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INFLUÊNCIA MULTIVARIADA NA ATRATIVIDADE DO INVESTIMENTO EM MICROGERAÇÃO FOTOVOLTAICA DISTRIBUÍDA

MULTIVARIATE INFLUENCE ON THE INVESTMENT DESIRABILITY IN DISTRIBUTED PHOTOVOLTAIC MICROGENERATION

INFLUENCIA MULTIVARIANTE EN EL ATRACTIVO DE LA INVERSIÓN EN MICROGENERACIÓN FOTOVOLTAICA DISTRIBUIDA

Camila Stefanello
Engª. Eletricista, Universidade Tecnológica Federal do Paraná, Medianeira, Brasil
stefanellocamila@outlook.com

Cristiane Lionço de Oliveira
Profª. Dra., Universidade Tecnológica Federal do Paraná, Medianeira, Brasil
cristianel@utfpr.edu.br

Elder Elisandro Schemberger
Prof. Dr., Universidade Tecnológica Federal do Paraná, Toledo, Brasil
eschemberger@utfpr.edu.br

Eliane Colla
Profª. Dra., Universidade Tecnológica Federal do Paraná, Medianeira, Brasil
ecolla@utfpr.edu.br

Elias Lira dos Santos Junior
Prof. Dr., Universidade Tecnológica Federal do Paraná, Medianeira, Brasil
eliasjunior@utfpr.edu.br

Evandro André Konopatzki
Prof. Dr., Universidade Tecnológica Federal do Paraná, Toledo, Brasil
eakonopatzki@utfpr.edu.br

Filipe Marangoni
Prof. Dr., Universidade Tecnológica Federal do Paraná, Medianeira, Brasil
filipemarangoni@utfpr.edu.br

Rodrigo Luiz Machado de Cardoso
Mestrando., Universidade Tecnológica Federal do Paraná, Medianeira, PR, Brasil
E-mail: rocardo@itaipu.gov.br

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Resumo

Este estudo investiga a viabilidade econômica do investimento em Microgeração Fotovoltaica Distribuída (MFD) no Brasil, analisando a influência de variáveis-chave, incluindo o Custo Atual de Aquisição de Energia Elétrica (CAEEE), Impostos Relacionados à Conta (IRC), Taxa de Juros para Investimentos (TJI), Nível Tecnológico Atual (NTA) e Solarimetria (SOL). Um Delineamento Composto Central Rotacional (DCCR) foi empregado para avaliar os efeitos dessas variáveis independentes sobre os indicadores econômicos Payback Descontado (PBd) e Valor Presente Líquido (VPL). A metodologia envolveu análise de regressão estatística para modelar as relações entre as variáveis independentes e as respostas. Os resultados indicaram que o CAEEE impactou significativamente tanto o PBd quanto o VPL, sendo um CAEEE mais elevado desejável para a adoção da MFD. TRF e TJI também apresentaram efeitos significativos, com o TRF influenciando positivamente o VPL, enquanto o TJI teve um impacto inverso. As condições mais favoráveis para a promoção da geração distribuída foram identificadas como CAEEA a R$ 1,57/kWh, TRF a 37,5%, TJI a 8,75% ao ano, NTA a R$ 497,98/kWp e SOL a 175,30 kWp/m².dia. Esses resultados sugerem que o aumento dos custos da energia elétrica, dos impostos e dos níveis tecnológicos, aliado a taxas de juros mais baixas, pode incentivar o investimento em geração distribuída, contribuindo para a difusão de fontes de energia renováveis no Brasil.

Palavras-chave: Brasil; Consumo e produção responsáveis; Energias renováveis; Planejamento de energia solar; Políticas públicas; Sustentabilidade.

Abstract

This study investigates the economic feasibility of investing in Distributed Photovoltaic Microgeneration (DPM) in Brazil by analyzing the influence of key variables, including the Current Acquisition Cost of Electric Energy (CAEEA), Taxes Related to the Bill (TRF), Interest Rate for Investments (TJI), Current Technology Level (NTA), and Solarimetry (SOL). A Central Composite Rotatable Design (CCRD) was employed to evaluate the effects of these independent variables on the economic indicators Discounted Payback (PBd) and Net Present Value (NPV). The methodology involved statistical regression analysis to model the relationships between the independent variables and the responses. Results indicated that CAEEA significantly impacted both PBd and NPV, with a higher CAEEA being desirable for DPM adoption. TRF and TJI also showed significant effects, with TRF positively influencing NPV, while TJI had an inverse impact. The most favorable conditions for promoting DPM were identified as CAEEA at R$ 1.57/kWh, TRF at 37.5%, TJI at 8.75% per annum, NTA at R$ 497.98/kWp, and SOL at 175.30 kWp/m².day. These findings suggest that increasing electricity costs, taxes, and technology levels, coupled with lower interest rates, can encourage investment in DPM, contributing to the diffusion of renewable energy sources in Brazil.

Keywords: Brazil; Planning of solar energy; Public policies; Renewable energy; Responsible consumption and production; Sustainability.

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Resumen

Este estudio investiga la viabilidad económica de invertir en Microgeneración Fotovoltaica Distribuida (MPD) en Brasil mediante el análisis de la influencia de variables clave, incluyendo el Costo Actual de Adquisición de Energía Eléctrica (CAEEA), Impuestos Relacionados con la Factura (TRF), Tasa de Interés para Inversiones (TJI), Nivel Tecnológico Actual (NTA) y Solarimetría (SOL). Se empleó un Diseño Compuesto Central Rotable (CCRD) para evaluar los efectos de estas variables independientes sobre los indicadores económicos Período de Recuperación Descontado (PBd) y Valor Actual Neto (VAN). La metodología incluyó análisis de regresión estadística para modelar las relaciones entre las variables independientes y las respuestas. Los resultados indicaron que el CAEEA impactó significativamente tanto el PBd como el VAN, siendo un CAEEA más alto deseable para la adopción de MPD. El TRF y el TJI también mostraron efectos significativos, con el TRF influyendo positivamente en el VAN, mientras que el TJI tuvo un impacto inverso. Las condiciones más favorables para promover la gestión distribuida de energías se identificaron como CAEEA a R$ 1,57/kWh, TRF al 37,5%, TJI al 8,75% anual, NTA a R$ 497,98/kWp y SOL a 175,30 kWp/m².dia. Estos hallazgos sugieren que el aumento de los costos de la electricidad, los impuestos y los niveles tecnológicos, junto con tasas de interés más bajas, pueden incentivar la inversión en gestión distribuida de energías, contribuyendo a la difusión de fuentes de energía renovables en Brasil.

Palabras clave: Brasil; Consumo y producción responsables; Energías renovables; Planificación de la energía solar; Políticas públicas; Sostenibilidad.

1. Introduction

Accelerating the deployment of distributed renewable energy systems is a crucial strategy for expanding energy access and advancing decarbonization goals globally. Distributed renewable energy systems can play a transformative role in achieving universal energy access by providing affordable, reliable, and clean power (IRENA, 2023).

Brazil has abundant natural resources and has built its energy matrix based on renewable energy, making it now necessary to project national demand for the National Energy Plan (PNE). In this context, demand scenarios are compared with the energy matrix to plan for new generating units (EPE, 2018).

National planning, aligned with the global trend of incorporating new renewable sources, predicted the expansion of solar and wind energy in Brazil. The first official analyses related to the integration of Photovoltaic Solar Generation

(PSG) into the Brazilian electricity matrix appeared in EPE's technical notes in 2012. These analyses addressed key applications and suggested that PSG integration would naturally occur through Distributed Generation (DG), especially in residential and commercial self-production (EPE, 2014).

Thus, public and private initiatives were necessary to enable the technological development of these energy sources (EPE, 2007). In 2012, aiming to combine financial savings, socio-environmental awareness, and self-sustainability, the National Electric Energy Agency (ANEEL) published Normative Resolution No. 482/2012, allowing consumers to generate electricity from renewable sources or qualified cogeneration.

This resolution along with its subsequent amendments, established the criteria for classifying self-generators and the rules for the credit system, billing, and energy compensation (ANEEL, 2012). These governmental actions can be analyzed within the framework of sustainable natural resource management and economic development, aligning with the Sustainable Development Goals (SDGs) outlined in the United Nations' 2030 Agenda in 2015. Specifically, these actions contribute to Clean and Affordable Energy (SDG 7); Sustainable Cities and Communities (SDG 11); and Responsible Consumption and Production (SDG 12).

The social dimension of sustainability has also been increasingly considered through studies on consumer behavior and usage patterns.

In 2015, the government established the Distributed Electricity Generation Development Programme (ProGD), with the potential to generate more than R$ 100 billion in investments by 2030 (FRONTIN et al., 2017). ProGD included fiscal incentives for distributed generation (DG) installations and aimed to achieve 23.5 GW of capacity, primarily from photovoltaic sources (PV MAGAZINE, 2015). Following this incentive framework, the installed capacity of photovoltaic solar generation (PSG) has grown annually, reaching 35.02 GWpeak in 2023 (STEFANELLO et al., 2024).

