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Prosumer policy options in developing countries: a comparative analysis of feed-in tariffs, net metering, and net billing for residential PV-battery systems

ABSTRACT: Developing countries face significant challenges in their electricity sector, including outdated infrastructure, insufficient generation capacity, and underdeveloped electricity markets. Solar photovoltaic systems combined with batteries (PV-BES) for residential consumers present a viable solution to help address these challenges. To support the deployment of such technologies, it is essential to establish well-designed compensation mechanisms that encourage investment in the sector. Using Ecuador as a case study, this research aims to analyze, through an optimization tool, the techno-economic performance of PV-BES systems for different consumer categories under various scenarios – Business as Usual (BAU) and Without Subsidies (NoSub) – as well as under different compensation mechanisms, namely Feed-in Tariff (FiT), Net Metering (NM), and Net Billing (NB). The results show that current electricity price subsidies significantly discourage investment in new solar capacity in the residential sector, particularly for low-electricity consumers. Eliminating

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subsidies would result in a more competitive LCOE across all consumer categories, making the adoption of PV-BES systems more viable. Finally, to promote PV-BES adoption while ensuring a fair distribution of benefits among all actors, customized compensation mechanisms tailored to each consumer category are necessary. Otherwise, high electricity consumption categories would receive the greatest benefits, potentially leading to inequities in the system.

KEYWORDS: prosumers, compensation mechanisms, net metering, net billing, feed-in tariffs

Introduction

Developing countries face significant challenges in electricity production, including outdated infrastructure, insufficient generation capacity, and underdeveloped electricity markets (Levin and Thomas 2016). These issues, coupled with structural and governance inefficiencies, lead to frequent power shortages and limited access to affordable and reliable electricity. Additionally, many developing nations rely heavily on hydropower due to its perceived long-term cost-effectiveness. However, this dependence puts their energy systems at risk during drought periods when water resources are insufficient to meet demand. This challenge is further exacerbated by the increasing uncertainty surrounding climate change, which could lead to more frequent and severe droughts, further threatening the stability of electricity systems.

To address these vulnerabilities, policymakers often turn to fossil fuels as a backup, but this strategy places additional strain on both the energy system and the national economy. Increased reliance on fossil fuels leads to higher electricity prices due to fluctuations in global fuel markets, often influenced by geopolitical factors (Komorowska et al. 2023). Moreover, the increased use of fossil fuels worsens environmental pollution and contradicts global climate commitments.

A viable solution to mitigate these risks is to diversify the electricity supply through the deployment of distributed renewable energy solutions, such as solar photovoltaics (PV) (Khawaja and Olczak 2024). Solar PV offers a decentralized approach to electricity generation, reducing dependence on centralized infrastructure and mitigating risks associated with hydropower variability and fossil fuel price volatility. Despite its potential, however, solar PV adoption in many developing countries remains slow due to regulatory barriers, unclear compensation mechanisms, and high initial investment costs (Zubi et al. 2016). Regulatory barriers in developing countries often include lengthy and complex bureaucratic procedures, inconsistent policies, contradictory rules, and a lack of clear regulations, among other challenges (Mansoor et al. 2024).

Therefore, to foster investments in PV systems, accurate and precise compensation mechanisms are needed. The most common compensation mechanisms used to support the deployment of PV systems are Feed-in Tariffs (FiTs), net-metering (NM), and net-billing (NB). Table 1 illustrates the main characteristics of the compensation mechanisms. FiTs have historically been the most widely adopted policy, as they guarantee a fixed price – often above market rates – for electricity fed into the grid (Dong et al. 2021; Gul et al. 2016; Le et al. 2022). This approach reduces financial risks and ensures stable revenue flows (Couture and Gagnon 2010; Dusonchet and Telaretti 2010). However, FiTs often exceed electricity market prices, leading to market distortions and higher costs for consumers, prompting a shift toward NM and NB mechanisms (Christoforidis et al. 2016; García-Álvarez et al. 2018; Kurdi et al. 2023).

Table 1. Characteristics of compensation mechanisms

Tabela 1. Charakterystyka mechanizmów kompensacyjnych

Characteristic	Net Metering (NM)	Net Billing (NB)	Feed-in Tariffs (FiT)
Compensation Type	Energy [kWh]: The injected energy is offset against the consumed energy	Monetary: The producer is paid based on a market price or an agreed rate	Monetary: A fixed or regulated tariff, typically set by the government or regulatory authority
Compensation Rate	Typically, at the retail electricity price	A wholesale or regulated/agreed price (usually lower than retail)	A fixed rate guaranteed by contract
Compensation for Surpluses	Credits based on the purchase tariff [netting kWh]	Different rates for buying and selling energy	Usually, a higher fixed tariff than the market price, designed to promote renewable energy
Settlement Period	Usually monthly or annual (consumption and surpluses are netted at the end of the period)	Generally monthly (monetary settlement for the energy injected into the grid)	Long-term contracts (10–20 years); payments can be monthly

Source: own work.

Under NM, PV adopters offset their electricity bills by injecting surplus electricity into the grid at full retail rates, effectively using the grid as a virtual storage system (Campoccia et al. 2014). However, this can create inequities, as PV adopters avoid paying grid maintenance costs, shifting the financial burden to non-PV users (Klein and Noblet 2017). In contrast, NB compensates PV-generated electricity at wholesale prices while charging retail rates for consumption, promoting broader system welfare despite offering lower financial returns for PV adopters (Forcan and Forcan 2023; Watts et al. 2015). Therefore, these different compensation mechanisms have their advantages and disadvantages that should be carefully analyzed according to the political, geographical, and market conditions of the geographic area to be affected (Ahsan Kabir et al. 2023; Du and Takeuchi 2020).

