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Effects of the Energy Communities: A Case of Application in Colombia

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ABSTRACT

This article examines the environmental and economic effects of energy communities, considering both short- and long-term impacts. For the long-term analysis, a simulation model was developed to observe the behaviour of variables within the electricity market and their impacts over a 20-year evaluation period. The environmental impact was quantified through avoided emissions in Mt of CO_2 equivalent. In economic terms, the savings from self-generation and the expected revenues from surplus energy sales were calculated, alongside a profitability analysis per user. The results indicate that energy communities could avoid 25 $MtCO_2e$, while the regulated market could achieve savings $ 18.5 Billion USD, in addition to potential revenues of $ 2 Billion USD. These outcomes arise from the aggregated implementation of photovoltaic systems in households and small businesses within the framework of energy communities.

Keywords: Communities Energy, Environment and Economy Effects, Simulation Model
JEL Classifications: A12, C53, D4, G10, L11

1. INTRODUCTION

According to the United Nations' Sustainable Development Goals and global agreements addressing the climate crisis, the energy transition constitutes a fundamental strategy for decarbonising the economy and ensuring long-term sustainability for both the population and the planet (UNDP, 2025).

The energy transition refers to the process of shifting from fossil-fuel-based to renewable-energy-based systems, both on the demand and supply sides. This shift requires new ways of consuming and producing energy across all sectors of the economy, including households.

Energy communities serve as a mechanism for accelerating the energy transition due to their dual impact: environmentally, they reduce CO_2-equivalent emissions; economically, they lower energy expenditures for households and companies, enhancing competitiveness and sustainability.

Global energy-related carbon dioxide emissions reached 37,723 $MtCO_2$ in 2023. These were distributed by fuel as follows: coal combustion activities emitted 15,667 $MtCO_2$ (45%), oil 11,334 $MtCO_2$ (33%), natural gas 7,520 $MtCO_2$ (22%), and bioenergy and waste 267 $MtCO_2$. The electricity and heat sector emitted 15,262 $MtCO_2$, originating 74% from coal, 4% from oil, and 21% from natural gas. In terms of final energy consumption, emissions reached 18,055 $MtCO_2$, of which 24% came from coal, 56% from oil, and 20% from natural gas. Total atmospheric emissions amounted to 20,167 $MtCO_2$, distributed across sectors as follows: industry 46%, transport 41%, and buildings 14%, of which 9% was residential and the remainder commercial and services (IEA, 2024).

In Colombia, sectors related to agriculture, livestock, forestry, and other land uses account for more than 55% of total emissions, while the energy sector contributes 32%. In 2021, the energy sector emitted 91.6 $MtCO_2$, with transport responsible for 46% of emissions, the energy subsector 21%, industry 15%, and fugitive emissions 8% (IDEAM, 2024).

Taken together, these figures show that Colombia's energy-sector emissions represent only 0.6% of global emissions, with the transport sector being the country's largest emitter.

Worldwide energy consumption in 2023 totalled 445 EJ, distributed across sectors as follows: transport 36%, industry 26%, buildings 19%, residential 13%, and services 6%. In terms of energy sources, 67% came from fossil fuels—39% oil, 16% natural gas, and 12% coal—followed by electricity (20%), biofuels (9%), and heat (4%) (EIA, 2024).

Colombia presents a similar structure, with total energy consumption reaching 1.5 EJ in 2023. Sectoral distribution was as follows: transport 42%, industry 23%, residential 19%, commercial and public services 6%, and other uses 10% (agriculture, mining, construction, and non-energy uses) (UPME, 2025). Regarding energy sources, fossil fuels accounted for 70% of consumption (47% oil, 17% natural gas, and 6% coal). Bagasse and firewood represented 13%, while electricity accounted for 16%, and auto- and co-generation for 1% (UPME, 2025).

This analysis shows that the transport, industrial, and residential sectors are the largest energy consumers, and that fossil fuels represent approximately 70% of final energy use. Colombia's final energy consumption accounts for 0.34% of global demand.

Global installed electricity capacity reached 9,414 GW in 2023, of which 45% was renewable and 55% non-renewable. Renewable capacity comprised solar (17%), hydropower (15%), wind (11%), and bioenergy (2%). Non-renewable capacity consisted of coal (24%), natural gas (21%), and oil (4%). Storage systems, mainly battery-based, represented 1%. Electricity generation worldwide reached 29,863 TWh, comprising 30% renewable, 9% nuclear, and 60% fossil fuels. Renewable generation included hydropower (14%), wind (8%), solar PV (5%), and bioenergy (2%). Fossil-fuel generation was composed of coal (36%), natural gas (22%), and oil (3%) (IEA, 2024).

Colombia's installed electricity-generation capacity reached 19,917 MW in 2023, of which 70% was renewable and 30% non-renewable. Among renewable sources, hydropower accounted for 66%, solar 2%, and other sources 1%. Non-renewable sources included natural gas (16%), coal (8%), and liquid fuels (6%). Centralised plants represented 91% of total capacity, and non-centralised plants 9%. Electricity generation in 2023 was 80,687 GWh, with 77% renewable—primarily hydropower (74%) and solar (1%)—and 23% non-renewable (gas 12%, coal 9%, and liquid fuels 2%) (XM, 2024).