In 2022, Federal Law No. 14.300 was enacted, establishing new rules for distributed generation, consolidating credit compensation mechanisms and setting deadlines for the gradual reduction of federal tax incentives (Brasil, 2022). It also

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Pages: 1-35

authorized participants of consortia, cooperatives, and voluntary condominiums to transfer energy account ownership to consumer-generators, facilitating the interpretation of shared generations as remote self-consumers, making such projects more appealing due to the exemption or reduction of the Tax on the Circulation of Goods and Services (ICMS) on electricity.

In April 2024, a Provisional Measure (PM) was issued, presenting new incentives for renewable energy. The PM adjusts the timelines for clean and renewable energy generation projects to align with the implementation schedule of transmission lines. It anticipates an increase of 34 GW of power to the National Interconnected System (SIN) from wind and photovoltaic energy sources (FONTE, 2024).

The public policies established to date have aimed to promote distributed generation (DG) with the intention of making this form of energy generation a significant component of Brazil's energy matrix in the coming decades. These incentives for DG are justified by its potential benefits to the electrical system, including postponing investments in the expansion of generation and transmission systems, reducing environmental impact, decreasing the electrical load of transmission networks, minimizing losses by enabling consumption closer to generation, and diversifying the energy matrix (ANEEL, 2015).

In the context of Brazil's energy transition, the relationship between price and technology adoption is not linear. Mendes (2025) observes that, while high tariffs signal the advantage of self-generation, the investor's income elasticity determines the speed of adoption. Without financing mechanisms to compensate for the loss of purchasing power generated by the increase in the TRF (Tariff Reference Rate), distributed microgeneration risks becoming an asset accessible only to high-income strata, deepening inequalities in the electricity sector. PS

From the perspective of public policy and energy planning, incentivizing this mode of energy generation enables an increase in electricity generation capacity without direct public investment. According to Stefanello et al. (2018), the role of subsidizing investments is seen as a function of the state, specifically in infrastructure investments. In this sense, DG somewhat outsources direct public investment in electricity generation, which should be strategically planned to accelerate the diffusion of DG in the country.

Investment in DG has been potentially favored not only by national energy demand but also by the consolidation and cost reduction of technology, fiscal incentives, and market interest rates. The interest rate applied in this segment has a crucial impact in determining the level of private investment. Higher interest rates tend to reduce private investment, while lower rates encourage it (Administradores, 2010).

In this context, despite still being considered high compared to developed countries, the Brazilian interest rate has reached its lowest levels in the last 20 years, currently standing at 5% per year (ADVFN, 2019), indicating a favourable trend for investments.

Regarding the pricing of electricity consumption and demand, ANEEL states the tariff is designed to ensure that service providers generate sufficient revenue to cover efficient operational costs and remunerate the necessary investments to expand capacity and maintain quality service. To fulfil this commitment, the tariff considers three distinct costs: generated energy, its transport, and social charges.

These costs are presented in two parts. The first, called Part A (53.5%), covers the purchase of energy, energy transmission, and sector charges. The second part, called Part B (17%), includes energy distribution. Additionally, the energy bill incorporates taxes (29.5%) at both the national level, such as the Social Integration Program (PIS) and the Contribution for Social Security Financing (COFINS), and at the state level such as the Tax on the Circulation of Goods and Services (ICMS) (MME, 2019).

The combined analysis of these components forms the tariff applied to electricity consumers, divided into two elements shown on the bill: 1) Energy Tariff (ET) and 2) Distribution System Usage Tariff (DSUT) (ANEEL, 2004).

Furthermore, a specific grid usage fee is charged for the energy injected into the distribution network by DG systems, often applied as a minimum charge on the electricity bill. Since the energy bill can represent a significant portion of household budgets, reducing taxes could encourage Distributed Photovoltaic Microgeneration

(DPM).

Regarding statistical techniques, Castanheira (2008) observed that the proper determination of investments and their impact factors can be defined through statistical techniques.

According to Rodrigues and Iemma (2009), contemporary statistics offer more efficient and precise methods than univariate analysis, which assesses one factor at a time while keeping other variables constant to determine optimal conditions. The factorial design methodology proposed by Box, Hunter, and Hunter (1978), combined with response surface analysis, is a statistically grounded tool that provides reliable information while minimising empiricism involved in trial-and-error techniques.

Consumer response to rising energy tariffs, although often treated as static in financial models, is mediated by the price elasticity of demand. As highlighted by Silva and Santos (2024), in scenarios of high energy inflation, elasticity tends to be higher in the short term for lower consumption classes, implying that the expected savings from microgeneration may be mitigated by a voluntary or forced reduction in overall consumption, altering the payback period of the initially calculated investment. PS

This research aimed to quantify and correlate the following variables influencing investment in DPM in Brazil: the Current Acquisition Cost of Electric Energy (CAEEA); the Taxes Related to the Bill (TRF); the Interest Rate for Investments in Distributed Microgeneration (TJI); the Current Technology Level (NTA); and the Solarimetry (SOL).

2. Methodology

This study is characterized as quantitative research with descriptive and explanatory objectives. It is descriptive as it identifies and characterizes the primary variables influencing investment in DPM in the Brazilian context. It is explanatory as it utilizes a simulation-based experimental procedure to model the causal relationships between the independent variables (CAEEA, TRF, TJI, NTA, and SOL) and the economic performance indicators (PBd and NPV). The core technical

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Pages: 1-35

procedure is a Central Composite Rotatable Design (CCRD), supported by documentary research for the parameterization of the model's variables based on data from official agencies and market sources.

Experimental Strategy

The steps involved in the development of the research are presented in Figure 1.

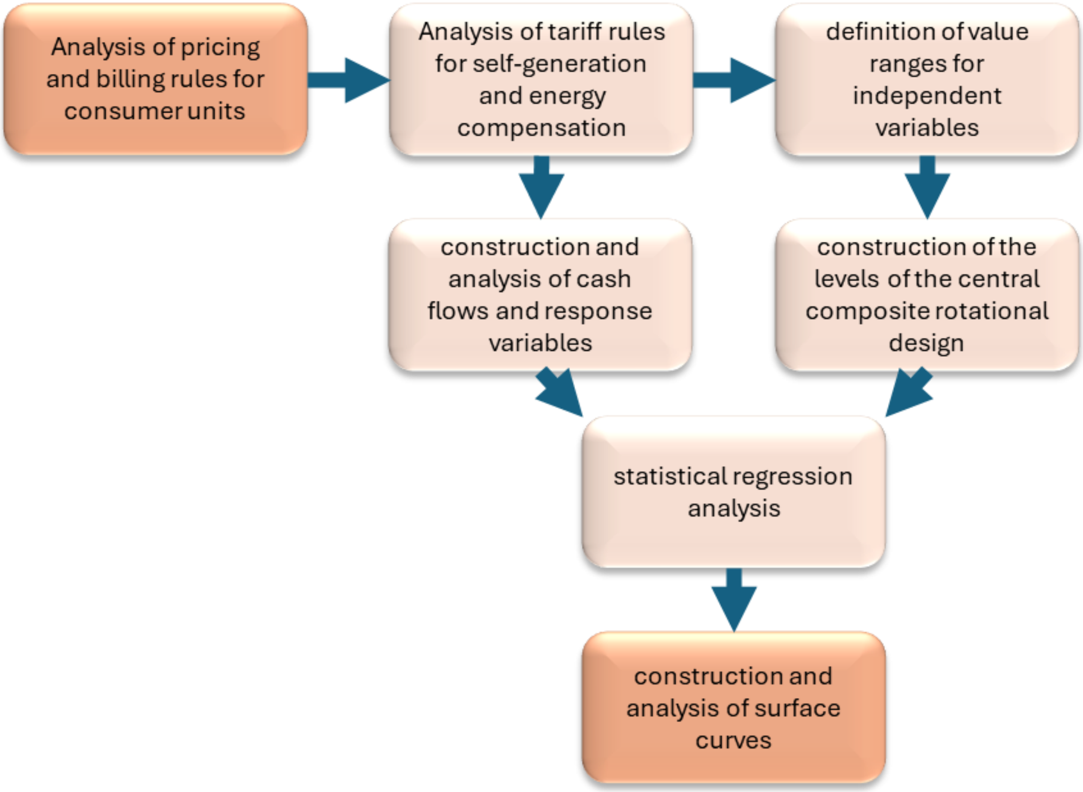

Figure 1 - Experimental Strategy. Source: Search results

Equation of Consumer Unit Bills

The financial billing for electricity consumption in Brazil is a structured process regulated by ANEEL (2021). The final amount paid by a consumer is a composite of energy costs, grid usage fees, and taxes. The foundational components of the bill are the Energy Tariff (TE) and the Distribution System Usage Tariff (TUSD), equivalent to the ET and DSUT mentioned previously. The TE remunerates the cost of energy generation, while the TUSD covers the costs associated with the transportation of this energy through transmission and

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Pages: 1-35

distribution lines to the consumer unit.

The pre-tax portion of the bill can be represented by the following equation 1.

$$Bill_{pre-tax} = (E_C * TE) + (E_C * TUSD) \tag{1}$$

where: EC is the total energy consumed in a month, measured in kilowatt-hours (kWh); TE is the energy tariff, measured in R$/kWh; and TUSD is the distribution system usage tariff, measured in R$/kWh.