Given these complexities, it is crucial to study the best strategies for deploying PV-Battery (PV-BES) systems in developing countries, providing policymakers with solid insights into how different tariff structures impact adoption. In this context, Ecuador serves as a particularly relevant case study, as it faces the aforementioned challenges while possessing significant untapped solar potential (Cevallos-Sierra and Ramos-Martin 2018; Echegaray et al. 2018).

According to Jara Alvear (2018), GIS-based calculations estimate that Ecuador's total photovoltaic potential could reach nearly 36 GW, with an expected annual output of 64 TWh – equivalent to 2.6 times the country's total electricity demand. More recently, CELEC EP (Corporacion Electrica del Ecuador – Electric Corporation of Ecuador) performed a calculation of the potential solar photovoltaic in Ecuador, finding that solar production could reach almost 2 GW of capacity with an expected output of 3 TWh (10% of the Ecuadorian Electric consumption) (CELEC EP 2024). According to Barragán-Escandón (2022), PV solar energy could supply 3.19 times the electricity consumed in 2016 in Cuenca, a city in southern Ecuador. Despite this potential, solar PV currently contributes only a marginal share of Ecuador's electricity mix, generating just 39 GWh in 2022 out of a total electric production in the country of 32 TWh (Guamán et al. 2024). Utility-scale solar PV projects, while promising, are often located far from major demand centers. This necessitates further development of the electric grid, leading to higher investment costs and making the advancement of the technology even more difficult for developing countries.

In contrast, deploying solar PV for self-consumption in residential buildings presents a more practical and cost-effective alternative, as it requires less infrastructure investment. Residential solar PV can help reduce reliance on the centralized grid, enhance energy resilience, and provide a decentralized alternative to meet growing energy demands. According to Tapia et al. (2023), rooftop solar PV in Quito, Ecuador's capital, has a potential capacity of more than 5 GW, which could generate almost 8 TWh annually, 2.3 times the city's electricity consumption in 2019. Moreover, integrating PV systems with battery storage can significantly enhance solar energy utilization by storing excess electricity generated during the day for use during peak demand hours or at night (Andrade et al. 2022). This not only maximizes self-consumption and reduces dependence on the grid but also mitigates intermittency issues, providing a more stable and reliable energy supply. Therefore, by unlocking this potential and pairing it with batteries, Ecuadorian households can boost the country's energy security, optimize their electricity consumption, and lower their electricity bill. However, well-designed and precise compensation mechanisms must be implemented to motivate investments and accelerate deployment.

The literature comparing FiTs, NM, and NB in the context of developing countries remains limited. With all this in mind, the objective of this research is to fill that gap by providing a comprehensive analysis of the economic and technical implications of PV-battery systems in developing electricity markets, focusing on a country at the crossroads of PV-battery prosumer policy choices. This paper makes several contributions to the existing literature. First, it evaluates the technical feasibility of deploying rooftop solar PV-battery systems for average residential consumers in Ecuador, providing a detailed assessment of their potential to enhance energy access and reduce dependence on the centralized grid. Second, it analyzes the profitability of these systems under different compensation mechanisms, including FiTs, NM, and NB, identifying scenarios in which these tariffs can be economically viable. Finally, the study provides actionable insights for decision-makers by evaluating the effects of different tariff structures under various scenarios. These findings aim to guide policymakers in developing effective strategies for sustainable energy adoption in developing regions, using Ecuador as a case study.

The paper is structured as follows: Section 2 reviews the methodology, including the compensation mechanisms designed to incentivize solar PV adoption and the optimization framework for PV system operation. Two case studies are considered: Business as Usual (BAU) and Without Subsidies (NoSub) for electricity purchase tariffs. Section 3 presents the results obtained for both scenarios (BAU and NoSub), analyzing residential users from three different socioeconomic strata with varying consumption ranges. Finally, Section 4 discusses the conclusions and key policy implications.

1. Methodology

1.1. Overview of analyzed compensation mechanisms

Numerous studies have examined and modeled the role of tariffs in the deployment of PV and PV-BES systems in the residential sector. The most extensively studied tariffs are FiTs. Under FiTs, producers are guaranteed a fixed price – typically higher than standard retail prices – for the electricity they generate and feed into the grid with contracts assuring the selling tariff for decades (Dusonchet and Telaretti 2010). It has been shown that FiTs have significantly influenced the expansion of solar production in developed and developing countries (Dong et al. 2021; Gul et al. 2016), by lowering risks and ensuring revenue stability, thus promoting greater participation and attracting significant capital investments (Couture and Gagnon 2010). Ahsan Kabir et al. (2023) argue that FiTs must be set above the market price of electricity to ensure a positive net present value (NPV) and an acceptable payback period for the system, while (Dijkgraaf et al. 2018) highlights that the duration of the contract is a critical factor affecting the effectiveness of FiTs in supporting new capacity deployment. Additionally, FiTs have proven efficient in facilitating the rapid deployment of new capacities at minimal social cost (Haas et al. 2011). However, recently, FiTs have been phased out by other compensation policies (Christoforidis et al. 2016; Kurdi et al. 2023) as they exceed electricity prices, leading to market distortions that ultimately affect end consumers with higher electricity prices (García-Álvarez et al. 2018).