Thus, Colombia contributes 0.21% of global installed capacity and 0.27% of global electricity generation. Unlike global trends, Colombia's electricity mix contains 20% more renewable energy, mainly hydropower. Globally, solar power surpassed hydropower in 2023, whereas in Colombia, solar penetration remains marginal.

In 2023, the world population reached 8.018 billion people, and global GDP was USD 175.981 trillion, corresponding to a per-capita income of USD 21,948.

Colombia's GDP in 2023 was USD 366 Billon, with a population of 52.314 million, yielding a per-capita income of USD 7,000 (DANE, 2024; 2024a; 2024b; World Bank, 2025).

These figures show that Colombia accounted for 0.65% of global population, but only 0.21% of global GDP. The world's per-capita income is three times higher than Colombia's.

The following chapters present a review of the state of the art on energy communities, a description of a simplified system-dynamics simulation model of the electricity market, and an assessment of the impacts of energy communities on the market, the economy, and the environment.

2. LITERATURE REVIEW ON ENERGY COMMUNITIES

The development of energy communities worldwide has become a fundamental component of the transition towards renewable energy sources. These communities facilitate decentralised energy production, thereby enhancing local resilience and reducing dependence on fossil fuels. They are increasingly recognised for their contribution to sustainability and energy self-sufficiency, particularly in Europe and the United States. The following sections summarise key advances in this field.

Energy communities have gained prominence as innovative models for achieving energy self-sufficiency, particularly in response to the challenges posed by climate change. By decentralising energy production, they strengthen local energy security. Despite facing challenges such as significant upfront investment requirements and regulatory barriers, their role in promoting sustainability and resilience within the energy transition is widely acknowledged (Bellini et al., 2024).

In addition, the shift from centralised to decentralised energy systems has been significant, with local energy needs increasingly being met through renewable resources (Ahmed et al., 2024). Energy communities have received global attention—especially in Europe—for promoting the local generation of renewable energy.

The European Union has established regulatory frameworks to support community-generated renewable energy, emphasising citizen participation (Energy Communities: Comparative Perspectives from the EU and the US, Savaresi and Outka, 2023). Energy communities have emerged globally as key actors within the renewable energy transition, challenging existing governance structures and market arrangements. The EU has regulated these communities through directives such as RED II and EMD II

(Koirala et al., 2021), while the United States introduced initiatives in 2021 promoting local energy generation under the federal administration of that period.

Energy communities contribute to economic, environmental, and social sustainability by promoting local energy production and consumption (Sessa and Malandrino, 2023). According to these authors, Renewable Energy Communities (RECs) support urban redevelopment, enhance energy efficiency, and encourage citizen participation in the production and consumption of energy. This, in turn, contributes to sustainable development and helps address resource scarcity and biodiversity loss in the context of the energy transition.

Despite their benefits, energy communities continue to face regulatory and financial challenges, such as substantial initial investment requirements and slow institutional adaptation (Bellini et al., 2024; Kyriakopoulos, 2022). Nevertheless, energy communities play a significant role in supporting the transition towards renewable energy through the integration of distributed energy resources, the enhancement of energy efficiency, and the promotion of self-consumption. They foster local participation, reduce greenhouse gas emissions, and require supportive regulatory frameworks to prosper and expand globally (Kyriakopoulos, 2022).

Successful examples, such as the Eastern Naples Energy Community, demonstrate the potential of local collaboration for the production and consumption of energy (Sessa and Malandrino, 2023).

Comparative analyses between the EU and the United States reveal differing approaches to integrating energy communities into existing energy systems, offering valuable lessons from both contexts (Energy Communities: Comparative Perspectives from the EU and the US, Savaresi and Outka, 2023).

There has been a rapid increase in the number of energy communities worldwide, driven by the transition to renewable energy sources. These communities play a crucial role in reducing carbon emissions, promoting sustainable practices, and facilitating the shift from centralised to decentralised energy systems (Stanescu et al., 2025). Although energy communities provide a promising pathway to advance the renewable energy transition, the complexities of governance structures and market interactions create significant challenges that must be addressed to fully harness their potential.

Energy communities have emerged globally as a response to the energy transition, supported by favourable regulations and financial incentives. They enable citizens and local authorities to invest in renewable energy, enhancing community participation and contributing to sustainable urban development (Lazaroiu et al., 2025). These communities allow users to actively participate in energy generation, sharing, and storage, facilitating the transition to renewable energy sources and innovative business models (Lopez et al., 2024).

2.1. Energy Communities in Colombia

Energy communities (ECs) were formally introduced into Colombian regulation as a new actor within the electricity market. Their most recent regulatory framework is established in CREG Resolution 101 072 of 2025, issued in compliance with the Ministry of Mines and Energy Decree 2236 of 2024, which forms part of the regulation of Law 2294 of 2022 (Congreso, 2022).

Article 235 of Law 2294 of 2022 states that:
"*Users or potential users of energy services may establish Energy Communities to generate, trade, and/or use energy efficiently through the use of non-conventional renewable energy sources (NCRES), renewable fuels, and distributed energy resources.*"

As this definition indicates, energy communities may generate and trade electricity through NCRES, positioning them as mechanisms for accelerating the energy transition. Their growth reduces fossil-fuel-based electricity consumption and, consequently, avoids CO_2 emissions. They are also a key element in promoting energy democratisation, decentralisation, and economic decarbonisation. Moreover, ECs serve as a tool for fostering local economic development, as they reduce household and business energy expenditures while enabling an additional source of income.

