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Risks, Rates, and Rays: Domestic financing shapes Brazil's utility-scale solar PV costs in regulated auctions

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ABSTRACT

Solar photovoltaic (PV) is the fastest growing electricity source by capacity, with global additions reaching 600 GW in 2024. At the same time, rising interest rates adversely affect solar PV's competitiveness. This study examines the financial dynamics of Brazil's solar energy sector, focusing on how financing conditions impact the Levelised Cost of Energy (LCOE) for solar PV projects. We estimate the nominal after-tax Weighted Average Cost of Capital (WACC) for solar PV projects in Brazil, calculate the nominal LCOE for projects awarded in energy auctions from 2014 to 2022. We build the WACC from observable domestic, public financing instruments and combine it with auction-specific costs to decompose LCOE for 195 awarded projects. This market is 36% of cumulative capacity and 10% of construction volume in 2024.

Brazil's WACC is significantly higher than in advanced economies, and our monthly, nominal after tax WACC series indicates values in the range of 10%–15%. Despite a 35% decline in capital expenditures (CAPEX) over the study period, financing costs increased from 47% of total project costs in 2014 to 62% in 2022, offsetting cost reductions and limiting LCOE decreases. Our novel intra-annual (monthly) WACC captures short-term macro-financial fluctuations. These findings highlight the critical role of macro-financial stability and access to competitive domestic debt for auctioned utility-scale PV in Brazil and capital-market design in other emerging markets.

1. Introduction

The global power sector is rapidly shifting to address climate change. Solar photovoltaic (PV) energy has become central to this shift, experiencing unprecedented growth and cost reductions, and is now the cheapest electricity source (IEA, 2024b). Global installation rates rose from one gigawatt annually in 2004 to an estimated 520–655 gigawatts in 2024 (The Economist, 2024). According to the (IEA, 2024b), this trend continues, with solar projected to attract over USD 500 billion in investment by 2024. The exponential growth of solar PV stems from a cycle of increasing production, demand-pull policies, falling costs through economies of scale and learning-by-doing, and rising demand (Nemet, 2019).

Brazil, with its vast landmass and high solar irradiation up to 6.5 kWh/m^2/day (Pereira et al., 2017), is well-positioned to use solar PV to meet rising energy demands and supporting decarbonisation. Despite this potential, significant growth in Brazil's solar PV capacity only started in the early 2010s, reaching 19% of total installed electricity capacity in Brazil by 2023 and becoming the second-largest source of electricity (ANEEL-SIGA, 2024a, 2024b). This rapid growth has been driven by declining technology costs, supportive policies like energy auctions or financing incentives by the Brazilian Development Bank (BNDES), and the introduction of net metering regulations in 2012, allowing distributed solar generation feeding into the grid (Iglesias and Vilaça, 2022; Leite et al., 2024; ABSOLAR, 2024). This expansion is critical for meeting rising electricity demand and diversifying an energy mix – long dominated by hydropower – a necessity highlighted by severe droughts that caused the 2001–2002 energy crisis (Carstens and Cunha, 2019).

Despite Brazil's solar PV growth, challenges remain with grid integration, permitting delays, and significant financing constraints (Damasio, 2024). The cost of capital for Brazilian solar PV can be two to three times higher than in advanced economies, reducing competitiveness (IEA, 2024a). This issue is further exacerbated by rising global interest rates, ending the ‘zero era’ of low rates (Martin et al., 2024). Limited understanding of how macroeconomic factors influence the cost

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of capital for solar PV projects in Brazil compounds the problem. Higher interest rates risk leading to suboptimal investments, inefficient resource allocation, and missed opportunities to accelerate Brazil's energy transition. Understanding these dynamics is vital for policymakers and investors, as a lack of context-specific data on the relationship between macroeconomic factors and capital costs hinders the development of effective policies and incentives to support sector growth.

This research addresses this gap by providing a detailed, context-specific analysis of how financing conditions shape solar PV project costs in Brazil, particularly highlighting the challenges faced by emerging markets. It also introduces intra-annual granularity by estimating a monthly weighted average cost of capital (WACC). This approach overcomes the limitations of studies using yearly estimates, lagging data, or failure to capture real-time fluctuations in financing conditions, ensuring short-term economic changes are reflected. The research enables investors and policymakers to construct long-term strategies.

This focus aligns with the study's primary aim of analysing how macroeconomic shifts, such as interest rate fluctuations, impact the cost of capital for solar PV projects in Brazil from 2014 to 2024, a period marked by significant macroeconomic changes. A model was developed to quantify the relationship between interest rates and the WACC, considering inflation, currency fluctuations, and policy shifts. We also explore different future interest rate scenarios to assess implications on financing costs (with detailed methods and results in Appendix A). These findings provide empirical insights to help policymakers and investors navigate interest rate fluctuations, supporting more effective renewable energy financing strategies tailored to Brazil's context and comparable economies.

2. Background

2.1. *Macroeconomic landscape*

Over the past two decades, Brazil has experienced significant economic fluctuations, characterised by periods of robust growth and deep recessions. The ‘Brief Golden Age’ in the early 2000s saw GDP growth averaging 4.5% annually, driven by a commodities boom and social programs boosting domestic consumption (Serrano and de Summa, 2022; Gerard et al., 2021). However, from 2011 onward, economic strain set in due to declining commodity prices, rising labour costs, the appreciation of the Brazilian real and falling public revenues, leading to fiscal imbalances and inflationary pressures (Vartanian and Garbe, 2019). This culminated in Brazil's worst recession in recent history during 2015–2016 with GDP contractions of over 3% and soaring unemployment (IBGE, 2024). The COVID-19 pandemic further contracted GDP by 4.1% in 2020, and while recovery followed with 4.6% growth in 2021, challenges like uneven economic benefits and persistent unemployment continued (Ministério de Minas e Energia (MME), 2024).

By 2022, Brazil's central bank raised the Selic rate (i.e., the central bank rate) to 13.75% to curb inflation, impacting investments in sectors like renewable energy (Martin et al., 2024). Solar PV projects rely heavily on upfront investment, making them sensitive to interest rate fluctuations (IEA, 2024a; Schmidt et al., 2019). The high cost of capital poses significant hurdles for solar PV financing, often twice as high as in advanced economies, largely due to macroeconomic factors and country-specific risks (IEA, 2024a). While clean energy investment has risen, high capital costs still hinder faster renewable energy deployment in the country (see Fig. B.1).

Furthermore, Brazil's fiscal landscape is marked by high public debt, rising from 60% of GDP in 2011 to 85% by 2024 (see Fig. B.2), and projected to reach 95% by 2029, increasing vulnerability to external shocks and exerting upward pressure on the cost of capital (IEA, 2024a; IMF, 2024). Brazil has a rigid budget structure, with government spending largely constitutionally mandated, thus efforts like the 2016 spending cap aimed at fiscal discipline, limited public investment. This has led to Lula 's 2023 ‘Sustainable Fiscal Regime’, promoting more flexible spending rules (Federal Government Brazil, 2023).

Monetary policy, driven by the *Banco Central do Brasil* (Brazil's Central Bank), has kept the Selic rate at 10.5% in mid-2024 to curb inflation currently at 4.3%. The solar PV sector is sensitive to interest rate hikes, especially in Brazil's free market environment (ACL - *Ambiente de Contratação Livre*), where short-term contracts dominate – less than 20% of energy contracted through the free market had a duration above 6 years – increasing perceived risks of these investments (Greener, 2022). Moreover, Brazil imports 99% of its solar panels (Martins and Jieqi, 2024), which are affected by currency depreciation of nearly 50% against US$ from 2013 to 2018 (Fig. B.3 and Fig. B.4). This has affected solar PV projects, reducing revenue from awarded Power Purchase Agreements (PPAs) by 36%, and resulting in the cancellation of several projects (IEA, 2024a).

Domestic financing through development banks, particularly the

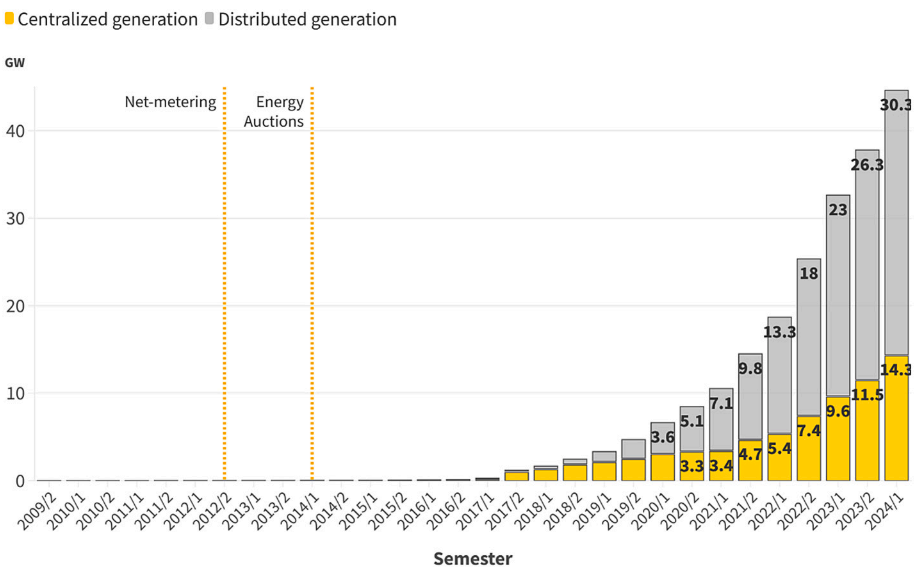

Fig. 1. Solar centralised and distributed generation installed capacity. Distributed generation accounts for around 70% of total solar energy capacity by June 2024. Source: ANEEL-SIGA, 2024a, 2024b.

Brazilian Development Bank (BNDES), plays an important role. BNDES provided concessional, long-term debt, subsidising interest rates, when market borrowing rates were prohibitive up until 2018 (IEA, 2021). This support has been critical in a high interest rates environment driving up the cost of capital for projects. Since then, capital markets and bonds have emerged as additional financing tools, although economic policies remain important in supporting investment viability (Greener, 2022).

2.2. Solar PV landscape

Brazil has a renewable-heavy electricity mix, which account for 86% of installed capacity (ANEEL-SIGA, 2024a, 2024b). Historically dominated by hydropower, around 65% of electricity generation, the system faces periodic droughts, exposing vulnerabilities and prompting diversification efforts, which laid the groundwork for renewable energy support mechanisms (EMBER, 2024b; Barbosa et al., 2020). The PROINFA program introduced in 2002 promoted set the precedent for the adoption of wind and biomass – but excluded solar PV initially – through long-term contracts (i.e., PPAs) and financial incentives.

More recently, solar PV has grown rapidly (see Fig. 1), adding about one gigawatt of capacity monthly between 2022 and mid-2024, accounting for 19% of installed capacity by June 2024, becoming the second largest source of electricity in the country (ANEEL-SIGA, 2024b). The expansion was supported by regulatory updates and the inclusion in the national energy auctions in 2014, critical for contracting new capacity (Viana and Ramos, 2018).

The auction system under the Regulated Contract Market (ACR) – the main study subject of this research – operates as a 'single buyer' model, where a central entity purchases electricity from producers (Tolmasquim et al., 2021). This allows solar developers to bid for long-term PPAs, typically 20 years, providing revenue certainty and facilitating project financing (Egli et al., 2023). Auctions have driven down utility-scale solar costs, with prices dropping from US$82–90/MWh in 2014 to US$17.6/MWh in 2019, before rising to US$30/MWh in 2022 (CCEE, 2024a; ABSOLAR, 2024), though remain competitive overall. This widespread shift towards low-cost solar PV highlights the interactions of macroeconomic volatility, currency depreciation, and rising financing costs interact with declining CAPEX and improving capacity factors in Brazil.