In this context, other market-driven tariffs that provide greater control over the electricity supplied to the grid and to grid access fees are being promoted. One such alternative is NM, which allows PV adopters to inject surplus electricity into the grid, thereby reducing their electricity bill or receiving payment based on the amount supplied (Poullikkas 2013). Under the NM mechanism, the electricity injected into the grid is valued equally to the electricity price when consumed, irrespective of the time of production or consumption (Campoccia et al. 2014). Essentially, the public electric grid acts as a temporary storage system, enabling the PV user to inject or draw electricity as needed. When it comes to billing, the prosumer only pays for the net energy used[1]. According to (Christoforidis et al. 2016) NM can serve as a suitable alternative for countries transitioning from FiTs and not yet focused on promoting storage solutions. Additionally, Górnowicz and Castro (2020) find that NM could yield a higher NPV when PV capacities are optimized. However, NM may disproportionately benefit PV adopters – though to a lesser extent than FiTs – as they do not pay for grid usage (Klein and Noblet 2017).

NB has been proposed as a more equitable approach. This tariff is similar to NM, with the primary difference being that the price of electricity varies between consumption and production (Watts et al. 2015). In NB, electricity injected into the grid is valued at the wholesale market price, while electricity consumed from the grid is charged at the retail rate. Comparatively, NM is more advantageous for prosumers as it maximizes financial returns, while NB is generally preferred by other energy system stakeholders as it promotes overall welfare (Forcan and Forcan 2023). Although NM is considered a more effective policy (than NB) for encouraging the adoption of PV systems due to compensation at the full retail rate for energy fed into the grid, this model often proves economically unsustainable, particularly in developing nations as final electricity consumers have to pay the extra fees incurred by higher electricity prices. NB, on the other hand, can be beneficial when energy is measured over longer intervals and for smaller capacity systems, as it supports self-consumption.

The implementation of these tariff structures is influenced by the specific political, geographical, and market conditions of the energy sector under study (Ahsan Kabir et al. 2023; Da Pereira Silva et al. 2019). Each region has distinct solar resource distribution, demand patterns, and economic conditions that affect the performance of PV solar systems. Therefore, understanding the impact of these compensation mechanisms in relation to the specific characteristics of the studied region is important for advancing the development of the country's electricity sector.

1.2. Modeling framework

This study utilizes a computational framework that adopts an optimization-based approach to analyze the effects of integrating photovoltaic systems and batteries at the residential level on energy bills and grid energy flows. The framework considers several factors, including system capacity, electricity generation, electricity purchases, investment costs, and other techno-economic parameters. Furthermore, it combines three distinct compensation mechanisms – Feed-in Tariffs, Net Metering, and Net Billing – into one platform, allowing for the evaluation of cash flows and energy flows linked to these mechanisms. It also incorporates long-term capital budgeting aspects such as net present value (NPV), simple payback period, and levelized cost of energy (LCOE), enabling assessments of the systems' profitability throughout their lifetime. A simplified diagram of the computational framework is presented in Figure 1.

Various studies have highlighted the benefits of optimization models (De Mel et al. 2022; Elkazaz et al. 2020), demonstrating their ability to provide global optimal solutions with well-

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[1] Consumption minus production.

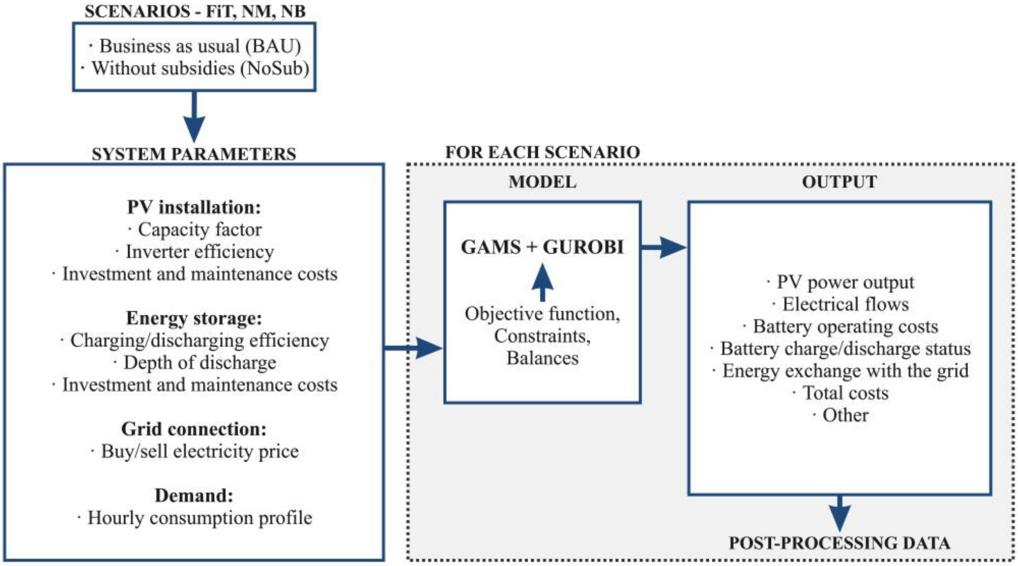


Fig. 1. Scheme of the computational framework

Rys. 1. Schemat struktury obliczeniowej

structured formulations and explicit constraints. In contrast, although heuristic methods are computationally efficient, they often sacrifice accuracy for faster solutions, while non-linear optimization models may face convergence and stability challenges. Among linear programming techniques, Mixed-integer Linear Programming (MILP) has gained increased importance due to its ability to model both discrete and continuous variables and its effectiveness in addressing large-scale problems with efficient solvers.

In this context, this work employs a computational framework that integrates a mixed-integer linear programming (MILP) model based on the formulations presented in (Benalcazar et al. 2024a, 2024b). The model is implemented using the General Algebraic Modeling System (GAMS) and solved with the Gurobi solver. The objective function aims to minimize the grid interaction costs of the residential PV-BES system. The model assumes perfect foresight over a one-year time horizon, with a temporal resolution of one hour. A model predictive control approach with a rolling horizon of 96 hours and a fixed control increment of 24 hours was applied. This strategy reduces the optimization runtime while ensuring solution trackability (Langer and Volling 2020). In a single optimization run, the solution average time was 64.3 seconds, using a personal computer with an Intel i9-14900K 6.00 GHz processor and 128 GB of RAM.