The Ministry of Mines and Energy of Colombia (MinEnergia, 2023) has developed an Energy Communities Management System, in which more than 15,000 potential groups are currently registered as initiatives that could evolve into formal energy communities (UPME, 2024).

At a centralised level, the national government, through the Ministry of Mines and Energy, launched the "Colombia 6 GW Solar" strategy. By the end of 2025, approximately 2 GW of solar capacity had been installed, leaving more than 60% of the 2026 target still pending (UPME, 2025a).

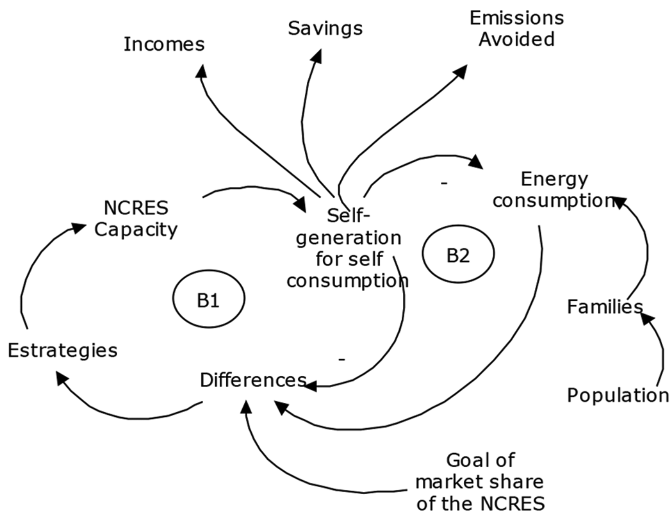
Energy communities in Colombia operate under the regulatory frameworks of collective self-generation and collective distributed generation. These models enable the development of new business opportunities and active user participation in the electricity market. Understanding their impacts on the market, the environment, and the economy is therefore essential.

3. MODEL

A system-dynamics simulation model was developed to represent the behaviour of self-generation and energy consumption in line with the government's NCRES integration target within the National Interconnected System (SIN), and to assess the associated economic and environmental impacts.

According to the Figure 1, the model is limited to electricity consumption among Colombian households and small businesses (regulated market) and simulates the adoption of photovoltaic systems. These systems reduce the energy demand observed by the centralised grid, allow households to save on energy expenditures through netting, and provide a source of income through surplus energy sales (CREG, 2021).

Figure 1: Causal diagram



Self-generation and distributed generation constitute the core variables that enable the formation of energy communities within the model, as their implementation at a collective or aggregated level is equivalent to the creation of a community.

A balancing feedback loop regulates the growth of installed NCRES capacity until the government's target of 4% participation in the electricity commercialisation market is reached. This growth depends on policy impacts and household investment decisions in local energy systems. Additionally, the balance between self-generation and energy consumption preserves the stability of both the electricity and economic systems.

Local energy systems—primarily residential and small-business photovoltaic installations—generate positive environmental impacts by reducing emissions and economic impacts by lowering household energy expenditures and creating revenue opportunities through surplus energy injections.

3.1. Energy Consumption of Households and Small Businesses

Population determines the number of households; one household per family is assumed. Each household consumes energy monthly, so total residential monthly consumption is calculated as:

$$P(t) = P(t-1) + \Delta P(t)$$

$$NH(t) = NF(t) = \frac{P(t)}{NPF}$$

$\Delta P(t)$: Population variation over time t is a function of the monthlyized annual growth rate

$\Delta P(t)$: Population in time t

$$\Delta P(t) = P(t-1) * r_p$$

NH(*t*)*:Number of households=NF* (*t*): number of families in period t

NPF: Number of people per family

r_p: Population growth rate

$$CE(t) = CEH(t)*NH(t)/1.000.000$$

CE(*t*): Energy consumption of all households in period t in GWh/month

CEH(*t*): Average energy consumption of a household in period t in kWh/month

$$CEH(t) = CEH(t-1) + \Delta CEH(t)$$

CEH(*t*): Average household energy consumption in period t depends on the change in household consumption $\Delta CEH(t) = CEH(t-1) * r_{CEH}$

r_{CEH}: Growth rate of household energy consumption.

3.2. Energy Community Model

Under CREG Resolution 101,072 of 2025, ECs are defined as aggregations of individual commercial boundaries that may be consumers, generators, or both—such as users with local self-generation systems.

Energy communities may be analysed through the amount of self-generated and distributed generation near end-users, as both reduce the demand that must be supplied by the centralised market. Self-generation reduces the consumption observed at the user's grid connection point (commercial boundary), while distributed generation reduces energy flows at the substation level.

The expansion of residential and small-business self-generation depends on investment decisions driven by financial profitability, which in turn depends on the electricity tariff and contract prices.

3.3. Energy Production

Self-generation *AG*(*t*) *en kWh/día*:

$$AG(t) = CAPAG(t)*FP$$

$$AG(t) = CAPAG(t)*HPS*(1-P)$$

HPS: Peak solar hours

P: Percentage of technical losses, due to shading, cloud cover, and dirt

FP: Plant factor.