The Free Contract Market (ACL) predates auctions and gained momentum in 2015 by allowing large consumers to directly contract energy from producers (Santa Catarina, 2022). Auctions, cost reductions, and regulatory changes have increased confidence in this deregulated environment, enabling consumers to choose electricity suppliers over regulated utilities (Baetas Gonçalves, 2015; CCEE, 2022b).

The Brazilian open market has been the primary driver of solar PV development, accounting for 90% of construction volume and 64% of operating plants as of 2024 (Greener, 2024). However, the dominance of short-term PPAs in this market creates significant bankability challenges, with typical PPA tenors on the free market of up to six years (Perez, 2024) unlikely to cover the entire debt repayment period over time at financial close. This may increase the perceived risk from revenue uncertainty after the initial PPA period and could increase the cost of financing for solar projects This study focuses on regulated market auctions, where public data enable transparent WACC and LCOE modelling. Distributed generation and ACL projects are excluded due to unavailable financing data.

BNDES role of providing subsidised interest rates and favourable loan repayment conditions for renewable projects until 2018 (BNDES, 2024b) helped developers to secure competitive financing (Silveira et al., 2024). BNDES and Banco do Nordeste together accounted for approximately R$45 billion of the R$54 billion identified in mapped public and publicly oriented energy-transition finance for solar in Brazil between 2015 and 2024 (about 83%), highlighting the central role of public and public-oriented finance in the segment (EPE, 2025). Additionally, bonds have emerged as a growing financing source. International investments now account for around half of utility-scale solar PV funding, reflecting the sector's increasing maturity (IEA, 2024a; Greener, 2022).

Brazil's solar PV plants are concentrated in the Northeast and Southeast, regions with exceptional solar resources (i.e., capacity factors reaching 29%) and land available (see Fig. B.5) (Pereira et al., 2017; Silveira et al., 2024). However, the sector faces challenges from grid integration issues, policy changes to net metering, and the introduction of import taxes on solar equipment.

3. Methodology

The research assesses the influence of financing conditions on the Levelised 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 (see Fig. 2). The analysis was conducted using Python in Jupyter Notebooks. All relevant data and code are available in the Zenodo repository https://doi.org/10.5281/zenodo.14529054.

Level 1 (Section 3.1) estimates the nominal after-tax WACC for solar PV projects in Brazil, establishing a clear estimate of financing costs. Level 2 (Section 3.2) 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 (Appendix A) explores scenarios for general interest rates and inflation in Brazil from 2024 through to 2029 for context, but they are not used in estimation or inference. We complement calculations with a sensitivity analysis where we compare the LCOE results with auction prices. Overall, 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.

3.1. Level 1: the weighted average cost of capital for solar PV in Brazil

The calculation of the WACC is critical for investors in evaluating the financial viability of solar PV projects in Brazil. As a key determinant of the LCOE, the WACC is essential for comparing energy generation costs across various sources (IEA, 2023; IRENA, 2023b). WACC functions as a project's aggregate discount rate, and is shaped by both project-level parameters and broader macroeconomic conditions, including interest rates, inflation expectations, and sovereign risk (Angelopoulos et al., 2016; Egli et al., 2018; Schmidt et al., 2019).

However, due to the private nature of project finance, estimating the components of the WACC (i.e., the cost of debt, cost of equity and leverage) remains challenging. It is very common in Brazil's capital markets that borrowing occurs in domestic currency (BRL), under

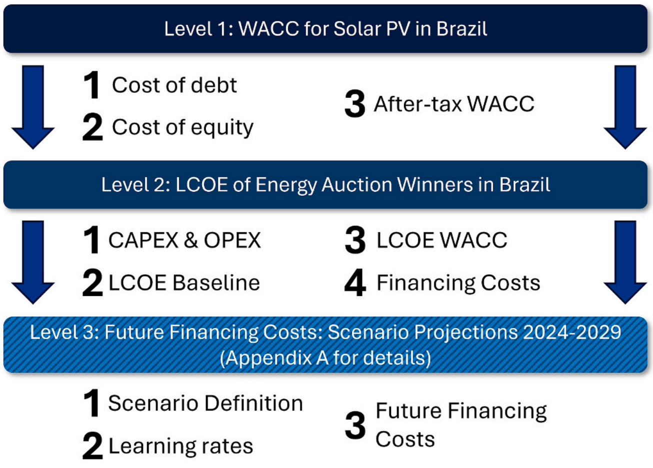

Fig. 2. Three-tiered methodological approach.

inflation-linked conditions, and often via state development banks such as BNDES. In the literature, the cost of debt is estimated through several formulations, typically using a risk-free rate plus a set of risk-related premiums. These include combinations of credit default spreads, bank margins, or technology premiums, as seen in IRENA (2023b), Kitzing et al. (2024), Egli et al. (2018), and Angelopoulos et al. (2016). The cost of equity is primarily derived using variations of the Capital Asset Pricing Model (CAPM), incorporating risk-free rates, equity risk premiums, country premiums, and technology premiums, based on frameworks from Steffen (2020), IRENA (2023b), Schmidt et al. (2019b), and Damodaran (2024). Contextual details and approaches to calculate the WACC are in Appendix C.

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 (IRENA, 2023b) 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. We adopt a standard project finance structure, in line with global utility-scale renewable norms, where 88% of projects follows this model IRENA (2023b). In Brazil, Greener (2023) identifies 336 solar Special Vehicle Purposes, confirming the dominance of project finance as financing structure for this type of project. Cost of debt calculation is the first step in determining the WACC. Using the IRENA methodology as a base, the cost of debt (K_D) is calculated with Eq. (A2). Note this equation includes the tax shield already and is thus not be applied to Eq. (3) again:

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

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 US$-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 and τ represents the corporate tax rate. LM and TP are often folded together and given jointly (IRENA, 2023b).

Applying this methodology to Brazil presents challenges. Using a USD-denominated sovereign bond underestimates Brazil's true cost of debt, as these bonds target foreign capital and exclude domestic inflation and currency risk. Conversely, nominal 10-year BRL bonds produce excessively high estimates that do not reflect real borrowing conditions in project finance, as Brazil's lending rates remained subsidised until recently. Using international benchmarks or nominal BRL bonds can misrepresent the effective cost of capital, as they fail to account for Brazil's inflation volatility and the impact of subsidised lending structures. We therefore base our estimate on NTN-B bonds, which are real return, inflation-linked federal bonds widely used as a proxy for Brazil's long-term interest rate (see Fig. B.6). Importantly, the NTN-B yield is not used directly as the nominal cost of debt in the WACC, rather, it serves as the real anchor for domestic long-term lending framework and is converted into nominal terms through the inflation adjustment embedded in the TLP methodology.

NTN-B yields were chosen due to their strong correlation with the 10-year government bond yield and the Selic Target rate. NTN-B yields reflect domestic inflation-linked borrowing conditions, while comparative U.S. Treasury yields are used to estimate Brazil's sovereign credit spread, capturing country and currency risk for international investors. BNDES, the primary financier of Brazil's solar PV projects, is the only major institution to publish a transparent lending methodology, having linked its rates to NTN-B bond yields through the Taxa de Longo Prazo (TLP) since 2018 (BNDES, 2024c).

The long-term rate (TLP) is a nominal rate comprising a real interest rate, derived from five-year NTN-B bond yields, and an inflation adjustment. It is calculated using the average of NTN-B yields from the past three months plus the previous monthly year-on-year inflation. An adjustment factor was applied to the NTN-B bond's real interest rate as lending rates gradually reflected the open market state, but since 2023, no adjustment factor is used. Historical NTN-B yield data were collected from LSEG (2024), and a moving average adjusted by the BNDES factor was calculated and compared with historical BNDES rates (BNDES, 2024c). These series also serve as inputs for the scenario analysis presented in Appendix A.

Observed long-term rates (TLP, introduced in 2018, see Fig. B.7.) were merged with historical TJLP rates, adjusting the latter for inflation to align with the TLP. The TJLP, a subsidised rate, included an inflation target, requiring an adjustment based on the Índice Nacional de Preços ao Consumidor Amplo (IPCA), Brazil's official inflation index. The final cost of debt calculation incorporated the BNDES rate, adjusted for inflation, as the Brazilian risk-free bond yield.

Due to limited public access to private financing contracts, our WACC model prioritises replicability using observable, benchmarked financial instruments. In particular, we use the BNDES rate as the foundational cost of debt, given the institution's historical dominance as the primary lender for utility-scale solar PV projects in the regulated market. While other sources like bonds and international capital are growing, they remain difficult to model due to data opacity (Steffen, 2020; IRENA, 2023a). Thus, we rely on a stylised, yet grounded, approach anchored in public debt benchmarks.

The CDS proxy was calculated by subtracting US Treasury bond yields from the BNDES rates. No 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, which is common practice (IRENA, 2023b). The study used three market maturity buckets: 'New Market' ($< 5\%$), 'Intermediate Market' (5%–10%), and 'Mature Market' ($\geq$10%). For each bucket, the premium decreases linearly or remains fixed from 10% onwards, with linear interpolation for exact percentages. This yields technology premiums of 3.25%–3.0% for new markets for solar shares between 0% and less than <5%, linearly interpolated between the two points. For intermediate markets (5–10% solar share), the premium is linearly interpolated from 3.0% down to 1.7%. A fixed premium of 1.5% is applied for mature markets ($\geq$10% solar share).

As of August 2024, BNDES Finem – a type of financing for big infrastructure projects – charges a 1.1% technology premium for solar infrastructure, but we apply a conservative 1.5% premium to account for potentially higher margins faced by non-BNDES financiers, especially in less mature market environments (BNDES, 2024a).

The total cost of debt for Brazil adds all variables and is then reduced by applying the 34% corporate tax rate to account for tax-deductible interest payments $(1 - \tau)$. This approach provides a realistic estimate of the cost of debt for subsequent calculations. The cost of equity, an essential component in the WACC calculation, is determined using the Eq. (A7). Note that GRF equals RF in Eq. (A7), but GRF is adapted within our methodological framework:

$$K_E = GRF + CP + ERP + TP \tag{2}$$

In this equation, 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. Rather than following IRENA's methodology using Damodaran's estimations, the Country Premium was derived from the country default spread used for the cost of debt (CDS), calculated as the difference between Brazil's bond yields, reflected in the BNDES rate, and the global risk-free rate. This 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 and 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 harmonisation of the WACC components as proposed by IRENA and Schmidt et al. (2019) ensures analytical consistency. Using the BNDES rate and BRL bond yields to estimate both debt and equity costs reflects Brazil's unique financial environment, where BNDES is pivotal. This approach also accounts for local interest rates and currency risks, key to solar PV project viability.

By adopting this methodology, the analysis maintains coherence and relevance, particularly when assessing how interest rate fluctuations impact solar PV project capital costs in Brazil. Integrating these components into the WACC equation provides a comprehensive financial view, essential for LCOE calculations. After estimating both the cost of debt and the cost of equity, leverage of solar PV projects was determined based on market maturity, measured by installed solar capacity as a percentage of total electricity capacity. Using IRENA's approach, three market maturity buckets were assigned fixed debt shares: 80% for 'Mature Market' ($\geq$10%), 70% for 'Intermediate Market' (5%–10%), and 60% for 'New Market' ($<$ 5%). This ensures debt financing reflects the relative risk of market maturity, with greater debt proportions as markets mature.