The following system relationships are defined as mathematical constraints to model the operation of the residential PV-BES system:

- Interaction between the residential system and the grid, governed by feed-in tariffs, net metering, and net billing schemes.

- Logical conditions that define the power exchange with the grid, including the costs and benefits associated with buying and selling electrical energy.
- Instantaneous power balances of the photovoltaic system and the battery system, considering their respective efficiencies.
- The total power balance of the PV-BES system, including total load, PV power injected into the grid, electricity purchased from the grid, and energy charged and discharged by the battery system.
- An objective function aimed at minimizing the grid interaction costs of the residential PV-BES system.

This study incorporates the economic indicators outlined in Eqs. (1)–(4) into the computational framework to assess the project's financial performance and feasibility. A key metric used to evaluate the financial performance of the system is the cash flow, expressed in Eq. (1) (Say and John 2021). The Net Present Value (NPV), which represents the difference between the present value of cash inflows (revenues) and outflows (costs) over the project's lifetime, discounted by a specific interest rate is defined in Eq. (2). NPV helps determine whether the PV-BES system is expected to generate more value than it costs, with a positive NPV indicating financial viability. Eq. (3) defines the Payback Period (PBP), which is the time required to recover the initial investment through the project's net cash inflows. While SPB provides a straightforward measure of how quickly the project can break even, it does not account for the time value of money (Zhang et al. 2020). Eq. (4) defines the Levelized Cost of Energy (LCOE), which represents the cost per unit of energy produced over the system's lifetime, factoring in all associated costs (capital, operational, etc.) (Lai and McCulloch 2017). LCOE allows for a comparison of cost-effectiveness across different energy generation methods.

$$CF = B_{Without\ PV-BES} - B_{With\ PV-BES} \tag{1}$$

$$NPV = \sum_{y=1}^{N} \frac{CF(y)}{(1+r)} - I \tag{2}$$

$$PBP = \frac{I}{\sum_{y=1}^{m} \frac{CF(y)}{(1+r)}} \tag{3}$$

$$LCOE = \frac{Total\ lifetime\ costs}{Total\ lifetime\ electrical\ energy\ generated} \tag{4}$$

where:

CF – the cash flow,

$B_{Without\ PV\text{-}BES}$, $B_{With\ PV\text{-}BES}$ – represent the total electricity bills for the residential customer with and without the PV-BES system,

I – the investment cost of the system,

r – the discount rate,

m – the minimum year in which the total revenue exceeds the investment cost.

Additionally, within the computational framework, the time series of photovoltaic generation, along with all values pertaining to the techno-economic parameters of the optimization model, are stored in a spreadsheet. Subsequently, these values are converted into a GAMS Data Exchange binary file utilizing the GAMS Connect agent.

1.3. Data and model assumptions

In this study, the residential electricity distribution system in Ecuador was analyzed as a case study. According to the Ecuadorian Agency for the Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR), it accounted for 34.10% of the country's electricity demand in 2023 (ARCERNNR 2023). Due to the absence of publicly available hourly electricity consumption data, annual demand profiles (representing 8,760 hours) were created using statistical methods to reflect daily and seasonal variations. These profiles were developed for the three major electricity distribution companies in Ecuador based on their customer base: (a) CNEL Guayaquil (part of the Corporación Nacional de Electricidad, CNEL), (b) Empresa Eléctrica Quito (EEQ) and (c) CNEL Guayas-Los Ríos.

The demand profiles incorporate social strata segmentation, historical consumption patterns, and stochastic adjustments to ensure a representative model. The process begins by defining input parameters, including the various social strata of consumers—low (E), lower-middle (D), middle (C), upper-middle (B), and high (A, A1)—each with a specific range of monthly consumption (see Table 2), as established in Ecuador's Master Electricity Plan (MEER, 2012). Additionally, differentiated electricity prices were assigned to each stratum based on the 2024 Electricity Tariff Schedule of Ecuador (ARCERNNR, 2024), allowing for the calculation of

Table 2. Energy consumption ranges and prices by social stratum in Ecuador (2023)

Tabela 2. Zakresy zużycia energii i ceny według warstwy społecznej w Ekwadorze (2023)

Stratum category	Type	Consumption scales [kWh/month/customer]	Prices [USD/kWh]	Users [%]
E	Low	0–100	0.093	37.10
D	Middle-Low	101–150	0.095	46.50
C	Middle	151–250	0.099	13.90
B	Middle-High	251–350	0.103	1.80
A	High	351–500	0.105	0.60
A1	High-Plus	501–900	0.145	0.10

Based on (ARCERNNR 2023).

monthly energy costs by the company and consumer stratum. For this study, only residential consumers in categories C, D, and E were considered, as together they represent 60.40% of total residential-sector consumers.

Daily demand profiles were created to address the absence of hourly data, ensuring consistency with a typical demand curve and the consumption ranges typical of each stratum. Hourly profiles for each day of the week were estimated from historical data by an electric company using an ARIMA model to capture trends and seasonality. A stochastic term ($\epsilon \sim N(0, 0.02)$) was introduced to reflect real-world variability, and a monthly adjustment factor was applied to uphold each stratum's consumption limits. Although no research specifically examines electricity demand on holidays in Ecuador (Guamán et al. 2025), similar studies indicate that calendar effects significantly influence electricity consumption (Trotter et al. 2016). Based on this evidence, a 10% reduction in residential demand on holidays is assumed, as consumers tend to shift their electricity use to hotels and tourist facilities (commercial sector) during these periods. Additionally, a subsidy covering 40% of the total investment in the PV-battery system is considered. Subsidies play a crucial role in accelerating the deployment of these technologies by attracting interest from electricity consumers. For example, in some EU countries, subsidies can cover up to 35% of the system's final cost (Benalcazar et al. 2024a).