This pre-tax value, however, serves as the calculation basis for federal and state taxes. The primary levies are the Social Integration Program (PIS), the Contribution for Social Security Financing (COFINS), and the Tax on the Circulation of Goods and Services (ICMS). The ICMS, a state-level tax, is calculated "over itself", meaning the tax amount is included in its own calculation base. Therefore, to arrive at the final bill amount, the pre-tax value must be divided by one minus the sum of the tax rates, as shown in the simplified general equation 2:

$$Bill_{final} = \frac{Bill_{pre-tax}}{1 - (\alpha_{ICMS} + \alpha_{PIS} + \alpha_{COFINS})} \tag{2}$$

where: Billfinal is the invoice of unit bills, αICMS, αPIS and αCOFINS represents the decimal rates of their respective taxes.

This final value is what appears on the consumer's bill and represents the total cost that can be partially offset by the adoption of Distributed Photovoltaic Microgeneration.

Equation of Self-Generation and the Energy Compensation System

The economic viability of DPM in Brazil is intrinsically linked to the Electric Energy Compensation System (SCEE), the country's net metering framework. Initially established by ANEEL's Normative Resolution No. 482/2012 and subsequently updated by Law No. 14.300/2022, the SCEE allows consumer-generators (prosumers) to inject their surplus energy into the local distribution grid and receive corresponding credits in kilowatt-hours (kWh).

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Pages: 1-35

The energy flow in a prosumer's installation can be described by the principle of energy balance (equation 3):

$$E_G = E_F + E_C + E_i \tag{3}$$

where: EG is the Total energy generated by the DPM system (kWh); EF is the Energy drawn from the grid (kWh); and Ei is the Surplus energy injected into the grid (kWh).

The energy injected into the grid (Ei) is converted into energy credits. These credits are then used to offset the energy drawn from the grid (EF) in the same billing cycle or in subsequent cycles for up to 60 months. The net energy to be billed, in kWh, it's presented in equation 4:

$$E_{Billed} = E_F - E_{Comp} \tag{4}$$

where: EComp is the energy compensated by the available credits (kWh), limited to the total energy drawn from the grid (EF).

The choice of a static analysis model is based on the need to isolate the effects of regulatory and technological variables (TRF and NTA) without the interference of temporal noise that is difficult to predict. According to Silva and Ferreira (2022), deterministic models are essential in the initial planning phases to establish a comparative 'baseline'. The exclusion of future tariff variations and uncertain regulatory changes is justified to ensure that the sensitivity observed in the CCRD purely reflects the structure of the electricity sector according to the National Expansion Plan (PNE) 2050, preventing subjective assumptions about the political-economic scenario from biasing the mathematical interpretation of the data.. PS

Crucially, under Law 14.300/2022, the monetary valuation of the compensated energy is no longer a simple 1-for-1 trade. For new installations, a portion of the grid usage tariff (TUSD) is now levied on the compensated energy. This tariff component, known as TUSD "line B," remunerates the distribution infrastructure. Consequently, while 1 kWh of injected credit still offsets 1 kWh of consumed energy, the prosumer must pay for the use of the distribution grid on that compensated kWh. This change directly impacts financial savings and, therefore, the economic indicators (NPV and PBd) evaluated in this study, making the analysis of tariff components and policy changes essential for determining investment desirability.

Definition of value ranges for independent variables

To define the variables that influence the Brazilian plan for expanding DG (Distributed Photovoltaic Microgeneration), the factors affecting electricity bills and the effects of DG on reducing the bill were analysed. Additionally, the study considered the interest rate for financing such investments, the installation cost of these systems, and their lifespan.

Financial variables related to future savings on electricity bills from DG were evaluated. The proposed generation systems in this study were sized at 157.9 kWh, which, according to the Ministry of Mines and Energy (2018), corresponds to the average monthly residential electricity consumption in Brazil. This energy estimate accounted for the total reduction in energy consumption for each residential unit.

This study did not focus on the generation of surplus energy, nor were the taxes related to future energy credits analyzed. It also excluded considerations regarding the sale or transfer of energy generated by DG to consortia, cooperatives, or voluntary condominiums.

The effects of the independent variables CAEEA, TRF, TJI, NTA, and SOL on the investment evaluation instruments Discounted Payback (PBd) and Net Present Value (NPV) were assessed. These variables aim to identify the factors that significantly influence the incentive for the diffusion of distributed photovoltaic microgeneration.

The incentive to invest in DG was evaluated based on the return on investment, using the response variables PBd and NPV, predicting – on a global scale – market fluctuations in both optimistic and pessimistic scenarios.

This quantitative study assigned values in data collection and employed data collection technical resources such as a literature review, documentary data, analysis of variance, and factorial statistical treatment, following the statistical techniques presented by Richardson (1999, p. 70).

Construction of CCRD levels

To evaluate the effects of the five independent variables, a Central Composite Rotatable Design (CCRD) was applied, comprising 25 factorial points, 10 axial points, and 1 central point, totalling 43 trials. This approach followed the methodology proposed by Box, Hunter, and Hunter (1978) and adapted by Rodrigues and Iemma (2009). The real and coded values of the variables are described in Table 1.

Table 1 – Real and coded levels of the variables in the CCRD.

independent variables		**Ranges of independent variables**				
		-2.38	**-1**	**0**	**+1**	**+2.74**
CAEEA [R$ / kWh]	x_1	0.33	0.69	0.95	1.21	1.57
TRF [%]	x_2	3.50	13.35	20.50	27.65	37.50
TJI [% a.a.]	x_3	5.75	6.76	7.50	8.03	8.75
NTA [R$ / kWp]	x_4	3,534.39	3,953.24	4,257.11	4,560.97	4,979.82
SOL [kWp / m^2.day]	x_5	1,387.00	1,493.06	1,570.00	1,646.94	1,753.00

NOTE: CAEEA (Current Electricity Acquisition Cost); TRF (Invoice-Related Taxes); TJI (Investment Interest Rate); NTA (Current Technology Level); and SOL (Solarimetry). Source: Search results

The study range for the Current Acquisition Cost of Electric Energy (CAEEA) was obtained through conventional tariff data published by ANEEL. The parameter for this variable was defined such that the minimum value reflected the lowest bill cost practiced in Brazil, while the maximum value represented the highest cost identified.

The Taxes Related to the Bill (TRF) included PIS, COFINS, and ICMS (ANEEL, 2011). The values were based on a long-term analysis of tax trends. In projections to 2050, ICMS was considered representative but stable, following a national approach to government incentives for the implementation of photovoltaic technology. This approach was grounded in the Federal Constitution, Article 155, §2, I and III, which state:

1. "it will be non-cumulative, offsetting the amount owed in each operation

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Vol: 13.03
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Pages: 1-35

related to the circulation of goods or services with the amount charged in previous transactions by the same or another State or by the Federal District";

2. "it may be selective, depending on the essentiality of goods and services" (Federal Constitution - Title VI of Taxation and Budget, 1988a).

Thus, according to the first clause, the exemption related to energy transmission remains in effect under the ICMS Agreement 16, of April 22, 2015. This agreement is valid in 24 states, the Federal District, and temporarily in Santa Catarina and Paraná. It "authorises the granting of exemption in internal operations related to the circulation of electric energy, subject to billing under the Electric Energy Compensation System regulated by Normative Resolution No. 482, of 2012, by the National Electric Energy Agency – ANEEL" (ICMS Agreement 16, 2016).

Additionally, the third clause recognizes electricity as essential for human, social, cultural, industrial, development, as well as for the provision of goods and services. Based on this variable's scope, a moderate real adjustment is projected through 2050.

The minimum and maximum ranges were applied to quantify the Interest Rate for Investments (TJI) in DG, based on market research and fiscal incentive policies.

The Current Technology Level (NTA), specifically the installation cost [R$ kWh-1], was estimated through quotations from regional companies. The estimates aimed to establish national and international values for systems designed for potential residential photovoltaic microgenerators. The values accounted for gradual wear and the replacement of the frequency inverter, considering its lifespan of approximately 10 years, while the panels have an average lifespan of 20 years.

For multivariate sensitivity analysis, the NTA (Current Technological Level) variable was operationalized as a Technological Accessibility Index, defined by the inverse of the unit installation cost (R$ / kWp^{-1}). Unlike a direct cost metric, this definition allows measuring how the reduction in equipment prices – driven by economies of scale and market maturity – increases economic attractiveness. Thus,

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Pages: 1-35

in the Net Present Value (NPV) equation, an increase in NTA represents a reduction in initial capital expenditure (CAPEX), justifying the positive correlation observed between the democratization of access to technology and the increase in the project's financial return.

In this context, NTA = f (C^{-1}), where C is the installation cost in R$ / kWp, considered an index of accessibility to technology. NTA acts as an inverse multiplier of the initial investment; as the technological cost decreases, the value of the NTA index increases, reducing the weight of the initial investment in the NPV calculation by equation 5.

$$NPV = \sum_{t=1}^{n} \frac{FC_t}{(1+i)^t} - I_0 \tag{5}$$

where NPV is Net Present Value (represents the wealth generated by the project in current values); FC_t is the Net Cash Flow at period t (represents the savings generated on the energy bill minus operational costs); n is the useful life of the photovoltaic system; k is the minimum attractive rate of return and I_0 is the initial investment (in the context of this article, represented the influence by the NTA). PS

Solarimetry (SOL) [kWp] was derived from a study presented by Solargis Co. (2019), which provided the average annual/daily electricity production potential of a 1 kWp generation plant from 1999 to 2015. The study analyzed ground-mounted systems with free-standing silicon crystalline modules, statically positioned at the Equator, with the ideal angular positioning to maximize annual energy yield. The range of the CCRD levels respected the minimum and maximum values presented in the study.