The cost of debt (K_D) and the cost of equity (K_E) are calculated using Eqs. (1) and (2), respectively. With these components and the corresponding leverage shares established, the nominal after-tax WACC is calculated using Eq. (3):

$$WACC = \delta \times K_D + (1 - \delta) \times K_E \tag{3}$$

In this equation, K_D represents the cost of debt, K_E is the cost of equity, and δ is the leverage (or debt share). The corporate tax rate τ often show here, is already include in Eq. (1). 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.

3.2. *Level 2: LCOE of energy auction winners in Brazil*

The second stage calculates the LCOE for solar PV projects that secured contracts in Brazil's energy auctions between 2014 and 2022, focusing on the evolution of financing costs using the WACC from Level 1. The analysis follows methodologies employed by Egli et al. (2018) and Schmidt et al. (2019) in their study of renewable energy projects in Germany.

Data was sourced from the Chamber of Electric Energy Commercialization (CCEE), which provides details on winning projects from energy auctions since 2004 (Tolmasquim et al., 2021; CCEE, 2024a). Key variables for LCOE calculations included auction date, seller name, investment amount, nominal capacity, and physical guarantee of individual projects.

This methodology draws on Santa Catarina (2022), who calculated LCOE for 758 Brazilian wind projects, and Egli et al. (2018), who analysed the impact of financing conditions on renewable energy costs. Our analysis included 195 solar PV projects from energy auctions (2014–2022), excluding two that participated in a specific auction type called the Simplified Competitive Procedure. Most projects originated from reserve and alternative power auctions, with contracts lasting 20 years (reduced to 15 years since 2021). Afterward, agreements can be renegotiated in either the regulated (ACR) or open (ACL) markets.

The LCOE calculation considers inputs like taxes, operating costs (OPEX), inflation assumptions, and WACC. Unlike Santa Catarina (2022), who included federal taxes directly in the LCOE, this analysis integrates them into the after-tax WACC (see Level 1), while Santa Catarina used a before-tax WACC from Brazil's Energy Research Company (EPE).

Following Santa Catarina (2022), the declared investment amount reported for each winning project in the CCEE auction records is used as an administrative proxy for project CAPEX. We assume that this variable is sufficiently informative for project-level CAPEX, although it may not perfectly equal ex post realized capital expenditure. This field is distinct from the awarded sale price reported in the same dataset. Accordingly, CAPEX is not inferred from the auction tariff, and financing costs are estimated separately through the WACC framework because the project-level financing terms required to identify them directly are not disclosed in the auction records.

Annual energy production was estimated by multiplying the capacity factor, nominal capacity in MW and total yearly hours. This calculation provided the expected annual energy production in MWh.[1] OPEX was calculated as 1.45% of project CAPEX, based on de Jong et al. (2015) who estimated OPEX as 1% of investment costs for onshore wind projects. The 1.45% percentage was derived from data provided by the Empresa de Pesquisa Energética (EPE), providing a consistent method for estimating annual OPEX across all projects. All cost inputs and outputs in our model are expressed in nominal BRL, consistent with developer-facing realities. CAPEX is taken directly from auction data set, and OPEX is inflated annually at 3.5% to reflect long-term cost increases, then discounted using the nominal WACC to yield a nominal LCOE.

$$OPEX_t = OPEX_{initial} \times (1 + inflation\ rate)^t \tag{4}$$

Based on Egli et al. (2018), the analysis established a baseline by calculating an LCOE excluding financing costs (0% WACC). This approach isolates the CAPEX and OPEX components over the 25-year project lifetime (Ministério de Minas e Energia (MME) and EPE, 2022). The baseline LCOE was calculated using the following equation:

$$LCOE_{it,WACC=0} = \frac{C_{it}}{\sum_{t=1}^{25} FLH_{it\tau}} + \frac{\sum_{t=1}^{25} C_{it\tau}}{\sum_{t=1}^{25} FLH_{it\tau}} \tag{5}$$

Eq. (5) expresses the baseline LCOE as the ratio of undiscounted CAPEX and OPEX to total lifetime energy production, excluding financing costs. This approach provided a nominal LCOE value, representing energy production costs without financing impacts.

To include financing costs, the LCOE was recalculated using the project-specific WACC from Level 1. This required discounting both OPEX and expected energy production over the 25-year project lifetime. Each year's OPEX and energy production were discounted to present value using the WACC corresponding to the month preceding the auction, assuming financing terms were set beforehand. This ensured consistency across all financial modelling aspects of the project:

$$LCOE_{WACC} = \frac{C_{it}}{\sum_{t=1}^{t=25} \frac{FLH_{it\tau}}{(1+WACC_{it})^{\tau}}} + \frac{+\sum_{t=1}^{t=25} \frac{C_{it\tau}}{(1+WACC)^{\tau}}}{\sum_{t=1}^{t=25} \frac{FLH_{it\tau}}{(1+WACC)^{\tau}}} \tag{6}$$

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

$$\delta_{it} = LCOE_{it} - LCOE_{it,WACC=0} \tag{7}$$

The change in financing costs over time (Δ_i) is assessed by comparing the financing expenditures across years:

$$\Delta_i = \delta_{it=1} - \delta_{it=2} \tag{8}$$

Here, $t = 1$ and $t = 2$ denote different auction years for project *i*. These calculations isolate financing's impact on LCOE, clarifying how financing conditions have shaped solar PV project costs over time.

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

3.3. Limitations and sensitivities

This research provides valuable insights but has several limitations. It relies on publicly available auction records; declared investment amounts are used as administrative proxies for CAPEX and are assumed to be sufficiently informative for project-level capital costs, although they may differ from ex post realized project costs and capture a broader all-in project budget than a narrow realized EPC-only measure. Project-level financing terms remain largely private and therefore must be approximated through observable public proxies rather than directly observed.

The auction price is a contractual market outcome that may reflect competition, strategic bidding and portfolio considerations, whereas project-level financing terms are not disclosed in the auction dataset. In addition, the generator may commercialise uncontracted physical guarantee in the ACL or settle differences in the Mercado de Curto Prazo (MCP), so the awarded tariff need not equal the project's full lifetime revenue (EPE, 2020). We therefore estimate WACC separately from observable domestic benchmarks and use the auction price only as an external check by solving a calibrated lower-bound WACC in which LCOE equals the cohort median bid. For this calibration and the accompanying diagnostics, we exclude 29 contracts that later were cancelled, rescinded or revoked, yielding a total of 166 contracts. For the rest of the analysis (i.e., WACC and LCOE calculation) the full set of 195 contracts was used. We also quantify robustness with WACC uncertainty bands and deterministic sensitivities (e.g., CAPEX -10%/−25%, cost of equity -2 pp, cost of debt -1/-2 pp, leverage +10 pp subject to an 85% cap, OPEX -10%). The analysis also includes a goal-seek CAPEX reduction to match the auction price. The results of these sensitivities and the WACC calibration based on auction results are reported in Table B.1.

Some analyses draw on historical relationships to assess financing conditions under varying macroeconomic environments, which may fail to anticipate sudden political or economic shifts in Brazil. Additionally, while Brazil boasts some of the highest solar irradiation globally, capacity factors calculated using Santa Catarina (2022) methodology appear unusually high. Although achievable in select locations, a lower average capacity factor might yield more generalisable results. The methodology assumes continuity in financing cost trends, potentially overlooking disruptive events or innovations in financial markets. Furthermore, while the study thoroughly analyses WACC and LCOE, it does not address all risks associated with project development, such as land acquisition, grid connection delays, or regulatory changes, which could also significantly affect project costs.

4. Results and discussion

4.1. WACC

The Level 1 analysis of the 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, supports Schmidt et al.'s (2019) framework on the rapid impact of interest rate fluctuations on renewable energy financing in emerging markets.

A critical juncture in the cost of debt trend occurred around 2018, coinciding with the transition from TJLP, the subsidised rate, to TLP, the open market rate. This shift introduced greater exposure to market volatility, reshaping the financing landscape for infrastructure projects. The heightened volatility in both cost of equity and debt, particularly after 2020, aligns with Steffen's (2020) findings on the role of country-specific risk factors in renewable project financing. Notably, significant fluctuations in the Country Default Spread during periods of economic uncertainty highlight Brazil's unique risk profile as an emerging market. These macroeconomic conditions increase the perceived risk of utility-scale projects, directly impacting their financial viability. Concurrently, the gradual decline in the technology premium for solar PV over the studied period reinforces Egli et al.'s (2018) concept of ‘financing experience effects'. Brazil's rapid expansion of solar PV capacity likely enhanced investor familiarity, contributing to a reduction in perceived technological risk and narrowing financing costs over time.

The comparison of WACC estimates in Fig. 3 with existing literature reveals significant disparities, highlighting the challenges of accurately assessing financing costs for solar PV projects in emerging markets. Egli et al. (2023) (dotted line) illustrates the limitations of applying models developed for mature economies to more volatile contexts like Brazil and recognise the higher uncertainty and methodological limitations in

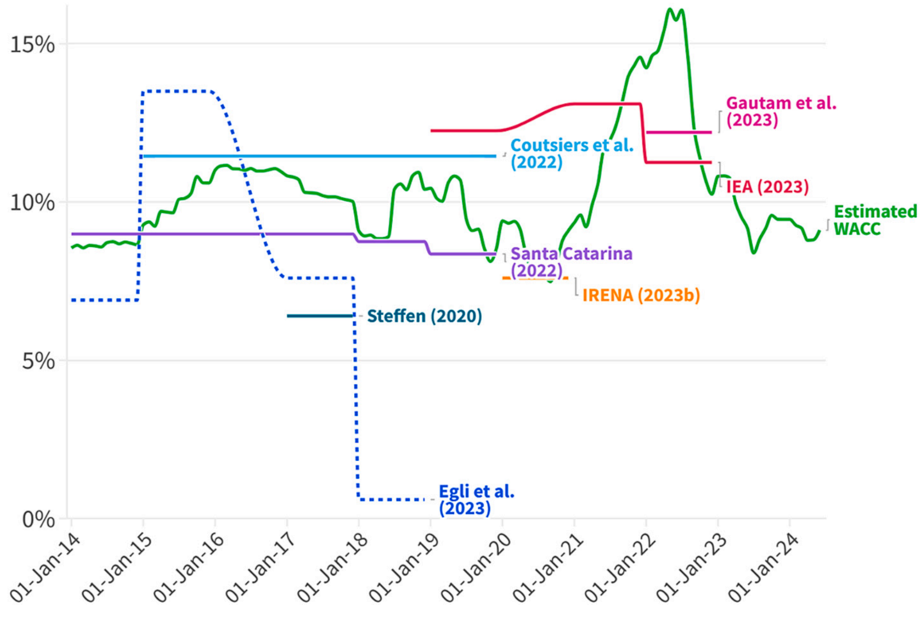

Fig. 3. Increased temporal granularity for estimated WACC in this study vs. Literature WACC. Our high-frequency series is compared with period averages/ranges from Egli et al. (2023), Coutsiers et al. (2022), Steffen (2020), Santa Catarina (2022), Gautam et al. (2023), IEA (2023) and IRENA (IRENA, 2023b).