1.4. Scenarios

The electricity tariff for the residential sector in Ecuador is among the lowest in Latin America. When comparing residential tariffs in neighboring countries such as Peru and Colombia, both exhibit higher prices. For example, for a consumption of 150 kWh per month, the tariff in Peru is 0.159 USD/kWh, and in Colombia is 0.206 USD/kWh, compared to Ecuador's tariff of 0.905 USD/kWh (OLADE 2021).

In this context, two scenarios for the electricity purchase price from the grid were defined:

- **BAU (Business as Usual):** In this scenario, the tariff remains as established in the 2025 tariff policy. The BAU prices are those provided in Table 1.
- **NoSub (Without Subsidies):** This scenario assumes the elimination of subsidies for the residential sector. The prices in the NoSub scenario are determined by applying a conversion factor obtained from the calculation of the real average cost of electrical service established in Resolution 053/18 (ARCONEL 2018). According to this resolution, electricity for the residential sector should be priced at 171.45% of the current value.

Regarding the selling prices of electricity, Table 3 details the values considered for the three compensation mechanisms reviewed in Section 2.1. In the case of Net Metering, the purchase and sale prices of energy are identical, as the bidirectional meter balances the energy flows at the same price. In contrast, for Net Billing, the sale price is always lower than the purchase price; these values were derived from the average generation cost established in Resolution 053/18 (ARCONEL 2018). Finally, under the FiT mechanism, the sale price of energy to the grid is always higher than the purchase price, thereby incentivizing photovoltaic energy production. These FiT values were obtained from Resolution 001/13 (CONELEC 2014), which was the last year that the FiT mechanism was in force in Ecuador.

TABLE 3. Compensation mechanisms energy consumption prices by social stratum

TABELA 3. Mechanizmy kompensacyjne cen zużycia energii według warstw społecznych

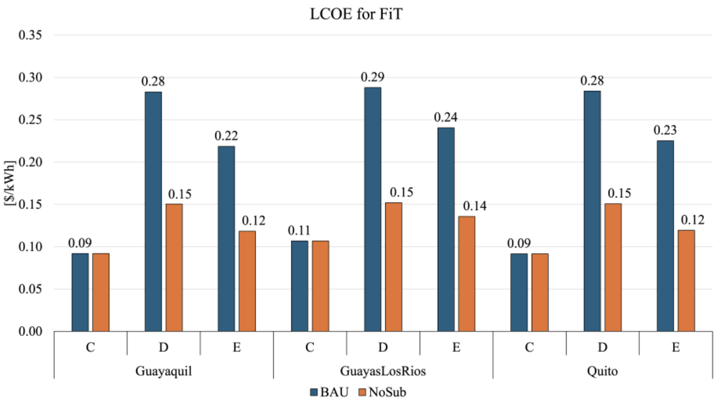
Scenario	Stratum Category	Net Metering [USD/kWh]	Net Billing [USD/kWh]	Feed-in Tariff [USD/kWh]
Business as usual	E	0.0930	0.0526	0.1180
	D	0.0950	0.0526	0.1180
	C	0.0990	0.0526	0.1180
Without subsidies	E	0.1595	0.0901	0.2023
	D	0.1629	0.0901	0.2023
	C	0.1697	0.0901	0.2023

2. Results and discussion

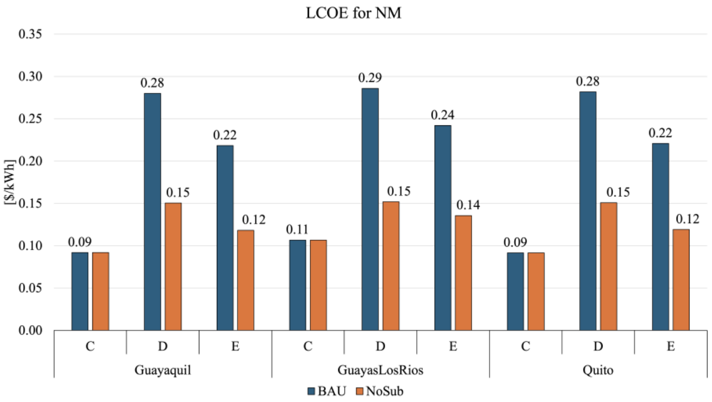
The results for the LCOE in each studied case are presented in Figure 2. First, it can be observed that, in both the BAU scenario and the no-subsidy (NoSub) scenario, the difference between the LCOE for type C users and that of type D and E users is significant, regardless of the compensation mechanism. Specifically, while for category C, the LCOE may approach or even be competitive with the current electricity price established in the 2025 tariff policy (around $0.09/kWh), for categories D, and E the values remain higher and are therefore less competitive. This highlights the direct influence that the consumption category has on the competitiveness of PV-BES systems.

In the absence of subsidies, the LCOE for consumers in categories “E” and “D” decreases significantly under a FiT and NM tariff (by approximately 47%). However, under a NB tariff, the LCOE remains almost unchanged compared to the BAU scenario. On the other hand, for consumers in category “C,” the LCOE remains unchanged between the BAU and NoSub scenarios, suggesting that higher electricity consumption already makes the system cost-effective, regardless of subsidy removal.