This local energy generation has several uses: for self-consumption, thus reducing the user's energy consumption; to inject surplus energy not self-consumed into the grid, which has two possible uses: to offset energy consumption from grid consumption and to sell surplus energy, resulting from an energy injection into the grid that exceeds consumption.

$$AG_{AC}(t) = AG(t)*F_{AC}$$

F_{AC}: Self-consumption factor

$AG_{AC}(t)$: Self-generation for self-consumption in the period t

$$AG_{SIN}(t) = AG(t)*F_{SIN}$$

F_{SIN}: Grid injection factor

$AG_{SIN}(t)$: Self-generation for injection into the grid during the period t,

In all cases, it must be fulfilled that

$$F_{AC}+F_{SIN} = 1$$

$$AG_{SINeto}(t) = AG_{SIN}(t)*F_{Neteo}$$

F_{Neteo}: Net factor, what part of the energy injected into the grid is netted

$AG_{\text{SINeto}}(t)$: Energy injected into the grid in period t that is netted with the energy consumption of the grid over time t.

$$AG_{venta}(t) = AG_{SIN}(t)*F_{ve}$$

$AG_{\text{venta}}(t)$: self-generated energy that is sold on the market during the period t

F_{ve}: Energy selling factor, what part of the energy injected into the grid is sold

In all cases, it must be fulfilled that

$$F_{Neteo}+F_{ve} = 1$$

3.4. Environmental Impacts — Avoided Emissions

Self-generated energy for self-consumption reduces energy consumption from the grid; therefore, the emissions avoided are calculated based on the SIN emissions factor, since energy from the SIN is no longer generated due to self-consumption.

Self-consumption avoids emissions by reducing the energy generated by the SIN

$$E_{AC} = AG_{AC}(t)*FE_{SIN}$$

E_{AC}: CO_2e emissions in period t due to self-consumption

FE_{SIN}: SIN emissions factor in tCO_2e/MWh

The self-generated energy that is injected into the grid was produced through an energy source, in this case, solar; therefore, the emissions avoided are calculated based on the emission factor of the generation source, i.e., the emission factor of solar energy.

$$E_{red} = AG_{SIN}(t)*FE_{Solar}$$

E_{red}: CO_2e emissions in period t due to injection into the grid

FE_{Solar}: Solar energy emissions factor, in this case photovoltaic, in tCO2e/MWh

3.5. Economic Impacts

The economic impact has two possibilities: savings and income.

Savings can come from two sources: self-consumption at the full energy rate and netting energy consumed from the grid at the full rate minus energy marketing costs. Revenues from selling surplus energy.

Savings from self-consumption

$$A_{AC}(t) = AG_{AC}(t)*Tarifa(t)$$

A_{AC}: Savings from self-consumption in period t in Millions of Colombian pesos

$Tarifa(t)$: User rate in the period t

The rate changes every month and usually increases, so it depends on the rate of rate increase, which is capped at a maximum growth of 3% in each period by regulation.

$$Tarifa(t) = Tarifa(t-1)*(1+r_{tarifa})$$

r_{tarifa}: energy tariff growth rate

The savings from netting, since this depends on the energy injected into the grid, this energy pays the marketing cost, but since it is netted with the energy consumption from the grid, it is calculated based on the tariff and the marketing cost.

$$A_{Neteo}(t) = AG_{SINeto}(t_)*(Tarifa(t)-CV(t))$$

$A_{Neteo}(t)$: Net savings in \$/month

$CV(t)$: Marketing cost in \$/kWh in the period t

The revenue comes from sales of surplus energy on the market at the average price of long-term energy contracts.

$$I(t) = AG_{venta}(t)*P_c$$

P_c: Average price of energy in long-term contracts in the wholesale energy market

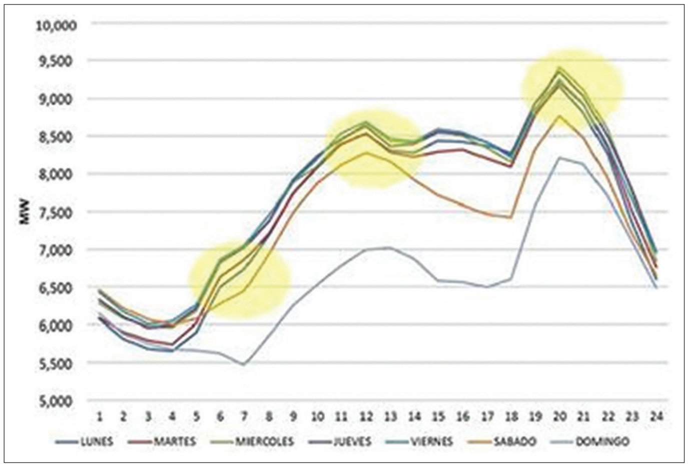
$I(t)$: Income in period t from sale of surpluses in the market

Since the model is in aggregate terms for all households, the calculations correspond to all the energy generated locally by all households and small businesses; the environmental and economic impacts are at the national level.

4. CASE STUDY

The case study used to apply the simulation model corresponds to the regulated electricity market in Colombia, which includes the residential sector and small businesses—both considered potential energy communities under the Colombian electricity market structure. Although the residential sector is categorised socio-economically into six strata (from lowest to highest income), the model treats all strata in aggregate form, as their general patterns of electricity consumption behave similarly. Figure 2 shows the

Figure 2: Average daily load curve in Colombia (XM, 2025)



typical daily electricity-load curve in Colombia, which reflects the predominance of residential consumption.

