trajectory is crucial for contextualising the environment in which Brazil's renewable energy sector, particularly solar PV, operates.

In the early 2000s, Brazil entered a period of robust economic growth, often referred to as its "Brief Golden Age" (Serrano & Summa, 2022). This era was marked by a commodities boom bolstering export earnings, while domestic consumption surged, driven by rising real wages and social programs like Bolsa Familia, which reduced poverty (Gerard, et al., 2021). Brazil's GDP growth averaged 4.5% annually between

2004 and 2010, demonstrating resilience even during the 2008 global financial crisis (IBGE, 2024a).

However, from 2011 onward, Brazil's economy began to experience strain as global economic conditions shifted (Serrano & Summa, 2015). The deceleration of China's economy led to declining commodity prices, impacting export revenues. Domestically, an appreciated real and rising labour costs reduced industrial competitiveness. Government's efforts to stimulate the economy through tax exemptions resulted in falling public revenues, contributing to fiscal imbalances and inflationary pressures (Raffy & Souza, 2018). As a result, GDP growth slowed significantly, averaging just 2.3% between 2011 and 2014.

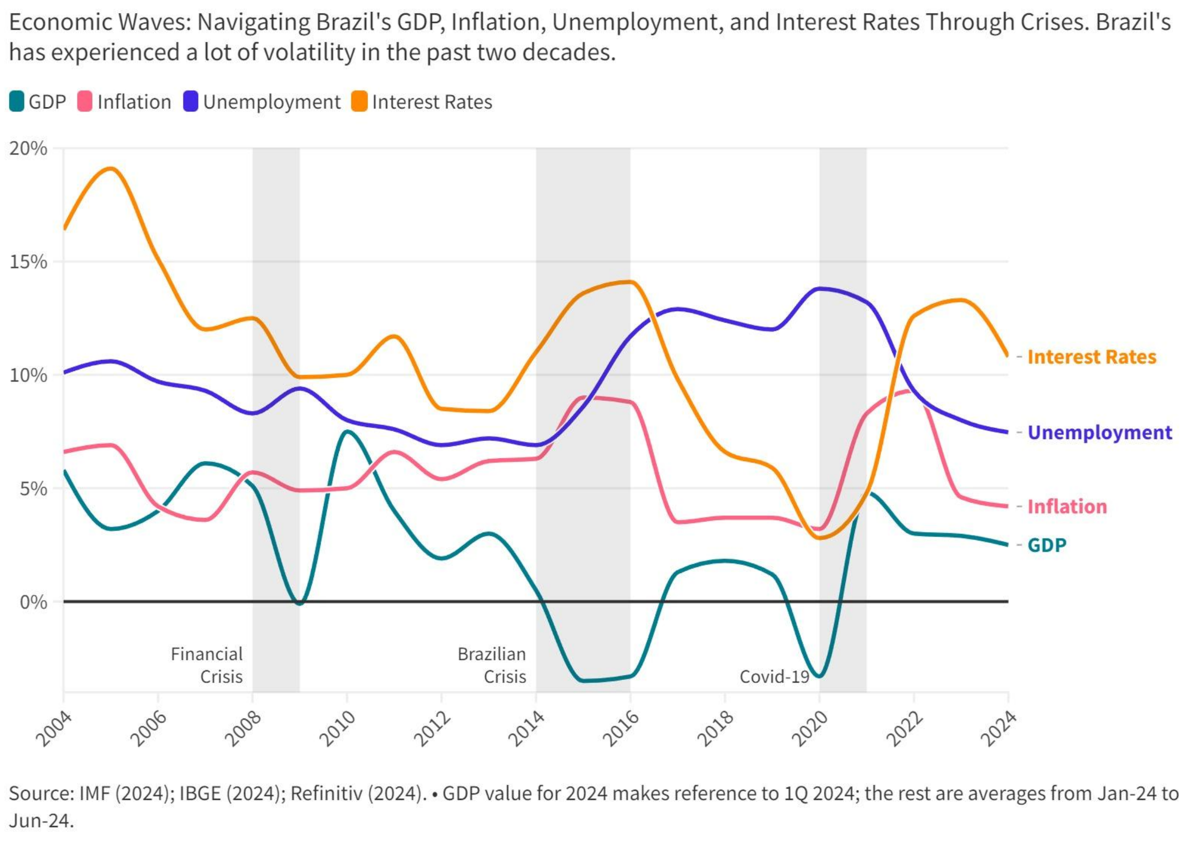
The situation deteriorated further with Brazil plunging into its worst recession in recent history during 2015-2016, marked by severe political instability and widespread corruption investigations. The economic contraction was dramatic, with GDP shrinking by 3.5% in 2015 and a further 3.3% in 2016. Unemployment surged, reaching 13.7% by March 2017 (IBGE, 2024b). The recovery that followed was sluggish, with GDP growth averaging just 1.3% annually from 2017 to 2019, reflecting the challenges in translating economic stabilization into broad-based improvements in living standards (IMF, 2024).

The onset of the COVID-19 pandemic in 2020 dealt another severe blow to Brazil's economy, leading to a 4.1% contraction in GDP. The government responded with substantial fiscal support, including emergency cash transfers to low-income households, which helped mitigate some of the pandemic's economic impacts. Nevertheless, the recovery was uneven, with GDP rebounding by 4.6% in 2021, but unemployment remained high, and the benefits of recovery were not evenly distributed across sectors and income groups (MME, 2022).

By 2022, the economy showed signs of recovery, with GDP expanding by 2.9%, surpassing pre-pandemic levels. However, this growth was accompanied by mounting inflationary pressures, driven by global supply chain disruptions and rising commodity prices. In response, the central bank embarked on an aggressive cycle of monetary tightening, raising the Selic rate to 13.75% in 2022. This tightening, while necessary to curb inflation, also raised concerns about the sustainability of Brazil’s economic recovery and its impact on investment in sectors like renewable energy, a dynamic observed throughout various countries (Martin et al., 2024).

The cost of financing solar PV projects, which rely heavily on upfront investment, is especially sensitive to interest rate fluctuations and policy predictability (Schmidt et al., 2019; IEA, 2024a). High real interest rates increase the cost of capital, making it more challenging to achieve the attractive risk-adjusted returns necessary to justify investments in renewable energy (IEA, 2024b). As of 2024, Brazil's economic landscape presents a mixed picture. Growth has returned, and inflation has moderated somewhat, but significant challenges persist. Unemployment remains stubbornly high at around 8%, and public debt has risen to approximately 85% of GDP (IMF, 2024).

Figure 2. Brazil's GDP, Inflation, Unemployment, and Interests Rates



The cost of capital for clean energy projects in emerging markets and developing economies like Brazil is often at least twice as high as in advanced economies (IEA, 2024b). This disparity is largely due to macroeconomic factors and country-specific risks, which significantly impact the financing landscape for solar PV projects.

Brazil's economic environment continues to be shaped by external factors like global commodity prices and geopolitical risks, and internal factors including fiscal policy and monetary decisions. Luiz Inácio Lula da Silva's return to the presidency in 2023 has signalled potential shifts towards greater social spending and public investment, which must be balanced against fiscal discipline to maintain investor confidence and control borrowing costs.

Despite these challenges, Brazil has seen notable increases in clean energy investment, particularly in renewable power and grid improvements. However, the high cost of capital[2] remains a significant barrier to accelerating renewable energy deployment in the country.

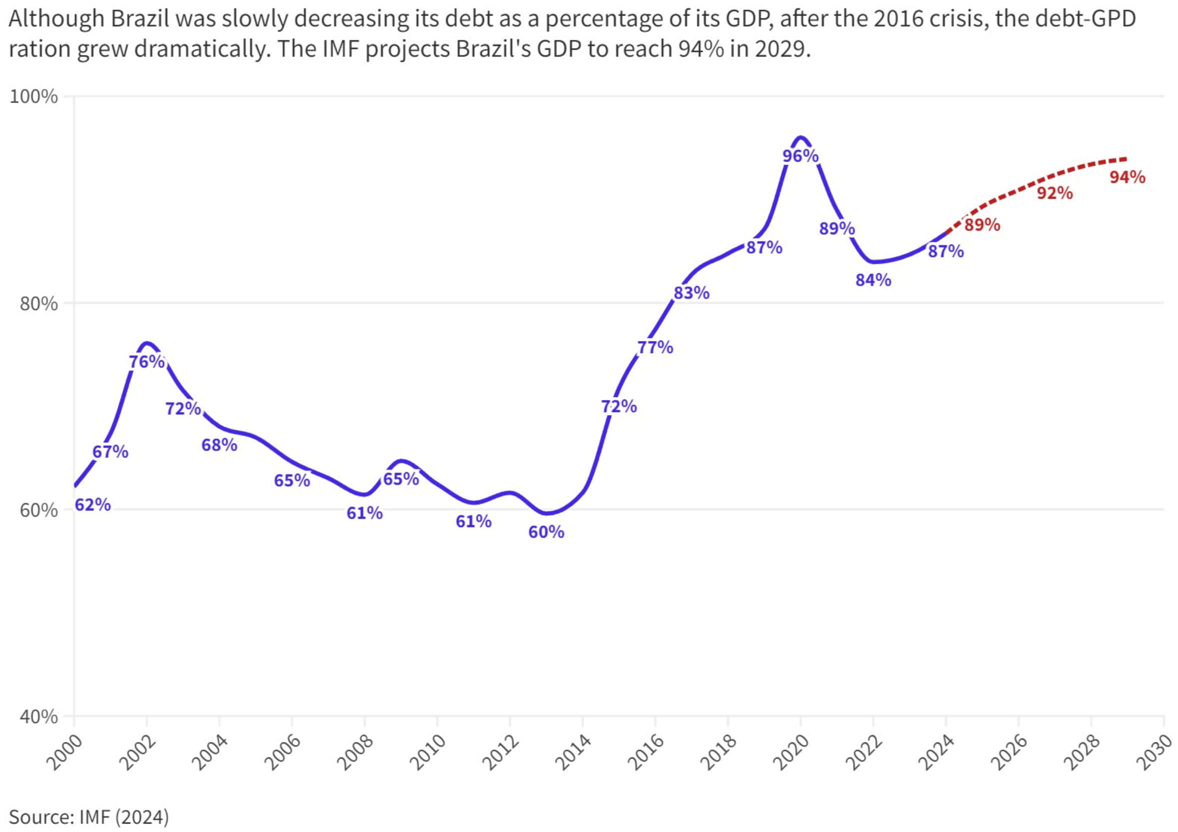
Fiscal, Monetary and Inflation dynamics

The interplay of Brazil's fiscal and monetary policies, alongside its inflation dynamics, plays a crucial role in shaping the investment landscape for renewable energy projects. The cost of capital, critical for solar PV projects' viability, is significantly influenced by these macroeconomic factors (Martin et al., 2024).

Brazil's fiscal challenges are deeply rooted in its high levels of public debt and recurring budget deficits. Public debt has increased from 60% of GDP in 2011 to approximately 85% by 2024, reflecting expansionary fiscal policies, economic downturns, and significant fiscal responses to crises like the COVID-19 pandemic (Bresser-Pereira, 2020). This growing debt burden has raised concerns about Brazil's long-term fiscal sustainability, especially given the country's rigid budget structure, where a large portion of government spending is constitutionally mandated (IMF, 2023a).

[2] Terms like cost of capital, weighted average cost of capital, financing costs are used interchangeably and refer to the same concept of a private discount rate of return.

Figure 3. Rising Tide: Brazil's Debt/GDP Ratio Past Peaks and Future Projections



The 2016 constitutional spending cap ("*teto de gastos*") aimed to impose fiscal discipline but faced criticism for potentially constraining necessary public investments and social spending and exacerbating inequalities (IMF, 2023b). Lula da Silva's return to the presidency brought the "Sustainable Fiscal Regime" in 2023, aiming to balance fiscal responsibility with public investments (Federal Government Brazil, 2023). This new framework aims to balance fiscal responsibility with the need for public investments, allowing for more flexible spending rules compared to the previous cap.

Despite these policy efforts, Brazil's fiscal situation remains precarious. The International Monetary Fund projects public debt could reach 95% of GDP by 2029 (IMF, 2024). High public debt levels increase vulnerability to external shocks and keep interest rates high, affecting the cost of capital throughout the economy, particularly for long-term investments like renewable energy (IEA, 2024b).

Fiscal constraints also limit the government's ability to provide subsidies or tax incentives for renewable energy development, particularly significant for the solar PV sector (IEA, 2024a). The broader macroeconomic effects of fiscal instability, such as exchange rate volatility, further complicate the financial landscape for renewable energy investments.

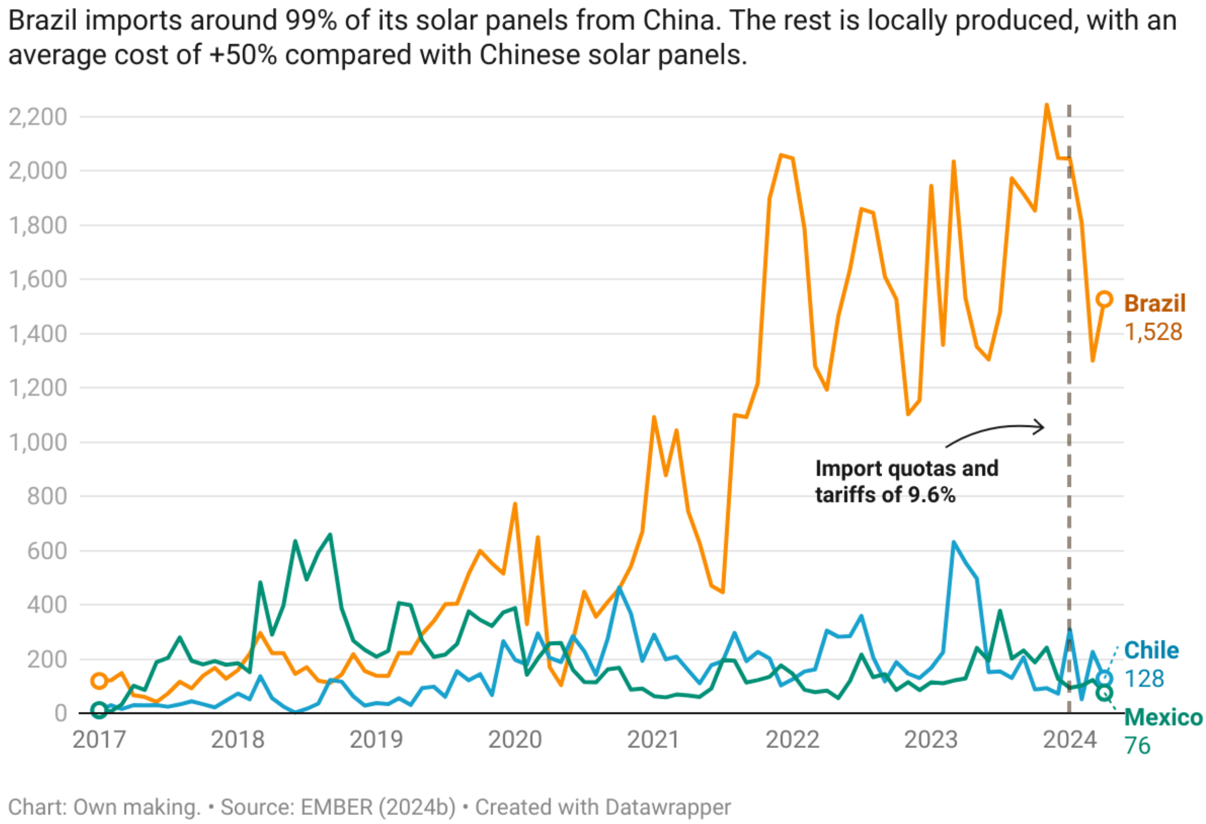
The *Banco Central do Brasil* (Brazil’s Central Bank) manages monetary policy primarily via the Selic rate, which also serves as the remuneration rate for a significant portion of public debt (Zanon & Ribeiro, 2024). As of mid-2024, with the Selic rate at 10.5% and inflation around 4.3%, Brazil's real interest rate remains one of the highest globally, impacting borrowing costs and investment in capital-intensive sectors like renewable energy.

The impact of high interest rates on solar PV projects is particularly pronounced in Brazil’s free market environment (ACL - *Ambiente de Contratação Livre*), where short-term contracts dominate. According to Greener (2022), less than 20% of energy contracted through the free market had a duration above 6 years, creating significant bankability challenges for such projects. This short-term nature of contracts, combined with high interest rates, increases the perceived risk of solar PV investments, potentially leading to higher required returns and overall project costs.

Brazil's monetary system structure, where the policy rate directly impacts public debt costs, creates additional complexities. When Brazil’s Central Bank raises interest rates to combat inflation, it simultaneously increases government debt servicing costs, potentially exacerbating fiscal pressures and constraining economic growth (Zanon & Ribeiro, 2024). This dynamic, often referred to as "fiscal dominance," limits the effectiveness of monetary policy and creates a challenging environment for long-term investments (Moreira et al., 2021).

Brazil's inflation dynamics and exchange rate fluctuations further complicate the investment landscape. The country’s inflation has been historically influenced more by cost-push factors and distributive conflicts than by demand-side pressures. Currency depreciation can lead to higher inflation by increasing import costs, including critical components for solar PV projects. As Brazil imports as much as 99% of its solar panels, this is a critical issue (Martins & Jieqi, 2024).

Figure 4. Solar Panel Imports from China in MW



For instance, Brazil's currency depreciation by nearly 50% against the US dollar from 2013 to 2018, had a severe impact on solar PV projects. The value of power purchase agreements (PPAs) awarded fell by 36%, resulting in the cancellation of several projects as they became economically unviable (IEA, 2024b). This illustrates the significant risk that currency fluctuations pose to long-term infrastructure projects like solar PV installations. This is particularly relevant, as domestic financing through development banks -such as the Brazilian Development Bank (BNDES) or Banco do Nordeste- plays a big role and energy auctions held in the country are in local currency (Steffen, 2023).

Figure 5. BRL/USD exchange rate 2004-2024

High inflation expectations contribute to higher nominal interest rates, further increasing the cost of capital for renewable energy projects. The interaction between inflation, exchange rates, and interest rates creates a complex environment requiring careful financial modelling and risk management for solar PV sector investors.

Despite these challenges, there have been positive developments in the financing landscape for solar PV projects in Brazil. The BNDES has played a crucial role in providing concessional, long-term debt for renewable energy projects when market-based interest rates were high, effectively subsidising interest rates up to 2018. This has helped unlock funding when domestic capital was constrained (IEA, 2021). Additionally, as the market has matured, there has been a shift towards using capital markets for financing, with bonds becoming increasingly popular to finance renewable power in Brazil (Greener, 2022).

Understanding these dynamics is essential for assessing solar PV investments' financial viability in Brazil. The ongoing challenges in controlling inflation and managing exchange rates, alongside the high-interest rate environment, underscore the need for robust economic policies to support renewable energy growth.