The relationship between electricity consumption and LCOE is crucial for understanding the competitiveness of a PV-BES system. LCOE is calculated by dividing the total system cost by the total electricity produced by the system, with the latter being directly influenced by electricity consumption. Since the model optimizes system operation based on consumption



(a)



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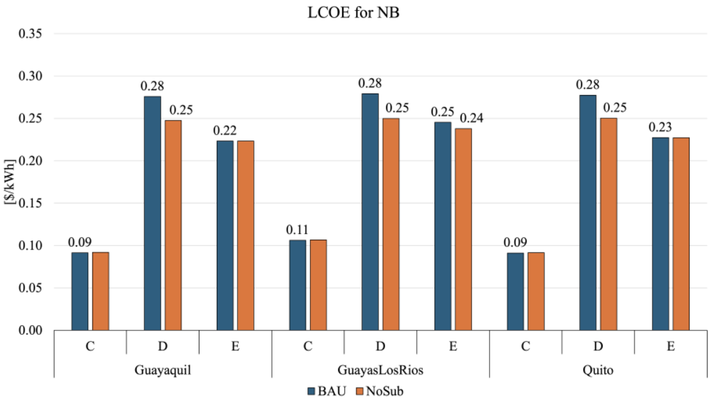


(c)

Fig. 2. LCOE by region and consumer category for each scenario and compensation tariff

Rys. 2. Koszt LCOE według regionu i kategorii konsumenta dla każdego scenariusza i taryfy kompensacyjnej levels and electricity prices, higher electricity generation spreads fixed and variable costs over a larger production volume, leading to a lower LCOE. Conversely, consumers with lower electricity consumption face relatively higher costs per unit of energy produced, resulting in a higher LCOE.

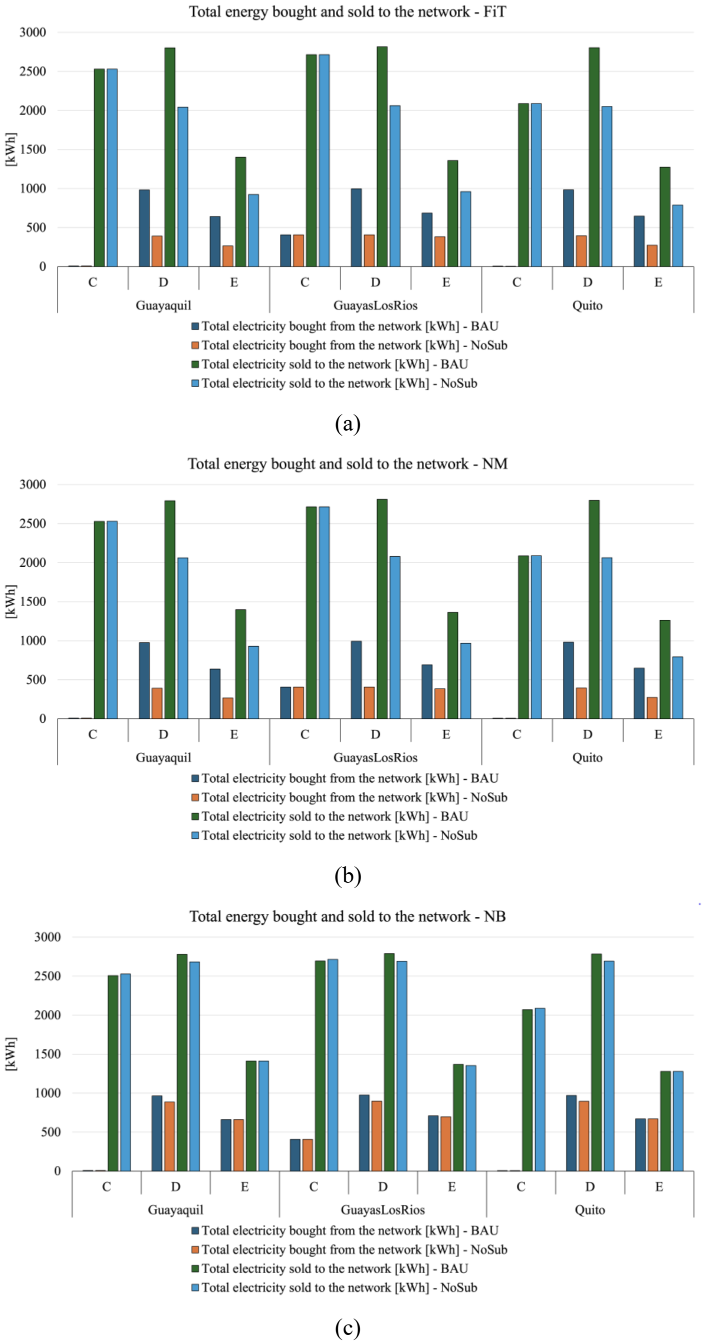
Consequently, electricity consumption plays a key role in determining whether PV-BES systems can compete with grid electricity prices. However, even with optimized systems, economic feasibility is ultimately constrained by the final electricity price. Therefore, as long as electricity subsidies persist, residential users have little incentive to transition from grid electricity to self-generation with PV-BES systems. In the BAU scenario, the cost of purchasing energy from the grid is always equal to or lower than the LCOE under all compensation mechanisms. Thus, the current cost structure of distributed PV-BES systems does not allow residential users in categories D and E to reach economic parity with grid electricity prices.

Subsidized electricity prices also significantly impact how the PV-BES system interacts with the grid in terms of electricity purchases and sales. As shown in Figure 3, subsidized electricity prices result in higher energy sold to the grid for most consumer categories (except for “C” users) under FiT and NM tariffs. As the tariffs are higher than the retail electricity price, they allow to obtain greater benefits for new prosumers. When subsidies are removed, the electricity sold to the grid under the same tariffs decreases for most consumers, as electricity is now preferred for self-consumption due to higher retail electricity prices. Therefore, this indicates that subsidies should be eliminated, as this can help promote self-consumption and increase electricity-producing capacities at the same time. Moreover, reducing subsidies will decrease pressure on the national budget as the government will no longer have to cover these costs.