Construction and analysis of cash flows and response variables in Excel®

The economic analysis of the technology and application of the systems was based on the correlation between the generation estimate curves for Distributed Photovoltaic Microgeneration (DG) systems and the national electricity demand curve projected for 2050. These estimates were derived from economic outcomes and data presented by Stefanello et al. (2024), (Figure 2).

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	x1		x2		x3			x4		x5		Y1	Y2	Y3	Y4	Y5
	CAEEA	TRF	TRF	TRF	TJI (%am)	% aa	TRF	NTA	TRF	SOL	TRF	PB (ano)	NVP (R$)	TIR (%aa)	TIR (%am)	ROI (%)
1	0.75	-1	13.35	-1	0.00486	6.00%	-1	3953.24	-1	1493.06	-1	11.67	8514.33	10.51	0.82	1.71
2	1.23	1	13.35	-1	0.00486	6.00%	-1	3953.24	-1	1493.06	-1	6.08	13061.58	19.53	1.92	2.62
3	0.75	-1	27.65	1	0.00486	6.00%	-1	3953.24	-1	1493.06	-1	8.38	10443.43	14.49	1.25	2.09
4	1.23	1	27.65	1	0.00486	6.00%	-1	3953.24	-1	1493.06	-1	4.57	16251.48	25.40	2.89	3.26
5	0.75	-1	13.35	-1	0.00671	8.35%	1	3953.24	-1	1493.06	-1	14.81	6736.77	10.33	0.80	1.35
6	1.23	1	13.35	-1	0.00671	8.35%	1	3953.24	-1	1493.06	-1	6.80	10484.05	19.28	1.88	2.10
7	0.75	-1	27.65	1	0.00671	8.35%	1	3953.24	-1	1493.06	-1	9.80	8326.49	14.28	1.23	1.67
8	1.23	1	27.65	1	0.00671	8.35%	1	3953.24	-1	1493.06	-1	4.98	13112.77	25.08	2.83	2.63
9	0.75	-1	13.35	-1	0.00486	6.00%	-1	4560.97	1	1493.06	-1	14.46	8753.65	8.46	0.63	1.52
10	1.23	1	13.35	-1	0.00486	6.00%	-1	4560.97	1	1493.06	-1	7.24	13300.90	16.62	1.52	2.31
11	0.75	-1	27.65	1	0.00486	6.00%	-1	4560.97	1	1493.06	-1	10.13	10682.75	12.08	0.98	1.86
12	1.23	1	27.65	1	0.00486	6.00%	-1	4560.97	1	1493.06	-1	5.39	16490.80	21.82	2.27	2.87
13	0.75	-1	13.35	-1	0.00671	8.35%	1	4560.97	1	1493.06	-1	20.19	6890.99	8.30	0.61	1.20
14	1.23	1	13.35	-1	0.00671	8.35%	1	4560.97	1	1493.06	-1	8.27	10638.27	16.39	1.49	1.85
15	0.75	-1	27.65	1	0.00671	8.35%	1	4560.97	1	1493.06	-1	12.32	8480.71	11.89	0.96	1.47
16	1.23	1	27.65	1	0.00671	8.35%	1	4560.97	1	1493.06	-1	5.95	13266.99	21.55	2.22	2.31
17	0.75	-1	13.35	-1	0.00486	6.00%	-1	3953.24	-1	1646.94	1	10.18	8368.87	12.02	0.98	1.85
18	1.23	1	13.35	-1	0.00486	6.00%	-1	3953.24	-1	1646.94	1	5.41	12916.12	21.74	2.26	2.86
19	0.75	-1	27.65	1	0.00486	6.00%	-1	3953.24	-1	1646.94	1	7.40	10297.97	16.29	1.47	2.28
20	1.23	1	27.65	1	0.00486	6.00%	-1	3953.24	-1	1646.94	1	4.09	16106.02	28.12	3.42	3.56
21	0.75	-1	13.35	-1	0.00671	8.35%	1	3953.24	-1	1646.94	1	12.40	6643.03	11.84	0.96	1.47
22	1.23	1	13.35	-1	0.00671	8.35%	1	3953.24	-1	1646.94	1	5.98	10390.32	21.46	2.21	2.30
23	0.75	-1	27.65	1	0.00671	8.35%	1	3953.24	-1	1646.94	1	8.48	8232.75	16.07	1.44	1.82
24	1.23	1	27.65	1	0.00671	8.35%	1	3953.24	-1	1646.94	1	4.42	13019.03	27.78	3.35	2.88
25	0.75	-1	13.35	-1	0.00486	6.00%	-1	4560.97	1	1646.94	1	12.46	8585.83	9.84	0.76	1.65
26	1.23	1	13.35	-1	0.00486	6.00%	-1	4560.97	1	1646.94	1	6.42	13133.08	18.58	1.78	2.52
27	0.75	-1	27.65	1	0.00486	6.00%	-1	4560.97	1	1646.94	1	8.88	10514.93	13.71	1.16	2.02
28	1.23	1	27.65	1	0.00486	6.00%	-1	4560.97	1	1646.94	1	4.81	16322.98	24.23	2.68	3.13
29	0.75	-1	13.35	-1	0.00671	8.35%	1	4560.97	1	1646.94	1	16.19	6782.84	9.67	0.74	1.30
30	1.23	1	13.35	-1	0.00671	8.35%	1	4560.97	1	1646.94	1	7.22	10530.13	18.34	1.75	2.02
31	0.75	-1	27.65	1	0.00671	8.35%	1	4560.97	1	1646.94	1	10.50	8372.57	13.51	1.14	1.60
32	1.23	1	27.65	1	0.00671	8.35%	1	4560.97	1	1646.94	1	5.26	13158.85	23.93	2.62	2.52
33	0.41	-2	20.50	0	0.00578	7.17%	0	4257.11	0	1570.00	0	57.95	5179.17	3.91	0.26	1.01
34	1.57	2	20.50	0	0.00578	7.17%	0	4257.11	0	1570.00	0	4.28	16209.04	27.74	3.34	3.17
35	0.99	0	3.50	-2	0.00578	7.17%	0	4257.11	0	1570.00	0	11.00	8462.43	12.07	0.98	1.66
36	0.99	0	37.50	2	0.00578	7.17%	0	4257.11	0	1570.00	0	5.07	14215.23	23.88	2.61	2.78
37	0.99	0	20.50	0	0.00359	4.40%	-2	4257.11	0	1570.00	0	6.56	14138.20	17.11	1.58	2.77
38	0.99	0	20.50	0	0.00797	10.00%	2	4257.11	0	1570.00	0	8.99	8316.72	16.57	1.51	1.63

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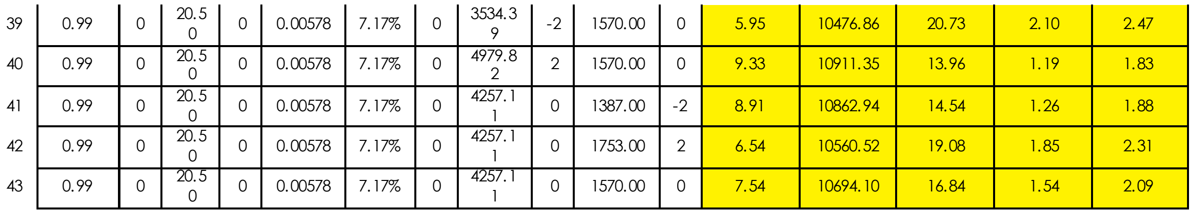

39	0.99	0	20.50	0	0.00578	7.17%	0	3534.39	-2	1570.00	0	5.95	10476.86	20.73	2.10	2.47
40	0.99	0	20.50	0	0.00578	7.17%	0	4979.82	2	1570.00	0	9.33	10911.35	13.96	1.19	1.83
41	0.99	0	20.50	0	0.00578	7.17%	0	4257.11	0	1387.00	-2	8.91	10862.94	14.54	1.26	1.88
42	0.99	0	20.50	0	0.00578	7.17%	0	4257.11	0	1753.00	2	6.54	10560.52	19.08	1.85	2.31
43	0.99	0	20.50	0	0.00578	7.17%	0	4257.11	0	1570.00	0	7.54	10694.10	16.84	1.54	2.09

Figure 2 - Section of the organization of independent variables and calculation of response variables in Excel software®. Source: Search results

The definition of the sample size of 43 experiments is based on the properties of the Central Composite Rotational Design (CCRD), which is structured to optimize the estimation of second-order parameters and multivariate interactions with statistical efficiency. Although a priori power analysis was not performed, the robustness of the sample is evidenced by the high adjusted coefficient of determination and the significance of the model terms. Following Montgomery's (2020) experimental design analyses, the choice of n=43 allows a balance between the coverage of the experimental space and computational feasibility, ensuring sufficient degrees of freedom for the estimation of pure error and the validation of lack of fit. PS

Statistical analysis

The data obtained from the CCRD were used to calculate the regression coefficients of the models generated for the responses, based on the studied variables. The adjustment of the second-order model equations was expressed by the coefficient of determination (R^2), and statistical significance was determined by the F-Test (analysis of variance - ANOVA) using the Statistica 11.0 software (Statsoft Inc., Tulsa, OK, USA).