Solar PV Landscape

Brazil’s energy profile is characterized by a diverse and relatively clean electricity matrix, setting it apart from many large economies. Renewable sources account for around 86% of the country’s electricity installed capacity as of June 2024 (ANEEL-SIGA, 2024a & 2024b). While hydroelectric power has historically dominated, contributing about 65% of total electricity generation, recent years have seen significant diversification, particularly in solar and wind energy (EMBER, 2024a).

This reliance on hydropower stems from Brazil's abundant water resources and large-scale hydroelectric projects dating back to the mid-20th century (Hochberg & Poudineh, 2021). The “robust hydropower foundation acts like a ‘big battery’ in the Brazilian electricity system” (Damasio, 2024). Brazil's current energy mix originated from the country's industrialization efforts in the 1950s and 1960s, with heavy investments in large hydroelectric projects to support rapid economic growth and urbanization (Hesla, 2011). These investments established hydropower as the backbone of Brazil's electricity system, a position it continues to hold today.

However, hydropower dominance has faced challenges. Periodic droughts and environmental concerns have highlighted the vulnerabilities of over-reliance on a single energy source. The severe energy crisis of 2001-2002, known as the "*Apagão*" (blackout), was a turning point that these vulnerabilities and catalysed efforts to diversify the energy matrix (Carstens & Cunha, 2019). This has also pushed the country to resort to thermoelectric plants during certain periods (Damasio, 2024). In response, the government implemented a series of reforms aimed at restructuring the electricity sector and promoting alternative energy sources (Barbosa et al., 2020).

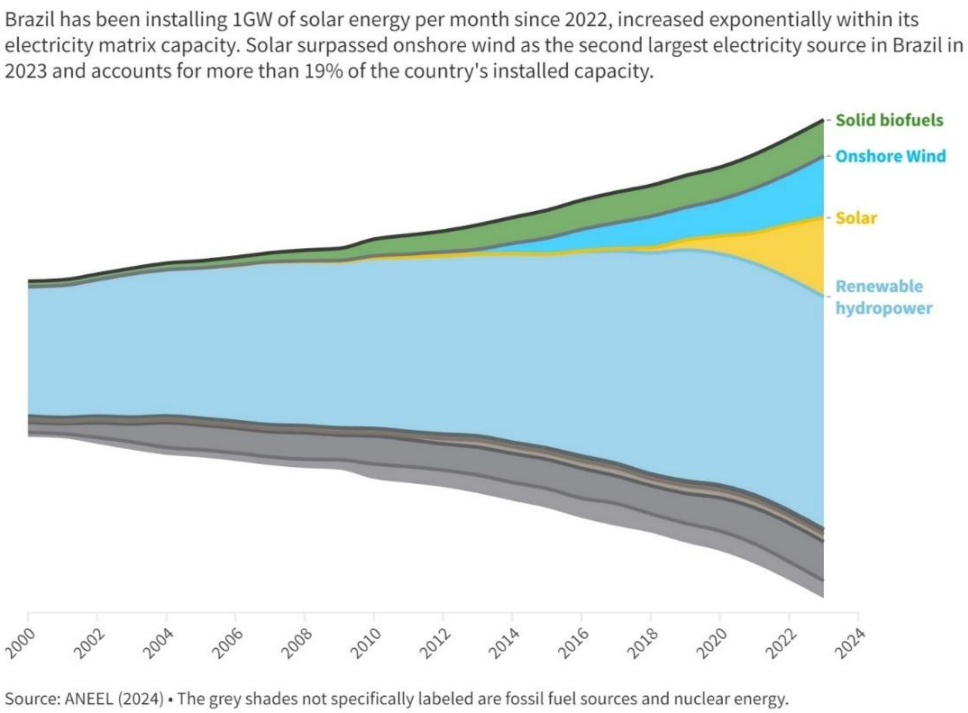
A pivotal moment in this policy evolution was the introduction of the Incentive Program for Alternative Sources of Electric Energy (PROINFA) in 2002. PROINFA aimed to increase renewable energy's share in Brazil's electricity mix by providing long-term contracts and financial incentives for wind, biomass, and small hydroelectric projects

(Werner & Lazaro, 2023). While PROINFA did not initially include solar PV, it set an important precedent for renewable energy support mechanisms in the country (Aquila et al., 2017).

Since then, onshore wind has seen remarkable growth, increasing from just 342 GWh in 2006 to 93,680 GWh in 2017, representing almost 14% of the total electricity generated in the country in December 2023 (EMBER, 2023). This rapid expansion was facilitated by favourable geographical conditions, particularly in the Northeast region, and supportive government policies, including energy auctions. Biomass has also played a significant role in Brazil's energy mix.

The rapid growth of solar PV energy in Brazil's energy mix is particularly noteworthy. From minimal contribution in the early 2010s, solar PV has experienced exponential growth, making Brazil one of the top producers of solar energy by 2022 and the second largest importer of solar panels in 2023 (EMBER, 2024b). From 2022 to June 2024, the country has added around one gigawatt of solar capacity every month (ABSOLAR, 2024). In 2023, solar energy became the second largest source of electricity in the country, surpassing onshore wind. In June 2024, it accounts for 19% of installed capacity, according to the Brazilian National Electricity Agency (ANEEL, 2024a).

Figure 6. Solar energy installed capacity in Brazil has increased exponentially



Solar energy has been regulated since 1995, with ANEEL establishing regulations for large-scale projects and technical standards (Portal Solar, 2023). However, solar PV has only recently taken priority (Burin et al., 2023).

Onshore wind played a precursor role for solar, both because of familiarity with the resource and because it was cheaper than solar. "In effect, wind power allowed policymakers to test policies when solar was too expensive", writes Nemet (2019, p. 42), as seen above with the PROINFA scheme. In addition, 2004 marked the implementation of a new regulatory framework for the electricity sector, introducing energy auctions as the primary mechanism for contracting new generation capacity. The auction system, which continues to be a cornerstone of Brazil's energy policy, aims to ensure efficient contracting mechanisms, security of supply, and universal access to electricity (Viana & Ramos, 2018). Solar energy would be included in the national energy auctions from 2014 onwards.

This auction system framework operates under the Regulated Contract Market (ACR), functioning as a "single buyer" model where a central entity purchases electricity from producers and sells it to distributors through energy auctions (Tolmasquim et al., 2021). The auction system allows solar developers to bid for long-term PPAs, typically lasting 20 years, providing revenue certainty and facilitating project financing (Egli et al., 2023).

These auctions have been instrumental in driving down the costs of utility-scale solar projects and attracting significant investment to the sector. The success is evident in the dramatic decline in solar energy prices, from US$82-90/MWh in 2014 to a low of US$17.6/MWh in 2019 (Viana & Ramos, 2018; ABSOLAR, 2024). However, as the economy entered the Covid-19 crisis, with GDP contracting and inflation and interest rates surging, solar PV auction prices rebounded to the US$30/MWh range (CCEE, 2024).

There’s also a Free Contract Market (ACL), which existed pre-solar energy auctions, allowing large consumers to directly contract energy from producers, it gained momentum in 2015 (Santa Catarina, 2022). Factors such as benchmark-setting auction results, continued reduction in technology costs, and regulatory changes boosted confidence and interest outside the government-regulated environment

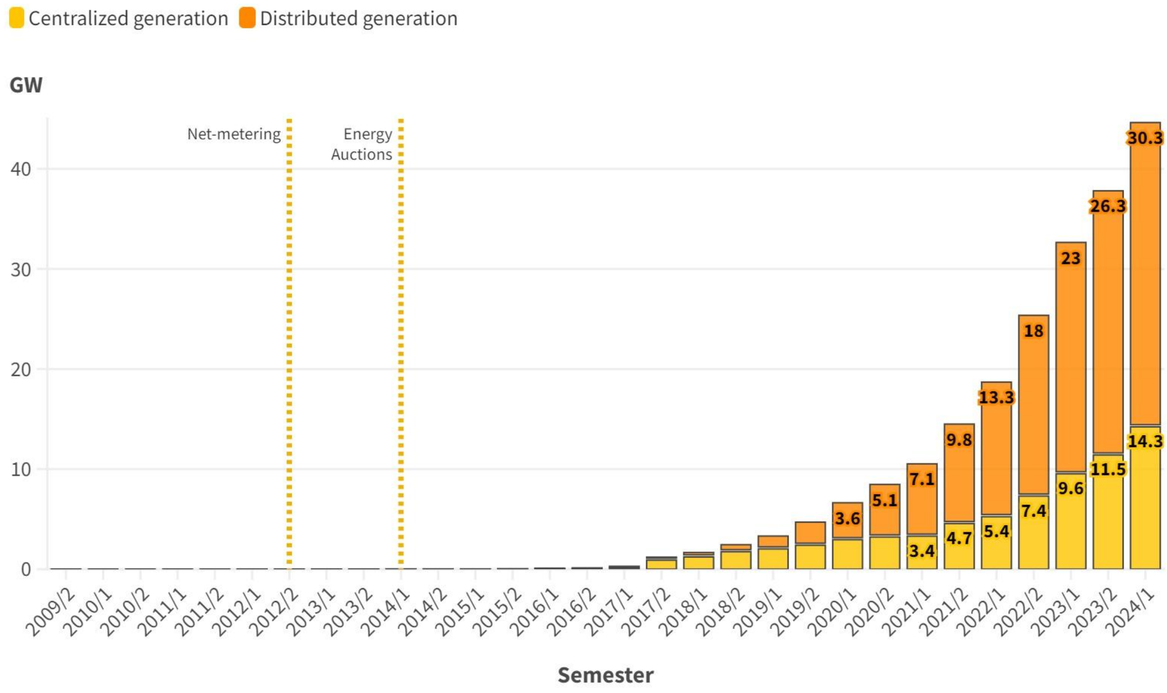
(Baetas, J., 2015; CCEE, 2024). The deregulatory movement within the electricity sector in Brazil is called "*abertura do mercado*" (market opening) and is represented by progressive steps taken to allow consumers more freedom to choose their electricity suppliers, instead of being bound to purchase electricity from a local utility at regulated rates (CCEE, 2022).

The market has seen significant growth in recent years. According to Greener (2024), 58 GW of new solar projects were authorized between March 2023 and February 2024, reaching a total expected capacity of 144 GW. The growth is further bolstered by the government's "growth acceleration" plan unveiled in 2023, allocating substantial funds for renewable energy projects, particularly 196 solar power projects (Federal Government Brazil, 2024).

The introduction of net metering regulations in 2012 through ANEEL's Normative Resolution 482 was crucial for distributed solar generation (Iglesias & Vilaça, 2022). This policy allows small-scale producers, including residential and commercial consumers, to feed excess electricity back into the grid in exchange for credits. These credits can be used to offset future electricity consumption, effectively reducing electricity bills and improving the economic viability of rooftop solar installations (Leite et al., 2024). Distributed generation account for around 70% of installed capacity as of June 2024 in the country (ABSOLAR, 2024).

Figure 7. Solar Centralised and Distributed Generation Installed Capacity

Solar Centralised generation and Distributed generation capacity have grown exponentially in Brazil. As of June 2024, distributed generation accounts for around 70% of total solar energy capacity.



Source: ANEEL-SIGA (2024a & 2024b)

The average size of solar PV projects has increased, driven by efficiency gains from economies of scale. This trend has encouraged developers to design larger projects, optimizing investment returns and reducing operational costs (Greener, 2023). The Brazilian open market has been the primary driver of solar energy contracting, representing 90% of the volume under construction and 64% of the plants already operating as of February 2024 (Greener, 2024). However, this dominance of the free market presents challenges, particularly in terms of project bankability -as short-term PPAs dominate-, as discussed in the macroeconomic landscape section. On the other hand, the last solar energy auctions took place in 2022, presumably because of technological maturity, declining costs and excess of projects available in the open market (CCEE, 2024; Greener, 2024).

The financing of solar PV projects in Brazil has evolved significantly. BNDES, one of the largest development banks in the world, provided a subsidised interest rate for infrastructure projects until 2018 (BNDES, 2024a). The bank has established specific credit lines with lower interest rates and extended repayment periods for renewable energy investments, making it easier for developers to secure financing for solar projects (Silveira et al., 2024).

As of 2024, BNDES and *Banco do Nordeste* continue to be the principal sources of financing for large-scale PV plants, providing R$6.3 billion in financing in 2022 (Greener, 2023). In recent years, debenture bonds have emerged as a fast-growing financing source for new projects, becoming an important alternative to traditional bank financing (Greener, 2022). Additionally, in maturing markets like Brazil, international investment spending currently accounts for around half of the total investment for utility-scale solar PV deployment (IEA, 2024b).

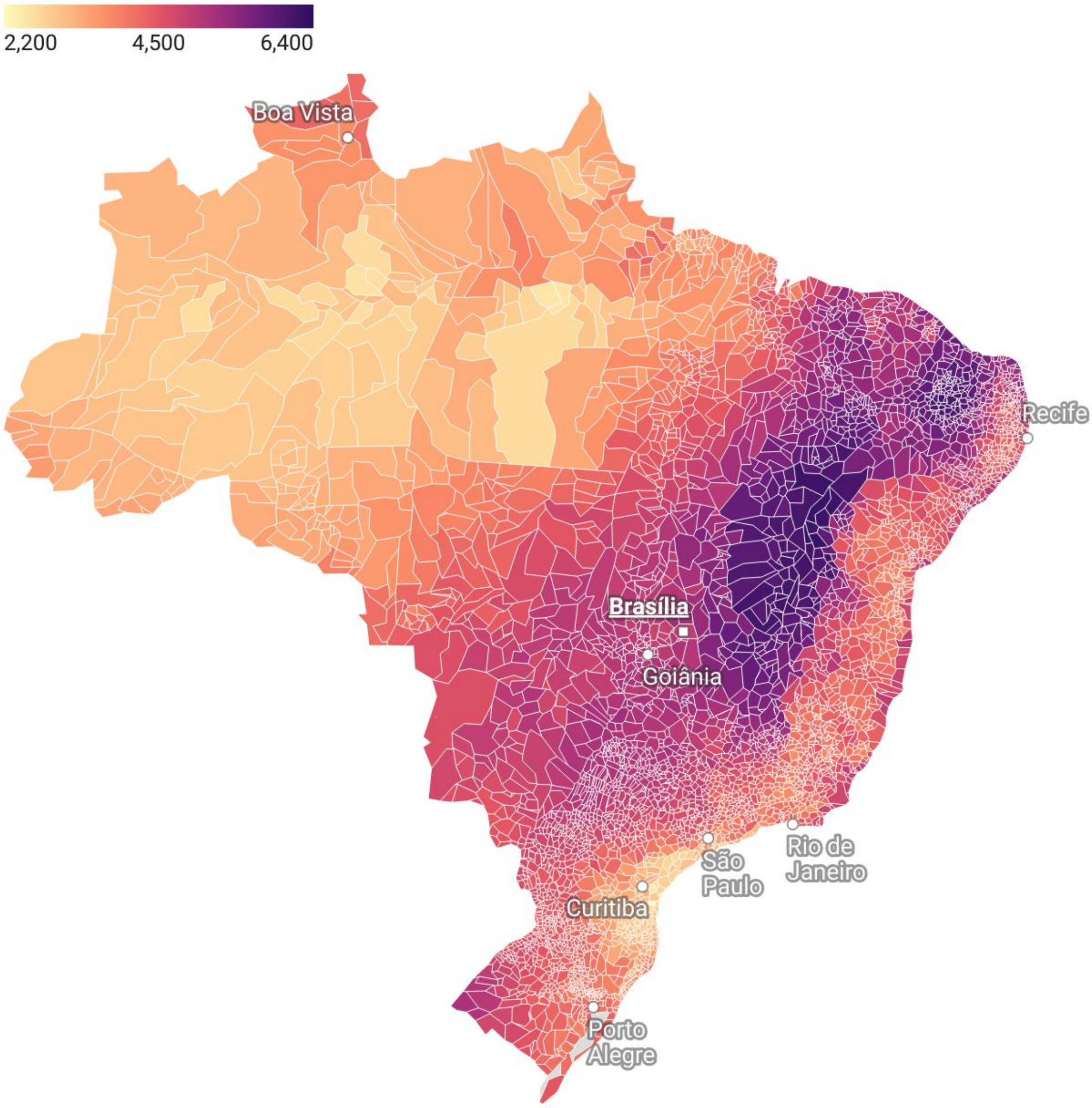
The performance of solar PV plants in Brazil has been impressive, with the top performing plants achieving capacity factors of up to 29.31% (Greener, 2024). This high performance is due to Brazil's favourable solar resources and technological improvements in solar PV equipment. Solar PV plants are mostly concentrated in the Northeast and Southeast regions, where the country experiences among the highest insolation rates globally. The Northeast region has emerged as a hotspot for solar energy development, benefiting from both abundant sunlight and available land for large-scale installations (Pereira et al., 2017; Silveira et al., 2024).

Tax incentives, such as the Special Incentive Regime for Infrastructure Development, have benefited solar installations (Aquila et al., 2017). Furthermore, R&D support initiatives like ANEEL's Strategic R&D Call 13/2011 have provided funding for solar PV research projects (Carstens & Cunha, 2019).

Despite rapid growth and supportive policies, the solar PV sector in Brazil faces several challenges. These include grid integration issues due to rapid growth, high financing costs as discussed in the macroeconomic landscape section, and policy uncertainty stemming from recent changes to net metering policies and the gradual reduction of incentives as well as the introduction of import taxes on solar equipment, which may impact the sector's growth trajectory (Damasio, 2024). Looking forward, continued growth of solar PV in Brazil will depend on addressing these challenges while capitalizing on the country's abundant solar resources and increasing cost-competitiveness of solar technology.