In general, the NPV when adopting a PV-BESS system is positive across all scenarios and tariffs, except in some cases under an NB tariff for “D” and “E” consumers, where it is negative (see Table 4). This suggests that the NB tariff might not be the most suitable option for low-electricity consumers. Again, this highlights that electricity consumption is a key driver in adopting self-consumption technologies and the optimal configuration of the system. For “E” consumers in Guayaquil, the NB tariff can be a positive investment, but it is never favorable for the “D” category. Although electricity consumption for category “D” consumers is only 50% higher than that of “E” consumers, the optimal operation of the PV-BES system is twice as expensive.

The highest NPV is obtained under a FiT tariff in a NoSub scenario, which is significantly higher than in cases with other tariffs. On the other hand, the lower benefits are obtained under a NB tariff when subsidies are applied. The elimination of subsidies for electricity prices has a positive effect on NPV across all cases, with the more significant impact under the FiT mechanism, as the sale price of energy produced by the PV system is higher than the purchase price, making it much more profitable than the other two mechanisms. This further demonstrates that subsidized electricity prices would discourage investment in new electric power capacities.

High electricity-consuming users benefit the most from the transition to a PV-BES system. In fact, consumers in category “C”, across all scenarios and tariffs, achieve near-complete autarky from the grid. With a PV-BES system, they can generate all the energy they require for their consumption and sell excess electricity to the grid, allowing them to obtain more significant financial benefits.


Total energy bought and sold to the network - FiT

(a)

Total energy bought and sold to the network - NM

(b)

Total energy bought and sold to the network - NB

(c)

Fig. 3. Electricity withdrawn and sold to the grid by region and consumer category in every scenario and for each tariff

Rys. 3. Energia elektryczna pobrana i sprzedana do sieci według regionu i kategorii odbiorców w każdym scenariuszu i dla każdej taryfy

TABLE 4. NPV and PBP by region and consumer category for each compensation tariff and scenario

TABELA 4. NPV i PBP według regionu i kategorii konsumenta dla każdej taryfy kompensacyjnej i scenariusza

Compensation mechanism/Scenario		FiT				NM				NB			
		BAU		NoSub		BAU		NoSub		BAU		NoSub	
		NPV ($)	PBP (years)	NPV ($)	PBP (years)	NPV ($)	PBP (years)	NPV ($)	PBP (years)	NPV ($)	PBP (years)	NPV ($)	PBP (years)
Guayaquil	C	2,831	9.4	7,009	5.3	2,358	10.3	6,200	5.8	1,195	13.6	4,222	7.5
	D	1,722	10.5	4,025	6.4	1,088	12.7	3,266	7.4	–72	20.8	1,554	11.0
	E	944	10.3	2,112	6.4	602	12.5	1,728	7.3	33	19.4	907	10.5
Guayas Los Rios	C	2,658	9.7	6,712	5.5	2,151	10.8	5,841	6.0	904	14.7	3,721	8.1
	D	1,725	10.5	4,041	6.4	1,089	12.7	3,272	7.4	–77	20.8	1,545	11.1
	E	855	10.8	2,000	6.6	520	13.1	1,607	7.7	–34	20.7	798	11.1
Quito	C	2,322	10.4	6,135	5.8	1,932	11.3	5,467	6.3	971	14.4	3,835	7.9
	D	1,723	10.5	4,039	6.4	1,089	12.7	3,265	7.4	–74	20.8	1,548	11.1
	E	791	11.1	1,829	7.1	467	13.6	1,504	8.0	–45	20.9	774	11.3

Concerning the payback period, it varies from 5 to 20 years depending on the scenario and tariff structure. The shortest payback period occurs in cases without subsidies under a FiT tariff, while the longest payback period is observed for "E" consumers under an NB tariff in a BAU scenario. This trend closely follows the behavior of the NPV.

Regarding the monthly electricity bill (see Table 5), it is evident that in all cases, with the exception of the NB mechanism for type D and E users, installing the PV-BES system results in savings and generates revenues from the injection of excess electricity into the grid. However, these results depend on the assumption that the PV-BES system is subsidized at 40% of the investment cost, as mentioned in Section 2.3. This is a reasonable assumption, as such subsidies are common in developing countries to promote the adoption of distributed generation among low-income residential users. These types of policies not only aim to accelerate the deployment of more sustainable energy-producing technologies but also look to increase energy access, provide more affordable and reliant electricity, and reduce inequalities. However, it is crucial to assess their impact on system design to ensure that benefits are distributed equitably and efficiently across all consumer categories in the long term. Moreover, subsidizing new investments in self-consumption is more beneficial than subsidizing electricity prices, as it enables the development of new power capacities that make better use of existing infrastructure and enhance electricity access.

Table 5. Annual net cash flow for PV-BES residential users [USD]

Tabela 5. Roczny przepływ środków pieniężnych netto dla użytkowników indywidualnych PV-BES [USD]

Distribution company		Guayaquil			Guayas Los Rios			Quito		
Compensation mechanism/Stratum category		C	D	E	C	D	E	C	D	E
Feed-in Tariff	BAU	247.26	198.92	85.69	229.64	199.21	76.61	195.45	199.03	70.15
	NoSub	459.93	310.89	124.73	429.75	312.58	113.31	371.11	312.45	95.93
Net Metering	BAU	199.05	134.34	50.89	177.91	134.37	42.48	155.70	134.43	37.11
	NoSub	377.55	233.65	85.59	341.02	234.24	73.22	303.09	233.59	62.88
Net Billing	BAU	80.54	16.17	–7.13	50.94	15.65	–13.96	57.83	16.05	–15.02
	NoSub	176.09	59.22	2.00	125.12	58.31	–9.14	136.79	58.72	–11.51

As observed, the transition towards different compensation mechanisms for electricity users in Ecuador is a complex process, as its impact varies depending on the total electricity consumption of each consumer category. High electricity-consuming actors are the most benefited from the adoption of PV-BES. Therefore, accurate tariffs following each consumption category could help reduce potential inequalities in the system. This means, for example, implementing lower prices for electricity sold to the grid by high electricity consumers while allowing low electricity consumers to benefit from slightly higher selling prices could create a more balanced framework. Additionally, more targeted financial support for PV-BES investments could also be a beneficial policy. Nonetheless, subsidies for final electricity prices should be gradually reduced as they completely distort market conditions and weaken incentives for new investments and self-consumption projects.