The wholesale electricity market in Colombia is divided into two segments: the regulated market (69%) and the non-regulated market (31%). The former consists primarily of households and small businesses, whereas the latter is composed largely of industrial users and large enterprises (XM, 2025). For this reason, analysing the regulated market is particularly relevant.

The average monthly electricity demand of the National Interconnected System (SIN), from January 2018 to July 2025, was 6,282 GWh/month, of which the regulated market accounted for 4,335 GWh/month.

According to the National Administrative Department of Statistics (DANE), Colombia's population in 2024 was 53,057,212 inhabitants, with an average of 3.4 persons per household (DANE, 2024a). This corresponds to 15,805,066 households and an electricity-coverage level of 93% (UPME, 2023). The average per-household electricity consumption was 161 kWh/month (SUI, 2025). However, because the regulated market includes both households and small businesses, the consumption value is adjusted to reflect their combined 69% share in total demand. This yields an adjusted average consumption of 274 kWh/month (XM, 2025).

The average electricity tariff is 17¢USD/kWh, with a growth rate of 5%, according to the tariff bulletin of the Superintendence of Public Utilities (Superservicios, 2025) with a 4,330 COP/USD (Banrep, 2025). The average long-term contract price of electricity is 7¢USD/kWh (XM, 2025a), with an annual growth rate of 3%.

Additionally, the emission factor of the Colombian SIN is 0.117 tCO_2e/MWh, and that of solar PV generation—used for avoided-emissions accounting in projects—is 0.34 tCO_2e/MWh (UPME, 2023a, 2024a).

The national target for integrating NCRES into the NIS is 4% of the electricity-commercialisation market (CREG, 2021).

The time required for households to adopt NCRES technologies—mainly rooftop PV systems—as well as the time needed for group formation, administrative processes, investment decisions, and installation until systems become operational ranges between 12 and 18 months.

The case study considers a 20-year analysis horizon, with monthly periods, based on the official and publicly available historical information from 2018 to 2025.

5. ANALYSIS OF RESULTS

The first stage consists of evaluating the profitability of a unit-scale photovoltaic system (1 kWp) for an individual user. Based on this assessment, the aggregated analysis for energy communities is conducted, estimating national-level environmental and economic impacts.

5.1. Profitability Analysis for an Individual User

A 1 kWp photovoltaic system costs approximately USD 1,048 (IRENA,2024). This capacity generates the following energy:

$$AG(t) = CAPAG(t)*FP$$

$$AG(t) = 1\ kWp*HPS*(1-P)$$

PS (*Solar Peak Hours*): *approx.4.5 h/day in Colombia* (*IDEAM,2017*)

P (*Losses*): 20-25% *due to shading, cloudiness, dirt, etc.*

CF (*Capacity Factor*): *approx*.15%

$$AG(t) = 1kWp*4.5*(1-20\%)$$

$$AG(t) = 3.6\frac{kh}{d}\,o\ 108\ kWh/mes$$

5.2. Savings and Incomes

5.2.1. Savings from self-consumption

Assuming that 50% of the generated energy is self-consumed (while Colombia receives 12 hours of sunlight, only 4-5 h/day correspond to peak solar conditions), the savings amount to: COP 9.2 USD/month, for a typical electricity bill (without self-generation) of 18.4 USD/month.

$$A_{AC}(t) = 108\frac{kWh}{mes}*50\%*17\ ¢USD/kWh$$

5.2.2. Savings from netting

Assuming that 50% of injected energy is netted against grid consumption, the savings amount to: 4 USD/month, This calculation considers typical tariff-component shares: Generation (33%), Transmission (6%), Distribution (35%), Commercialisation (13%), Losses (7%).

These values are representative of the national electricity market due to the scale of Empresas Públicas de Medellín (EPM), which accounts for more than 25% of national electricity generation and 13% of users (EPM, 2024; 2025).

$$A_{Neteo}(t) = 50\%*54kWh/mes*(17-2)¢USD$$

Total Savings=9.2+4=13.2 USD/month

Equivalent to 72% of a typical electricity bill.

5.3. Revenue from Surplus Energy Sales

If 50% of the injected energy is sold at the long-term contract price, the expected revenue is: 2 USD/month, equivalent to 11% of a typical electricity bill.

$$I(t) = 50\%*54\frac{kWh}{mes}*7\ ¢USD/kWh$$

5.4. Investment Recovery Period

Given the combined value of savings and revenue, a residential user installing a 1 kWp system with a cost of approx. $ 1,048 USD recovers the investment in around six years. If we include the tax benefits of Law 1715 of 2014, especially the 50% deduction of the investment from income tax, the investment recovery period could drop to 4.6 years.

5.5. Environmental Impact

Avoided Emissions from Self-Consumption

$$E_{AC} = 54\frac{kWh}{mes}*0.112\ \text{tCO}_2\frac{\text{eq}}{\text{MWh}} = 6\ kg\text{CO}_2$$

Avoided Emissions from Grid Injection

$$E_{red} = 54\frac{kWh}{mes}*0.493\ \text{tCO}_2\frac{\text{eq}}{\text{MWh}} = 27\ kg\text{CO}_2$$