Figure 8. Brazil's Solar Direct Irradiation

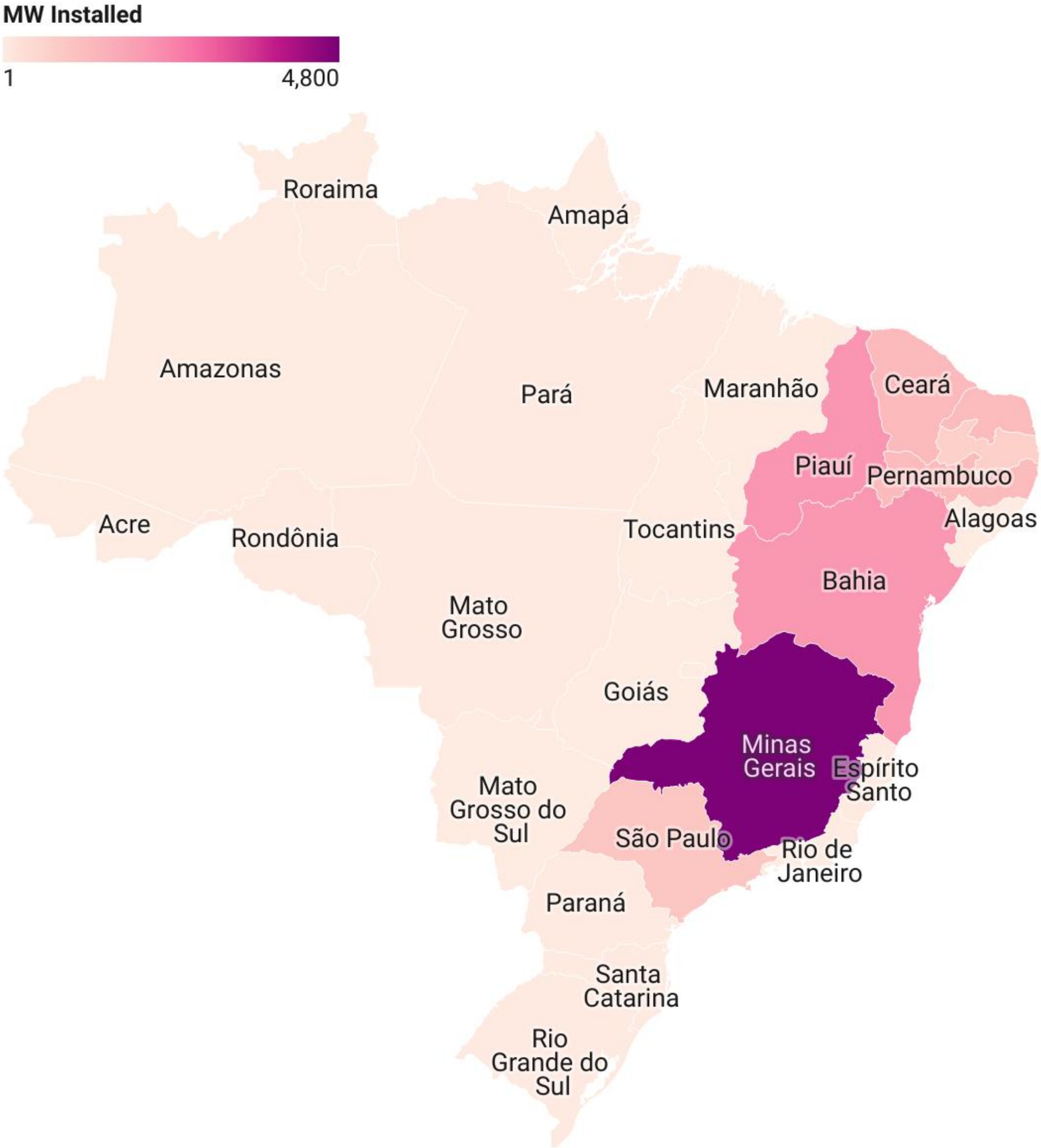
Solar radiation per municipality in Brazil in Wh/m2 per day. Brazil has among the highest direct solar irradiation globally. The Northeastearn region is a hotspot for solar PV projects.



Map: Own making. • Source: Pereira et al. (2017) • Created with Datawrapper

Figure 9. Utility-Scale Solar PV Installed Capacity in Brazil

As of June 2024, according to ANEEL (2024a) there were more than 16 thousand inidividual projects of Solar PV in Brazil. CCEE (2024b) reports around 500 Solar PV power plants. Usually hundreds of individual projects make up a single Solar PV power plant.



Map: Own making. • Source: ANEEL (2024a) • Created with Datawrapper

Literature Review

The WACC and its Characteristics

The significance of WACC in renewable energy investment

The emergence of renewable energy as a dominant investment sector has necessitated a re-evaluation of energy cost modelling methodologies, particularly when comparing renewable technologies with their fossil-fuel based counterparts (Borenstein, 2012; Creutzig et al., 2017; IRENA, 2023). The distinctive cost structures of renewable energy projects, exemplified by utility-scale solar PV installations, diverge significantly from fossil fuel-based energy projects due to variations in capital intensity, operational expenditures, fuel costs, and risk profiles (Schmidt, 2014; Schmidt et al., 2019).

Renewable energy projects typically require substantial upfront capital investment but benefit from lower ongoing operational costs. Conversely, fossil fuel-based projects often have lower initial costs but incur continuous expenditures related to fuel procurement, transportation, and storage. This fundamental difference in cost structure underscores the critical role of financing costs, or the “cost of capital,” in determining the economic viability of renewable energy projects (Gohdes et al., 2022).

In this context, the weighted average cost of capital (WACC) emerges as a crucial metric. Defined as "the expected rate of return that market participants require in order to attract funds to a particular investment" (Pratt & Grabowski, 2014, p. 3), the WACC effectively serves as the project's aggregate "interest rate." In other words, if a project’s return is below the WACC rate it’s essentially destroying value rather than creating it. For capital-intensive renewable energy projects, a lower WACC can significantly enhance investment attractiveness (Steffen, 2020).

The WACC incorporates two fundamental financial concepts: the time value of money and the risk premium. It is utilized in investment evaluations, such as net present value calculations, to determine project feasibility (IRENA, 2023). Moreover, the WACC is a crucial input for calculating the Levelized Cost of Energy (LCOE), a key metric representing the lifetime costs of a power-generating asset divided by its total energy output (Chase, 2023).

As the discount rate in LCOE calculations, the WACC significantly influences the capital cost component, particularly for capital-intensive renewable projects (Egli et al., 2018). As such, the WACC serves as a critical tool for comparative analysis of diverse energy investments, facilitating a more equitable financial assessment of renewable and fossil fuel-based energy projects (EPE, 2022; Lazard, 2024).

Financing structures

Renewable energy projects, particularly utility-scale installations, often employ project finance structures rather than corporate finance (Steffen, 2018). IRENA (2024) reports that 88% of renewable energy projects use project finance across 46 countries. In project finance, a separate legal entity -Special Purpose Vehicle- is created for each project, and the financing is based solely on the project's cash flows without recourse to the sponsor's other assets (Kann, 2009; Steffen, 2018).

Steffen (2020) notes that project finance structures typically allow for higher leverage (debt-to-equity ratio) compared to corporate finance, as the risk is isolated to the specific project. He observes that the debt share can reach 80% in mature markets for renewable energy projects.

The use of project finance in renewable energy has important implications for the cost of capital, as it allows for more precise allocation of risks, potentially leading to lower overall financing costs (Steffen, 2018). Higher leverage can reduce the overall cost of capital, as debt is typically cheaper than equity (Schmidt et al., 2019). The cost of capital can vary significantly between projects, even within the same country or for the same technology, based on project-specific risks and characteristics (Steffen, 2020). Given high leverage, debt financing terms become crucial determinants of project viability (Egli et al., 2018).

Egli et al. (2018) provide empirical evidence of evolving project finance structures for solar PV and wind projects in Germany, noting trends towards higher debt shares and longer loan tenors over time.

Schmidt et al. (2019) highlight how the prevalence of project finance in renewable energy investments necessitates a more nuanced approach to modelling financing costs. They argue that using corporate finance assumptions for renewable energy projects can lead to significant biases in cost estimates.

Sparse and unavailable data

A recurring theme across the literature is the difficulty in obtaining accurate and up-to-date data on the cost of capital for renewable energy projects. This challenge stems from several factors:

Steffen (2020) points out that many RE projects use project finance, keeping financial details private. This lack of transparency hinders access to reliable financing cost data. The rapid technological advancements and cost reductions in the renewable energy sector, particularly solar PV, make it challenging to keep cost of capital estimates current (Egli et al., 2018). Polzin et al. (2021) highlight significant variations in the cost of capital across countries and technologies, complicating generalized assumptions.

Donovan and Nuñez (2012) note the scarcity of suitable empirical data, while Steffen (2018) describes the intricate nature of project finance arrangements, adding complexity to data collection and analysis. Egli et al. (2019) emphasize the time lag in data availability, potentially leading to outdated model calibrations. These challenges significantly impact research and policymaking in the renewable energy sector. Egli et al. (2019) argue that assuming a standard discount rate is often inappropriate given the high sensitivity of results to this parameter.

Researchers have employed various strategies to address these challenges. Steffen (2020) proposes synthesizing available data through systematic review. Egli et al. (2018) combine multiple data sources, including interviews and auction bid analysis. Schmidt et al. (2019) develop a benchmarking tool estimating the cost of capital based on public data, calibrated with expert input.

Heterogeneity in the Cost of Capital for Renewable Energy Projects

Steffen (2020) provides a comprehensive analysis of the variability of the cost of capital for renewable energy projects, illustrating the diverse landscape of financing costs in the sector.

Significant differences exist between countries, particularly between developed and developing countries. The WACC for solar PV projects ranges from as low as 2.5% in Germany, to over 10% in some developing countries, like Brazil, largely due to differences in country risk premiums, policy environments, and financial market maturity (Angelopoulos et al., 2016; Egli et al., 2019).

The cost of capital also varies across renewable energy technologies. Offshore wind projects typically face higher financing costs compared to onshore wind or solar PV, attributed to differences in technological maturity, perceived risks, and project complexity (Voormolen et al., 2016).

Steffen (2020) emphasizes that individual project characteristics, such as project size, developer track record, and specific contractual arrangements, can significantly influence the cost of capital even within the same country and technology segment (Steffen, 2018).

Furthermore, the cost of capital for renewable energy projects evolves over time. Egli et al. (2018) demonstrated a significant decrease in financing costs for solar PV and wind projects in Germany between 2000 and 2017, while Schmidt et al. (2019) estimate potential changes based on different macroeconomic scenarios from 2018 to 2023.

Estimation methods

Estimating the cost of capital for renewable energy projects presents a complex challenge, given the private nature of many project finance deals. Steffen (2020) provides a comprehensive overview of four main approaches used to tackle this issue.

The first method, direct elicitation of project finance data, involves collecting cost information from specific renewable energy deals. Lorenzoni & Bano (2009) pioneered this approach by surveying Italian market investors, while Wood & Ross (2012) compiled data from national authorities as part of an International Energy Agency initiative. This method offers the advantage of directness and potential accuracy. However, as Steffen (2020) points out, assessing the representativeness of individual projects or deals can be problematic. Egli et al. (2018) addressed this limitation by gathering data from numerous German projects with predefined characteristics, thereby enhancing representativeness.

The second approach, expert surveys, relies on interviews with renewable energy market participants to estimate typical costs of capital. For instance, Ardani et al. (2013) interviewed 70 U.S. market participants, while Krupa and Harvey (2017) combined sector discussions with archival research. IRENA (2023) expanded on this method by conducting both quantitative surveys and in-depth interviews with finance professionals, allowing for a more nuanced understanding of financing trends. While this approach can involve a broader set of interviewees, Steffen (2020) cautions that vague selection criteria may increase uncertainty about estimate representativeness. To mitigate this, some researchers have developed more structured processes, such as Angelopoulos et al. (2016 & 2017), who used financial market data as a starting point for expert discussions.

The third method, replication of auction results, has emerged in response to the growing use of competitive auctions for renewable energy procurement. Apostoleris et al. (2018) and Dobrotkova et al. (2018) pioneered this approach, which involves reverse-engineering LCOE models based on publicly available non-financing information from winning bids. Egli et al. (2023) further developed this methodology, analysing thousands of projects across multiple countries. While this method benefits from real-world, competitive market outcomes, it depends on the availability of detailed auction data and assumes realistic cost assumptions by auction winners.

The fourth approach involves analysing financial market data, adapting methods typically used for listed companies. As Steffen (2020) notes, researchers must use market proxies since renewable energy projects are usually unlisted entities. IRENA (2023) incorporates this approach in their benchmark tool, using public financial data to estimate country- and technology-specific costs of capital.

Recent trends, as evidenced by IRENA's report and studies like Egli et al. (2018) and IEA's World Energy Investment 2024, show a move towards integrated approaches that combine multiple estimation methods. This triangulation of results potentially offers more robust and comprehensive financing cost estimates for renewable energy projects.

Components of the WACC

Investors view renewable energy projects as relatively new and risky compared to traditional ones, leading to a higher cost of capital due to risk premiums. Higher perceived risk increases financing costs, affecting project viability. Understanding the cost of capital is crucial for accurate project assessments in the renewable sector. The WACC is the standard measure for overall financing costs. Steffen (2020) outlines three WACC formulas:

$$(1) \quad WACC\ vanilla\ =\ \delta\ \times K_D + (1-\delta) \times K_E$$

$$(2) \quad After - tax\ WACC =\ \delta\ \times (1-\tau) \times K_D + (1-\delta) \times K_E$$

$$(3) \quad Pre - tax\ WACC =\ \delta\ \times K_D + (1-\delta) \times \frac{1}{(1-\tau)} K_E$$

The cost of capital consists of the cost of equity (K_E), cost of debt (K_D), and their relative weights -the debt-equity ratio denoted by δ-, and a tax rate (Jagannathan et al., 2016). Steffen (2020) notes the after-tax WACC is most common due to tax-deductible interest payments but assumes the debt tax shield is discounted at the cost of debt, which may not always be accurate.

Egli et al. (2018) use after-tax WACC, emphasizing technology-specific values due to financing cost variability between technologies. Schmidt et al. (2019) use a similar approach but stress the importance of country-specific factors in calculating WACC for renewable energy projects. Although historically done, uniform WACC assumptions across countries can lead to significant biases (IRENA, 2023b; IEA, 2022).

The cost of debt is crucial in WACC, especially since renewable projects often rely heavily on debt financing. In project finance, where projects are highly leveraged, the cost of debt is vital due to significant upfront costs (Steffen, 2018). Steffen (2020) notes that the cost of debt for project-financed renewable assets is often not directly observable since project finance loans are typically not traded and their terms are confidential. Researchers often rely on expert estimates or derived market values.

The cost of debt for renewable energy firms is initially higher than for non-renewable firms due to perceived risks, but this trend reverses as technologies mature (Kempa et al., 2021). Angelopoulos et al. (2016) explain that debt providers demand higher returns for riskier investments, resulting in higher costs of debt.

Various methods estimate the cost of debt. Steffen (2020) notes that for listed companies, it’s available through current interest expenses or bond yields. Courtois et al. (2012) use bond yields from comparable companies with similar credit ratings. For private renewable assets, bank loan data can be used (Kempa et al., 2021).

Egli et al. (2023) estimate the cost of debt for solar PV projects by deriving it from auction prices reflecting the Levelized Cost of Electricity (LCOE), using project-specific capital and operational costs. Partridge (2018) determines it by adding a risk premium to long-term government bond rates, adjusting for tax benefits, and slightly increasing the rate for renewable projects due to higher perceived risks.

IRENA (2023) calculates the cost of debt across regions and technologies by combining the global risk-free rate (GFR), country-specific default spread (CDS), lender margin (LM), and a technology premium (TP), adjusted for tax to reflect the actual project cost. This yields the cost of debt for financing renewable energy projects:

$$(4) \quad K_D = GFR + CDS + LM + TP$$

Kitzing & Weber (2014) estimate the cost of debt for wind power projects in Germany using a formula that combines the risk-free rate (RF), a credit spread (P_{swap}), and an additional bank margin (BM), assessing borrowing costs specific to the German wind energy sector:

$$(5) \quad K_D = RF + P_{swap} + BM$$

Egli et al. (2018) estimate the cost of debt for solar PV and onshore wind in Germany by analysing debt margins (DM), added to the risk-free rate (RF) to compensate for specific project risks. In Brazil, BNDES charges a 1.1% premium for solar PV projects (BNDES, 2024c). The debt margin decreases as cumulative investments grow, reflecting reduced lender-perceived risk over time:

$$(6) \quad K_D = RF + DM$$

Angelopoulos et al. (2016) calculate the cost of debt for onshore wind investments in EU countries using the European risk-free rate (RF), country-specific credit default spread (CDS), and a project-specific spread (PS), capturing country-specific risks and project uncertainties across EU states:

$$(7) \quad K_D = RF + CDS + PS$$

The cost of equity represents the return required by equity investors and is typically harder to estimate than the cost of debt due to its implicit nature. Steffen (2020) identifies the Capital Asset Pricing Model (CAPM) as the most common method for estimating it:

$$(8) \quad K_E = RF + \beta \times (MRP - RF)$$

However, CAPM’s application to renewable projects, especially in emerging markets, has been questioned. Donovan and Nuñez (2012) propose a "downside beta CAPM" to address non-normal return distributions, emphasizing context-specific approaches.

IRENA's (2023) cost of equity calculation incorporates country risk adjustments using Damodaran's data on risk premiums and default spreads, refining the global risk-free rate to account for specific country risks, ensuring accurate WACC estimates for renewable projects:

$$(9) \quad K_E = RF + ERP + CP + TP$$

Schmidt et al. (2019) build the cost of equity on the cost of debt, adding a premium to compensate for higher equity investor risk. The equity premium is added to the risk-free rate and debt margin to reflect higher return expectations:

$$(10) \quad K_E = RF + DM + ERP$$

Factors Influencing the Cost of Capital for Renewable Energy Projects

The cost of capital for renewable energy projects is influenced by a complex interplay of factors at different levels of the economy and energy sector. Steffen & Waidelich (2022) provide a comprehensive framework categorizing these determinants into four hierarchical levels: macroeconomic environment, energy sector, financial sector, and project/company level. This approach offers insights into how various factors impact financing costs for renewable energy investments.

At the broadest level, macroeconomic and country-specific factors play a crucial role in the cost of capital. Steffen & Waidelich (2022) identify two key components here: country risk and general interest rate environment. Economic and political stability significantly impacts investor risk perception. Angelopoulos et al. (2016) and Egli et al. (2019) demonstrate that country risk premiums can lead to substantial differences in the cost of capital between nations, even for similar renewable energy technologies. IRENA (2023) highlights this disparity, reporting WACCs ranging from 2.2% in Germany to 12.2% in Ukraine. Prevailing interest rates also directly affect financing costs. Egli et al. (2018) and Steffen (2020) show that changes in economy-wide interest rates can lead to significant fluctuations in the cost of capital for renewable energy projects over time. Martin et al. (2024) emphasize that the recent end of the 'zero era' for interest rates has profound implications for the energy transition, projecting higher nominal and real interest rates in the coming decades.

Polzin et al. (2021) reinforce this view, highlighting that country risk and general interest rate levels are key drivers of cost of capital differences across countries. Schmidt et al. (2019) show that rising interest rates could have a particularly adverse effect on the economics of renewable energy projects. They project significant increases in LCOE for solar PV and onshore wind if interest rates return to pre-financial crisis levels. Aguila & Wullweber (2024) extend this analysis by examining the implications of recent contractionary monetary policies on renewable energy financing. They argue that higher interest rates and quantitative tightening disproportionately affect capital-intensive renewable projects, potentially delaying the green transformation and contributing to medium-term inflation.

The energy sector level in Steffen & Waidelich's (2022) framework includes electricity market structure, renewable energy support policies, regulatory stability, and grid regulation. Market design, particularly price risk exposure, can significantly impact financing costs. Helms et al. (2015) and Rai & Nelson (2021) highlight how different market structures can lead to varying risk profiles for renewable energy projects. Polzin et al. (2021) emphasize the importance of policy design, noting that the introduction of auctions for renewable energy projects can significantly impact financing costs. Recent research emphasizes policy design considerations in changing macroeconomic conditions (Schmidt et al., 2019; Aguila & Wullweber, 2024).