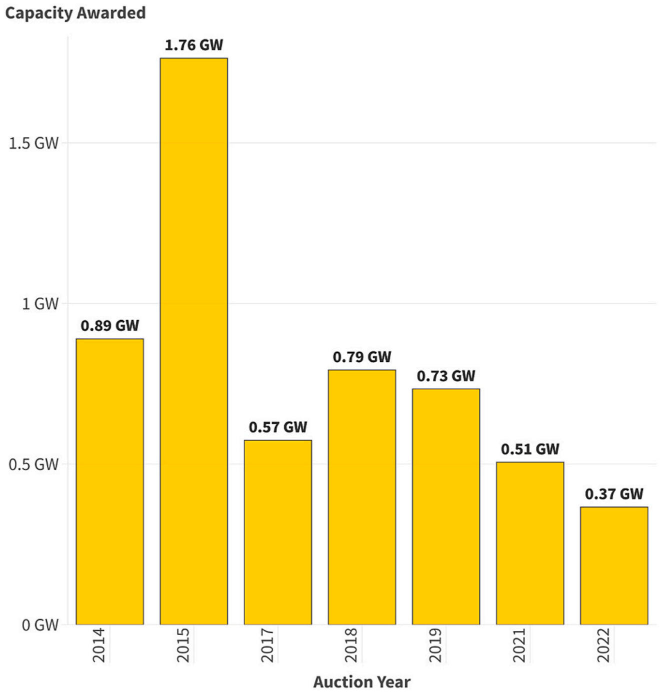

Fig. 4. Solar PV capacity awarded in energy auctions in Brazil. Source: CCEE (2024a).

their estimations. Other sources, such as Coutsiers et al. (2022) and Santa Catarina (2022), report more stable WACC estimates, likely a result averaging values over time, with 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 to 2017). In contrast, the higher WACC values reported by IEA (2023) and Gautam et al. (2023) align more closely with this study's estimates, suggesting that recent assessments better capture evolving risk perceptions in the Brazilian market. Nonetheless, 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, but final values are not publicly available. As we note the advancements of our own methodology, we also note that our WACC estimates reflect a stylised and highly responsive application of CAPM. In practice, equity return expectations (K_E) may adjust more slowly than debt pricing (K_D) in response to changes in financial market conditions (see (Simshauser, 2014)).

4.2. LCOE of solar PV

The variation in WACC estimates across studies highlights the complexity of assessing the cost of capital for renewable energy projects in emerging markets. Methodological differences, data sources, and time frames can produce divergent results. This study's estimates, which are more sensitive to short-term economic fluctuations, offer a nuanced perspective on evolving risk perceptions in Brazil's solar PV market. Building on this, the analysis of solar PV projects winning Brazil's energy auctions (Level 2) reveals several trends shaped by both global developments and domestic conditions.

Fig. 4 shows the solar PV capacity awarded in energy auctions in Brazil. Twelve auctions took place between 2014 and 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. The capacity awarded in auctions fluctuated significantly, peaking at 1.8 GW in 2015 before declining to 0.4 GW in 2022. This pattern likely reflects shifting policy priorities and market conditions, as noted by Tolmasquim et al. (2021) in their analysis of Brazil's electricity sector reforms. Importantly, it marks a broader shift from the regulated market to the open market. By 2018, 100% of accumulated capacity was under regulated auctions, but developers increasingly preferred bilateral negotiations, often due to more favourable terms (Greener, 2024). Brazil has not held a solar auction since 2022.

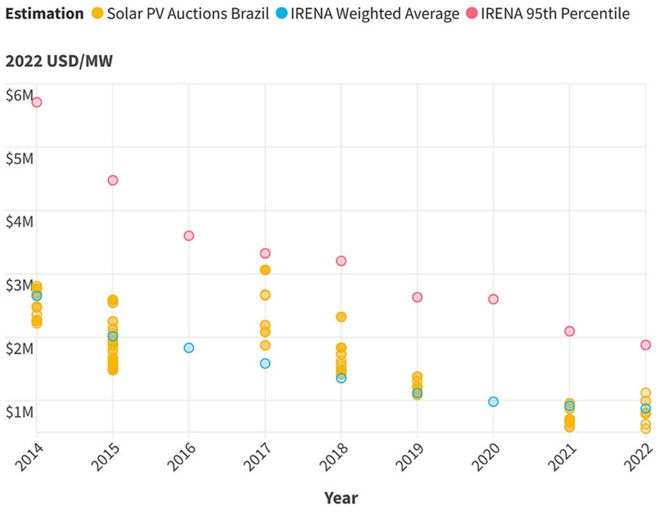

Fig. 5. Capital expenditures of solar PV auctions Brazil v. IRENA. Data sources: CCEE (CCEE, 2024a); IRENA (IRENA, 2023b).

CAPEX for Brazilian solar PV projects (Fig. 5) estimated for the projects on our dataset are in line with the IRENA's global weighted average estimation, which both show a clear downward trend (IRENA, 2023b; CCEE, 2024a). This trend supports Nemet's (2019) observations on cost reductions driven by technological advancements and learning effects in project development and construction. Solar panel costs have consistently declined, which reinforces this trend (EMBER, 2024a). Notably, Brazil's CAPEX values remain below IRENA's 95th percentile (Fig. 5), reflecting effective cost management within its competitive auction system.

Auction sale prices (Fig. 6) fell sharply from US$88/MWh in 2014 to US$17.6/MWh in 2019, before rising again to $37.2/MWh by 2022, reflecting shifting macroeconomic conditions. This trend is consistent with Dobrotkova et al. (2018) who documented price declines in emerging market solar auctions. The data reveals an interesting dynamic: while CAPEX steadily decline, auction prices exhibited more volatility after 2019. This divergence supports Egli et al.'s (2018) assertion that financing costs play a crucial role in determining LCOE for capital-intensive technologies like solar PV. However, auction prices should be interpreted with caution as benchmarks for full project costs (EPE, 2020). In the Brazilian context, project remuneration need not be limited to the regulated auction price, since generators may combine contracted auction revenues with revenues from uncontracted physical guarantee commercialized in other market segments (CCEE, 2022a). As a result, the awarded tariff does not necessarily represent the project's full revenue stream and should not be interpreted as a direct one-to-one reference for the cost of energy.

Performance improvements are also visible in the capacity factor (Fig. B.8.), which shows an upward trend for Brazilian projects, surpassing IRENA's global weighted average. A deeper understanding of Brazil's solar economics comes from analysis of LCOE between 2014 to 2022, presented in both Brazilian Reais (BRL) and US Dollars (US$), provide critical insights into the evolving economics of solar energy in the country. The LCOE trend in nominal BRL (Fig. 7) shows an initial decline followed by an uptick from 2018 to 2022. In contrast, the LCOE in nominal US$ shows a consistent downward trend, mirroring global solar PV cost reductions. This BRL-US$ divergence highlights the impact of currency fluctuations on project economics, a risk compounded by

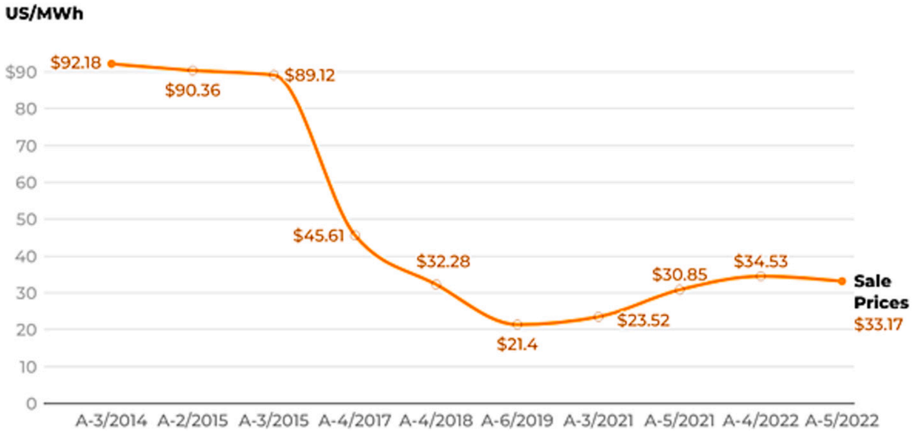

Fig. 6. Solar PV sale US$ prices in Brazil's energy auctions. Data source: CCEE (2024a).

Fig. 7. LCOE with WACC from 2014 to 2022 in nominal BRL values (pink graph) and in US$ (yellow graph). The left panel shows LCOE values in nominal BRL, reflecting local financing and cost conditions. The right panel shows LCOE values converted to US$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Brazil's reliance on imports for up to 99% of its solar panels (Martins and Jieqi, 2024).

Overall, Brazilian LCOEs have generally tracked below global levels since 2016. This indicates that despite macroeconomic challenges, Brazil retains a competitive edge in solar PV deployment, possibly due to its favourable solar resources and competitive auction system, as discussed in the solar PV landscape section. The widening LCOE ranges in recent years indicate growing project heterogeneity, likely due to increased diversity in project sizes, locations, and the shift towards the ACL (Greener, 2024).

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 Fig. B.9. 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 Fig. 8 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, 2020).

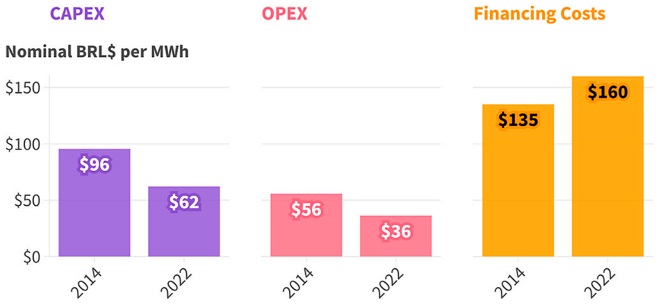

Fig. 8. Changes in financing costs from 2014 to 2022.

The findings align with broader literature on renewable energy finance in emerging markets. Egli et al. (2018) noted that financing costs can offset technological gains in certain market conditions. Fig. 9 presents a cross-country comparison of LCOE cost components, highlighting the role of (nominal after-tax WACC) financing costs in shaping cost structures with a breakdown into financing costs (orange), CAPEX (purple), and OPEX (salmon) for utility-scale solar PV across selected countries. IEA (2023) estimates using 2021 assumptions are shown alongside our own estimates for Brazil's 2014 and 2022 auctions (grey-shaded). This highlights Brazil's elevated financing cost share, and the importance of macroeconomic stability and financial sector development for improving solar competitiveness in emerging markets. However, caution is warranted when interpreting such comparisons: capacity factors differ across locations and are not held constant, which means both financing conditions and solar resource quality jointly influence LCOE outcomes.

As a diagnostic check, we calibrate a lower-bound financing case by solving for the positive WACC that would make modelled LCOE equal to the observed auction price for each project, using an active-contract subsample of 166 projects after excluding 29 contracts that were later cancelled, rescinded or revoked. For 36 projects (22%), this calibration does not yield a positive implied WACC, indicating that financing assumptions alone cannot explain the full gap between modelled LCOE and observed auction prices. We therefore also test deterministic sensitivities that reduce the main cost drivers one at a time and in combination, including CAPEX (−10% and − 25%), cost of equity (−2 pp), cost of debt (−1/−2 pp), leverage (+10 pp., capped at 85%), technology premium (−50%), OPEX (−10%), a combined finance-relief case, and an integrated lower-cost case. These scenarios reduce, but do not eliminate, the gap. In the baseline model, 120 projects remain above the observed auction price; for this subset, a CAPEX-only goal-seek implies a mean CAPEX reduction of approximately 46.5% to reconcile modelled LCOE with the tariff. We interpret this figure as a diagnostic residual under the maintained assumptions of the model, rather than as a literal estimate of realized CAPEX. Taken together, these checks suggest that the observed gap reflects a combination of financing uncertainty, heterogeneity between declared investment and realized project cost, and revenue stacking beyond the auction tariff, rather than a single mis-specified financing parameter. Numerical results are reported in Table B.1.

