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Decarbonisation dynamics through electrification: Sectoral pathways for Colombia

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ABSTRACT

Electrification facilitates decarbonisation; however, its effectiveness depends on the way. public policies shape demand-side technological substitution across end-use sectors. In Colombia, despite efforts to integrate renewable energy sources into the electricity mix, the energy transition remains constrained by insufficient policy coordination across transport, residential, tertiary, and industrial sectors, placing the country at risk of failing to meet its CO2 emissions reduction targets. While existing studies propose multiple transition pathways – largely focused on developed economies – demand-side dynamics and behavioural responses to policy-driven technological substitution remain marginal in analyses of developing countries. To examine these dynamics, a sectoral energy transition model for Colombia is developed using a system dynamics approach that captures feedback between public policy, consumer behaviour, and long-term energy demand. Results indicate that a transformation of the Colombian energy matrix by 2050 is achievable from the demand side, provided electrification policies prioritise transport, residential, and tertiary sectors. Residential electrification rises from 47% in 2024 to over 92% by 2050, while clean technologies exceed 80% of the transport fleet. Economy-wide electrification increases electricity demand by a factor of 3.5, requiring a 4.3-fold expansion of fully renewable electricity generation capacity.

Keywords

Energy transition;
System dynamic;
Energy uses;
Renewable energy;

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Abbreviations

ACPM	Diesel fuel in Colombia	IPCC	Intergovernmental Panel on Climate Change
BAU	Business as Usual	LCOE	Levelised Cost of Energy
BECO	Colombian Energy Balance	LEAP	Low Emissions Analysis Platform
BEU	Useful Energy Balance	LED	Light-Emitting Diode
BRT	Bus Rapid Transit	NDC	Nationally Determined Contribution
CNG	Compressed Natural Gas	NEMESIS	New Econometric Model of Evaluation by Sectoral Interdependency and Supply
DANE	National Administrative Department of Statistics of Colombia	NGV	Natural Gas Vehicle
E7	Group of seven emerging economies	OECD	Organisation for Economic Co-operation and Development
E2050	Colombian's Long-Term Climate Strategy to 2050	PRIMES	Price-Induced Market Equilibrium System
EE	Electricity	R&D	Research and Development
ET	Energy Transition	TIMES	The Integrated MARKAL–EFOM System
FeliX 2.0	Integrated model of climate, economy, environment, and society interactions	TPC	Collective Public Transport
FW	Firewood	UPME	Mining and Energy Planning Unit of Colombia
G7	Group of Seven		
GDP	Gross Domestic Product		
GEM-E3	General Equilibrium Model for Economy, Energy, and Environment		
GHG	Greenhouse Gas		

1. Introduction

Limiting global temperature increase to well below 2 °C, and preferably not more than 1.5 °C, requires sustained and economy-wide reductions in greenhouse gas emissions, as established by the Paris Agreement [1] and reinforced by successive IPCC assessment reports [2]. In response, energy transition strategies have been widely adopted [3], predominantly focusing on transforming electricity generation through the deployment of renewable energy sources [4]. For example, Indonesia's energy transition strategy assesses replacing coal with biomass in the electricity generation mix [5], whilst Japan investigates the governance factors driving municipal decision-making in cities towards the development of decentralised renewable energy [6].

However, in many countries, this supply-oriented focus has not been accompanied by an equivalent transformation of final energy consumption. In Chile, neglecting climate change's impact on demand projections leads to overestimating system costs and incompletely characterising the optimal technological transition pathway [7].

In line with its international commitments, Colombia has pledged to reduce greenhouse gas emissions by 51% by 2030, relative to a business-as-usual trajectory, and to achieve carbon neutrality by 2050 [8]. These targets, articulated in the country's Nationally Determined Contributions (NDCs) and its Long-Term Climate Strategy (E2050) [9], have driven recent policies aimed at diversifying the electricity generation mix through the deployment of unconventional renewable energy sources. Nevertheless, policies targeting structural changes in final energy use across the residential, transport, industrial, and commercial sectors remain limited [10]. This imbalance constrains the effectiveness of the energy transition and poses a significant challenge to advancing towards an integrated framework that jointly addresses energy supply and demand.

The literature on energy transition policies reflects this fragmentation. Some studies rely on simplified relationships or correlations to explain transition dynamics, often abstracting from the complexity of the energy system [11-12]. Others employ comprehensive modelling frameworks but are typically grounded in assumptions of perfect competition or fully rational agents, which limits their ability to represent dynamic, non-linear interactions and behavioural responses [13]. System dynamics approaches have been applied to analyse specific sectors [10,14-17], yet these studies

frequently lack a detailed representation of energy demand behaviour under technological substitution driven by either cost competitiveness or public policy interventions [18-19].

Against this background, this article's central contribution lies in proposing a detailed demand-side modelling framework for Colombia that captures fuel switching dynamics by sector, explicitly accounting for technological substitution and sector-specific end-use characteristics – a dimension that national-level transition studies have largely overlooked. The model incorporates feedback mechanisms between productive sectors through GDP-energy linkages, enabling a more integrated treatment of demand dynamics than prior approaches have provided. This, in turn, enables a rigorous assessment of the challenges and opportunities associated with Colombia's energy transition, including the implications for electricity demand growth and power generation capacity requirements to 2050.