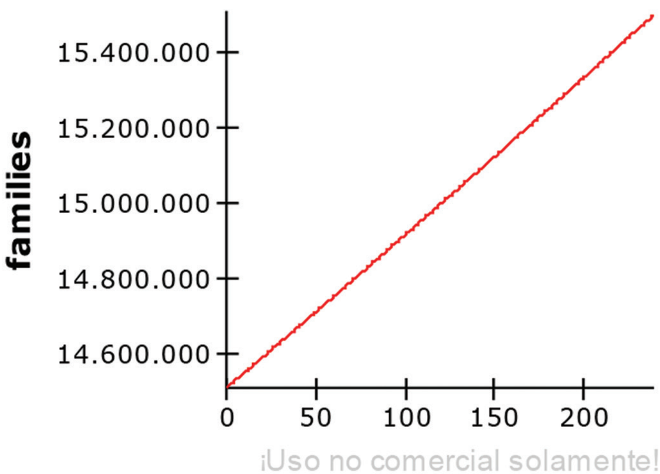
5.6. Electricity-market Impacts

According to the Table 1, the behaviour of population (households), electricity demand, tariffs, and long-term contract prices exhibits exponential or near-exponential growth. For example: Households grow from 14.5 million to 15.5 million over the simulation horizon.

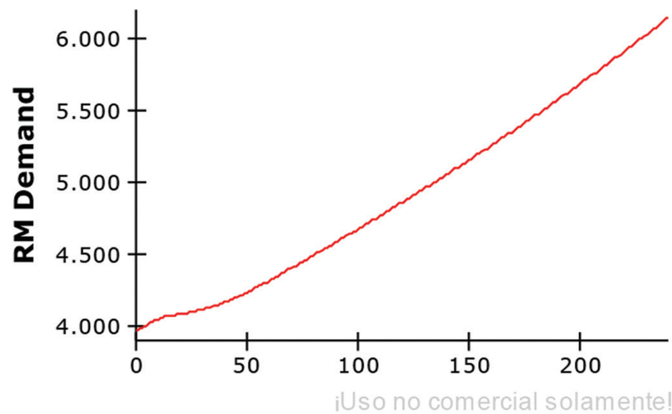
Tariffs triple over 20 years, and long-term contract prices increase by 82%.

Table 1: Behaviour of households, demand, tariffs, and contract prices

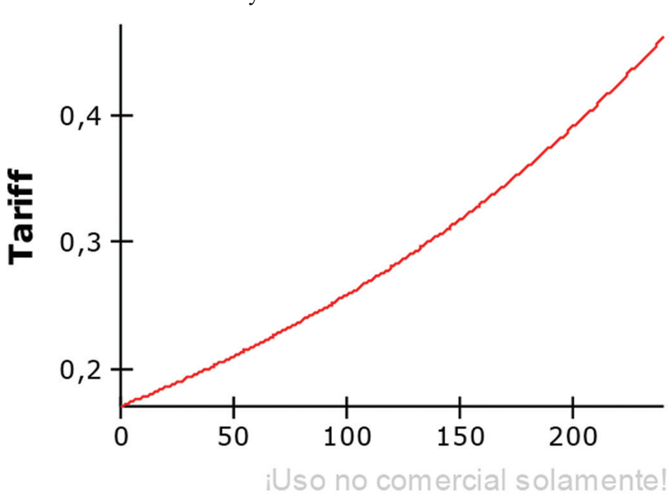
Growth of regulated user households



Behaviour of regulated energy demand



Behaviour of the electricity tariff



Energy price behaviour in long-term contracts

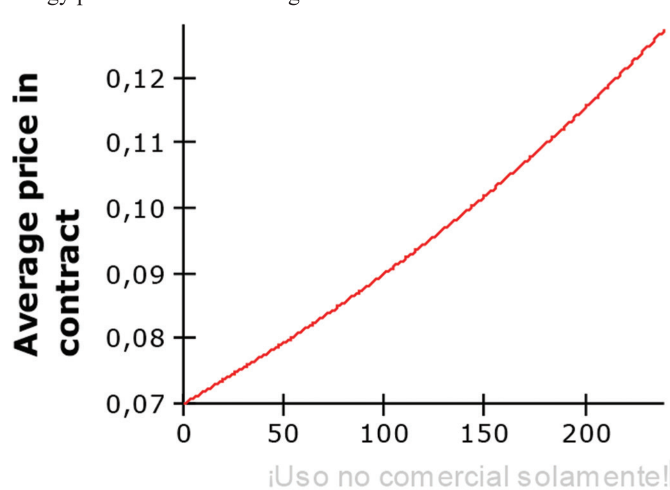
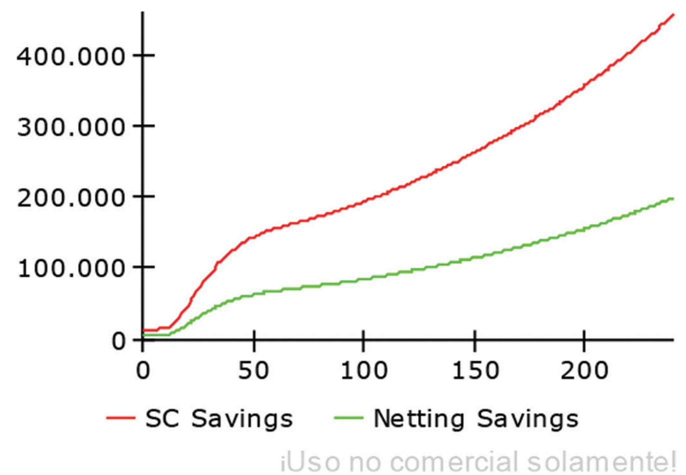
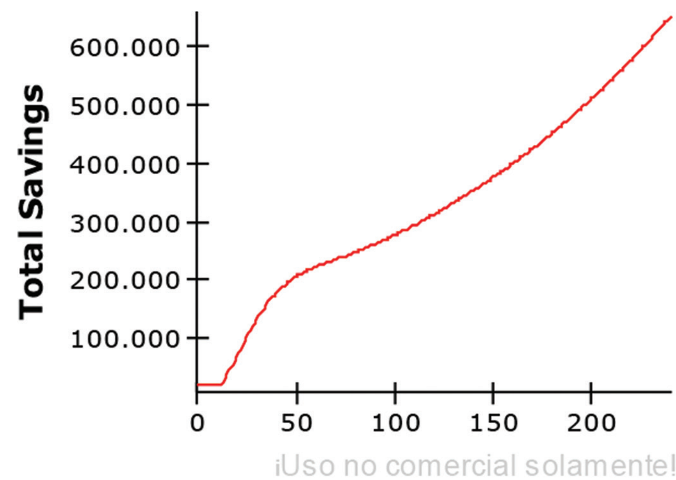