5. Policy implications

A central finding is that rising financing costs for solar PV projects in Brazil are closely linked to inflation dynamics, not just nominal interest rate levels, which drives inflation through two channels: (1) Monetary tightening from the Central Bank's aggressive Selic rate hikes, which raises borrowing costs across the economy, and (2) elevated (perceived) investment risk, prompting higher risk premiums from both domestic and international lenders, especially in long-term infrastructure projects.

These effects are magnified in Brazil due to its history of fiscal instability, frequent currency depreciation, limited inflation-targeting credibility and import-dependence in solar panels, highlighting the importance of credible macroeconomic management. On the policy side this is realized through fiscal discipline, predictable regulatory frameworks, and the expansion of hedging instruments for currency and inflation risk, which could reduce the inflation-risk premium for projects. Moreover, development banks like BNDES can play a countercyclical role by offering concessional financing during inflationary cycles, partially insulating the sector from macroeconomic volatility.

This shift towards market-based long-term interest rates for BNDES financing shows the significant impact of policy changes on renewable energy financing, a theme emphasised by Polzin et al. (2021). The uptake of open market contracting warrants revisiting support policies, such as auction design and regulatory frameworks. The volatility in auction prices reflects increasing merchant risk exposure, as noted by IRENA (2023b), as well as higher risk premiums, linked to macroeconomic challenges. As regulated auctions increasingly contract only part of project output, auction clearing prices become a less informative standalone benchmark for full project economics, reinforcing the need for policy frameworks that explicitly address merchant exposure and revenue-risk management.

Thus, renewable energy markets in emerging economies must account for both technological advancements and broader country-specific economic and policy factors, when assessing renewable energy competitiveness (see Schmidt et al. (2019)). We thus caution against an overreliance on technological improvement in solar PV to pre-empt eternally falling CAPEX, which may be offset by costlier project sites and grid connection challenges (Klingler et al., 2023).

These findings have significant implications for policymakers and

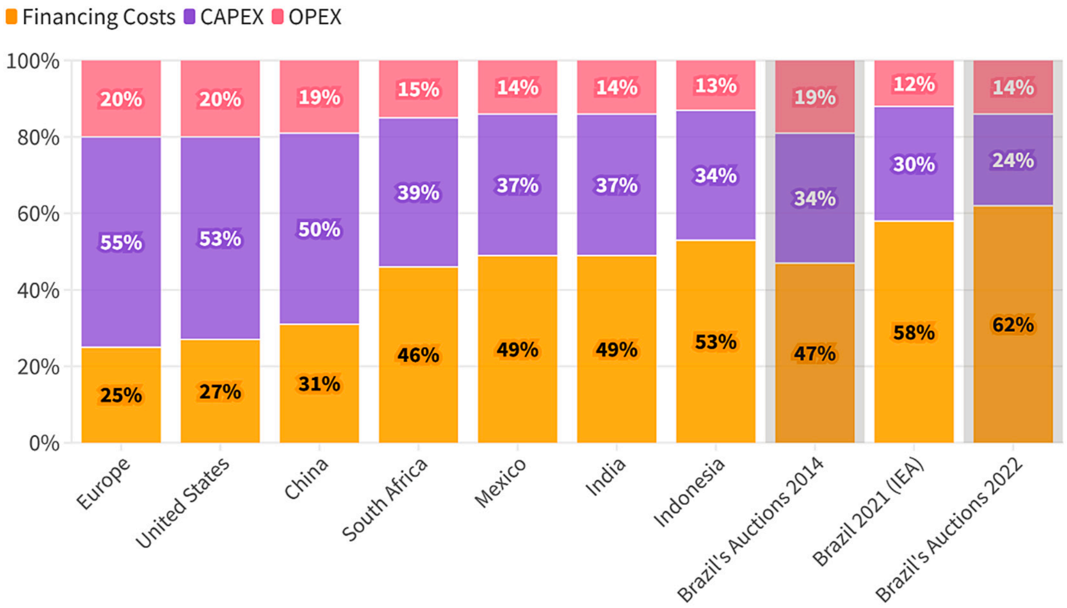

Fig. 9. Comparison of LCOE components for utility-scale solar PV across selected countries. Financing costs shown in orange, CAPEX in purple, and OPEX in salmon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

investors: (1) For policymakers, the rising LCOE in BRL terms highlights the need for measures to mitigate macroeconomic volatility, such as supporting local manufacturing or introducing innovative financial instruments to hedge against currency risks. (2) For investors, the divergence between BRL and US$ trends creates a complex decision-making environment. Those with access to BRL financing benefit from inflation-indexed auction contracts, providing a natural hedge against local inflation, though BRL volatility increases perceived risk. Conversely, investors using US$ financing may enjoy more stable returns in US$ terms but face considerable currency risk.

A key takeaway from this study is the 18.5% increase in financing costs (from R$135 to R$160/MWh between 2014 and 2022) despite falling CAPEX and OPEX. This highlights that financial conditions, not technology, now constrain solar competitiveness. This trend aligns with the findings of Schmidt et al. (2019), who emphasised the critical role of financing costs in determining the overall competitiveness of renewable energy in emerging markets. These results add nuance to the understanding of solar PV economics in Brazil, demonstrating that technological improvements alone do not guarantee lower overall costs. The cancellation of several solar PV projects due to currency depreciation illustrates the tangible risks developers face in emerging markets, particularly when exposed to exchange rate fluctuations and inflation at the same time.

This has led to higher financing costs in Brazil when compared to similar economies such as Mexico and India, according to IEA (2024b) data. To mitigate these challenges, policymakers should prioritise efforts to improve the overall investment climate for renewable energy (IEA, 2024b). Reducing import dependence through local manufacturing and promoting inflation-indexed contracts can help to mitigate risk for investors using local currency. For the private sector, there is a requirement for sophisticated financial structuring and robust risk management strategies. Access to low-cost capital alone is no longer sufficient; projects must also be shielded from external shocks, mandating investors to hedge macroeconomic exposure to remain competitive in volatile markets.

Looking towards 2029 (see Appendix A for context) shows how possible macro-financial conditions propagate into project WACC and ultimately the LCOE of utility-scale PV. Our results shows that financing likely remains the dominant cost driver, despite learning-driven reductions in CAPEX and OPEX, highlighting macroeconomic stability and risk premia, and not technology costs, now set the pace for further LCOE reductions. Thus, macro-financial policy is now a decisive factor in the competitiveness of solar PV in Brazil, and potentially other emerging economies. Sustained inflation control, fiscal credibility, and investor confidence are not only sound economic policy, but prerequisites for delivering affordable, low-carbon electricity.

6. Conclusion

Solar PV is expanding rapidly, with global manufacturing capacity set to exceed 1 TW per year by the end of 2024, while costs continue to decline. 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, with twice the amount of money spend on clean energy than on fossil fuels (IEA, 2024b). Despite these positive trends, the financial structure of renewable energy substantial requires upfront investment, making them susceptible to macroeconomic shocks and country-specific risks.

This study examines the complex interactions between financing conditions and the LCOE for solar PV projects in Brazil, from 2014 to 2024, using a multi-tiered empirical approach (see Methodology). By estimating a monthly WACC and calculating project-level LCOEs for auction-awarded projects, the analysis shows that while CAPEX and OPEX decrease over time, these reductions were partly offset by rising financing costs, especially during periods of macroeconomic instability.

As a result, the volatility in financing conditions has prevented a smooth decline in LCOE, despite consistently falling technology costs. Financing costs – which now account for a significant portion of total project costs – have remained elevated owed to inflation, high interest rates, and country risk premiums. This research thus emphasises the impact of finance in Brazil and other emerging markets, where financing costs will determine the pace of renewable energy adoption. Macroeconomic conditions can significantly alter the cost structure of projects (IEA, 2021), highlighting the need for financial risk mitigation strategies that go beyond technology cost reductions (Aguila and Wullweber, 2024). While technological advancements are imperative, a stable financial environment is equally critical for unlocking the full potential of renewable energy in emerging markets, such as Brazil.

Between 2014 and 2018, BNDES acted as the de facto primary provider of finance for utility-scale solar PV in Brazil. While this concessional support naturally raises concerns about fiscal burden and potential risks to taxpayers, in practice, these risks did not materialise. On the contrary, BNDES financing helped significantly reduce the cost of capital at a time when private markets offered prohibitively expensive terms. This contributed to lower energy costs overall and enabled the sector's early growth. This experience may offer useful lessons for other economies facing similar financing constraints.

Future research could incorporate project-level finance data, particularly from private investors and outside of auctions. It should also study the impact on the WACC by newly implemented import tariffs on solar PV panels. Furthermore, Brazil's free market environment (ACL) deserves attention, which is likely more competitive than the auction markets. Of further interest would be the overall project profitability, not just cost. A broader, comparative understanding in the context of other emerging markets would help piecing together an understanding of macroeconomic environments affect renewable energy financing globally.

The findings of this study reinforce the critical role of financial stability in complementing technological advancements to drive renewable energy adoption in emerging markets. Bridging the gap between investment needs and financial risks in emerging markets allows solar PV's contribution to a resilient and sustainable energy future globally. This will become even more relevant as solar PV becomes central to satisfying global energy demand, thus creating stable financing frameworks in emerging markets, like Brazil, will be key to meeting climate and energy goals.

Data and code availability

The datasets and code produced in this study are available in the ZENODO repository, DOI: https://doi.org/10.5281/zenodo.14529054. The code is organised in Jupyter notebooks for Python. See ReadMe file in the Zenodo repository for instructions.

CRediT authorship contribution statement

Santiago Monroy Gomez: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Malte Jansen:** Writing – review & editing, Supervision, Conceptualization.

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Appendix A. Level 3: future financing costs: scenario projections 2024–2029

Forward-looking scenarios for Brazil's financing environment (2024–2029) quantify how macroeconomic conditions could propagate into the WACC and, in turn, the LCOE of utility-scale solar PV. We implement three macro paths (Flat, Upward, Downward) parameterised by the empirical relationship between 10-year government bond yields and 5-year NTN-B real yields, with the BNDES TLP constructed from a moving-average NTN-B plus contemporaneous IPCA. CAPEX and OPEX trajectories follow learning-curve assumptions, while non-finance cost components are inflated at a constant long-term rate to isolate the financing effect. Data and code are available via the Zenodo repository (see Data and code availability and Appendix D).

A.1. Methodology

This stage projects future financing conditions and their impact on LCOE for solar PV projects in Brazil from 2024 to 2029, focusing on how macroeconomic variables, particularly bond yields and inflation, affect financing costs. The approach is based on methodologies from Schmidt et al. (2019) and Egli et al. (2018), adapted to Brazil's economic context.

The analysis utilised a dataset from LSEG (2024), covering monthly yields of 5-year NTN-B bonds, 10-year government bond yields (BR10YT), and year-on-year inflation changes from October 2017 to June 2024. Augmented Dickey-Fuller (ADF) tests confirmed the data was non-stationary, requiring differencing to achieve stationarity. Subsequent ADF tests validated the transformation for regression analysis.

Regression analysis on the differenced series revealed a strong relationship between the 10-year government bond yield and the 5-year NTN-B yield, with a 1 percentage point increase in the former raising the latter by 0.43 percentage points. This relationship guided NTN-B yield projections under three scenarios: a flat scenario with bond yields stable at the 2024 average of 11.4%; a downward scenario with yields dropping to the 2020 low of 6.3%; and an upward scenario with yields peaking at the 2015 high of 16.5%.