Financial sector characteristics also play a crucial role. More developed financial sectors and increased investor experience can lead to lower financing costs (Kempa et al., 2021). Egli et al. (2018) and Đukan & Kitzing (2021) provide evidence for this learning effect in the financial sector. Polzin et al. (2021) introduce the concept of "financing experience curves," suggesting that cumulative deployment of renewable technologies decreases financing costs. Aguila and Wullweber (2024) propose an active role for central banks in shaping the financial sector's approach to renewable energy financing.

At the technology level, factors such as technology portfolio, emission intensity, and technology maturity impact financing costs. Companies with higher carbon intensity face higher financing costs, and rising interest rates disproportionately affect capital-intensive renewable technologies (Koch & Bassen, 2013; Lozano & Reid, 2018; Schmidt et al., 2019). Aguila and Wullweber (2024) argue for monetary policies that actively support the competitiveness of renewable technologies in high-interest rate environments.

Steffen & Waidelich (2022) distinguish between corporate and project finance structures. For project finance, relevant factors include the project development stage, project size, and specific project finance structure. Higher debt share in low-carbon energy sectors increases vulnerability to interest rate fluctuations (Steffen, 2018; IRENA, 2024; Martin et al. 2024). Aguila and Wullweber (2024) suggest that central banks could support green project finance structures through preferential treatment in monetary policy operations or targeted credit allocation policies.

The framework recognizes interactions and feedback effects between levels. Recent studies demonstrate how these interactions can lead to complex dynamics in the energy transition process and emphasize the potential role of central banks in addressing both environmental and economic challenges (Martin et al., 2024; Polzin et al., 2021; Schmidt et al., 2019; Aguila & Wullweber, 2024).

The cost of capital for renewable energy projects is influenced by a complex array of factors operating at multiple levels. The energy finance literature underscores the importance of considering differentiated costs of capital in energy system modelling and policy design for accurate energy transition planning. It also highlights the need for policymakers to carefully consider macroeconomic factors, particularly interest rates, and the potential role of central banks, when designing renewable energy support mechanisms to ensure the continued viability of the sustainable energy transition and adopt a more integrated approach to addressing both environmental and economic challenges.

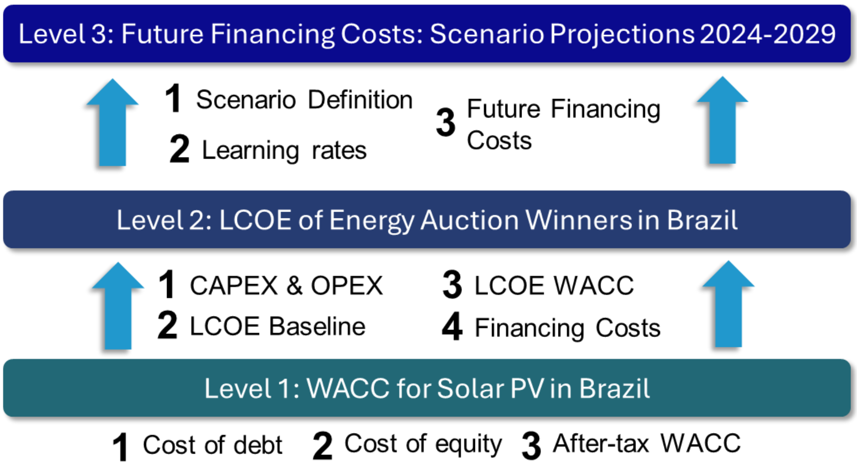
Methodology

The dissertation assesses the influence of financing conditions on the Levelized Cost of Energy (LCOE) for solar PV projects in Brazil. The research employs a three-tiered methodological approach, with each stage building on insights from the previous one. The analysis was conducted using Python in Jupyter Notebooks.

Level 1 focuses on estimating the nominal after-tax WACC for solar PV projects in Brazil, establishing a clear estimate of financing costs. Level 2 calculates the LCOE for solar PV projects that won energy auctions in Brazil between 2014 and 2022, evaluating how financing costs have evolved. Level 3 constructs economic projection scenarios for general interest rates and inflation in Brazil, exploring how anticipated changes in these factors from 2024 to 2029 could impact the WACC and LCOE for solar PV projects.

This approach provides a comprehensive assessment of past and current financing conditions affecting solar PV projects in Brazil, offering valuable insights on costs and future projections [see Annex for more data source description].

Figure 10. Three-tiered Methodological Approach



Source: Own Making

Level 1: WACC for solar PV in Brazil

The calculation of the WACC is critical in evaluating the financial viability of solar PV projects in Brazil. It represents the average rate of return required by investors to finance a project. As a key determinant of the LCOE, the WACC is essential for comparing energy generation costs across different sources (IEA, 2023; IRENA, 2023; Lazard, 2024; EPE, 2021).

This analysis calculates the WACC within Brazil's unique macroeconomic environment. A thorough examination of debt and equity components, particularly the influence of fluctuating interest rates and inflation, was conducted. The methodology draws on the IRENA report (2023) and Egli et al. (2018), with adaptations to suit the Brazilian context.

To ensure robustness, various methodological approaches were considered, including Schmidt et al. (2019), Santa Catarina (2022), and Damodaran (2024), allowing for a comprehensive analysis tailored to the Brazilian renewable energy market.

1.1. Cost of debt

Cost of debt calculation is the first crucial step in determining the WACC. Using the IRENA methodology as a base, the cost of debt (K_D) is calculated with the formula (4):

$$K_D = (GRF + CDS + LM + TP) \times (1 - \tau)$$

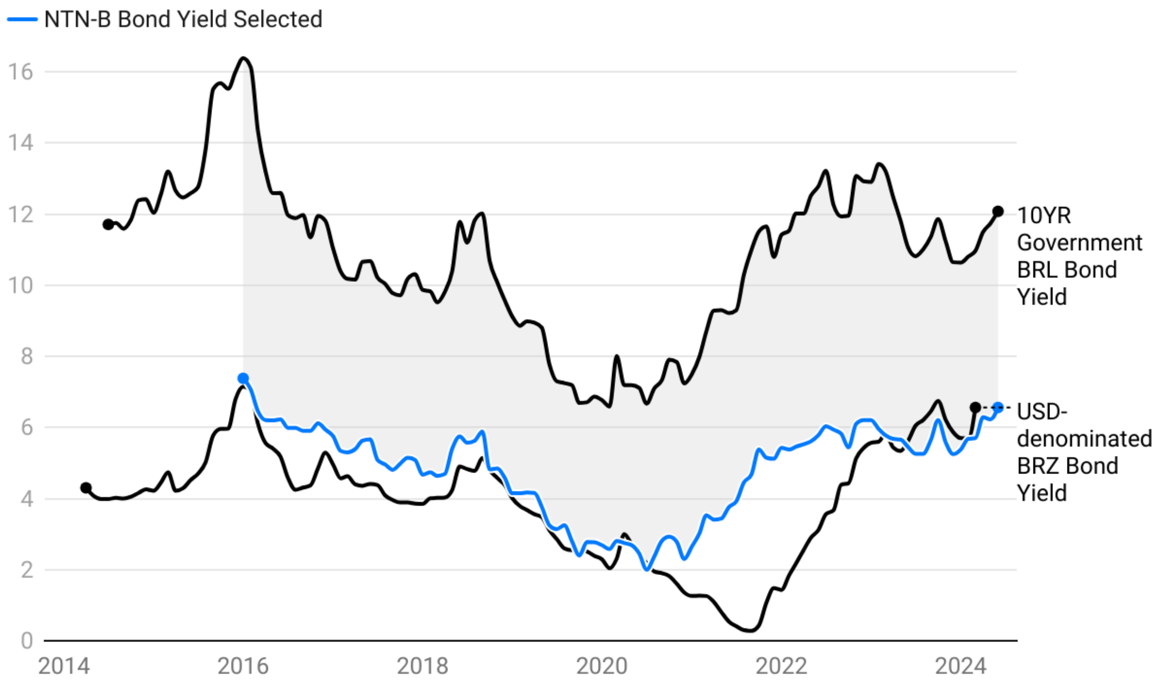
In IRENA's report, GRF represents the Global Risk-Free rate (10-year US Treasury bond yield). The Country Default Spread (CDS) is the spread between the 10-year US Treasury bond and a USD-denominated sovereign bond of the same duration. The Lender Margin (LM) is the premium added by lenders for infrastructure projects. The Technology Premium (TP) accounts for the additional risk associated with solar PV technology, and τ represents the corporate tax rate.

Applying this methodology to Brazil presented challenges. Using a USD-denominated bond yield for Brazil's risk-free rate produced an unrealistically low cost of debt, failing to capture local risks like inflation, currency risk, and economic volatility. Conversely, using a BRL-denominated 10-year government bond yield resulted in an excessively high cost of debt, as lending interest rates in Brazil remained subsidised until recently.

To address these issues, the cost of debt calculation was based on NTN-B bond yields, Brazilian government bonds offering a real rate of return above inflation. This approach was chosen because NTN-B yields correlate highly with the 10-year government bond yield and the Selic Target rate, and the BNDES, the primary financier of solar PV projects in Brazil, offers rates linked to NTN-B yields, particularly since the introduction of the *Taxa de Longo Prazo* (TLP, Long-term rate) in 2018 (BNDES, 2024b).

Figure 11. Bonds Considered for the Methodology

Bond yields of three different instruments considered for the WACC methodology.



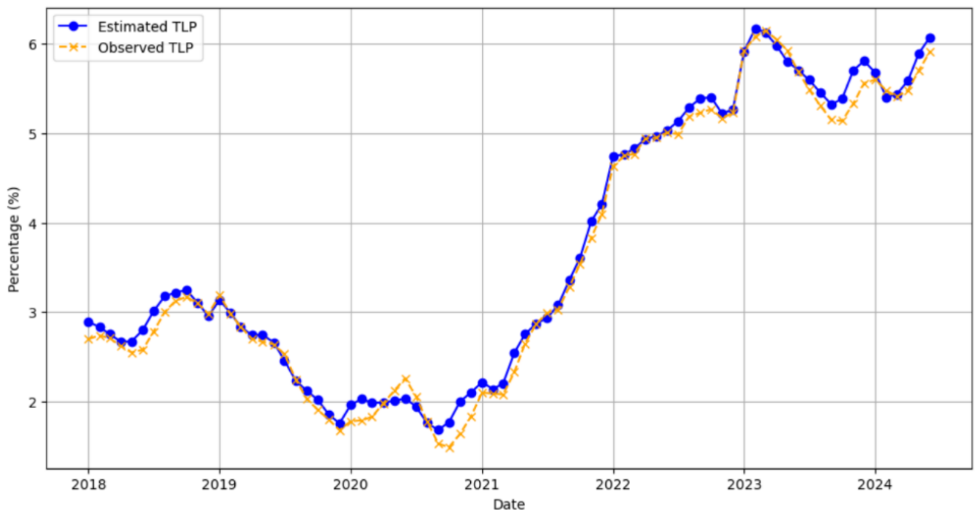
The USD-denominated bond yield was not incorporated in the final estimate, as it is considered that USD-denominated bond yields for country-specific estimations were used by IRENA to exclude currency risks and make comparison between countries straightforward. Furthermore, the yield on the bond has unrealistically low periods, even having a negative spread during some months when compared to the 10YR US Treasury bond yield. Moreover, the 10YR Government BRL Bond Yield has incredibly high yields, which if considered for both cost of debt and cost of equity would've resulted in unrealistic cost of equities. So a nuanced approach was selected: NTN-B bond yield.

Chart: Own making. • Source: Bloomberg, LSEG, Brazil's Central Bank. • Created with Datawrapper

The long-term rate (TLP) is a nominal rate including both a real interest rate, derived from five-year NTN-B bond yields, and an inflation adjustment. It's calculated using a fixed real interest rate, derived from the average of NTN-B yields over the preceding three months plus the previous monthly YoY inflation value. An adjustment factor was applied to the NTN-B bond's real interest rate as lending rates gradually reflected the open market state, but as of 2023, there is no adjustment factor.

Historical NTN-B yield data were collected from Refinitiv Workspace (2024), and a moving average adjusted by the BNDES factor was calculated and compared with historical BNDES rates for future projections (see level 3) (BNDES, 2024b).

Figure 12. Estimated Long-term Rate (TLP) v. Observed TLP given rate (without inflation) 2018 - 2024



Source: Refinitiv Workspace (2024).

Observed long-term rates (TLP, introduced in 2018) were merged with historical TJLP rates, adjusting the latter for inflation to align with the TLP. The TJLP, a subsidized rate, included an inflation target, requiring an IPCA adjustment. The final cost of debt calculation incorporated the BNDES rate, adjusted for inflation, as the Brazilian risk-free bond yield.

The CDS was explicitly calculated by subtracting US Treasury bond yields from the BNDES rates. No additional Lender Margin was added as the BNDES rate already applies to infrastructure projects. The Technology Premium was calculated based on the percentage of installed solar capacity relative to Brazil's total installed capacity, reflecting technological maturity, a common practice (IRENA, 2023). The study used three market maturity buckets: "New Market" (< 5%), "Intermediate Market" (5%-10%), and "Mature Market" (≥10%). For each bucket, the premium decreases linearly or remains fixed from 10% onwards, with linear interpolation for exact percentages.

As of August 2024, BNDES Finem -a type of financing for big infrastructure projects- charges 1.1% as a remuneration rate for solar technology, aligning with this approach. The slightly higher premium (1.5%) reflects that commercial banks may offer less competitive rates than BNDES (BNDES, 2024c).

The total cost of debt for Brazil was determined by summing all variables. The effective cost of debt was then reduced by applying the 34% corporate tax rate to account for tax-deductible interest payments $(1-\tau)$. This comprehensive approach provides a realistic estimate of the cost of debt for subsequent WACC and LCOE calculations in solar PV projects.

1.2. Cost of equity

The cost of equity, an essential component in the WACC calculation, is determined using the formula (9):

$$K_E = (GRF + CP + ERP + TP)$$

In this formula, the GRF is represented by the yield on 10-year US Treasury bonds. The Equity Risk Premium (ERP), as calculated by Damodaran (2024), reflects the mature market equity risk and is based on the premium of US sovereign bonds adjusted by the volatility of the S&P 500. Damodaran’s ERP values were linearly interpolated to obtain a monthly cost of equity over the study period.

The Country Premium (CP) component accounts for the additional risk specific to the Brazilian market. Damodaran (2024) offers three methodologies for calculating this premium: based on sovereign ratings, a market-based measure, and using bond default spreads.

In this study, rather than following Damodaran's approach, the Country Premium was derived from the country default spread used for the cost of debt (CDS). This was calculated as the difference between Brazil's bond yields, reflected in the BNDES rate, and the global risk-free rate. This method directly ties the country premium to local interest rates, aligning with the focus on understanding how interest rates influence the cost of capital in Brazil.

This approach resonates with energy finance literature, such as Donovan & Nuñez (2012) and Schmidt et al. (2019), where the cost of equity is defined as the cost of debt plus an equity premium. The Technology Premium (TP) component, previously calculated, is added to this equation.

The harmonization of the WACC components, as proposed by IRENA and Schmidt et al. (2019), ensures consistency in the analysis. The decision to use the BNDES rate and related BRL bond yields for estimating both the cost of debt and the cost of equity reflects the unique financial environment in Brazil, where BNDES plays a crucial role. This approach also considers local interest rates and currency risks, central to the financial viability of solar PV projects in the country.

By adopting this methodology, the analysis maintains coherence and relevance, particularly when projecting how fluctuations in interest rates might impact the cost of capital for solar PV projects in Brazil. The integration of these components into the WACC formula provides a comprehensive view of the financial landscape, essential for the subsequent LCOE calculations.

1.3. WACC calculation

To calculate the WACC, after estimating both the cost of debt and the cost of equity, it was necessary to consider the leverage of solar PV projects. The IRENA report recommends assigning the debt share based on the market maturity, determined by the installed capacity of solar PV as a percentage of the total installed electricity capacity. This approach ensures that the level of debt financing reflects the relative risk associated with the market's maturity.

n mature markets, where the installed solar capacity is equal to or greater than 10% of the total installed electricity capacity, the debt share is set at 80%. For intermediate markets, where installed solar capacity ranges between 5% and less than 10%, the debt share is reduced to 70%. In new markets, where installed solar capacity is less than 5%, the debt share is further reduced to 60%. These markets are considered riskier, thus limiting the proportion of debt financing that can be secured.

With these debt shares established, the nominal after-tax WACC was calculated using the (2) equation:

$$WACC = \delta \times (1-\tau) \times K_D + (1-\delta) \times K_E$$

In this formula, K_D represents the cost of debt, K_E is the cost of equity, δ is the leverage (or debt share), and τ is the corporate tax rate. This calculation integrates the respective costs of debt and equity, weighted by the project's leverage, and adjusts for the tax deductibility of interest payments. The result is a comprehensive measure of the overall cost of capital, which is crucial for assessing the financial viability of solar PV projects in Brazil.

Level 2: LCOE of Energy Auction Winners in Brazil

The second stage of this analysis involves calculating the LCOE for solar PV projects that secured contracts through energy auctions in Brazil between 2014 and 2022. The primary objective is to quantify the evolution of financing costs over this period by incorporating the WACC derived in Level 1, following a methodology similar to that employed by Egli et al. (2018) and Schmidt et al. (2019) in their study of renewable energy projects in Germany.

The dataset utilised for this analysis is made publicly available by the Chamber of Electric Energy Commercialization (CCEE), the authority responsible for conducting energy auctions in Brazil. This dataset includes comprehensive details on all winning projects from energy auctions dating back to 2004, with annual updates (Tolmasquim et al., 2021; CCEE, 2024). Among the 48 variables available, the most critical for LCOE calculations were the auction date, seller name, investment amount, nominal capacity, and physical guarantee of the projects.

This methodology builds on two key studies: Santa Catarina (2022), who calculated the LCOE for 758 wind projects in Brazil, and Egli et al. (2018), who modelled the impact of changing financing conditions on the lifetime generation costs of renewable energy technologies.

The analysis covered 195 solar PV projects from energy auctions held between 2014 and 2022. Two projects were excluded due to their participation in a specific auction type called the Simplified Competitive Procedure. The remaining projects primarily stem from reserve power auctions and alternative power auctions. Contracts from these auctions typically have a duration of 20 years (reduced to 15 years since 2021). After the initial contract period, new agreements can be negotiated within either the regulated (ACR) or open (ACL) markets.

The LCOE equation requires careful consideration of various inputs such as taxes, operating costs (OPEX), inflation assumptions, and WACC. Unlike Santa Catarina (2022), who included federal taxes directly in the LCOE calculation, this analysis incorporated these taxes within the WACC itself -see level 1-, applying an after-tax WACC, whereas Santa Catarina used a general before-tax WACC estimated by Brazil's Energy Research Company (EPE).