It is worth noting that the high coefficient of determination observed (R^2 = 99.9%) stems from the intrinsically deterministic nature of the Net Present Value (NPV) model. Unlike biological or social phenomena subject to experimental noise and difficult-to-control random variables, NPV is governed by exact financial equations, where variations in results are direct and mathematical derivations of the inputs.

Therefore, the high adherence of the statistical model does not necessarily indicate overfitting, but rather the ability of the response surface to accurately mimic the behavior of the underlying financial function under the boundary conditions established in the experimental design.PS

The software was also used to generate the response surfaces for the CCRD. Once the predictive models for each response were validated, the Desirability Function was employed as a multicriteria optimization tool to identify the most favorable combination of input variables. This technique first transforms each response variable (PBd and NPV) into an Individual Desirability score (ID) that ranges from 0 to 1, where 0 represents a wholly unacceptable outcome and 1 represents a fully desirable one (BARROS NETO et al., 2010).

For the PBd response, a value of 0 was used as the desirable outcome (minimization of the response), whereas for the NPV response, a value of 1 was the desired outcome (maximization of the response). These individual scores were then aggregated into a single global desirability index (D), and the software identified the specific levels of CAEEA, TRF, TJI, NTA, and SOL that optimize PBd and NPV, thus revealing the optimal conditions to promote investment in DPM.

3. Results and Discussion

Analysis of the CCRD Responses

The results obtained for the PBd and NPV responses can be observed in Table 2.

Table 2 - Central composite rotatable design matrix with code and real values of the variables studied and responses to PBd and VLP.

Run	x_1[a]	x_2[b]	x_3[c]	x_4[d]	x_5[e]	PBd[f]	NPV[g]
1	-1	-1	-1	-1	-1	11.67	8,514.33
2	1	-1	-1	-1	-1	6.08	13,061.58
3	-1	1	-1	-1	-1	8.38	10,443.43
4	1	1	-1	-1	-1	4.57	16,251.48
5	-1	-1	1	-1	-1	14.81	6,736.77
6	1	-1	1	-1	-1	6.80	10,484.05
7	-1	1	1	-1	-1	9.80	8,326.49
8	1	1	1	-1	-1	4.98	13,112.77

Run	x_1[a]	x_2[b]	x_3[c]	x_4[d]	x_5[e]	PBd[f]	NPV[g]
9	-1	-1	-1	1	-1	14.46	8,753.65
10	1	-1	-1	1	-1	7.24	13,300.90
11	-1	1	-1	1	-1	10.13	10,682.75
12	1	1	-1	1	-1	5.39	16,490.80
13	-1	-1	1	1	-1	20.19	6,890.99
14	1	-1	1	1	-1	8.27	10,638.27
15	-1	1	1	1	-1	12.33	8,480.71
16	1	1	1	1	-1	5.95	13,266.99
17	-1	-1	-1	-1	1	10.18	8,368.87
18	1	-1	-1	-1	1	5.41	12,916.12
19	-1	1	-1	-1	1	7.40	10,297.97
20	1	1	-1	-1	1	4.09	16,106.02
21	-1	-1	1	-1	1	12.40	6,643.03
22	1	-1	1	-1	1	5.98	10,390.32
23	-1	1	1	-1	1	8.48	8,232.75
24	1	1	1	-1	1	4.42	13,019.03
25	-1	-1	-1	1	1	12.46	8,585.83
26	1	-1	-1	1	1	6.42	13,133.08
27	-1	1	-1	1	1	8.88	10,514.93
28	1	1	-1	1	1	4.81	16,322.98
29	-1	-1	1	1	1	16.19	6,782.84
30	1	-1	1	1	1	7,22	10,530,13
31	-1	1	1	1	1	10.50	8,372.57
32	1	1	1	1	1	5.26	13,158.85
33	-2.38	0	0	0	0	57.95	5,179.17
34	2.38	0	0	0	0	4.28	16,209.04
35	0	-2.38	0	0	0	11.00	8,462.43
36	0	2.38	0	0	0	5.07	14,215.23
37	0	0	-2.38	0	0	6.56	14,138.20
38	0	0	2.38	0	0	8.99	8,316.72
39	0	0	0	-2.38	0	5.95	10,476.86
40	0	0	0	2.38	0	9.33	10,911.35
41	0	0	0	0	-2.38	8.91	10,862.94
42	0	0	0	0	2.38	6.54	10,560.52
43	0	0	0	0	0	7.54	10,694.10

NOTE: [a] CAEEA (Current Electricity Acquisition Cost); [b] TRF (Invoice-Related Taxes); [c] TJI (Investment Interest Rate); [d] NTA (Current Technology Level); [e] Solarimetry; [f].PBd (discounted payback); [g].NPV (Net Present Value). Source: Search results

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Pages: 1-35

The results for the 43 experimental runs of the Central Composite Rotatable Design (CCRD) are presented in Table 2. The data reveal a wide range of outcomes for the economic indicators, underscoring the high sensitivity of the investment's attractiveness to the variables under study. The Discounted Payback (PBd) varied significantly, from a highly favorable 4.05 years (Run 20) to a prohibitive 57.95 years (Run 32). Similarly, the Net Present Value (NPV) ranged from R$ 5,179.17 (Run 32) to a maximum of R$ 16,490.80 (Run 12). A noteworthy initial finding is that all simulated scenarios yielded a positive NPV, suggesting that investment in DPM is economically viable across all tested conditions, with the analysis therefore focusing on the

A direct inspection of the axial points in the design provides a clear preliminary assessment of each variable's impact. The Current Electricity Acquisition Cost (CAEEA, x_1) demonstrated the most dominant influence. The shift from its lowest axial level (Run 32, PBd = 57.95 years, NPV = R$ 5,179.17) to its highest (Run 33, PBd = 4.28 years, NPV = R$ 16,209.04) confirms that high electricity tariffs are the primary driver for DPM feasibility.

In a similar vein, higher Taxes Related to the Bill (TRF, x_2) and lower Investment Interest Rates (TJI, x_3) were shown to significantly improve the economic returns. For instance, Run 28, which combines high levels of CAEEA and TRF with a low level of TJI, resulted in one of the most attractive scenarios, with a PBd of 4.81 years and a NPV of R$ 16,322.98. As expected, higher technology costs (NTA, x_4) negatively impacted the returns. The influence of Solarimetry (SOL, x_5), while still relevant, appeared less pronounced than the economic and policy-related variables, indicating that while local solar resource is important, the financial and regulatory environment plays a more decisive role in the investment desirability within the studied ranges.

Contemporary literature in energy economics reinforces that consumer response to price signals is complex and non-linear. Silva and Ferreira (2022) demonstrate that the elasticity of demand in developing markets is strongly influenced by capital constraints. In this context, tariff increases may not result in the immediate adoption of microgeneration technologies if the opportunity cost and compression of household income are high, highlighting the need to integrate consumer behavior models into financial projections. PS

Statistical Analysis

By analyzing the results of the CCRD, the regression coefficients for the two evaluated responses were determined, as presented in Table 3. Considering significant parameters ($p \leq 0.05$), Equations 1 and 2 were derived, representing the models for PBd and NPV as a function of the studied variables. Non-significant parameters were incorporated into the residuals for the calculation of the analysis of variance (ANOVA), presented in Table 3.

Table 3 – Regression coefficients for DCCR 25 models to responses of PBd and NPV

Factors	**PBd**				**NPV**			
	RC	**Standard error**	**t (22)**	**p-value**	**RC**	**Standard error**	**t (22)**	**p-value**
Média	4.61	5.17	0.89	0.3826	10,689.26	47.90	223.17	0.000*
x_1 (L)	-5.15	0.83	-6.18	0.000*	2,350.04	7.71	304.67	0.000*
x_1 (Q)	4.29	1.18	3.62	0.0015*	0.20	10.97	0.02	0.9853
x_2 (L)	-1.49	0.83	-1.79	0.0875	1,178.20	7.71	152.75	0.000*
x_2 (Q)	0.21	1.18	0.18	0.8602	114.18	10.97	10.41	0.000*
x_3 (L)	0.73	0.83	0.88	0.3884	-1,212.64	7.71	-157.21	0.000*
x_3 (Q)	0.17	1.18	0.14	0.8904	94.49	10.97	8.62	0.000*
x_4 (L)	0.88	0.83	1.06	0.3002	93.15	7.71	12.08	0.000*
x_4 (Q)	0.14	1.18	0.12	0.9062	0.20	10.97	0.02	0.9853
x_5 (L)	-0.61	0.83	-0.74	0.4693	-64.18	7.71	-8.32	0.000*
x_5 (Q)	0.16	1.18	0.13	0.8961	3.32	10.97	0.30	0.7649
$x_1.x_2$	0.70	0.97	0.72	0.4763	287.47	8.97	32.03	0.000*
$x_1.x_3$	-0.51	0.97	-0.52	0.6056	-227.72	8.97	-25.38	0.000*
$x_1.x_4$	-0.43	0.97	-0.44	0.6617	0.00	8.97	0.00	1.0000
$x_1.x_5$	0.30	0.97	0.31	0.7601	0.00	8.97	0.00	1.0000
$x_2.x_3$	-0.31	0.97	-0.32	0.7533	-112.57	8.97	-12.54	0.000*
$x_2.x_4$	-0.25	0.97	-0.26	0.7999	0.00	8.97	0.00	1.0000
$x_2.x_5$	0.17	0.97	0.18	0.8590	0.00	8.97	0.00	1.0000
$x_3.x_4$	0.19	0.97	0.20	0.8425	-20.28	8.97	-2.26	0.0341*
$x_3.x_5$	-0.14	0.97	-0.14	0.8885	13.92	8.97	1.55	0.1350
$x_4.x_5$	-0.11	0.97	-0.11	0.9115	-4.60	8.97	-0.51	0.6136