Conclusions and policy implications

This study analyzes the technical and economic implications of deploying a PV-BES system under different compensation mechanisms (FiT, NM, and NB) in a developing country. The analysis focuses on Ecuador, a country facing significant climatic and demand pressures on its electricity system, alongside a centralized energy governance structure that has implemented strong electricity price subsidies. These subsidies are not applied symmetrically to all consumers but are allocated based on final electricity consumption. Consumers are classified into categories from A to E, with category E having the lowest consumption. This study considers only consumers in categories E to C, as they represent more than half of Ecuador's total electricity consumption. Two different scenarios are proposed for analysis. The first is a Business-as-Usual (BAU) scenario, where the different compensation mechanisms compete against subsidized electricity prices. The second scenario assumes that electricity prices in Ecuador are no longer subsidized. In both cases, a PV-BES investment subsidy of 40% has been considered.

The results indicate that deploying PV-BES systems in the residential sector presents a significant opportunity for the Ecuadorian government to address current challenges in the national electricity sector. However, careful considerations must be taken into account. First, the elimination of electricity price subsidies is necessary to make the transition to PV-BES attractive for all consumers. In the BAU scenario, the LCOE for consumers in categories E and D is not competitive with current electricity prices, but this changes when subsidies are removed.

The adoption of the different compensation mechanisms always results in positive net present values for the prosumers, except for the NB tariff for consumers in categories "E" and "D". For consumers in category "C", transitioning to a PV-BES is always advantageous under all compensation mechanisms, as the LCOE remains comparable to or lower than the electricity price in both BAU and NoSub scenarios. Consequently, increased electricity consumption greatly influences tariff performance and the cost-effectiveness of PV-BES systems, since larger capacities facilitate economies of scale. Consequently, consumers in categories "C" are receiving most of the benefits when transitioning towards a PV-BES under any compensation mechanism. Among the tariff options, FiT provides the highest benefits to prosumers, as it consistently offers higher compensation for electricity injected into the grid.

Finally, the transition to PV-BES in developing countries, and in particular in Ecuador, should involve more dynamic tariff structures. This means implementing differentiated compensation mechanisms for each consumer category to ensure a more equitable and just transition. However, the policy to be implemented will depend on the government's goal regarding its electricity system, whether to encourage self-consumption or to supply excess energy to the grid for other consumers' needs. Additionally, a more targeted approach to capital investment subsidies should be considered to achieve a fairer distribution of benefits. However, it is also essential to evaluate the potential impacts of removing electricity price subsidies on consumers who do not opt to transition to PV-BES.

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Warianty polityki prosumenckiej w krajach rozwijających się: analiza porównawcza taryf gwarantowanych, net-meteringu i net-billingu dla systemów fotowoltaicznych z magazynem energii dla odbiorców indywidualnych

Streszczenie

Kraje rozwijające się stają przed znaczącymi wyzwaniami dotyczącymi ich sektorów elektroenergetycznych, takimi jak przestarzała infrastruktura, niewystarczająca moc zainstalowana oraz słabo rozwinięte rynki energii. Systemy fotowoltaiczne z bateryjnymi magazynami energii (PV-BES) dla konsumentów indywidualnych stanowią realne rozwiązanie mogące pomóc w przezwyciężeniu tych problemów. Aby wspierać wdrażanie takich technologii, niezbędne jest ustanowienie dobrze zaprojektowanych mechanizmów kompensacyjnych, które zachęcają do inwestowania w ten sektor. Wykorzystując Ekwador jako studium przypadku, to badanie ma na celu analizę, za pomocą narzędzia optymalizacyjnego, wydajności techniczno-ekonomicznej systemów PV-BES dla różnych kategorii konsumentów w różnych scenariuszach – Standardowym (BAU) i Bez Dopłat (NoSub) – oraz przy różnych mechanizmach kompensacyjnych, takich jak Taryfy Gwarantowane (FiT), Net-Metering (NM) i Net-Billing (NB). Wyniki pokazują, że obecne dopłaty do cen energii elektrycznej znacznie ograniczają inwestycje w nową moc słoneczną w sektorze indywidualnym, zwłaszcza wśród konsumentów o niskim zużyciu energii elektrycznej. Eliminacja dopłat doprowadziłaby do bardziej konkurencyjnego LCOE we wszystkich kategoriach konsumentów, czyniąc adopcję systemów PV-BES bardziej opłacalną. W celu promocji adopcji systemów PV-BES i zapewnienia sprawiedliwego podziału korzyści między wszystkich uczestników, konieczne jest stworzenie dostosowanych mechanizmów kompensacyjnych, dopasowanych do każdej kategorii konsumentów. W przeciwnym razie, kategorie konsumentów o wysokim zużyciu energii elektrycznej otrzymałyby największe korzyści, co mogłoby prowadzić do nierówności w systemie.

Słowa kluczowe: prosumenci, mechanizmy kompensacyjne, net metering, net billing, taryfy gwarantowane