This analysis follows Santa Catarina (2022) in utilising the investment amounts declared by project owners during the auctions, as reported in the dataset, as the CAPEX of the individual project. To estimate the total expected energy production for each project, the capacity factor was multiplied by the nominal capacity in MW and then by the total number of hours in a year. This calculation provided the expected annual energy production in MWh.[3] Applying the methodology of De Jong, Ascher, and Torres (2015), who estimated O&M costs as 1% of the investment projects of onshore wind, the OPEX was calculated as 1.45% of individual solar PV projects CAPEX. This percentage was derived from data provided by the Empresa de Pesquisa Energética (EPE) in their 2021 Power Generation Costs Report. This ratio provided a consistent method for estimating annual OPEX across all projects. This annual OPEX was then adjusted for inflation over the project's lifetime, assuming an annual inflation rate of 3.5%, which was compounded annually:

$$(11) \quad OPEX_t = OPEX_{initial} \times (1 + inflation\ rate)^t$$

Based on Egli et al. (2018), the analysis established a baseline, calculating an LCOE free of financing costs -meaning 0% WACC-. Excluding financing costs permits to identify the CAPEX and OPEX components over the 25-year project lifetime (EPE, 2021). The baseline LCOE was calculated using the following formula:

$$(12) \quad LCOE_{it,WACC=0} = \frac{C_{it}}{\sum_{t=1}^{25} FLH_{it\tau}} + \frac{\sum_{t=1}^{25} C_{it\tau}}{\sum_{t=1}^{25} FLH_{it\tau}}$$

This approach provided a nominal LCOE value, reflecting the cost of energy production excluding the impact of financing costs.

[3] $Expected\ energy\ production = Capacity\ factor \times Nominal\ capacity \times 8{,}760$

To incorporate actual financing costs, the LCOE was calculated using the project-specific WACC derived in Level 1. This approach required discounting both the OPEX and the expected energy production over the 25-year project lifetime using the WACC. The LCOE calculation, which includes the impact of financing, discounted each year's OPEX to present value using the WACC derived from Level 1 that corresponded to the month preceding the auction, assuming financing terms are contracted before the auction is held. Similarly, each year's energy production was discounted using the same WACC, ensuring consistency in the financial modelling across all aspects of the project:

$$(13) \quad LCOE_{WACC} = \frac{C_{it}}{\sum_{t=1}^{t=25} \frac{FLH_{it\tau}}{(1 + WACC_{it})^{\tau}}} + \frac{+\sum_{t=1}^{t=25} \frac{C_{it\tau}}{(1 + WACC)^{\tau}}}{\sum_{t=1}^{t=25} \frac{FLH_{it\tau}}{(1 + WACC)^{\tau}}}$$

The impact of financing costs is then quantified by calculating the financing expenditure (δ_{it}), which is the difference between the LCOE calculated with the observed WACC and the baseline LCOE:

$$(14) \quad \delta_{it} = LCOE_{it} - LCOE_{it,WACC=0}$$

Finally, the change in financing costs over time, denoted as Δ_i , is assessed by comparing the financing expenditures across different years:

$$(15) \quad \Delta_i = \delta_{it=1} - \delta_{it=2}$$

These calculations allow for the isolation of the impact of financing on the overall LCOE, providing a clear understanding of how financing conditions have influenced the costs of solar PV projects over time.

Level 3: Future Financing Costs: Scenario Projections 2024-2029

In this final stage, scenarios for future financing conditions and their impact on the LCOE for solar PV projects in Brazil from 2024 to 2029 are projected. This projection is critical for understanding how macroeconomic variables, particularly government bond yields and inflation, influence the cost of financing solar PV projects in Brazil. The approach is informed by methodologies from Schmidt et al. (2019) and Egli et al. (2018), adapted to fit the specific economic landscape of Brazil.

The analysis began with a dataset from LSEG (2024), which included monthly yields of a 5-year NTN-B bond, the 10-year government bond yield (BR10YT), and year-on-year changes in inflation, covering the period from October 2017 to June 2024. Initial tests using the Augmented Dickey-Fuller (ADF) method confirmed that the time series data were non-stationary, necessitating differencing to achieve stationarity. This transformation was validated by subsequent ADF tests, rendering the data suitable for regression analysis.

Regression analysis on the differenced series revealed a significant relationship between the differenced 10-year government bond yield and the 5-year NTN-B yield. Specifically, the analysis indicated that for every one percentage point increase in the 10-year government bond yield, the 5-year NTN-B yield increased by approximately 0.43 percentage points. This relationship was pivotal in projecting NTN-B yields under three distinct scenarios: a flat scenario, where bond yields remain stable at the 2024 average of 11.40%; an extreme downward scenario, where bond yields decrease to the historical low of 6.3% observed in 2020; and an extreme upward scenario, where bond yields increase, peaking at the historical high of 16.49% observed in December 2015.

Recognizing the interdependence of inflation and interest rates, particularly in a volatile economic environment like Brazil's, dynamic inflation rates tailored to each scenario were introduced. In the flat scenario, inflation remains stable at 4.4%, reflecting recent historical averages. In the upward scenario, inflation increases to an average of 6.3% by 2029, reflecting the upward pressure typically associated with rising interest rates. In the downward scenario, inflation decreases to an average of 3.4% by 2029, corresponding with anticipated economic stability and lower bond yields.

To calculate the WACC across these scenarios, a consistent starting point was established by using the average NTN-B yield from January to June 2024. Technology premium, equity risk premium of mature market, the leverage and the tax rate are held constant at 1.5%, 4.27%, 80% and 34% respectively. Projections for the NTN-B yields for each scenario from July 2024 to December 2029 were then made, leading to yearly averages for the NTN-B yields from 2025 to 2029.

The future CAPEX values were then projected using a learning curve approach, a method widely accepted in energy economics to model how costs decrease with cumulative installed capacity (Schmidt et al., 2019). A learning rate of 15% was adopted, meaning that with every doubling of cumulative installed capacity, the cost decreases by 15%. The baseline CAPEX was BRL 167,735,285.6 per 40 MW, based on the average CAPEX of solar auction projects in Brazil in 2022. Using global cumulative installed capacity data from 2023 to 2029, sourced from IRENA and IEA reports, CAPEX projections for each year were made. This projection reflects anticipated cost reductions due to technological advancements and economies of scale.

The nominal OPEX for 2022 was BRL 2,430,484.288 per year, equivalent to 1.449% of the CAPEX for that year. A conservative OPEX learning rate of 5% per capacity doubling was also applied, assuming learning-by-doing, economies of scale and innovation, following Steffen (2020). The OPEX was adjusted for the average inflation of 4% to the OPEX baseline, ensuring that it accurately reflected the evolving economic conditions (Mercopress, 2024).

The decision to maintain a constant inflation rate of 4% for the long-term LCOE calculation while varying it for the WACC scenarios was methodologically sound. This approach ensures that the LCOE comparisons across scenarios are based solely on the impact of financing conditions, without introducing variability due to long-term inflation assumptions. It provides a consistent basis for analysing how current macroeconomic conditions influence the economic viability of solar PV projects in Brazil. By integrating these dynamic elements into the LCOE calculation, this methodology offers a nuanced understanding of the financial dynamics affecting solar PV projects over the next five years.

The LCOE was recalculated for each year and scenario, integrating the dynamically adjusted CAPEX, OPEX, and WACC values. The BNDES rate, a key component of the WACC, was recalculated starting from October 2023. This rate was determined by averaging the previous three months' NTN-B yield and adding the inflation rate of the last month in that period. This ensured that the WACC reflected the most recent economic data, aligning with the prevailing macroeconomic conditions. For the LCOE calculation, the established methodology was adhered to, while incorporating the dynamic variables specific to each scenario. The LCOE was broken down into its components: the OPEX baseline, CAPEX baseline, and financing costs. The financing costs were determined by subtracting the LCOE baseline (assuming 0% WACC) from the LCOE calculated with the respective WACC, thereby isolating the impact of financing on the overall cost of energy production.

The OPEX baseline and expected energy production of the LOCE were derived following the same methodology as in level 2. This calculation provided the OPEX contribution to the LCOE without considering the impact of the WACC and the annual energy output expected from the project. The CAPEX baseline represented the portion of the LCOE attributed to the initial capital expenditure of the project, distributed over the total energy produced during the project’s lifetime.

The financing costs were calculated as the difference between the LCOE that included the WACC and the LCOE baseline, which assumed a 0% WACC. This step was crucial for isolating the impact of financing on the total cost of energy production. For each scenario (Flat, Upward, Downward), the financing cost was derived by subtracting the LCOE baseline from the LCOE calculated with the respective WACC. This calculation highlighted the additional cost incurred due to financing under varying economic conditions.

In this phase of the methodology, these steps were integrated to finalize the LCOE calculations under each scenario. By breaking down the LCOE into its components—OPEX, CAPEX, and financing costs—the analysis provided a clear understanding of how different economic conditions affect the overall cost of solar PV energy production.

Discussion and Results

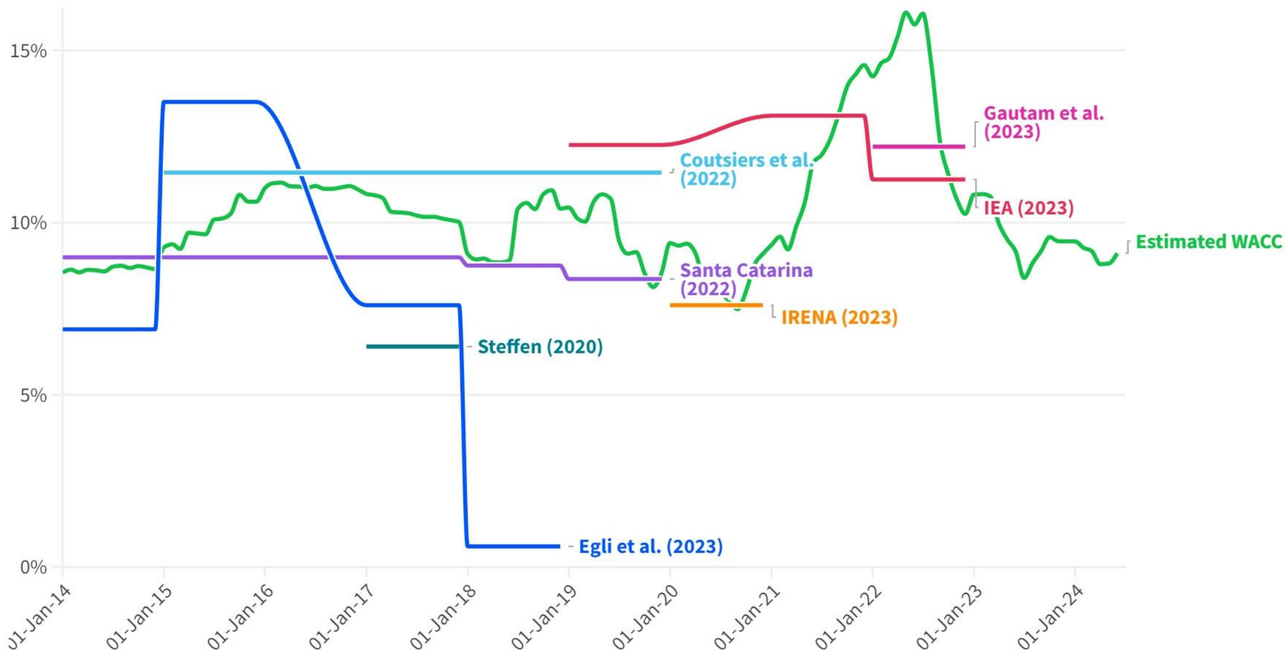
The analysis on level 1 of cost of equity and debt for Brazilian solar PV projects from 2014 to 2024 reveals a complex interplay of macroeconomic factors, policy shifts, and technological maturation. The sharp increases in financing costs from 2020 to 2022 directly reflect Brazil's economic challenges during the COVID-19 pandemic, including GDP contraction, currency depreciation, and inflationary pressures. This period of instability, leading to significant monetary tightening by Brazil’s Central Bank, provides empirical evidence for Schmidt et al.'s (2019) theoretical framework on how interest rate fluctuations can rapidly alter the renewable energy financing landscape in emerging markets.

A critical juncture in the cost of debt trend is observable around 2018, coinciding with the transition from TJLP -the subsidised rate- to TLP -open market rate-. This shift, marking a move towards market-based long-term interest rates for BNDES financing, underscores the significant impact of policy changes on renewable energy financing, a theme emphasized by Polzin et al. (2021). The clear demarcation in trends before and after this transition suggests that while this policy change may have increased short-term volatility in financing costs, it has also potentially created a more transparent and market-responsive financing environment.

The heightened volatility in both cost of equity and debt, particularly post-2020, aligns with Steffen's (2020) observations on the importance of country-specific risk factors in determining financing costs for renewable projects. The significant fluctuations in the Country Default Spread component, especially during periods of economic uncertainty, highlight Brazil's unique risk profile as an emerging market economy. This volatility underscores the challenges faced by renewable energy investors in such markets, where macroeconomic instability can rapidly alter project viability.

The gradual decrease in the technology premium for solar PV over the studied period supports the concept of "financing experience effects" described by Egli et al. (2018). This trend aligns with Brazil's rapid expansion of solar PV capacity, likely contributing to increased investor familiarity and reduced perceived technological risks.

Figure 13. Granularity: Estimated WACC v. Literature WACC



Egli et al. (2023) reognise their estimations are unreliable. Coutsiers et al. (2022) estimate a 2015-2019 average. Santa Catarina (2022) uses a non-technology specific EPE renewable energy estimated after-tax WACC (average from 2014-2017). Gautam et al. (2023) do not specify if their methodology is after or before taxes, plus, they innovate the cost of capital methodology through a regression between the WACC and a Climate Risk Score, nevertheless, those final values are not publicly available.

The comparison of the estimated WACC values with those from the literature reveals significant disparities, highlighting the challenges in accurately assessing financing costs for solar PV projects in emerging markets like Brazil. The stark contrast between the estimates from this paper and those of Egli et al. (2023) is particularly noteworthy, underscoring the potential limitations of applying methodologies developed for mature markets to emerging economies.

The more stable WACC estimates provided by Coutsiers et al. (2022) and Santa Catarina (2022) diverge from the volatility observed in the calculations. This difference may be attributed to their use of averaged values over extended periods, potentially smoothing out short-term fluctuations that this study's methodology captures. Interestingly, the higher WACC values reported by IEA (2023) and Gautam et al. (2023) for recent years align more closely with the estimated WACC, suggesting that more recent assessments may be better capturing the evolving risk perceptions in the Brazilian market.

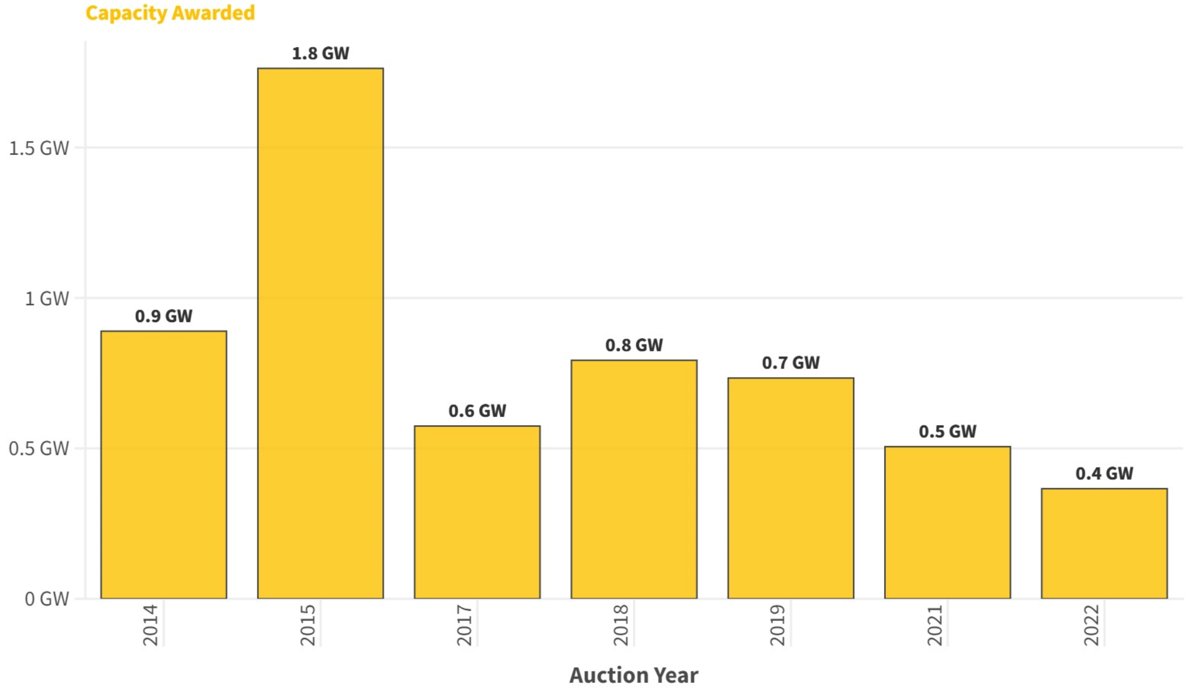
The variation in WACC estimates across different studies emphasizes the complexity of accurately assessing the cost of capital for renewable energy projects in emerging markets. Factors such as methodological differences, data sources, and the specific time frames considered can lead to divergent results. The estimates presented in this study, which show greater sensitivity to short-term economic fluctuations, may provide a more nuanced view of the changing risk perceptions in the Brazilian solar PV market over time.

The analysis of solar PV projects winning Brazil's energy auctions of level 2 reveals several key trends that reflect both global industry developments and Brazil-specific factors.

The capacity awarded in auctions shows significant fluctuations, peaking in 2015 at 1.8 GW and declining to 0.4 GW in 2022. This pattern may reflect changing policy priorities and market conditions, as discussed by Tolmasquim et al. (2021) in their analysis of Brazil's electricity sector reforms. This is important, as it marks an absolute shift from the regulated market to the open market. In 2018, 100% of the accumulated capacity was under the regulated environment -through auctions-. Of course, this has been happening because it is very possible that developers are finding better conditions through bilateral negotiations than through the energy auctions (Greener, 2024). The last energy auctions for solar were in 2022.

Figure 14. Solar PV Capacity Awarded in Energy Auctions in Brazil

Twelve auctions took place between 2014-2022 with participation of solar PV projects. 195 projects won the auctions, accounting for 5.6 GW. No auctions took place in 2016 or 2020. Last auctions were in 2022.



Source: CCEE (2024)

CAPEX for Brazilian solar PV projects -figure 15- demonstrates a clear downward trend, aligning closely with IRENA's global weighted average. This trend supports Nemet's (2019) observations on cost reductions driven by technological improvements and learning effects in project development and construction. Solar panels have consistently reduced in costs (EMBER, 2024c). Notably, Brazil's CAPEX consistently falls below IRENA's 95th percentile, suggesting effective cost management within the country's competitive auction system.