Recognising the link between inflation and interest rates in Brazil's volatile economy, dynamic inflation rates were applied to each scenario. In the flat scenario, inflation stays at 4.4%, reflecting recent trends. In the upward scenario, inflation to 6.3% by 2029, aligning with rising interest rates, while in the downward scenario, inflation falls to 3.4% by 2029, suggesting economic stability and lower bond yields.

To calculate the WACC across scenarios, the average NTN-B yield from January to June 2024 served as a starting point. A technology premium of 1.5%, equity risk premium of 4.27%, leverage of 80%, and a tax rate of 34% were held constant. NTN-B yield projections for each scenario (July 2024–December 2029) were used to calculate yearly averages from 2025 to 2029.

Future CAPEX values were projected using a learning curve approach, which models cost reductions with cumulative installed capacity (Schmidt et al., 2019). A (global) 15% learning rate was applied, meaning costs decrease by 15% with each capacity doubling. Baseline CAPEX, based on 2022 solar auction projects in Brazil, was BRL 167,735,285 per 40 MW. Projections utilised global capacity data (2023-2029) from IRENA and IEA reports, reflecting expected reductions from technological advancements and economies of scale.

The nominal OPEX for 2022 was BRL 2,430,484 per year, or 1.45% of CAPEX for that year. A conservative OPEX learning rate of 5% per capacity doubling, based on learning-by-doing, economies of scale, and innovation, was applied (Steffen, 2020). OPEX was adjusted for an average inflation rate of 4% to reflect evolving economic conditions (MercoPress, 2024).

Maintaining a constant 4% inflation rate for the long-term calculation of LCOE cost components (i.e., all costs other than finance costs) and varying inflation for WACC scenarios only ensures that LCOE comparisons focus solely on financing impacts. This consistent approach avoids introducing variability from inflation assumptions, enabling a clear analysis of how macroeconomic conditions influence the economic viability of solar PV projects. By integrating these dynamic elements, this methodology offers a nuanced understanding of the financial factors shaping solar PV projects over the next five years.

The LCOE was recalculated annually for each scenario, incorporating dynamically adjusted CAPEX (nominal), OPEX (nominal), and WACC values. The BNDES rate, a key WACC component, was updated starting from October 2023 by averaging the prior three months' NTN-B yield and adding the inflation rate for the latest month. This ensured that the WACC reflected current economic data and macroeconomic conditions. The established methodology was applied integrating scenario-specific variables.

The LCOE was broken into OPEX baseline, CAPEX baseline, and financing costs. Financing costs were isolated by subtracting the LCOE baseline (0% WACC) from the LCOE calculated with the respective WACC. The OPEX baseline and expected energy production were derived as in Level 2, showing OPEX's contribution to the LCOE without the WACC's impact. The CAPEX baseline represented the LCOE portion from initial capital expenditure, distributed across the project's total lifetime energy production.

Financing costs were determined by subtracting the LCOE baseline (0% WACC) from the LCOE calculated with the respective WACC, isolating the financing impact on the energy production costs. For each scenario (Flat, Upward, Downward), this calculation revealed the additional cost incurred due to financing under varying economic conditions.

These steps were integrated to finalise LCOE calculations for each scenario. By breaking down the LCOE into 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.

A.2. Results and discussion

The comparison of solar PV financing costs across regions reveals significant disparities, with Brazil's case highlighting unique challenges in emerging markets (IEA, 2024b). 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. The scenario analysis for Brazil's bond yields and inflation rates from 2024 to 2029 in Level 3 provides critical 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. All scenarios begin with the same mid-2024 values: a 10-year government bond yield of 11.4% and annual inflation of 4.4%. In the *Flat* scenario, both indicators remain constant through 2029. The *Upward* scenario is reflecting economic deterioration, and yields rise to 16.5% and inflation to 6.3% by 2029. The *Downward* scenario represents improved macroeconomic conditions, and foresees a drop in yields to 6.3% and inflation to 3.4%. These projected values feed into the estimation of NTN-B bond yields, which in turn shape the BNDES lending rate and ultimately the WACC applied in LCOE calculations.

The historical data in Fig. B.1 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 16.5%, 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. In the Flat scenario (Fig. A.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.

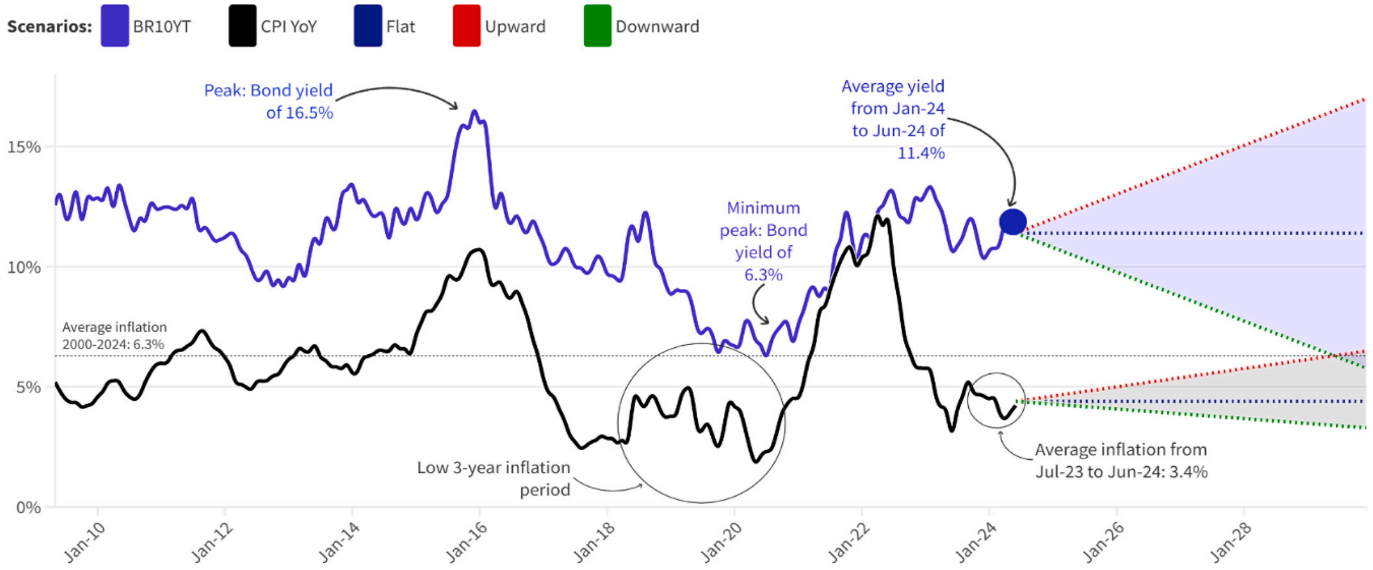

Fig. A.1. Three scenarios for bond yields and inflation until 2029.

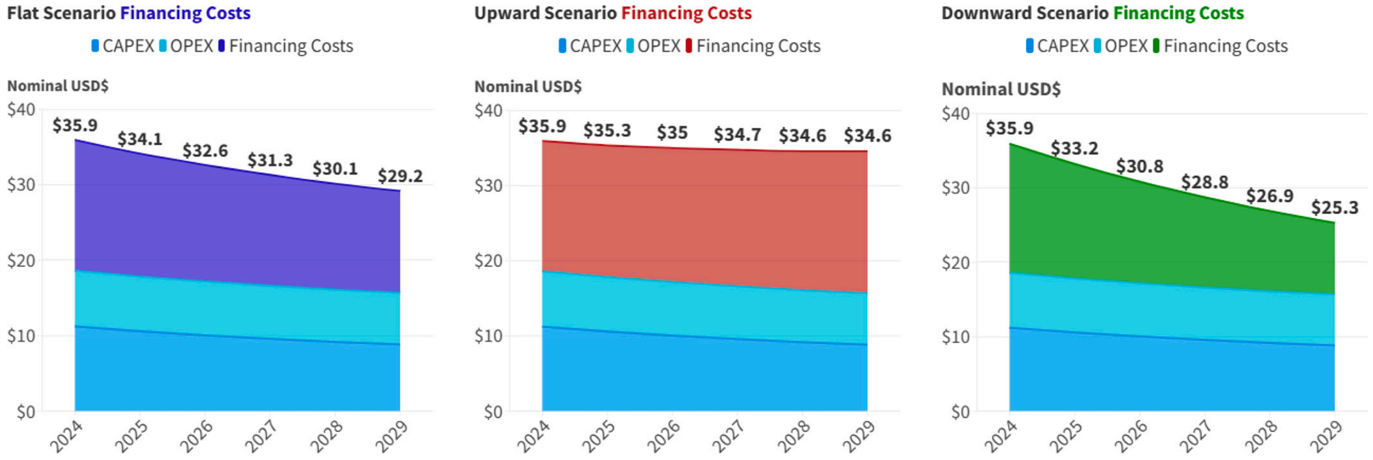

Fig. A.2. Development of financing costs per scenario.

Conversely, the Downward scenario shows financing costs decreasing from 48% to 38%, representing a significant improvement in investment conditions. 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 challenge is further compounded by the increasing share of merchant solar PV projects in Brazil. This merchant exposure increases revenue uncertainty, potentially raising risk premiums and financing costs. This trend is not unique to Brazil; Gohdes (2025) and Gohdes et al. (2023) document similar developments in Australia, where partially merchant investment models are becoming common. The analysis highlights the need for a holistic approach to renewable energy policy in emerging markets, one that considers the broader economic context alongside sector-specific measures.

A.3. Policy implications

Our scenario analysis reveals a stark reality: macroeconomic and fiscal policy choices will significantly shape the cost of capital for Brazil's energy transition. The approach in this study allows quantifying the potential impacts of macroeconomic volatility on solar PV financing costs, addressing a key gap identified by Steffen (2020). In our 'Downward' scenario, financing costs could fall to 'only' 38% of total project costs. This is exemplifying that stability and credible economic management can materially reduce financing costs, reinforcing Egli et al.'s (2018) 'financing experience effect'. Conversely, the 'Upward' scenario assumes a deterioration in fiscal conditions and inflation control, driving financing costs up to 55%, making many solar PV projects financially unviable. 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). As Schmidt et al. (2019) discuss, instability deters in investment, and this 'Upward' scenarios is a good representation of such conditions. Policymakers should view the results of this scenario modelling as a warning and a roadmap: maintaining investor confidence requires clear, coordinated economic policy. Brazil should work towards the conditions of the Downward scenario by pursuing structural reforms, ensuring central bank independence, and improving the predictability of public investment strategies. Doing so will not only reduce financing costs but also unlock the full potential of solar PV as a cost-effective energy source for long-term decarbonisation.

Appendix B. Additional figures and tables

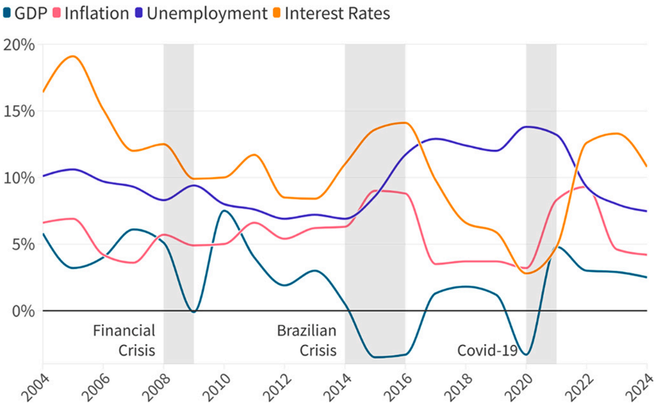

Fig. B.1. Brazil's GDP, Inflation, Unemployment, and Interests Rates. Brazil has experienced a lot of volatility in the past two decades with volatility in all macroeconomic indicators. Data source: IMF (2024); IBGE (2024); Refinitiv (2024). GDP value for 2024 makes reference to IQ 2024; the rest are averages from Jan-24 to Jun-24.