NOTE: x_1 CAEEA (Current Electricity Acquisition Cost); x_2 TRF (Invoice-Related Taxes); x_3 TJI (Investment Interest Rate); x_4 NTA (Current Technology Level); x_5 SOL (solarimetry); *p-value < 0.05.
Source: Search results

Following the statistical analysis, second-order polynomial equations were developed to mathematically describe the relationship between the independent variables and the responses of interest. The final coded models, containing only the statistically significant terms ($p \leq 0.05$), are presented in equations 6 and 7.

$$PBd = 5.34 - 5.14x_1 + 4.16x_1^2 - 1.49x_2 + 0.08x_2^2 \tag{6}$$

Equation 6 models the behavior of the Discounted Payback (PBd), revealing that the Current Electricity Acquisition Cost (x_1) has a strong negative linear effect and a positive quadratic effect on the investment return time. This indicates that while higher electricity costs fundamentally reduce the payback period, there is a degree of curvature in this relationship. The Taxes Related to the Bill (x_2) also exhibited a significant negative linear effect, confirming that higher tax loads improve the project's financial return by increasing the value of the energy savings.

$$\begin{aligned} VPL = 10695.16 + 2350x_1 + 1178x_2 + 113.1x_2^2 - 1212{,}6x_3 + 93.4x_3^2 + 93.1x_4 \\ - 64.2x_5 + 287.5x_1x_2 - 227.7x_1x_3 - 112.6x_2x_3 - 20.28x_3x_4 \end{aligned} \tag{7}$$

Equation 7 represents the model for the Net Present Value (NPV). The model's intercept indicates a baseline NPV of R$ 10,695.16 at the central point of the experimental design. The strong positive linear coefficients for x_1 (+2350) and x_2 (+1178) and the strong negative linear coefficient for the Interest Rate, x_3 (-1212.6), highlight them as the most dominant variables influencing the project's long-term value. The model also captured significant interaction effects, such as the positive synergy between electricity cost and taxes (x_1x_2) and the negative interplay between interest rates and the other economic variables (x_1x_3, x_2 x_3).

The statistical validity and predictive capability of these models were assessed through the Analysis of Variance (ANOVA), with the results summarized in Table 4.

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Vol: 13.03
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Pages: 1-35

Table 4 – ANOVA of the CCRD models to PBd and NPV.

Source of variation		SQ	DF	MQ	Fcalculated	Ftest	p-value	R^2 (%)
PBd	**Regression**	2,142.56	4	535.64	26.20	2.62	<0,0000	73.40
	Residual	776.96	38	20.45				
	Total	2,919.52	42					
NPV	**Regression**	369,185,975.66	11	33,562,361.42	16,248.96	2,11	<0,0000	99.90
	Residual	64,031.00	31	2,065.51				
	Total	369,250,006.00	42					

Notes: SQ-Sum of Squares; DF -Degrees of Freedom; MQ – Mean Squares. Source: Search results

The ANOVA results confirm the robustness of both generated models. For the PBd model, the high calculated F-value (26.20) greatly exceeds the tabulated F-value (2.62), and the associated p-value is exceedingly low (< 0.0000), indicating that the model is statistically significant and not a result of random chance.

The application of the Central Composite Rotational Design (CCRD) allowed us to identify that the attractiveness of photovoltaic microgeneration is not linear, but rather the result of complex interactions between regulatory, technical, and market factors (x_1 to x_5).

The interactions involving the Energy Tariff (x_1) and the Technological Cost (x_2) reveal a leverage effect: reductions in the price of modules (x_2) produce significantly larger increases in NPV when they occur in positive tariff readjustment windows (x_1), demonstrating that the economic benefit of the technology is maximized by the cost pressure of the electricity sector.

In parallel, the interaction between Solar Potential (x3) and cost variables (x_2 and x_4) shows that the sensitivity of the investment to local radiation is mitigated as the cost of capital and the price of equipment decrease, making the system resilient even in regions with lower solarimetric index. As discussed by Costa and Lima (2024), this multivariate dynamic proves that the success of the energy transition depends on the convergence between technological maturity and the stability of public policies, where failure or delay in one variable (such as an unexpected increase in installation costs) can be compensated for by efficiency gains or tariff incentives, provided that the breakeven point is monitored systematically. PS

The coefficient of determination (R^2) of 73.40% signifies that the model successfully explains 73.40% of the variation in the Discounted Payback response. The NPV model demonstrated an exceptionally strong fit to the experimental data. Its R^2 value of 99.90% indicates that the model accounts for virtually all the variability in the Net Present Value.

This is further corroborated by an extremely high calculated F-value (16,248.96) and a p-value of less than 0.0000, affirming its outstanding statistical significance and predictive power within the studied domain.

The models demonstrated an adequate fit to the experimental data (Fcalculated > Ftabulated), enabling the construction of the response surfaces in Figures 3 and 4.

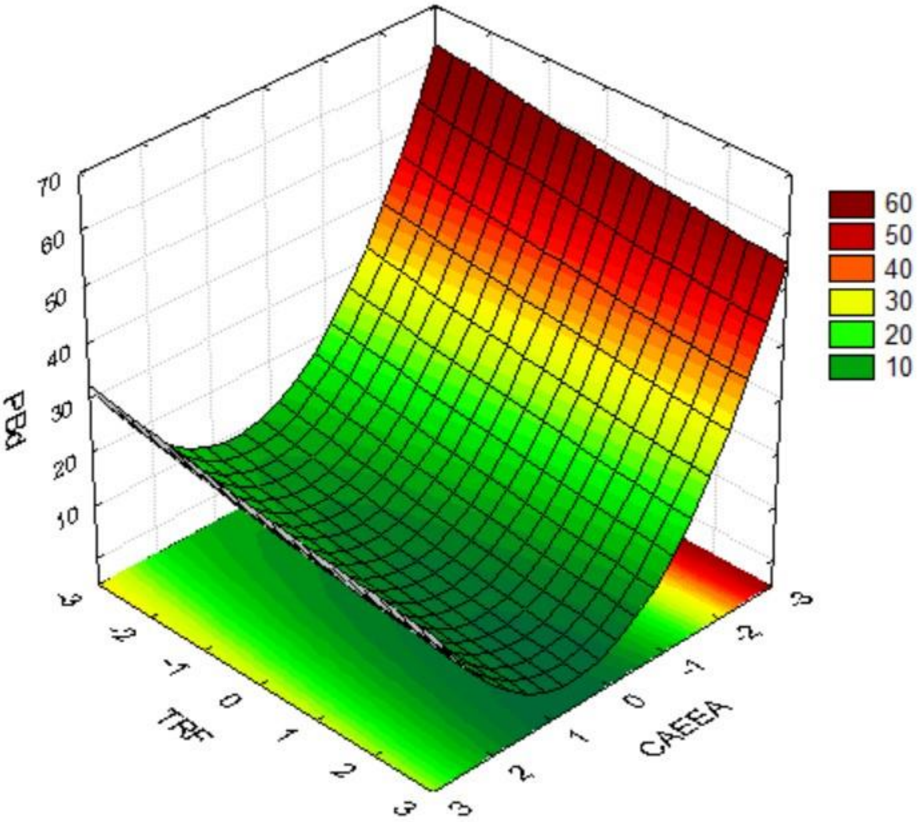

Figure 3 - Response surface for PBd as a function of the variables Current Electricity Acquisition Cost and Taxes Related to the Bill. Source: Search results

According to Figure 3, the variable Current Electricity Acquisition Cost significantly affected the PBd responses ($p < 0.05$ – Table 3). Similarly, the variable

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Pages: 1-35

Taxes Related to the Bill also had a significant influence ($p < 0.10$ – Table 3). A reduction in CAEEA within the studied range led to an increase in PBd (range represented by the red colour in Figure 3).

The application of the Central Composite Rotational Design (CCRD) allowed us to identify that the attractiveness of photovoltaic microgeneration is not linear, but rather the result of complex interactions between regulatory, technical, and market factors (x_1 to x_5).

The interactions involving the Energy Tariff (x_1) and the Technological Cost (x_2) reveal a leverage effect: reductions in the price of modules (x_2) produce significantly larger increases in NPV when they occur in positive tariff readjustment windows (x_1), demonstrating that the economic benefit of the technology is maximized by the cost pressure of the electricity sector.