Table 2: Table of figures showing the behaviour of savings and the level of expected income

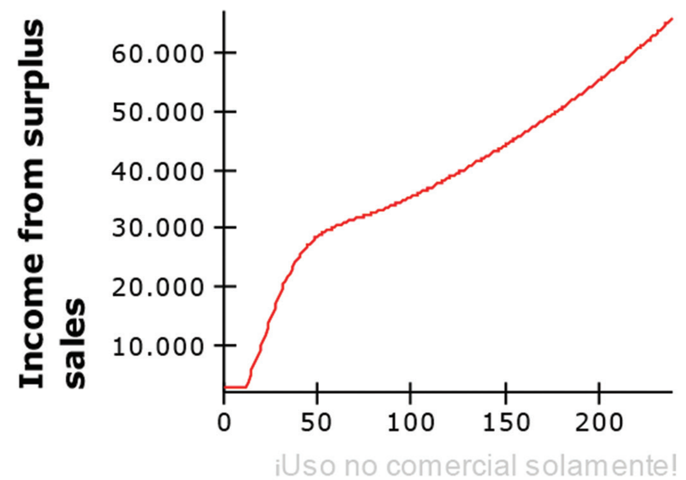
Savings through self-consumption



Total savings



Incomes



Total savings plus income

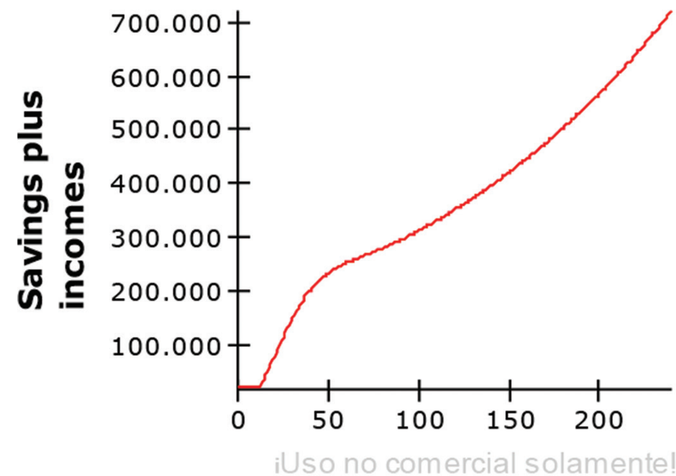


Figure 3: Behaviour of avoided emissions

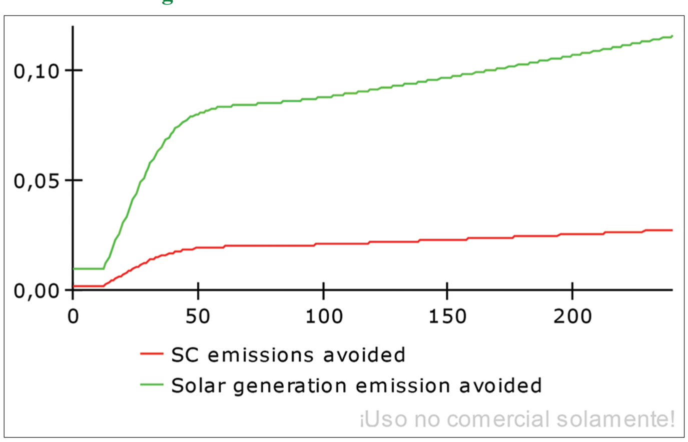
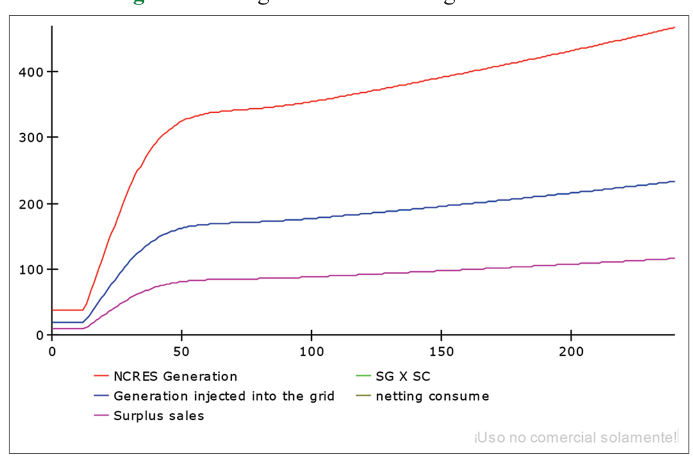


Figure 4: Self-generation in the regulated market



Electricity demand increases from 3,960 GWh/month to 6,144 GWh/month, equivalent to a 55% increase, despite reductions from self-generation.