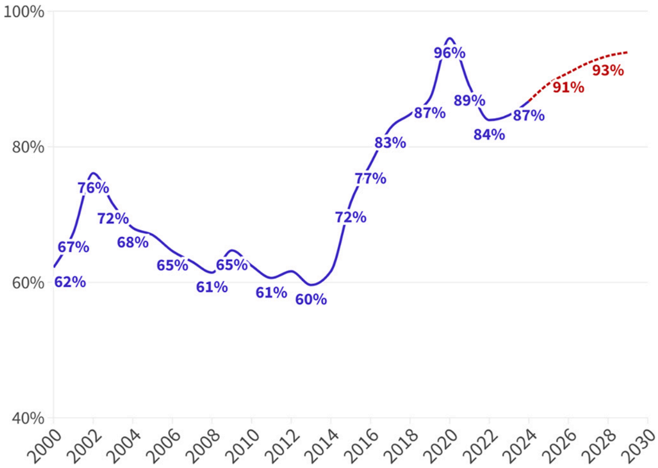

Fig. B.2. Rising tide: Brazil's Debt/GDP ratio past peaks and future projections. Although Brazil was slowly decreasing its debt as a percentage of its GDP, after the 2016 crisis, the debt-GPD ratio grew dramatically. The IMF projects Brazil's GDP to reach 94% in 2029. Data source: IMF (2024).

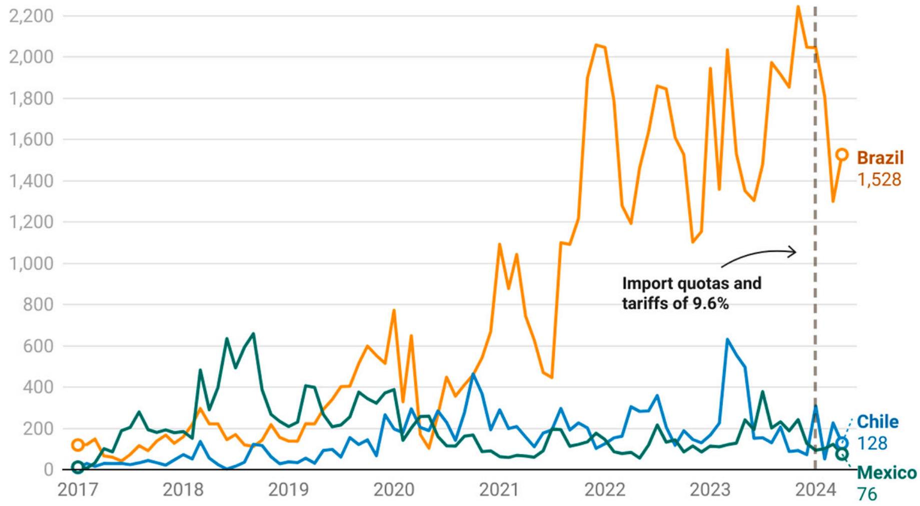

Fig. B.3. Solar panel imports from China in MW. Brazil imports around 99% of its solar panels from China. The rest is locally produced, with an average cost of +50% compared with Chinese solar panels. Data source: EMBER (2024b).

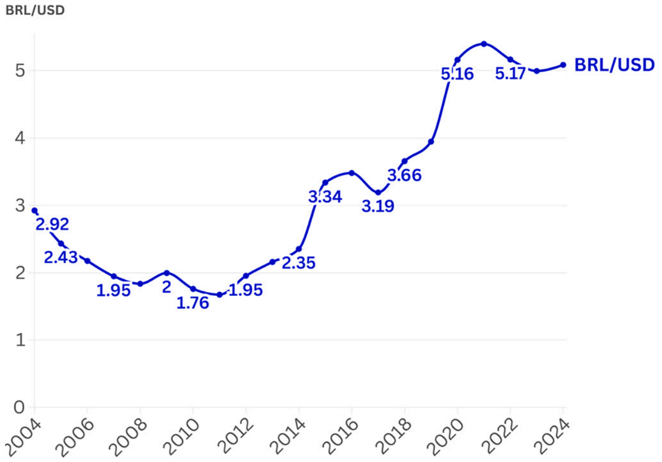

Fig. B.4. BRL/US$ exchange rate 2004–2024. The Brazilian real weakened against the dollar in the past two decades. It is one of the most depreciated currencies. Data source: Bloomberg (2024).

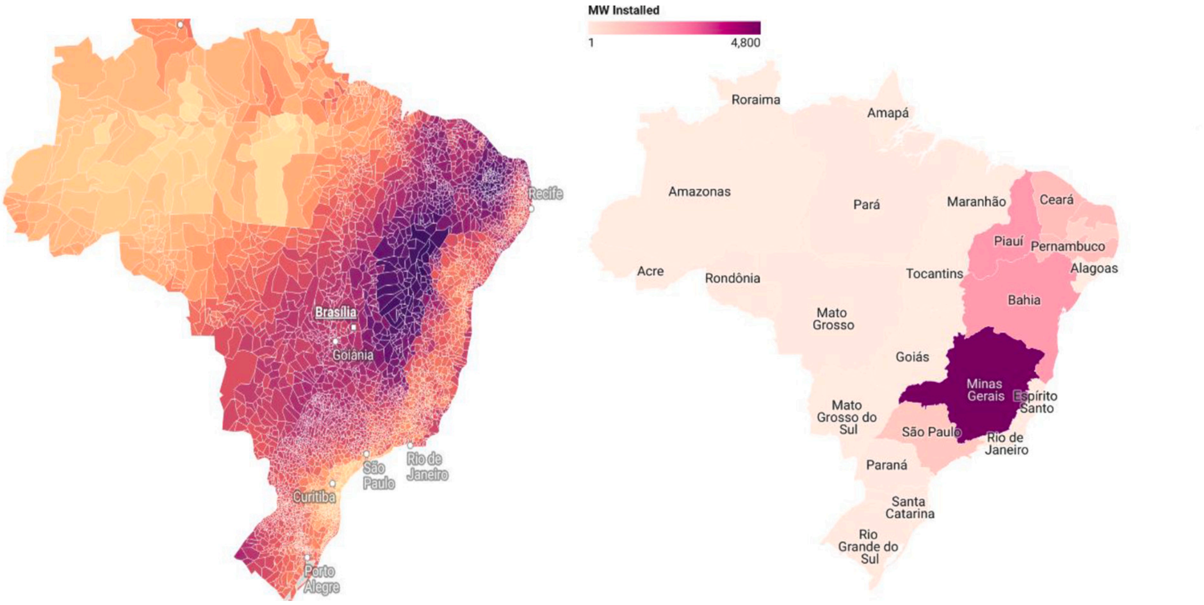

Fig. B.5. Utility-scale solar pv installed capacity in Brazil. Panel (a) show the solar radiation per municipality in Brazil in Wh/m^2 per day. Brazil has among the highest direct solar irradiation globally. The Northeastern region is a hotspot for solar PV projects. In panel (b) the installed capacity if shown. As of June 2024, according to (ANEEL-SIGA, 2024b) there were more than 16,000 individual 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.

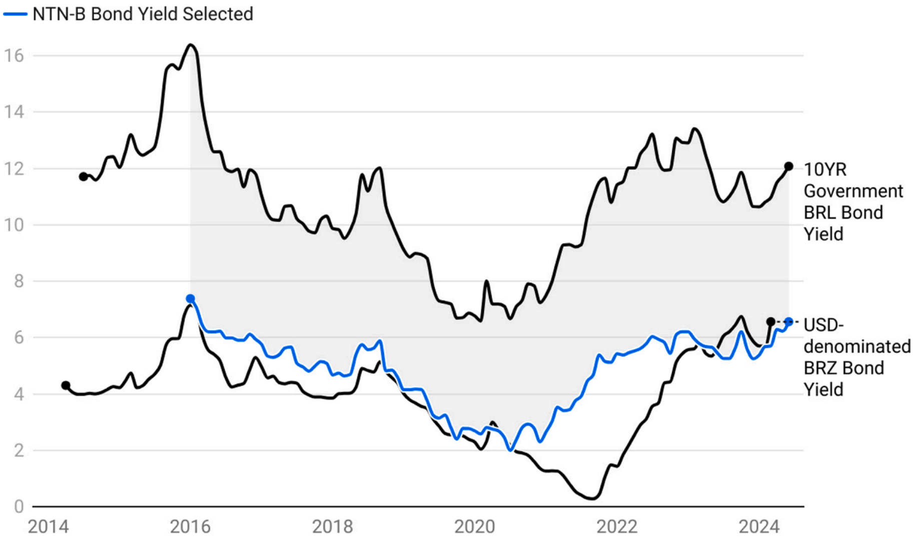

Fig. B.6. Bond yields of three different instruments considered for the WACC methodology. The US$-denominated bond yield was not incorporated in the final estimate, as it is considered that US$-denominated bond yields for country-specific estimations were used by IRENA to exclude currency risks and make 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 10 YR US Treasury bond yield. Moreover, the 10 YR 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. Data sources: Bloomberg, LSEG, Brazil's Central Bank.

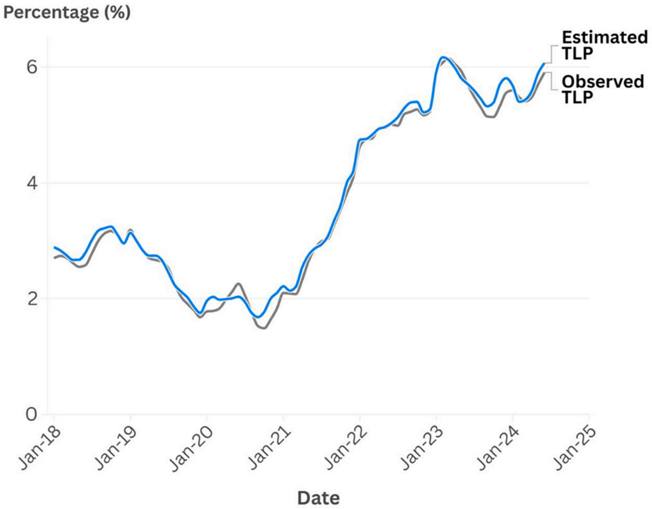

Fig. B.7. Estimated long-term rate (TLP) v. Observed TLP given rate (without inflation) 2018–2024. Data source: Refinitiv Workspace (2024) (now owned by LSEG).

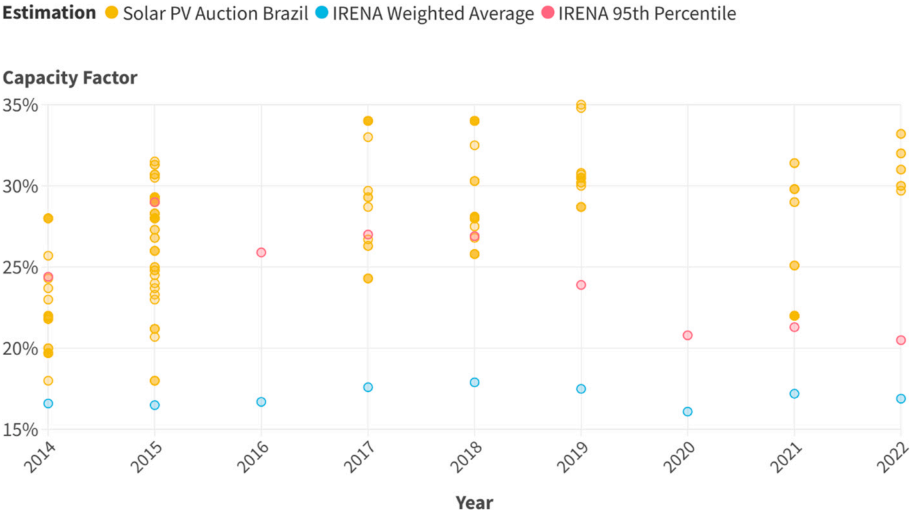

Fig. B.8. Capacity factors from solar PV projects in Brazil. Data sources: CCEE (2024); IRENA (2023).