In order to complement the experimental design, a local sensitivity analysis was applied using a Tornado diagram, allowing us to identify the elasticity of the NPV in response to individual variations in each input. As pointed out by Costa and Lima (2024), this technique is essential to distinguish 'noise' variables from critical value drivers, revealing that fluctuations in energy tariffs and capital costs exert a statistical dominance over economic viability, overcoming the isolated effects of variations in solar radiation within the operational limits of the model. PS

A higher cost of electricity (CAEEA) directly increases the monetary savings generated by each kWh produced by the DPM system. This accelerated accumulation of savings allows the initial investment to be recouped in a significantly shorter timeframe, thus reducing the PBd and making the investment more appealing.

It is crucial to consider that increased taxes and tariffs generate a negative 'income effect' that compresses family budgets or business cash flow. Oliveira and Pereira (2023) argue that this reduction in disposable income acts as a barrier to entry for low-carbon technologies, since the capital that would be allocated to the initial investment in the photovoltaic system is redirected to cover basic or immediate operational needs, making the investment decision less likely despite the favorable NPV. PS

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Vol: 13.03
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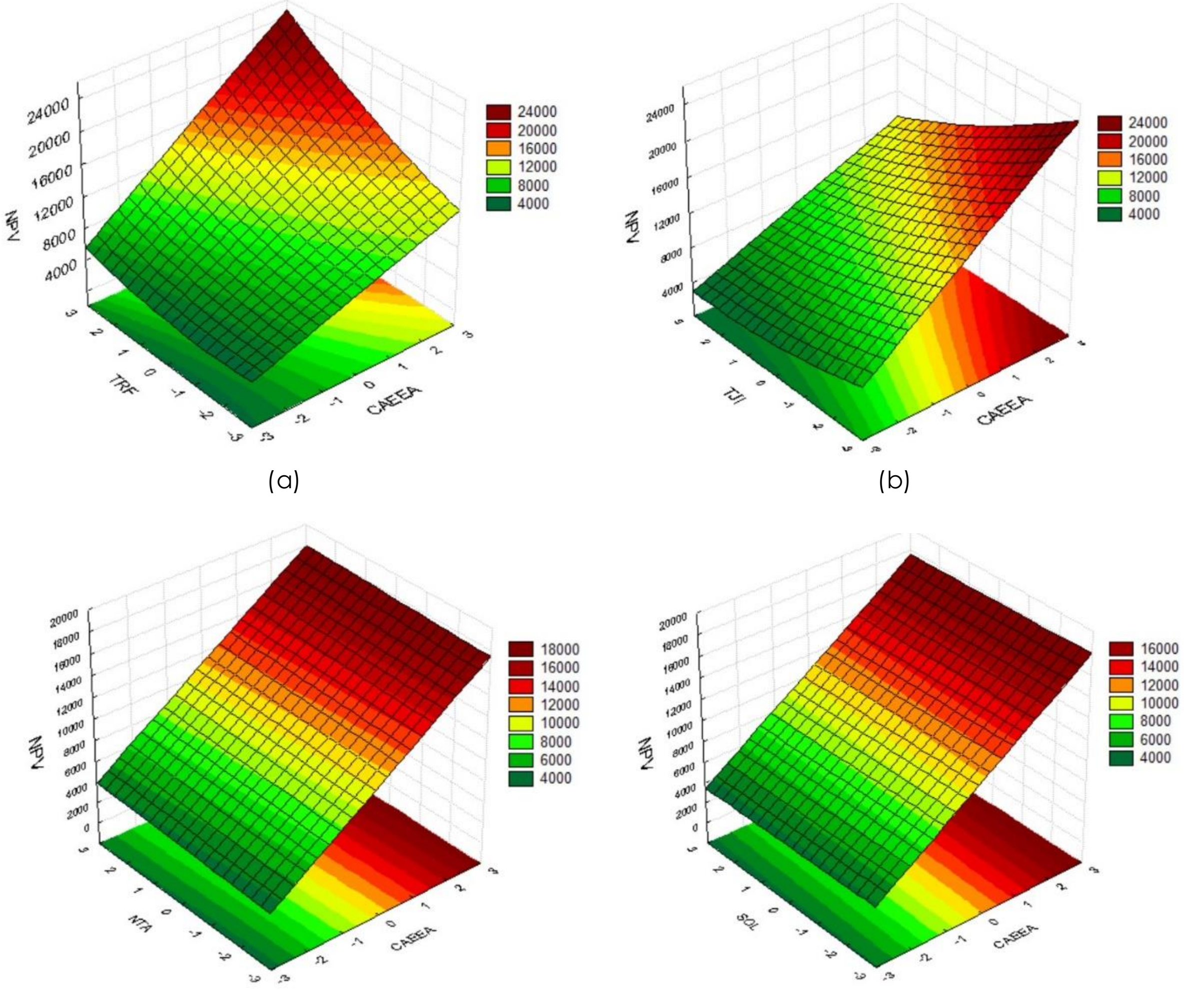
Pages: 1-35

Regarding the NPV response, as shown in the regression coefficient table (Table 3), all independent variables (linear terms) had significant effects. The response surfaces are presented in Figure 4.



(a) (b)

(c) (d)

Figure 4 - Response surfaces for NPV as a function of TRF and CAEEA (a), TJI and CAEEA (b), NTA and CAEEA (c), SOL and CAEEA (d). Source: Search results

In Figures 4a and 4b, TRF is observed to have a positive effect on the NPV response, while TJI has a negative effect. CAEEA also shows a positive effect.

The response surfaces presented in Figure 4 provide a clear visual interpretation of the dependencies between the independent variables and the Net Present Value (NPV). Across all four plots (a-d), the Current Electricity Acquisition Cost (CAEEA) demonstrates a dominant, positive, and predominantly linear effect,

Received: 13/01/2026 - **Accepted:** 20/03/2026
Vol: 13.03
DOI: 10.66104/gjgbym86
Pages: 1-35

evidenced by the steep, consistent upward slope along its axis; this confirms that higher electricity tariffs are the single most powerful driver for increasing the project's NPV.

Figure 4(a) reveals that Taxes Related to the Bill (TRF) also have a direct relationship with NPV, exhibiting a positive linear effect with a slight upward curvature, which indicates a mild positive quadratic influence where the benefits of higher taxes marginally accelerate at higher levels. Conversely, Figure 4(b) illustrates the strong, negative linear dependency on the Investment Interest Rate (TJI), where higher rates directly correlate with a lower NPV.

Dynamic variables, such as panel degradation and energy inflation, have the potential to shift the investment breakeven point. Contemporary literature (HECK; VILLALVA, 2020) indicates that an average degradation of 0.5% to 0.8% per year in module efficiency can extend the discounted payback period to lifecycles exceeding 20 years.

On the other hand, energy inflation, which historically exceeds the IPCA (Brazilian Consumer Price Index) in Brazil, acts as an accelerator of attractiveness, since it increases the value of the savings generated. The omission of these variables in the direct calculation of the multivariate model aims to simplify the analysis of the interaction between the main factors, but their inclusion in future stochastic models is recommended to refine the accuracy of economic viability. PS

The effects of the remaining variables are less pronounced, yet still significant. As shown in Figure 4(c), the Current Technology Level (NTA) presents a positive linear correlation with NPV within the model, while Figure 4(d) indicates a minor negative linear relationship for Solarimetry (SOL).

In order to provide greater analytical precision to the model, the dimensions of cost and technological performance were treated as independent variables. The variable NTA (Current Technological Level) was restricted to representing the cost of acquisition and installation (CAPEX), capturing the direct impact of initial cash outflows.

In parallel, Conversion Efficiency was isolated as an operational performance variable, affecting the flow of monthly revenues and savings. This

Received: 13/01/2026 - **Accepted:** 20/03/2026
Vol: 13.03
DOI: 10.66104/gjgbym86
Pages: 1-35

distinction is fundamental to avoid masking distinct economic effects: while technological cost shows a historical trajectory of decline based on the 'Learning Curve' and economies of scale, technical efficiency follows an incremental upward curve.

This segregation allows us to identify whether the attractiveness of the NPV is primarily driven by the reduction in system costs or by the gain in energy productivity per square meter installed. PS

This analysis, by directly correlating tax increases with financial attractiveness, operates from a partial equilibrium perspective. As discussed by Bortoluzo et al. (2021), models that isolate tariff variables tend to overestimate economic viability by not considering the interdependencies of the electricity sector. Although the mathematical model demonstrates internal consistency, it assumes that the agent's behavior and the market remain static, ignoring equilibrium adjustments that occur in the system when there are significant changes in the energy cost structure. PS

Investment Desirability in Distributed Photovoltaic Microgeneration

The incentive for investment in DPM can be represented by the desirability profile, which identifies the best combination of values for the independent variables to achieve the desired responses. The optimal conditions are defined as the lowest PBd and the highest NPV.

It can be observed in Figure 5 that the desirable values for all the studied variables, considering both responses of interest, are located at the upper axial point, namely: CAEEA = 1.6 R$/kWh; TRF = 37.5%; TJI = 8.75% per year; NTA = 4,979.82 R$/kWp; and SOL = 1,753.00 kWp/m².day.