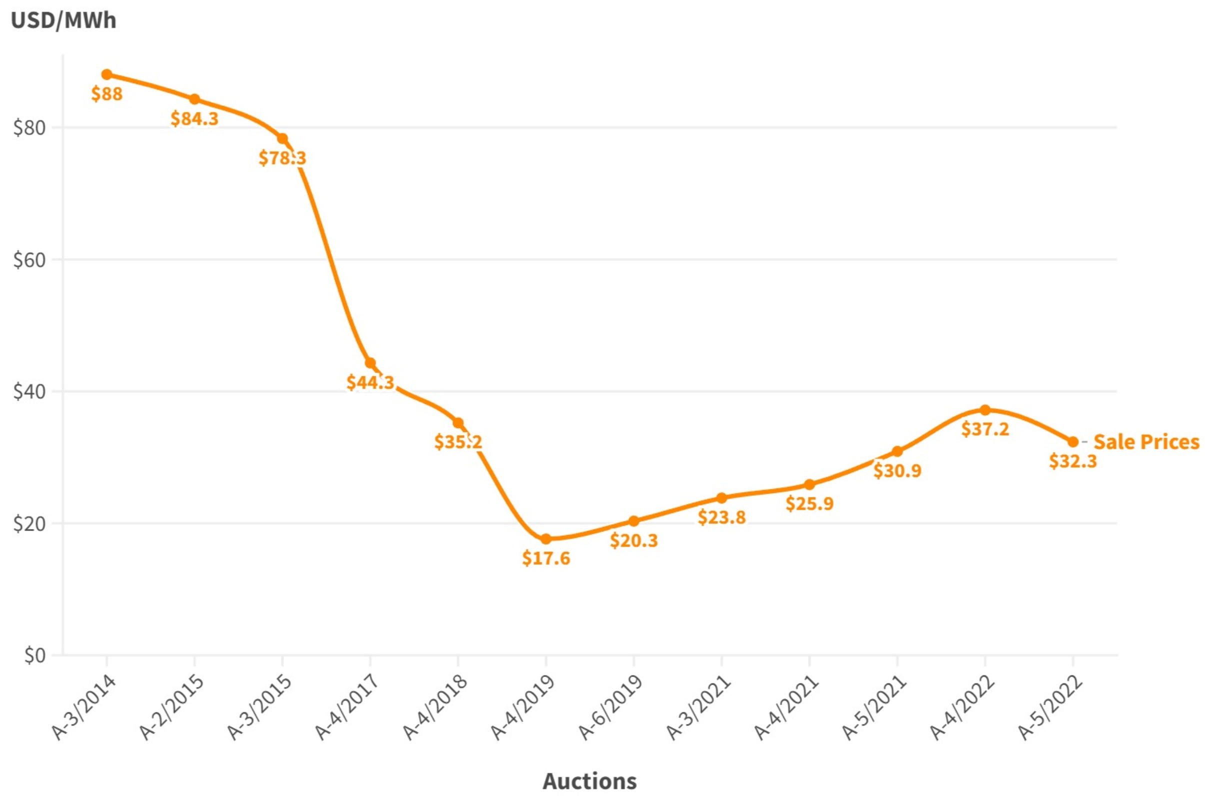
Figure 15. Capital Expenditures of Solar PV Auctions Brazil v. IRENA

Source: CCEE (2024); IRENA (2023)

Auction sale prices in figure 16 show a dramatic decline from $88/MWh in 2014 to a low of $17.6/MWh in 2019, followed by a slight increase. This trend aligns with Dobrotkova et al.'s (2018) findings on price declines in emerging market solar auctions. The data also reveals an interesting dynamic between CAPEX reductions and auction prices. While CAPEX continued to decline steadily, auction prices showed more volatility, particularly post-2019. This divergence aligns with Egli et al.'s (2018) findings on the crucial role of financing costs in determining the LCOE for capital-intensive technologies like solar PV.

This divergence could be explained by the increasing merchant risk exposure noted in the IRENA (2023) report, as developers may be pricing in higher risk premiums, possibly linked to Brazil's macroeconomic challenges and policy uncertainties discussed in the country context section. This observation highlights the need for a holistic approach when analysing renewable energy markets in emerging economies, considering not only technological advancements but also the broader economic and policy landscape.

Figure 16. Solar PV Sale Prices in Brazil's Energy Auctions



Source: CCEE (2024)

The capacity factor data in figure 17 shows an increasing trend for Brazilian projects, surpassing IRENA's global weighted average. This improvement likely reflects advancements in solar technology and/or could suggest that projects are being developed in increasingly optimal locations, which may come with higher land acquisition or grid connection costs not captured in the CAPEX figures (Klingler et al., 2023).

Figure 17. Capacity Factors from Solar PV projects in Brazil

Source: CCEE (2024); IRENA (2023)

The data underscores the importance of considering country-specific factors, including financing costs and macroeconomic conditions, in assessing renewable energy competitiveness, as emphasized by Schmidt et al. (2019).

Moreover, the analysis of the LCOE for solar PV projects in Brazil from 2014 to 2022, presented in both Brazilian Reais (BRL) and US Dollars (USD), offers crucial insights into the evolving economics of solar energy in the country.

The LCOE trend in nominal BRL -see figure 18- shows an initial decline followed by an uptick from 2018 to 2022. This pattern aligns with the macroeconomic challenges outlined in the Brazilian context section, particularly the economic instability during the COVID-19 pandemic and the subsequent monetary tightening. As Martin et al. (2024) noted, the end of the 'zero era' for interest rates has profound implications for the energy transition, which is reflected in the rising LCOE in BRL terms.

Conversely, the LCOE in USD demonstrates a more consistent downward trend, mirroring global solar PV cost reductions. This divergence between BRL and USD trends underscores the significant impact of currency fluctuations on project economics, a risk highlighted in the Brazilian context section where it was noted that Brazil imports up to 99% of its solar panels (Martins & Jieqi, 2024).

The comparison with IRENA global averages shows that Brazilian LCOEs have generally tracked below global averages since 2016. This suggests that despite macroeconomic challenges, Brazil has maintained a competitive edge in solar PV deployment, possibly due to its favourable solar resources and the competitive auction system discussed in the solar PV landscape section.

The widening LCOE ranges observed in later years indicate increasing project heterogeneity. This could be attributed to the growing diversity in project sizes and locations, as well as the shift towards the ACL (Greener, 2024).

These results have significant implications for policymakers and investors. For policymakers, the rising LCOE in BRL terms suggests a need for policies that can mitigate the impact of macroeconomic volatility on renewable energy projects. This could include measures to support local manufacturing or innovative financial instruments to hedge against currency risks.

For investors, the divergence between BRL and USD trends presents a complex decision-making landscape. An investor with access to local finance in BRL might benefit from the inflation-indexed nature of auction contracts, providing a natural hedge against local inflation. However, the volatility in BRL LCOE might increase perceived risk. Conversely, an investor with access to USD financing might see more stable returns in USD terms but would face significant currency risk.

Figure 18. LCOE with WACC from 2014 to 2022 in nominal BRL values (pink graph) and adjusted for inflation in 2022 USD v. IRENA (yellow graph)

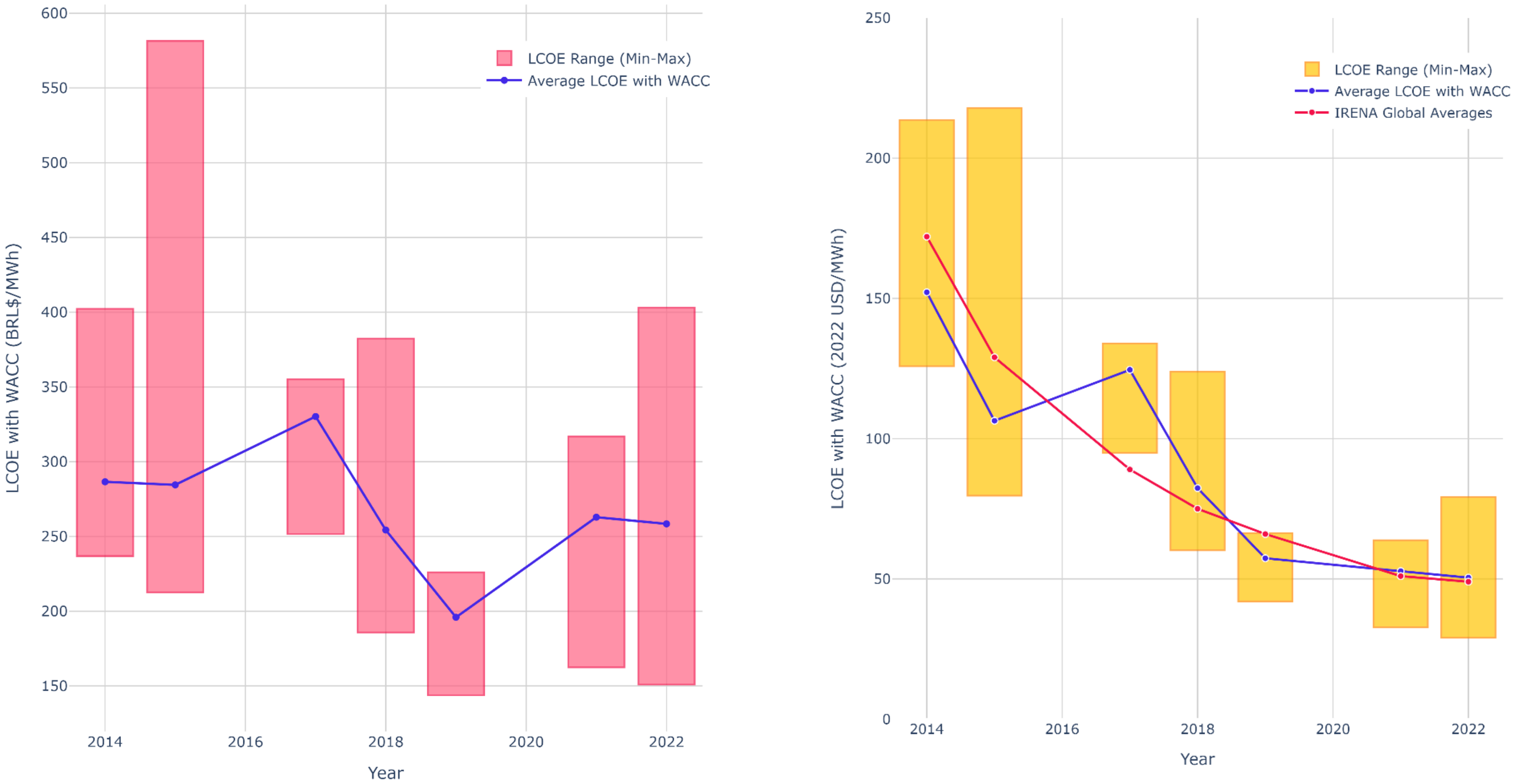
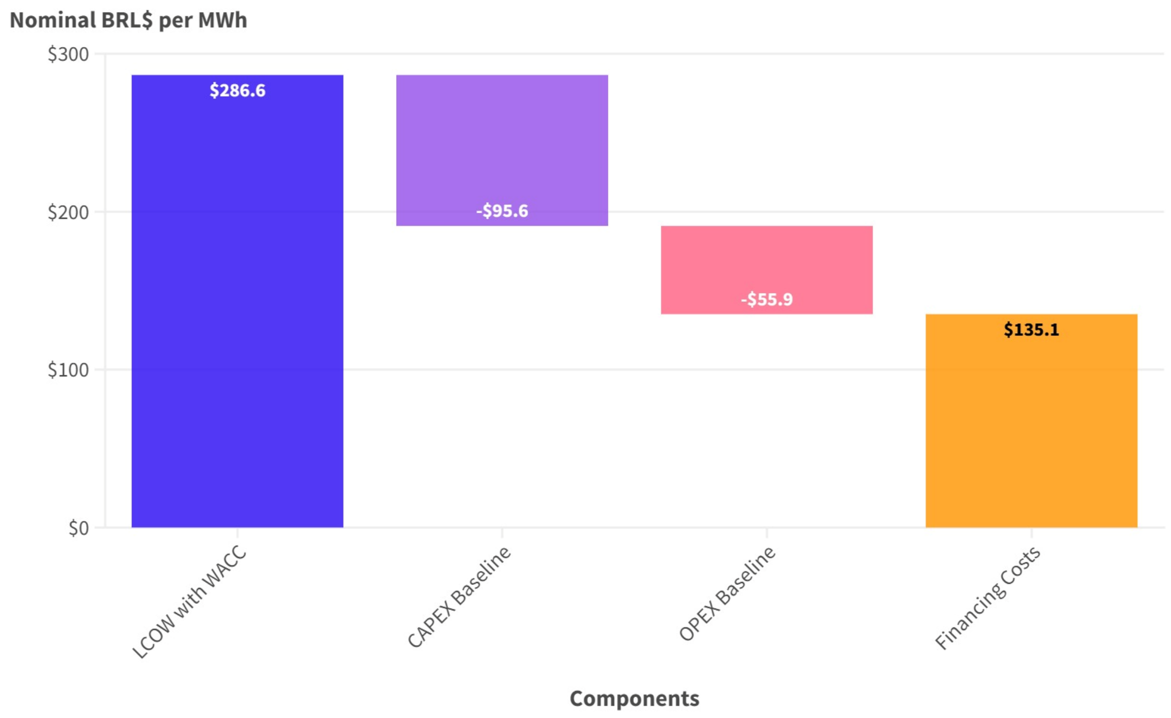


Figure 19. Financing Costs (Baseline LCOE needs to be subtracted from the LCOE with WACC)



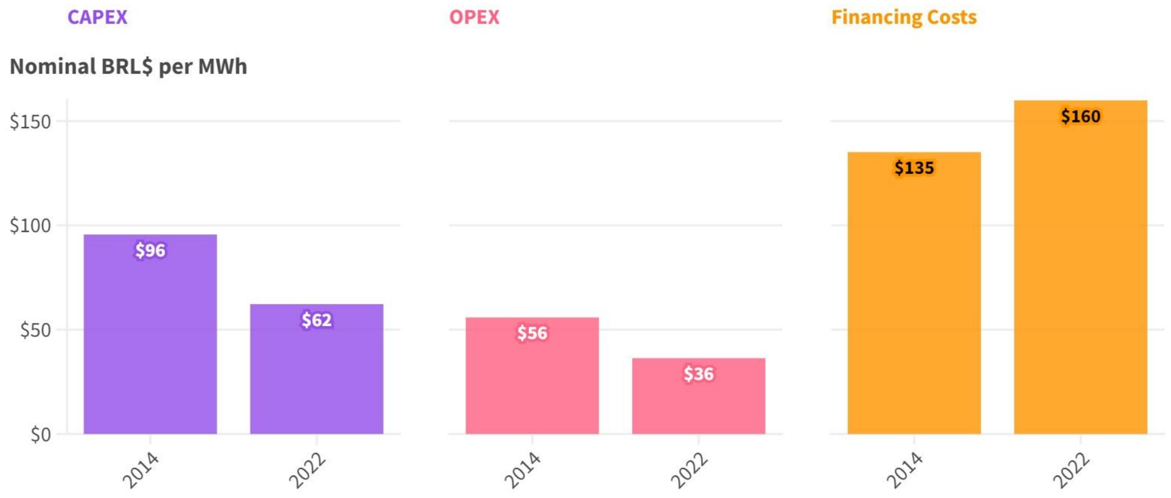
Source: Own making.

The results of financing costs for solar PV projects in Brazil from 2014 to 2022 also provides critical insights into the evolving economics of renewable energy in emerging markets. The waterfall chart in figure 19 illustrates the methodology used to isolate financing costs, like the approach employed by Schmidt et al. (2019) and Egli et al. (2018). This decomposition of LCOE into CAPEX, OPEX, and financing components allows for a nuanced understanding of the factors driving changes in the overall cost of solar electricity generation.

The comparison between 2014 and 2022 in figure 20 reveals a complex evolution of cost components. The CAPEX reduction from R$96/MWh to R$62/MWh aligns with the global trend of declining solar PV equipment costs noted in the literature review section. Similarly, the OPEX reduction from R$56/MWh to R$36/MWh reflects improvements in operational efficiency and maintenance practices, consistent with the learning effects and economies of scale observed in maturing solar markets worldwide (Nemet, 2019; Steffen et al., 2020).

However, the most striking finding is the increase in financing costs from R$135/MWh to R$160/MWh, an 18.5% rise. This trend aligns with the findings of Schmidt et al. (2019), who emphasized the critical role of financing costs in determining the overall competitiveness of renewable energy in emerging markets. The increase in financing costs, despite reductions in CAPEX and OPEX, can be attributed to several factors discussed in the Brazilian context section, including macroeconomic volatility, policy changes (such as the transition from the subsidised rate to the unsubsidised one), and the complex interplay between market maturity and broader economic challenges.

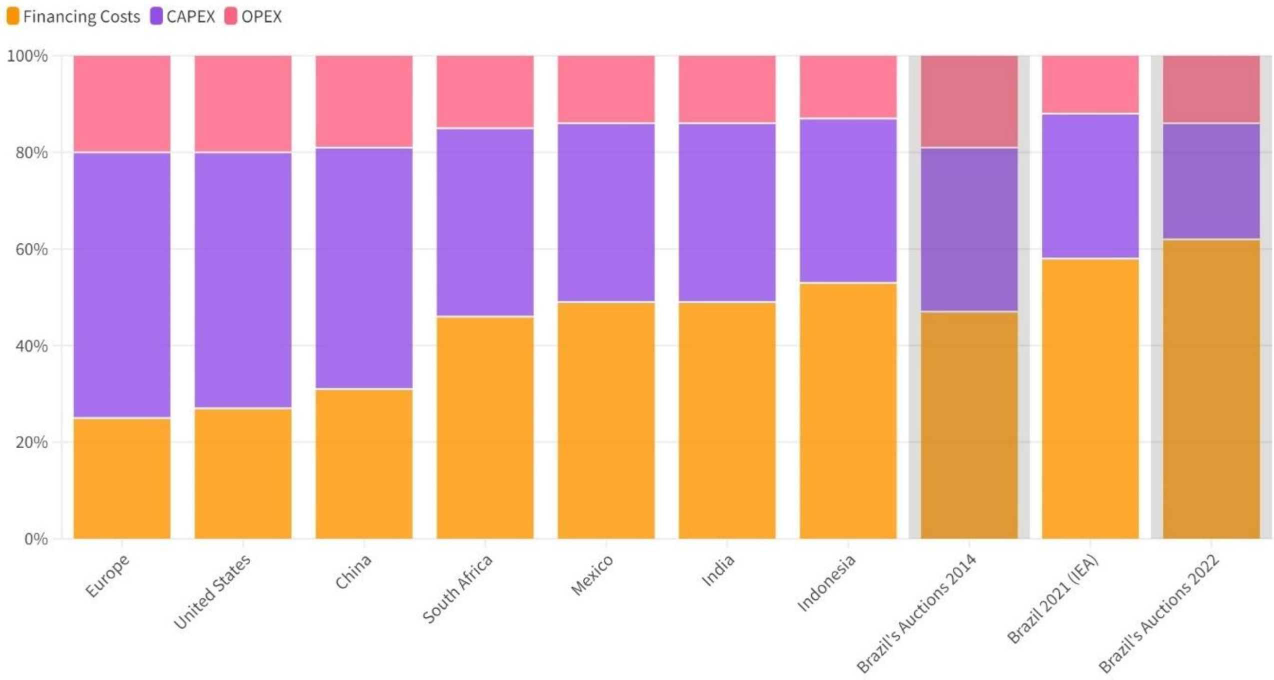
Figure 20. Changes in Financing Costs from 2014 to 2022



Source: Own making.