Environmental impacts under collective self-generation and collective distributed generation are quantified through avoided greenhouse-gas emissions. The emission factors used were: SIN emission factor (2024): 0.112 tCO_2e/MWh, Solar project emission factor: 0.493 tCO_2e/MWh

5.7. Environmental Impacts of Energy Communities

Avoided Emissions from: Self-consumption and Grid injection of solar electricity.

These follow an asymptotic curve, constrained by the maximum NCRES penetration limit allowed in the SIN.

Due to the energy consumption avoided as a result of self-generation for self-consumption

$$E_{AC} = 19\frac{GWh}{month} * 0.112\ \mathrm{tCO_2}\frac{\mathrm{eq}}{\mathrm{MWh}} = 2{,}128$$
$$\mathrm{tCO_2}\frac{\mathrm{eq}}{\mathrm{month}}\, o\, 25{,}536\ \mathrm{tCO_2\ eq / year}$$

By injecting electricity generated from solar energy into the grid

$$E_{red} = 19\frac{GWh}{month} * 0.493\ \mathrm{tCO_2}\frac{\mathrm{eq}}{\mathrm{MWh}} = 9{,}367$$
$$\mathrm{tCO_2}\frac{\mathrm{eq}}{\mathrm{month}}\, o\, 112{,}404\ \mathrm{tCO_2\ \ eq / year}$$

As can be seen in the Figure 3, the behaviour of emissions avoided by self-generation for self-consumption and injection into the grid, an asymptotic curve shape limited by the generation limits determined by the integration limit of the NCRES to the NIS.

According to the Figure 4, household and small-business generation for self-consumption, netting, and surplus sales exhibits:
An initial constant period due to adoption delays, followed by asymptotic growth limited by the 4% NCRES integration cap, with PV generation split equally between self-consumption and injection, and injection equally divided between netting and surplus sales.

5.8. Economic Impacts

Savings from self-consumption and netting are presented as follows in the Table 2:
The behaviour of these variables follows an extended S-curve, showing: exponential growth in the first 4 years, asymptotic behaviour over the next 4 years, renewed exponential growth during the final 10 years.

Total economic impacts increase from: 4.5 Million USD/month (1st year) to 151 Million USD/month (last year), equivalent to 18,505 Million USD accumulated.

Expected revenues increase from: 8.1 Million USD/year (1st year) to COP 183 Million USD/year (year 20) equivalent to 2,065 Million USD accumulated.

6. CONCLUSION

With Colombia contributing less than 1% to global energy indicators—0.21% of installed capacity, 0.27% of electricity generation, 0.34% of global energy consumption—and similarly limited participation in demographic (0.65% of world population) and economic terms (0.21% of global GDP, with the global per-capita income being 3.2 times that of Colombia), the country's share of global environmental pollution is likewise minimal, representing only 0.6% of global energy-related CO_2 emissions.

In this context, Colombia must reconsider the strategic direction of its energy policy in the short and medium term. As in the global scenario, the transport and industrial sectors are the largest consumers of energy and the main contributors to environmental pollution.

Fossil fuels—coal, oil, and natural gas—continue to dominate both supply and consumption, representing around 70% of total energy use at global and national levels. Therefore, the energy transition requires more effective public-policy measures aimed at achieving economic decarbonisation.

A comparison between Colombia and the rest of the world regarding renewable electricity capacity shows that Colombia has a 20% higher share of renewable energy in its electricity mix. However, with respect to non-conventional renewable sources such as solar PV, Colombia remains significantly behind: only 2% solar participation, compared with the 17% global level. This discrepancy stems from the predominance of hydropower in Colombia's electricity mix, whereas the global mix is largely fossil-fuel-based.

Higher income levels are closely associated with higher energy consumption: in other words, energy is a driver of economic development. Consequently, if energy consumption is primarily supplied by renewable sources, the energy sector contributes directly to sustainable development by mitigating climate change.

Colombia's energy-community policy should, in practice, encompass not only electricity but all forms of energy consumption across daily activities and economic sectors, both urban and rural.

The environmental and economic impacts of energy communities are substantial. Under the assumptions and modelling conditions presented in this article, energy communities could: Avoid 25 $MtCO_2e$, generate $ 18.5 Billion USD in savings, and produce approximately 2 Billion in additional from incomes, for the regulated market, which is composed primarily of households and small businesses.

The results demonstrate that increasing the allowable integration limit of NCRES into the SIN beyond the current 4% would generate even greater environmental and economic benefits for Colombia. These benefits would be reflected in the consumer surplus and could be further leveraged through the creation and expansion of energy communities, provided that their development is effectively implemented under the current regulatory framework.

An individual profitability analysis was carried out so that households and small businesses find investing in their own (solar) energy system attractive. Not only should the legal tax incentives continue, but alternative ways of capturing these incentives should also be sought, since few households and small businesses can take advantage of these tax benefits, for example, direct refund of part of the investment through the payment of the value added tax (VAT) or deduction of the payment of property tax on the properties

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