The inverse relationship between the Current Acquisition Cost of Electric Energy (CAEEA) and the Discounted Payback (PBd) is a cornerstone of the economic analysis for DPM investments. As illustrated in Figure 3 [142], lower values of CAEEA result in a substantially longer payback period, represented by the red-colored region on the response surface.

This phenomenon occurs because the primary financial benefit of a DPM

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Vol: 13.03
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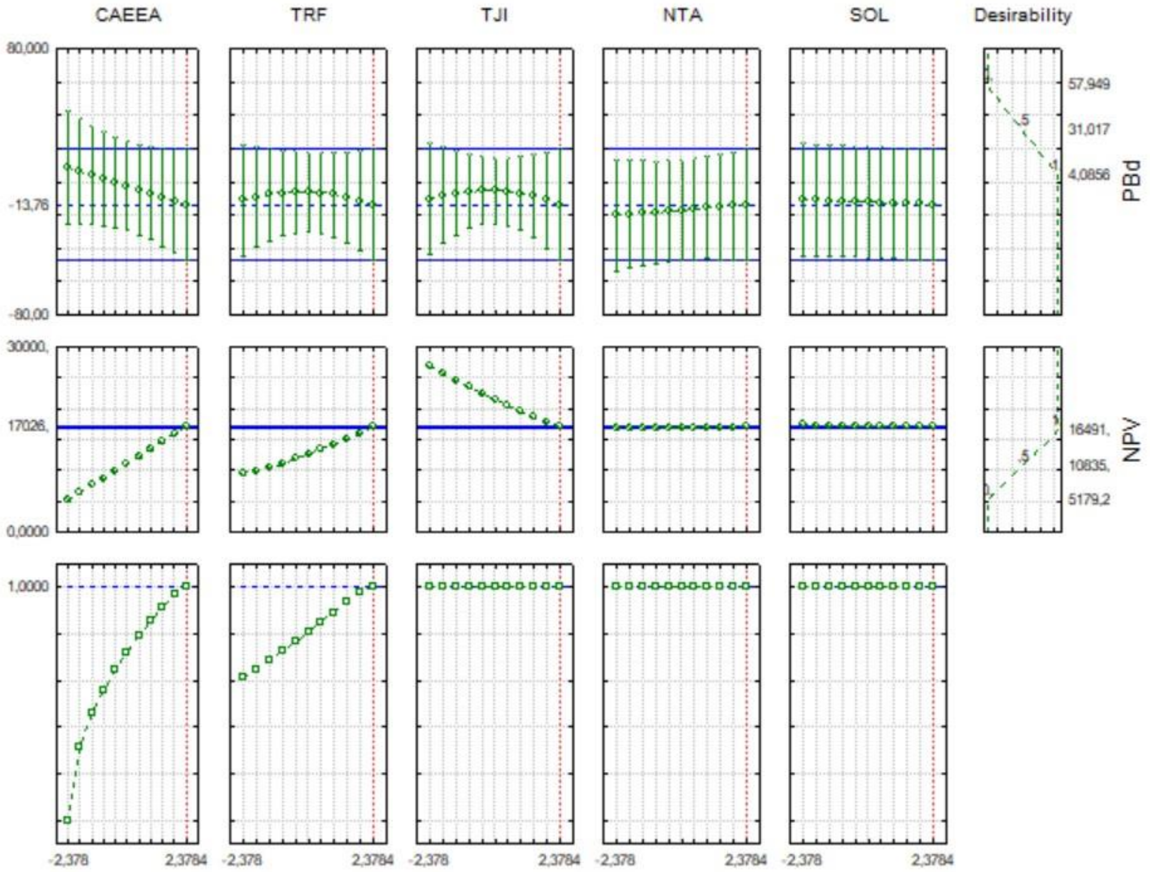
Pages: 1-35

system is the savings generated by avoiding the purchase of electricity from the grid. When the cost of grid electricity (CAEEA) is low, each kilowatt-hour produced by the photovoltaic system yields a smaller monetary saving. Consequently, the accumulation of revenue required to offset the initial investment is slower, extending the PBd and diminishing the short-term attractiveness of the investment.

Figure 5 - Profile of predicted/optimised values and desirability for the



CCRD. Source: Search results

Conversely, a high CAEEA accelerates the return on investment, making DPM a more compelling financial proposition, as it directly increases the value of the self-generated energy. This dynamic underscore the high sensitivity of DPM project viability to regulated electricity tariffs and highlights why energy price is a critical driver for the diffusion of this technology.

This trend can be attributed to the structure of the credit compensation model, where the valuation of the injected kWh reduces the capital recovery period, corroborating the economic incentive theory of Silva and Ferreira (2022). PS

However, the inference that increased taxes favor microgeneration should be weighed against macroeconomic and behavioral factors. According to the IEA (2023), rising energy costs exert direct negative pressure on disposable income, which may paradoxically make the initial capital investment required for photovoltaic systems unfeasible. Furthermore, Heck and Villalva (2020) emphasize that the price elasticity of demand and the 'income effect' can lead consumers to prioritize reducing consumption instead of investing in new assets, radically altering the load curve and the projected profitability of the model. PS

Recent literature reinforces that the viability of distributed systems is not an absolute given, but a function of the stability of incentive policies and the cost of capital. As discussed by Mendes (2025), the perception of profitability is sensitive to 'regulatory risk', which requires that academic conclusions rigorously delimit the sample space and boundary conditions to avoid generalizations in scenarios of high economic volatility. PS

Given the inherent volatility of regulatory and economic variables in Brazil, the transition from a deterministic model to a stochastic approach via Monte Carlo Simulation allows for quantifying the probability of investment success. As discussed by Mendes (2025), the exploration of probabilistic scenarios reveals that the risk of negative NPV is minimized when there is a combination of technological maturity and tariff stability. This analysis lends greater robustness to the study, transforming static projections into a risk management tool that anticipates the uncertainties of the electricity sector for the next decade. PS

4. Conclusions and Recommendations

To quantify the incentive for investment in DPM in Brazil, this study aimed to analyze the effects of the independent variables CAEEA, TRF, TJI, NTA, and SOL on the economic indicators PBd and NPV.

The results indicated the following:

1) The CAEEA showed an inverse linear and a direct quadratic effect on PBd.

Received: 13/01/2026 - **Accepted:** 20/03/2026
Vol: 13.03
DOI: 10.66104/gjgbym86
Pages: 1-35

CAEEA also had a significant direct linear relationship with NPV. The results showed that the CAEEA with the highest desirability for encouraging investment in DPM is 1.6 R$ / kWh.

2) The TRF exhibited significant direct linear and quadratic relationships with NPV, with the most desirable value being 37.5%.
3) The TJI showed a significant inverse linear and direct quadratic relationship with NPV, with 8.75% per year being the most desirable value for encouraging investment in DPM.
4) The NTA demonstrated a significant direct linear relationship with NPV, with 4,979.82 R$/kWp being the most desirable value for encouraging investment in DPM.
5) The SOL showed an inverse linear correlation with NPV, with 1,753.00 kWp/m².day being the most desirable value for encouraging investments in DPM.

Thus, it can be concluded that an increase in the cost of electricity, taxes related to the bill, and the current technology level can contribute to encouraging DPM. Similarly, the incentive for DPM is also driven by a reduction in the interest rate for investments in distributed microgeneration.

The results indicate that, within the parametric limits explored in this study—which reflect the current and projected conditions of the Brazilian electricity sector—photovoltaic microgeneration presents economic viability in all tested combinations. However, it should be noted that this attractiveness is conditional on the modeled ranges for the tariff (TRF) and technological cost (NTA) variables. Structural changes that exceed these limits, such as drastic reductions in the cost of conventional energy or sharp increases in interest rates above those foreseen in the PNE 2050, may alter the breakeven point and compromise the observed viability. PS

The interpretation of financial indicators (NPV and discounted payback) should not be limited to point values, but understood within confidence intervals that reflect the dispersion of experimental data. According to Silva and Santos (2024), the inclusion of statistical error margins allows for more prudent decision-making,

Received: 13/01/2026 - **Accepted:** 20/03/2026
Vol: 13.03
DOI: 10.66104/gjgbym86
Pages: 1-35

mitigating the risk of model overfitting. By establishing 95% confidence limits, it is ensured that the attractiveness of investment in photovoltaic microgeneration remains valid even in the face of residual fluctuations not captured by the independent variables of the CCRD. PS

Despite the statistical robustness of the multivariate model presented, the results should be interpreted in light of certain methodological simplifications necessary for the convergence of the CCRD (Cost, Depreciation, and Reliability).

The main limitation lies in the static nature of some financial assumptions. As discussed by Bortoluzo et al. (2021), the long-term viability of photovoltaic systems is sensitive to exogenous factors not fully captured in partial equilibrium models, such as the annual degradation of module performance and the volatility of energy credit compensation policies. Recognizing these limitations allows investors to use the data presented here as a benchmark, and not as an absolute cash flow forecast. PS

For future projections, such as those in the National Expansion Plan (PNE) 2050, the integration of elasticity models is indispensable. Research by Costa and Lima (2024) demonstrates that the attractiveness of microgeneration is extremely sensitive to economic volatility; in periods of stagnation of real income, even significant tariff increases may not boost the photovoltaic market at the expected rate, highlighting that the mathematical efficiency of the cash flow model must be accompanied by a macroeconomic sensitivity analysis. PS

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