The findings align with the broader literature on renewable energy finance in emerging markets. Egli et al., (2018) noted the potential for financing costs to offset gains from technological improvements in certain market conditions. These findings have significant implications for investors, for example, by underscoring the importance of sophisticated financial structuring and risk management strategies. The ability to access low-cost capital and effectively hedge against macroeconomic risks may become a key differentiator in project competitiveness.

Figure 21. Financing Costs Estimated by IEA with 2021 assumptions v. own estimations of Brazil's Auctions in 2014 and 2022



Source: IEA (2023) • Grey-shaded areas are estimations done in this paper, the rest were done by the IEA.

The comparison of solar PV financing costs across regions reveals significant disparities, with Brazil's case highlighting unique challenges in emerging markets. The increase in Brazil's financing costs from 47% in 2014 to 62% in 2022, despite global trends of decreasing technology costs, underscores the complex interplay between macroeconomic factors and renewable energy economics discussed in the Brazilian context section (IEA, 2024a). The higher financing costs in Brazil compared to Mexico and India suggest country-specific factors at play, potentially including the currency depreciation and inflation risks noted previously.

These results add nuance to the understanding of solar PV economics in Brazil, demonstrating that technological improvements alone may not guarantee cost reductions. The cancellation of several projects due to currency depreciation, further emphasizes the critical impact of macroeconomic volatility on project viability. This reinforces the need for policies that can mitigate currency risks and improve the overall investment climate for renewable energy in Brazil (IEA, 2024a).

The fact that Brazil's financing costs are higher than those of comparable developing countries like Mexico and India highlights the need for targeted policy interventions to reduce capital costs, which could include measures to enhance policy stability, improve macroeconomic conditions, or develop innovative financing mechanisms tailored to the Brazilian context. Addressing these high financing costs should be a priority for policymakers aiming to accelerate solar PV deployment in Brazil and similar emerging markets.

The scenario analysis for Brazil's bond yields and inflation rates from 2024 to 2029 in level 3 provides crucial insights into the potential trajectories of solar PV financing costs. This approach, incorporating Flat, Upward, and Downward scenarios, addresses the significant uncertainty in Brazil's economic outlook highlighted in the macroeconomic landscape analysis.

The historical data in figure 22 illustrates Brazil's economic volatility over the past decade. The peak bond yield of 16.5% in 2015-2016 coincides with Brazil's deepest recession in recent history, as described in the macroeconomic landscape analysis. This period was marked by severe political instability, including the impeachment of President Dilma Rousseff, and widespread corruption investigations that disrupted major economic sectors. The subsequent decline in bond yields and inflation rates from 2016 to 2020 reflects the gradual economic recovery and the implementation of more orthodox economic policies under the Temer and early Bolsonaro administrations.

The sharp rise in both bond yields and inflation in 2021-2022 aligns with the global inflationary pressures and supply chain disruptions following the COVID-19 pandemic, compounded by domestic factors such as severe drought affecting hydroelectric power generation and increasing political uncertainty leading up to the 2022 elections. This recent volatility underscores the challenges in predicting Brazil's macroeconomic trajectory, justifying the multi-scenario approach.

The Flat Scenario, maintaining the average yield of 11.4% from January to June 2024, represents a cautious middle ground. It assumes that Brazil's central bank will successfully navigate the current inflationary pressures without significant economic disruption. The Upward scenario, projecting yields to return to the historical peak of 16.49%, reflects the potential for continued economic challenges and policy uncertainties. It also accounts for the potential fiscal pressures that could arise from expansionary policies under the new Lula administration.

Conversely, the Downward scenario, with yields decreasing to the historical low of 6.3%, represents an optimistic outlook. This scenario assumes successful implementation of fiscal reforms, inflation control, and a stable political environment conducive to investment. Such conditions could potentially lead to a "financing experience effect" as described by Egli et al. (2018), where improved macroeconomic conditions and policy stability contribute to lower financing costs for renewable energy projects over time.

This approach allows for quantification of the potential impacts of Brazil's macroeconomic volatility on solar PV financing, addressing a key gap identified by Steffen (2020) in the literature on renewable energy financing in emerging markets.

The impact of these scenarios on financing costs is striking. In the Flat scenario (Image 2), financing costs remain relatively stable, decreasing slightly from 48% to 46% of total project costs. This scenario aligns with the cautious optimism expressed by some analysts regarding Brazil's economic stability post-2023. As noted in the macroeconomic landscape analysis, the return of Luiz Inácio Lula da Silva to the presidency in 2023 signalled potential shifts in economic policy, with a greater emphasis on social spending and public investment. This flat scenario could represent a delicate balance achieved between expansionary policies and fiscal discipline.

The Upward scenario paints a more challenging picture, with financing costs rising from 48% to 55% of total project costs. This scenario reflects the potential risks highlighted in the macroeconomic analysis, including the possibility of rising public debt (projected by the IMF to potentially reach 95% of GDP by 2029) and the challenges of maintaining investor confidence while implementing new social and economic policies. This scenario aligns with the concerns raised by Schmidt et al. (2019) regarding the vulnerability of renewable energy investments to macroeconomic instability in emerging markets.

Conversely, the Downward scenario shows financing costs decreasing from 48% to 38%, representing a significant improvement in investment conditions. This optimistic outlook could be realized if Brazil successfully implements fiscal reforms, controls inflation, and creates a stable political environment conducive to investment and the “financing experience effect”.

All scenarios include a learning rate for both CAPEX and OPEX, reflecting global trends in solar PV technology. However, the divergence in financing costs across scenarios underscores the crucial role of country-specific economic factors in determining overall project viability. These projections also highlight the potential limitations of relying solely on technology cost reductions to drive solar PV deployment in emerging markets. As demonstrated in the Level 2 analysis, despite significant reductions in CAPEX and OPEX from 2014 to 2022, the overall LCOE for solar PV projects in Brazil increased due to rising financing costs.

This scenario analysis reveals a critical tension in Brazil's renewable energy future. While global trends continue to drive down technology costs, the country's macroeconomic management emerges as the pivotal factor in determining the viability of solar PV projects. This suggests that the most effective policy interventions for accelerating solar deployment in Brazil may lie more in the realm of macroeconomic policy and financial market development than in renewable energy-specific incentives. The analysis underscores the need for a holistic approach to renewable energy policy in emerging markets, one that considers the broader economic context alongside sector-specific measures.

Figure 22. Three Scenarios for Bond Yields and Inflation: Flat, Upward and Downward

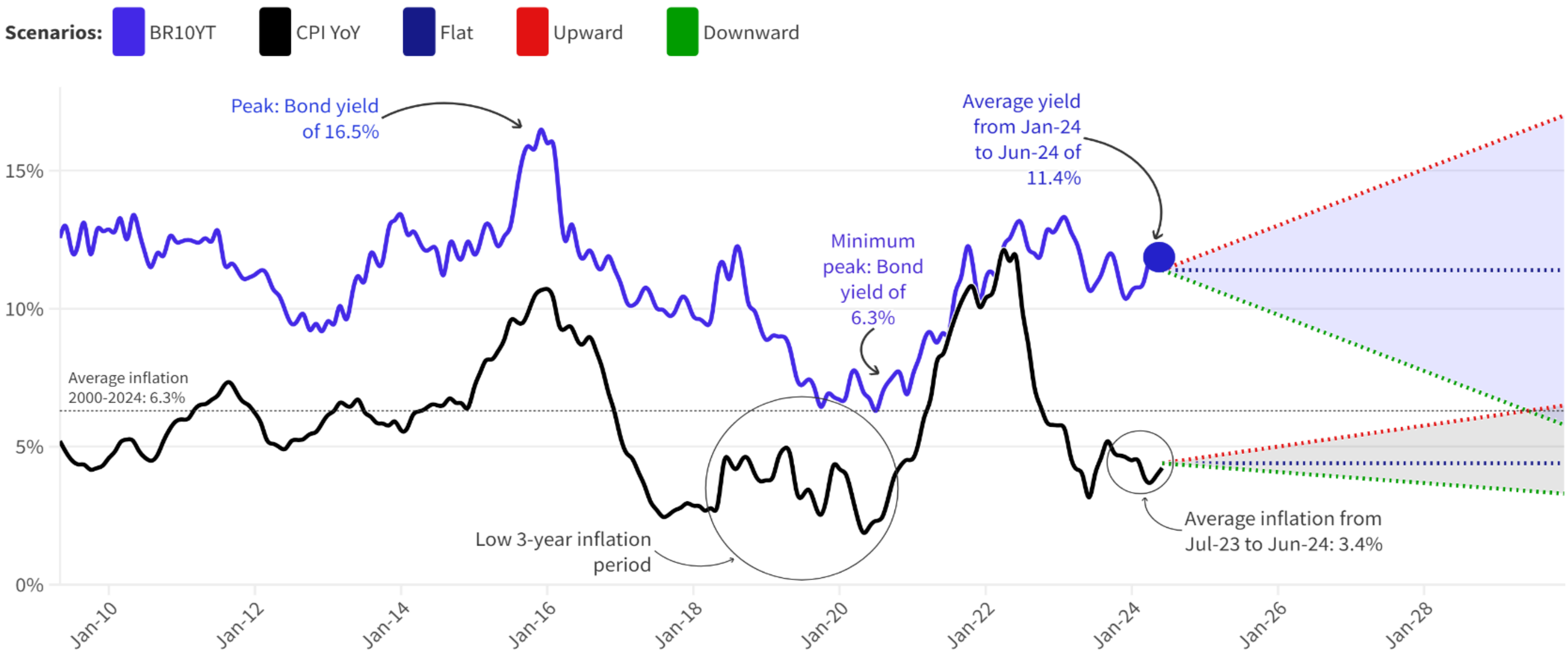
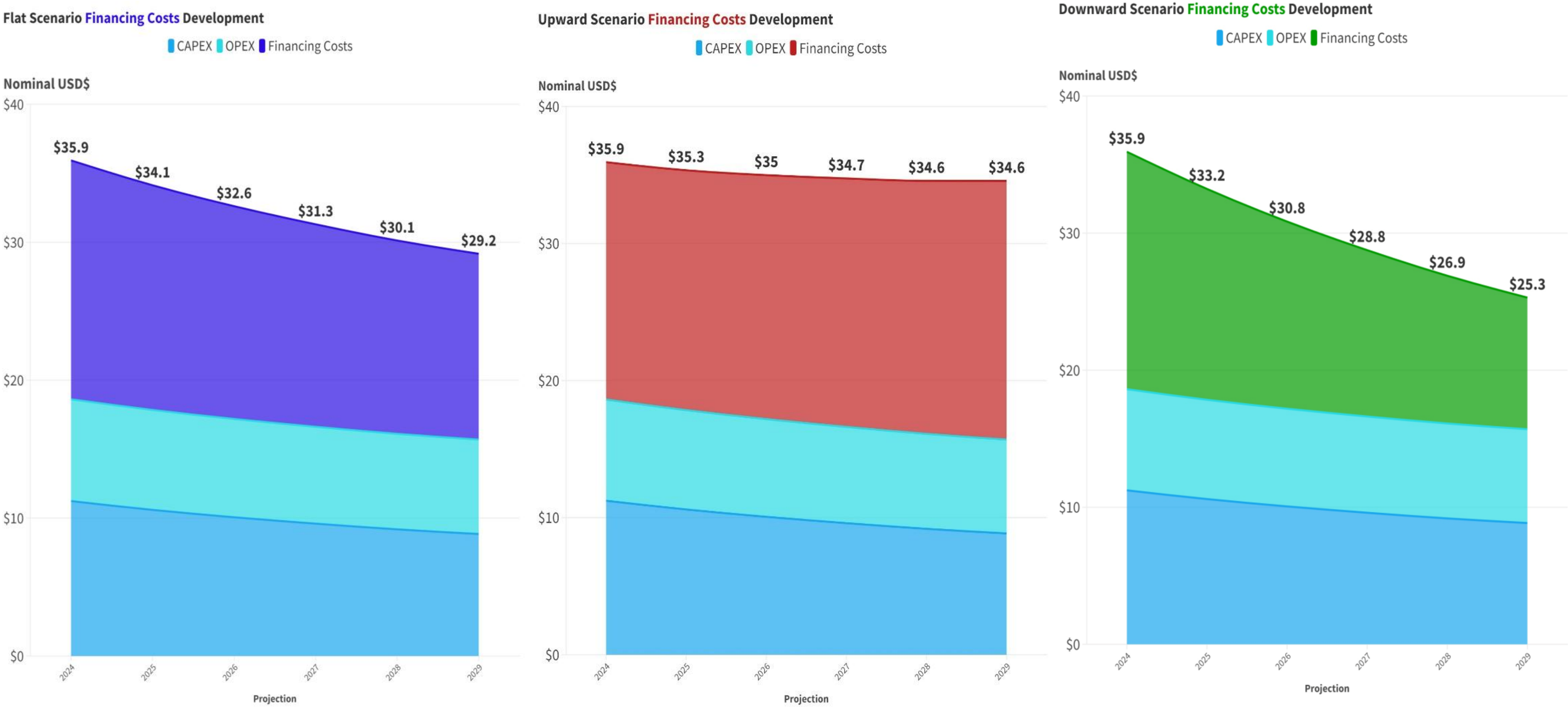


Figure 23. Development of Financing Costs per Scenario



Conclusion

Renewable energy sources of electricity are expanding rapidly. Global solar PV manufacturing capacity is forecast to reach 1,100 GW by the end of 2024, positioning solar PV as a key player in meeting global energy demands. According to the IEA, solar PV is expected to satisfy nearly half of the growth in global electricity demand over 2024 and 2025.

Investment patterns reflect this shift, as for every dollar allocated to fossil fuels today, nearly two dollars are being funnelled into clean energy (IEA, 2024). Solar module prices have dropped significantly, outpacing predictions from Wright's law of technology learning curves (EMBER, 2024c). Despite these positive trends, the inherent financial structure of renewable energy technologies makes them particularly susceptible to macroeconomic shocks and country-specific risks, which could slow, affect, or even reverse these advancements.

Summary

This study examined the complex interactions between financing conditions and the LCOE for solar PV projects in Brazil, covering the period from 2014 to 2024. The research utilized a multi-tiered methodological approach: first, calculating the WACC for solar PV projects under Brazil's fluctuating macroeconomic conditions; second, estimating the LCOE for solar PV projects awarded through energy auctions; and third, projecting future financing scenarios from 2024 to 2029. This analysis highlighted a clear reduction in both capital CAPEX and OPEX over time, driven by technological advancements and scale. However, these cost reductions were counteracted by rising financing costs, especially during periods of macroeconomic instability, such as inflation spikes and interest rate hikes in recent years.

The results demonstrate that while Brazil's solar PV sector has matured, the volatility in financing conditions has prevented a smooth decline in LCOE. Specifically, the data shows that while solar technology costs have fallen consistently, financing costs—which account for a significant portion of total project costs—have remained elevated due to economic factors such as inflation, interest rates, and country risk premiums. This dynamic is crucial to understanding the broader energy transition in Brazil and other emerging markets, where financing conditions play a pivotal role in determining the pace of renewable energy adoption.

Why This Research Matters

This research is particularly significant as it underscores the critical role of financial conditions in determining the success of solar PV projects, especially in emerging markets like Brazil. While most studies focus on the technological and operational cost reductions, this thesis sheds light on the financial barriers that can impede the expected growth of renewable energy despite technological advances (Schmidt et al., 2019). As demonstrated by the Brazilian case, macroeconomic instability—including inflationary pressures, interest rate hikes, and volatile currency movements—can significantly alter the cost structure of solar PV projects (IEA, 2022). This highlights the need for comprehensive financial frameworks and risk mitigation strategies that go beyond technology cost reductions (Aguila & Wullweber, 2024).

Furthermore, the Brazilian solar PV sector serves as a case study for how country-specific risks, such as political uncertainty, currency devaluation, and high interest rates, can hinder renewable energy growth. Brazil's struggle to reduce financing costs, despite declining CAPEX and OPEX, demonstrates that renewable energy policies must consider macroeconomic factors if they are to achieve long-term success. The broader implication is clear: while technological advancements are crucial, stable financial environments are equally essential for unlocking the full potential of renewable energy in emerging markets.

Novelty of the Research

This research contributes to the existing literature by providing a detailed, context-specific analysis of how financing conditions influence solar PV project viability in Brazil. Unlike studies that focus solely on mature economies, this work emphasizes the unique challenges faced by emerging markets (Egli et al., 2018). It also introduces granularity in calculating WACC, with this study estimating a monthly WACC, as opposed to the yearly estimates or multi-year averages common in other studies. This level of detail is crucial, particularly when comparing the estimates in this paper against the literature, where there is often a lag of a couple of years, failing to capture real-time fluctuations in financing conditions. The ability to calculate WACC monthly ensures that even short-term economic changes are accounted for, offering a more accurate reflection of financing conditions.

Additionally, by employing scenario analysis for future financing conditions (2024–2029), the research offers forward-looking insights into how Brazil's solar PV sector might evolve under different economic conditions. This level of foresight is crucial for investors and policymakers aiming to develop long-term strategies that account for both technological advancements and economic volatility.

Limitations of the Research

While this research offers valuable insights, it is not without its limitations. One major constraint is the reliance on publicly available data from energy auctions, which may not fully capture the intricacies of private financing arrangements or bilateral contracts in Brazil’s solar market. Moreover, the study's projections for future financing conditions are based on historical trends, which may not fully anticipate sudden shifts in Brazil’s political or economic landscape. Additionally, although Brazil has among the highest solar irradiation in the world, the capacity factors calculated using Santa Catarina (2022) methodology are exceptionally high compared to other regions. While some projects can reach these levels depending on location, the average capacity factor should be potentially lower to reflect more generalizable results.

The methodology also assumes that past trends in financing costs will continue into the future, which may overlook potential disruptive events or innovations in financial markets. Furthermore, while this study provides an extensive analysis of WACC and LCOE, it does not account for the full range of risks associated with project development, such as land acquisition, grid connection delays, or regulatory changes, which could also significantly affect project costs.

Future Research Directions

Future research could expand on these findings by incorporating more granular, project-level data, particularly from private investors and non-auction-based financing structures. Research should also focus on how newly implemented tariffs on solar PV panel imports by the Brazilian government might affect the WACC, adding a critical dimension to future financing studies. Furthermore, an integrated approach should be taken when researching the conditions in Brazil’s free market environment (ACL), which likely offers better contracting terms. This could involve mixed methods, combining semi-structured interviews with investor experts, surveys, and estimation models—a methodology not included in this study due to time constraints. In addition to analysing financial viability, future research should also assess project profitability, a crucial aspect that has been underexplored in this context.