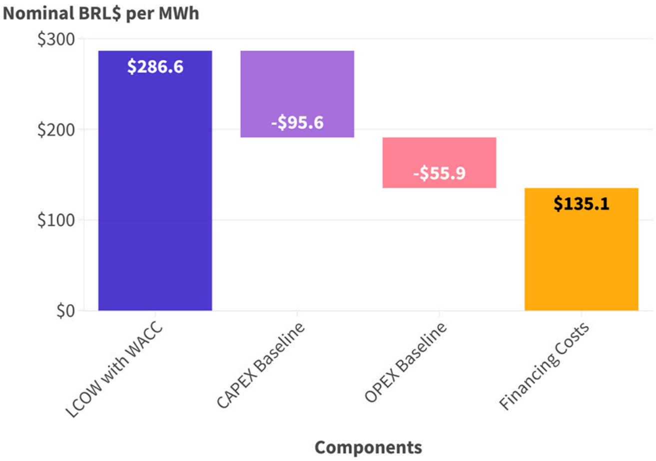

Fig. B.9. Financing costs. Note: Baseline LCOE needs to be subtracted from the LCOE with WACC.

Table B.1
Sensitivities and gap between closing exercise the LCOE and the auction price. Scenario analysis of auction-equivalent LCOE outcomes under variations in CAPEX, OPEX, financing assumptions, and technology premiums. The table reports modelled LCOE values for three auction periods (2014, 2022–1, 2022–2) and the corresponding mean gaps relative to observed auction prices, along with a description of the underlying assumptions for each scenario.

Scenario	A-3/ 2014	A-4/ 2022	A-5/ 2022	Mean Gap Between Scenario and Auction price (2014)	Mean Gap Between Scenario and Auction (2022-1)	Mean Scenario and Auction price (2022-2)	Assumptions
Auction Sale Price	**92.2**	**34.5**	**33.2**				
Model LCOE	**120.8**	**58.2**	**48.6**	**28.7**	**23.7**	**15.4**	**Baseline model.**
LCOE = Auction price	**92.2**	**34.5**	**33.2**	**0**	**0**	**0**	**Auction-consistent implied-WACC sensitivity scenario where auction price equals LCOE.**
CAPEX −10%	110.8	53	44.4	18.6	18.5	11.2	Reduction of CAPEX by 10%.
CAPEX − 25%	**95.7**	**45.1**	**38.1**	**3.5**	**10.6**	**4.9**	**Reduction of CAPEX by 25%.**
CoE −2%	114.5	56.5	47.4	22.4	22	14.3	Reduction of Cost of Equity by 2%.
TP -50%	110.8	56	47	18.6	21.5	13.8	Reduction of Technology Premium by half.
CoD -1%	116.1	56.2	46.3	23.9	21.7	13.1	Reduction of Cost of Debt by 1%.
CoD -2%	111.5	54.2	44	19.3	19.6	10.8	Reduction of Cost of Debt by 2%.
Leverage +10%	114.4	54.9	47	22.2	20.3	13.8	Increase of debt share by 10%, using a hard ceiling of 85%.
Combined Finance Relief	**104.6**	**51.4**	**43.7**	**12.4**	**16.9**	**10.6**	**Reduction of CoE by 2%, CoD by 1%, and increase of Debt Share by 10% (subject to same cap).**
OPEX −10%	118.8	57.6	47.9	26.6	23.1	14.7	Reduction of OPEX by 10%.
Integrated Cost Relief	**94.1**	**46.3**	**39.4**	**1.9**	**11.8**	**6.2**	**Combined financing relief and 10% reduction to CAPEX and OPEX.**

Appendix C. Context and approaches to the calculation of the weighted average cost of capital (WACC)

C.1. Approaches to deriving the cost of capital

The weighted average cost of capital (WACC) is a critical metric for evaluating the economic viability of renewable energy projects, particularly capital-intensive technologies like utility-scale solar PV. Unlike fossil fuel-based projects with lower initial costs but ongoing fuel expenses (procurement, transportation, storage), renewable projects require significant upfront investment, making financing costs a key determinant of competitiveness (Gohdes et al., 2022; Schmidt, 2014, 2019).

WACC acts as the project's aggregate 'interest rate,' with lower WACC rates improving investment attractiveness (Pratt and Grabowski, 2014; Steffen, 2020). It influences Levelised Cost of Energy (LCOE) which determines project feasibility (IRENA, 2023b), enabling comparisons of cost dynamics between renewable and fossil fuel investments (IRENA, 2023a; Chase, 2024; Lazard, 2024).

Globally, 88% of renewable energy projects use project finance structures, particularly for utility-scale installations (IRENA, 2023b). Using a 'Special Purpose Vehicle' isolates risk within the project without recourse to the sponsor's other assets, enabling higher debt-to-equity ratios of up to 80% in mature markets (Kann, 2009; Steffen, 2018), with debt typically cheaper than equity (Schmidt et al., 2019). Debt financing terms, including interest rates and loan tenors, are thus critical to project viability (Egli et al., 2019). Project finance needs tailored modelling of financing costs, as applying corporate finance assumptions risks significant inaccuracies (Schmidt et al., 2019).

Accurate data on the cost of capital for renewable energy projects is scarce due to the private nature of project finance, rapid technological advancements, and cross-country variations (Steffen, 2020; Polzin et al., 2021). Lack of transparency complicates model calibration and policymaking, as assuming a standard discount rate can lead to imprecisions (Egli et al., 2019). Researchers address these challenges through strategies like systematic reviews, auction bid analyses, and benchmarking tools calibrated with expert input (Schmidt et al., 2019; Steffen, 2020).

The cost of capital for renewable energy projects varies widely across countries, technologies, and project characteristics. WACC ranges from 2.2% in Germany to over 10% in developing countries like Brazil, driven by country risk premiums, policy environments, and financial market maturity (Angelopoulos, 2016; Egli et al., 2019). Costs have declined over time, as seen in Germany's solar PV and wind projects from 2000 to 2017 (Egli et al., 2018). Project-specific factors, such as size and developer experience, also significantly influence financing costs (Steffen, 2020).

Estimating the WACC is complex due to the private nature of project finance deals. Four primary approaches address this challenge (Steffen, 2020). The most direct method involves collecting data from specific deals, as seen in Lorenzoni and Bano's (2009) surveys of Italian investors and Egli et al.'s (2018) dataset of German projects. Given data scarcity, a second approach uses expert surveys, involving interviews with market participants, exemplified by IRENA's (2023b) interviews with finance professionals and Angelopoulos et al. (2016, 2017), who used financial market data as a baseline for expert discussions.

A third method reverse-engineers winning bids from competitive auctions, leveraging publicly available non-financing data to estimate financing parameters (Apostoleris et al., 2018; Egli et al., 2023). This requires detailed auction data and realistic cost assumptions (i.e., LCOE). Finally, financial market data serves as a proxy for unlisted renewable projects, as seen in IRENA's benchmark tool (IRENA, 2023b). Recent studies, including this one, combine these methods, integrating data, expert input, and market proxies for improved estimates (Egli et al., 2018; IEA, 2024a; IRENA, 2023b).

Egli et al. (2018) use after-tax WACC (Eq. (A1)), emphasising technology-specific values due to financing cost variability between technologies, where K_D is the cost of debt, K_E the cost of equity, δ the leverage, and τ is the corporate tax rate. Schmidt et al. (2019) use a similar approach but stress the importance of country-specific factors in calculating WACC. Uniform WACC assumptions across countries can lead to significant biases (IEA, 2021; IRENA, 2023a).

$$After-tax\ WACC = \delta \times (1-\tau) \times K_D + (1-\delta) \times K_E \tag{A1}$$

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

C.2. The cost of debt

Cost of debt is determinant for the WACC, as highly leveraged renewable projects with significant upfront costs mostly rely on debt financing (Steffen, 2018). However, Steffen (2020) notes that the cost of debt is often not directly observable as finance deals are privileged information, thus researchers rely on expert estimates or derived market values.

Various methods estimate the cost of debt. Steffen (2020) notes that for listed companies, it is available through current interest expenses or bond yields. Egli et al. (2023) estimate it for solar PV projects by deriving it from auction prices reflecting the Levelised 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 (2023b) calculates the cost of debt across regions by combining the global risk-free rate (*GRF*), country-specific default spread (*CDS*), lender margin (*LM*), and a technology premium (*TP*), adjusted for tax to reflect the actual project cost, yielding Eq. (A2):

$$K_D = GRF + CDS + LM + TP \tag{A2}$$

Kitzing and Weber (2014) estimate the cost of debt for wind power projects in Germany using an equation 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:

$$K_D = RF + P_{swap} + BM \tag{A3}$$

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, which constitutes as combination of the lender margin and technology premium in Eq. (1) (BNDES, 2024a). The debt margin decreases as cumulative investments grow, reflecting reduced lender-perceived risk over time:

$$K_D = RF + DM \tag{A4}$$

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:

$$K_D = RF + CDS + PS \tag{A5}$$

C.3. The cost of equity

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, which uses, using the risk-free rate (*RF*), the equity beta, which accounts for the volatility of the capital structure (β), and the market return (*MRP*):

$$K_E = RF + \beta \times (MRP - RF) \tag{A6}$$

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, emphasising context-specific approaches.

IRENA's (2023b) cost of equity calculation incorporates country risk adjustments using Damodaran's data on risk premiums and default spreads, expressed in the equity risk premium (*ERP*), the country premium (*CP*) and the technology premium (*TP*). This is refining the global risk-free rate to account for specific country risks, ensuring accurate WACC estimates for renewable projects:

$$K_E = RF + ERP + CP + TP \tag{A7}$$

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:

$$K_E = RF + DM + ERP \tag{A8}$$

WACC for renewable energy projects is shaped by macroeconomic factors such as country risk, interest rates, and financial market maturity. Country risk premiums significantly impact financing costs, with WACC varying from 2.2% in Germany to 12.2% in Ukraine (IRENA, 2023b). Rising interest rates complicate financing, with substantial increases in LCOE for solar PV and onshore wind under pre-financial crisis rate conditions (Aguila and Wullweber, 2024; Schmidt et al., 2019). The end of the ‘zero era’ for interest rates amplifies these challenges, with contractionary monetary policies disproportionately affecting capital-intensive renewable projects and potentially delaying the energy transition (Martin, 2024).

Steffen and Waidelich (2022) framework emphasises the influence of market design, renewable energy policies, and financial sector maturity on financing costs. Renewable energy auctions and stable regulatory environments can reduce perceived risk (Polzin et al., 2021). Project finance structures, characterised by high debt shares, increase sensitivity to interest rate fluctuations, particularly for low-carbon technologies (Steffen, 2018; Martin, 2024). This underscores the importance of integrating differentiated costs of capital into energy models and policy planning while exploring roles for central banks in supporting renewable energy financing through targeted credit policies or monetary interventions.

Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2026.109297.

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