Comparative studies that examine financing conditions in other emerging markets, such as India or South Africa, could provide a broader understanding of how different macroeconomic environments affect renewable energy financing globally.

Additionally, future work could delve into innovative financial mechanisms that mitigate currency risk and macroeconomic volatility, such as currency hedging, inflation-indexed contracts, or government-backed guarantees. These financial tools could help create a more stable investment environment for solar PV projects, particularly in countries like Brazil that experience high inflation and currency fluctuations. Research into the evolving role of bilateral contracts in Brazil's free electricity market (ACL) would also be valuable, as this market segment grows increasingly important.

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Wood, T., & Ross, N. (2012). The Financial Cost of Wind Energy: A Multi-National Case Study. Nova Science Pub Inc.

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Annex

Description of source and datasets used for the methodology

1. Refinitiv Workspace Data

Refinitiv Workspace was used to source monthly values for several key financial indicators:

- US government bond yields
- USD-denominated Brazilian Government bond yield
- 10-year BR10YT Government bond yield
- 5-year NTN-B bond yield
- IPCA (CPI) Year-over-Year

These data were crucial for calculating the cost of debt and assessing macroeconomic conditions in Brazil. The use of monthly values allowed for a detailed analysis of trends and fluctuations over time.

2. Bloomberg Terminal

- Exchange rate BRL/USD

3. BNDES (Brazilian Development Bank) Rates:

Data on BNDES rates were sourced directly from the official BNDES website. Two types of rates were collected:

a) Subsidized rate (TJLP - Taxa de Juros de Longo Prazo):

- Updated quarterly
- Determined by the National Monetary Council (Conselho Monetário Nacional - CMN)
- Historical data available from its inception

b) Unsubsidized rate (TLP - Taxa de Longo Prazo):

- Updated monthly
- Data available from its creation in January 2018

These rates are essential for understanding the financing conditions for infrastructure projects, including solar PV, in Brazil.

4. Energy Auction Dataset

This comprehensive dataset contains information on winning projects from energy auctions in Brazil since 2004. Key characteristics include:

- 48 variables for each project

- 2,139 total winning projects across all energy sources
- 195 solar PV projects
- Publicly available
- Updated monthly with inflation adjustments

For this study, nominal values were used to analyse macroeconomic and financing conditions at the time of each auction.

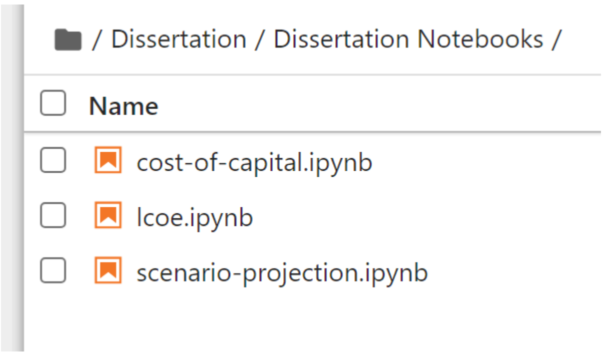
Table 1: Energy Auction Dataset Variables

Variable	**Description**
ID	Unique identifier for each project
Year of auction	Year the auction took place
Type of auction	Classification of the auction type
Auction	Specific auction identifier
Auction denomination	Full name or description of the auction
Notice number	Official notice number for the auction
Seller name	Name of the company or entity selling the energy
CNPJ	Brazilian company registration number
Product	Type of energy product being sold
CEG	Generation unit code
Power plant name	Name of the power plant
Status	Current status of the project
State	Brazilian state where the project is located
Source	Energy source (e.g., solar, wind, hydro)
River/fuel	Specific river for hydro or fuel type for thermal
Subdivisions	Any relevant subdivisions of the project
Investment at Auction Date (Million Reais)	Initial investment amount
Updated Investment (Million Reais)	Investment amount adjusted for inflation
Capacity (MW)	Installed capacity of the project
Physical guarantee (MW average)	Assured energy production
Energy Negotiated for Year A-A+3 (MW average)	Energy contracted for specific years
Energy Negotiated for Remaining Years (MW average)	Energy contracted for years beyond A+3
Total energy contracted (MWh)	Total amount of energy sold in the auction
Sale Price or ICB on Auction Date (R$/MWh)	Initial sale price
Price Unit	Unit of measurement for the price
Financial Amount Negotiated per Contract (R$)	Total financial value of the contract
Updated Sale Price (R$/MWh)	Sale price adjusted for inflation
Updated Financial Amount Negotiated	Financial value adjusted for inflation
Fixed Revenue per Contract for Years A-A+1 (R$/year)	Guaranteed revenue for initial years
Fixed Revenue per Contract for Remaining Years (R$/year)	Guaranteed revenue for later years
Supply Start Date	Date when energy supply is set to begin
Supply End Date	Date when energy supply contract ends

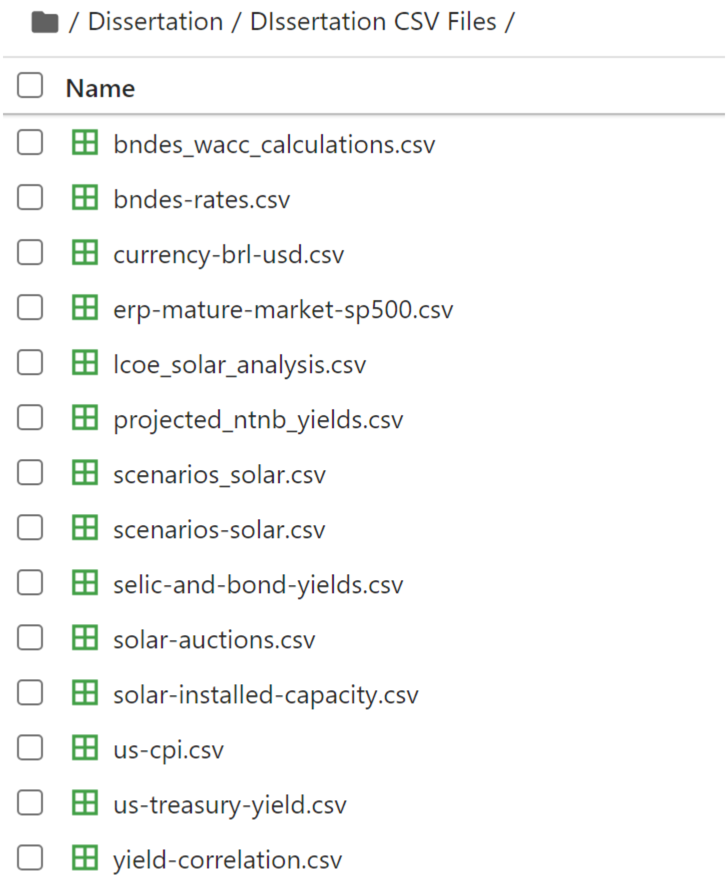
Variable	Description
IPCA on auction date	Inflation index at the time of the auction
IPCA June/2024	Inflation index used for updates

Dissertation methodology

Three Jupyter Notebooks:



CSV Files used throughout the Notebooks:



First Jupyter Notebook on Cost of Capital: Calculating the BNDES rate.

[3]:
```
bndes['date'] = pd.to_datetime(bndes['date'], format='%b-%y')
```

[4]:
```
alpha_factors = {
    2018: 0.57,
    2019: 0.66,
    2020: 0.74,
    2021: 0.83,
    2022: 0.91,
    2023: 1.00,
    2024: 1.00
}
```

[5]:
```
bndes['alpha'] = bndes['date'].dt.year.map(alpha_factors)
```

[6]:
```
bndes['ntnb_5yr_yield_ma'] = bndes['ntnb_5yr_yield'].rolling(window=3).mean().shift(1)
```

[7]:
```
bndes['est_bndes_tlp'] = bndes['alpha'] * bndes['ntnb_5yr_yield_ma']
```

[9]:
```
bndes['obs_tlp_ipca'] = bndes['cpi_ipca'].shift(1) + bndes['obs_bndes_tlp']
```

[10]:
```
bndes['bndes_rate'] = bndes['bndes_tjlp'].combine_first(bndes['obs_tlp_ipca'])
```

Calculating the Global risk-free rate, country default spread and technology premium:

[17]:
```
bndes['cds_brazil'] = bndes['bndes_rate'] - bndes['us_treasury_yield']
```

[18]:
```
bndes[['date', 'bndes_rate', 'us_treasury_yield', 'cds_brazil']].tail()
```

[18]:

	date	bndes_rate	us_treasury_yield	cds_brazil
121	2024-02-01	9.99	4.250	5.740
122	2024-03-01	9.91	4.200	5.710
123	2024-04-01	9.41	4.680	4.730
124	2024-05-01	9.39	4.499	4.891
125	2024-06-01	9.84	4.396	5.444

Adding the technology premium based on solar installed capacity

```
[23]: def calculate_technology_premium(solar_capacity_ratio):
          #For new markets a linear interpolation between 3.25% and 3% for 0% to <5% capacity
          if solar_capacity_ratio < 5:
              return 3.25 - (0.25 * (solar_capacity_ratio / 5))
          #For intermediate markets a linear interpolation between 3% and 1.7% for 5% to <10% capacity
          elif 5 <= solar_capacity_ratio < 10:
              return 3.0 - (1.3 * ((solar_capacity_ratio - 5) / 5))
          #For mature markets of 10% and above a fixed premium is assigned
          else:
              return 1.5
```

```
[24]: bndes['technology_premium'] = bndes['solar_capacity_ratio'].apply(calculate_technology_premium)
```

Applying the tax shield:

```
[28]: corporate_tax_rate = 0.34
      bndes['cost_of_debt'] = bndes['pre_tax_cost_of_debt'] * (1 - corporate_tax_rate)
```

Calculating cost of equity:

```
[34]: bndes['cost_of_equity'] = (
          bndes['us_treasury_yield'] +
          bndes['cds_brazil'] +
          bndes['erp_sp500'] +
          bndes['technology_premium']
      )
```

Debt share and WACC:

Debt share as per IRENA criteria (based on cumulative installed capacity)

```
[37]: def assign_debt_share(solar_capacity_ratio):
          #Mature market
          if solar_capacity_ratio >= 10:
              return 0.80
          #Intermediate market
          elif 5 <= solar_capacity_ratio < 10:
              return 0.70
          #New market
          else:
              return 0.60
```

```
[38]: bndes['debt_share'] = bndes['solar_capacity_ratio'].apply(assign_debt_share)
```

Calculating cost of capital (WACC)

```
[39]: bndes['cost_of_capital'] = (
          bndes['cost_of_debt'] * bndes['debt_share'] +
          bndes['cost_of_equity'] * (1 - bndes['debt_share'])
      )
```

Second Jupyter Notebook on LCOE:

Dataset:

[4]:
```
lcoe_solar.head()
```

[4]:

	date	name_auction	seller_name	power_plant_name	capex	nominal_capacity_mw	physical_guarantee_mwave	energy_contracted	sale_price_auction	fir
0	31/10/2014	06ºLER	RIO ENERGY EOL IV	SOLAR CAETITÉ 3	140007000	29.97	6.6	1157112.0	207.52	
1	31/10/2014	06ºLER	RIO ENERGY EOL IV	SOLAR CAETITÉ 2	140007000	29.97	6.6	1157112.0	207.52	
2	31/10/2014	06ºLER	RIO ENERGY EOL IV	SOLAR CAETITÉ 1	140007000	29.97	6.6	1157112.0	207.52	
3	31/10/2014	06ºLER	DRACENAS	DRACENA 4	128320000	30.00	5.9	1034388.0	217.75	
4	31/10/2014	06ºLER	DRACENAS	DRACENA 1	128320000	30.00	5.9	1034388.0	217.75	

LCOE Baseline for each project:

[16]:
```
lcoe_solar['lcoe_baseline'] = lcoe_solar['capex_baseline'] + lcoe_solar['opex_baseline']
lcoe_solar[['power_plant_name', 'capex_baseline', 'opex_baseline', 'lcoe_baseline']].head()
```

[16]:

	power_plant_name	capex_baseline	opex_baseline	lcoe_baseline
0	SOLAR CAETITÉ 3	96.863844	56.58174	153.445584
1	SOLAR CAETITÉ 2	96.863844	56.58174	153.445584
2	SOLAR CAETITÉ 1	96.863844	56.58174	153.445584
3	DRACENA 4	99.311199	58.01133	157.322529
4	DRACENA 1	99.311199	58.01133	157.322529

Cost of capital for each project:

[22]:

	power_plant_name	date	cost_of_capital
0	SOLAR CAETITÉ 3	2014-10-31	8.738336
1	SOLAR CAETITÉ 2	2014-10-31	8.738336
2	SOLAR CAETITÉ 1	2014-10-31	8.738336
3	DRACENA 4	2014-10-31	8.738336
4	DRACENA 1	2014-10-31	8.738336

LCOE with WACC for each project:

[30]:

	power_plant_name	capex_wacc	opex_wacc	lcoe_wacc
0	SOLAR CAETITÉ 3	241.326448	48.983134	290.309582
1	SOLAR CAETITÉ 2	241.326448	48.983134	290.309582
2	SOLAR CAETITÉ 1	241.326448	48.983134	290.309582
3	DRACENA 4	247.423785	50.220738	297.644524
4	DRACENA 1	247.423785	50.220738	297.644524

Financing Costs:

[32]:
```
lcoe_wacc_2022 = lcoe_solar[lcoe_solar['year'] == 2022]['lcoe_wacc'].mean()
lcoe_baseline_2022 = lcoe_solar[lcoe_solar['year'] == 2022]['lcoe_baseline'].mean()
delta_2022 = lcoe_wacc_2022 - lcoe_baseline_2022
print(delta_2022)
```

```
159.84377858181443
```

[33]:
```
delta_i = delta_2022 - delta_2014
```

[34]:
```
print(f"Change in financing costs from 2014 to 2022: {delta_i.round(2)} BRL/MWh.")
```

```
Change in financing costs from 2014 to 2022: 24.74 BRL/MWh.
```

Third Jupyter Notebook on Future Financing Costs:

Correlation and regression:

[4]:
```
correlation_matrix = df.corr()
correlation_matrix
```

[4]:

	ntnb_5yr_yield	cpi_ipca	yr10_gov_bond_yield
ntnb_5yr_yield	1.000000	0.354614	0.962594
cpi_ipca	0.354614	1.000000	0.490069
yr10_gov_bond_yield	0.962594	0.490069	1.000000

[13]:
```
X_diff = sm.add_constant(df_diff['diff_yr10_gov_bond_yield'])
model_diff = sm.OLS(df_diff['diff_ntnb_5yr_yield'], X_diff).fit()
```

[14]:
```
residuals_diff = model_diff.resid
```

```
[17]: model_diff_summary = model_diff.summary()
adf_diff_results, model_diff_summary
```

```
[17]: ({'diff_ntnb_5yr_yield': 3.2469943886149468e-12,
  'diff_yr10_gov_bond_yield': 4.5221297702752256e-10},
 <class 'statsmodels.iolib.summary.Summary'>
 """
                             OLS Regression Results
 ==============================================================================
 Dep. Variable:     diff_ntnb_5yr_yield   R-squared:                       0.614
 Model:                             OLS   Adj. R-squared:                  0.609
 Method:                  Least Squares   F-statistic:                     124.1
 Date:                 Sat, 07 Sep 2024   Prob (F-statistic):           8.47e-18
 Time:                         21:18:32   Log-Likelihood:                 15.086
 No. Observations:                   80   AIC:                            -26.17
 Df Residuals:                       78   BIC:                            -21.41
 Df Model:                            1
 Covariance Type:             nonrobust
 ============================================================================================
                                coef    std err          t      P>|t|      [0.025      0.975]
 --------------------------------------------------------------------------------------------
 const                        0.0067      0.023      0.295      0.768      -0.039       0.052
 diff_yr10_gov_bond_yield     0.4292      0.039     11.142      0.000       0.353       0.506
 ==============================================================================
 Omnibus:                        0.750   Durbin-Watson:                   2.281
 Prob(Omnibus):                  0.687   Jarque-Bera (JB):                0.360
 Skew:                           0.141   Prob(JB):                        0.835
 Kurtosis:                       3.167   Cond. No.                         1.70
 ==============================================================================

 Notes:
 [1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
 """)
```

Definition of scenarios for 2029:

```
[26]: avg_yield_inflation_2029 = projected_yields[projected_yields['Date'].dt.year == 2029].mean()
print(avg_yield_inflation_2029)
```

```
Date                   2029-06-16 12:00:00
Flat_10YR_Yield                       11.4
Upward_10YR_Yield                16.532417
Downward_10YR_Yield                 6.2575
Flat_Inflation                         4.4
Upward_Inflation                  6.315833
Downward_Inflation                3.391667
dtype: object
```

WACC Evolution under scenario assumptions:

[44]:

Year	WACC_Flat	WACC_Upward	WACC_Downward
2024	9.497786	9.497786	9.497786
2025	9.497787	10.064794	9.066732
2026	9.497787	10.660108	8.601831
2027	9.497787	11.255423	8.136930
2028	9.497787	11.850738	7.672029
2029	9.497787	12.446053	7.207129

Learning Rates Assumptions:

[45]:
```
capex_2022 = 167735285.6  # in nominal BRL for 2022
opex_2022 = 2430484.3  #EPE report 1.45%
capex_learning_rate = 0.15
opex_learning_rate = 0.05
inflation_rate = 0.04  # 4% annual inflation
nominal_power = 40  # Average MW for 2022
capacity_factor = 0.313447745 #Average 2022
lifetime = 25  # Project lifetime in years
hours_per_year = 8760  # Total hours in a year
```

[46]:
```
# Capacity totals for each year starting from 2023
capacity_total = {
    2023: 1628,
    2024: 2167,
    2025: 2781,
    2026: 3469,
    2027: 4241,
    2028: 5117,
    2029: 6000
}
```

LCOE Baseline and Scenarios:

[65]:

Year	LCOE_Baseline	LCOE_WACC_Flat	LCOE_WACC_Upward	LCOE_WACC_Downward
2024	94.661103	182.740612	182.740612	182.740612
2025	90.729005	173.569656	179.728889	168.957855
2026	87.409649	165.860944	177.932398	156.843084
2027	84.520325	159.177377	176.708222	146.234089
2028	81.925455	153.197274	175.799433	136.742334
2029	79.801921	148.320031	175.774645	128.628774

Financing Costs evolution:

[66]:

Year	Financing_Cost_Flat	Financing_Cost_Upward	Financing_Cost_Downward
2024	88.079509	88.079509	88.079509
2025	82.840651	88.999883	78.228850
2026	78.451295	90.522749	69.433435
2027	74.657051	92.187897	61.713764
2028	71.271819	93.873978	54.816879
2029	68.518109	95.972724	48.826853