Section 2 reviews the literature on models used to evaluate public policies for the energy transition. Section 3 describes the proposed modelling framework. Section 4 discusses the simulation results and their policy implications for Colombia. Section 5 presents the conclusions.

2. Literature review

The energy transition has been widely analysed as a central response to climate change in both developed and developing country contexts. Across the literature, recurring enabling factors include economy-wide electrification, the expansion of renewable electricity generation, improvements in energy efficiency, and the effectiveness of regulatory frameworks.

Using econometric techniques, several authors show that, for country groups such as the G7, E7, OECD, and the United States, regulatory effectiveness [11], revenues from minerals, oil, and natural gas extraction, alongside economic growth [20], mineral market dynamics [21], green energy production, and reduced political and financial risks [22] are associated with faster transition progress. By contrast, social inequalities [11], coal-related revenues [20,22], dependence on forest resources, and geopolitical risk [20] are consistently linked to slower or more constrained transition trajectories.

Despite their empirical value, much of this evidence rests on linear specifications and correlation-based inference. This framing is poorly suited to an energy system characterised by intersectoral interdependence, feedback effects, and time delays, in which policies can trigger non-linear responses. Approaches that make these dynamics explicit are therefore required to assess how public interventions reshape the system beyond immediate or isolated effects.

Plazas-Niño [23] provides a systematic review of optimisation models used in energy system planning and shows that these tools are routinely applied to map decarbonisation pathways, compare technological alternatives, assess policy effects, quantify environmental impacts, and support decision-making under uncertainty. In essence, optimisation frameworks seek the least-cost combination of technologies and fuels that meets final energy demand while satisfying constraints on resource availability, system costs, and emissions.

In this context, Vaillancourt [24] applies the TIMES optimisation model to examine Canada's decarbonisation pathway to 2050. The model minimises total system cost subject to demand satisfaction and national greenhouse gas (GHG) reduction targets. Results suggest that decarbonisation is technically feasible, but only under substantial structural change, including economy-wide electrification, full decarbonisation of electricity supply, and marked improvements in energy efficiency – together allowing emissions to fall by up to 60% by 2050. Osorio et al. [25] employ an hourly-resolution optimisation model to simulate the technical and economic feasibility of a 100% renewable system for Chile, demonstrating that a more efficient and cost-effective system than the current one is achievable, whilst also showing that zero GHG emissions could be attained.

At the European level, Capros et al. [12] review modelling families used to assess decarbonisation pathways under alternative technology and policy assumptions. These include partial equilibrium energy models (e.g., PRIMES and TIMES-PanEu), computable general equilibrium models (e.g., GEM-E3 and WorldScan), and the macroeconomic model NEMESIS. The general equilibrium models and NEMESIS focus on economy-wide implications, including effects on GDP, consumption, employment, and sectoral investments. Barkhordar [26] uses a computable general equilibrium model to analyse the impact of energy efficiency improvements in Iran's energy-intensive industries. Partial equilibrium models [12], by contrast, provide detailed representations of technology portfolios on both supply and demand sides, yet typically lack endogenous feedback linking climate policies, economic activity, and

demand evolution, thereby limiting their ability to represent the more complex dynamics through which policies propagate across the system.

Other strands of the literature adopt more comprehensive, multi-sectoral approaches to examine energy consumption, mitigation strategies, and the integration of social aspects into the energy transition [27]. Elizondo et al. [28], for instance, develop scenario analyses for Mexico covering transport, energy, agriculture, industry, and residential and commercial sectors. Using a system dynamics model, they link primary energy sources to greenhouse gas emissions through both supply and demand, thereby highlighting cross-sectoral synergies and binding constraints that shape mitigation outcomes.

Even where analyses span multiple sectors, important limitations remain. Econometric approaches frequently rest on assumptions such as perfect competition or fully rational agents and are therefore ill-equipped to represent feedback processes, non-linear interactions across systems, or discontinuities associated with disruptive technological change [12-13]. System dynamics offers a stronger basis for capturing such features; nonetheless, it is not without its constraints, insofar as it does not yield optimal solutions, and in aggregate-level models, sector-level behavioural and substitution dynamics risk being understated.

Notwithstanding these limitations, system dynamics is preferred in this study. Given that the primary interest lies in capturing consumer behaviour under non-optimal conditions and in analysing sectoral responses to technological change, it is better suited to the research objectives of identifying suitable policies than alternative approaches. Moreover, its greater tractability and its capacity to communicate model structure and underlying assumptions to policy-making stakeholders render it the more appropriate choice [3, 12-13].

This is evident in global system models. Ye et al. [29] present the FELIX 2.0 model, which represents feedback, delays, and non-linearities across nine interconnected systems, including population, economy, energy, water, land, food, the carbon cycle, climate, and biodiversity. Notwithstanding this integrative scope, energy demand is largely modelled on a per capita basis, driven by wealth, rather than disaggregated by sector and shaped by technological substitution or policy intervention. This aggregation, compounded by the model's global scale, limits its ability to capture inter-regional heterogeneity and constrains the design of targeted policies for localised energy challenges.

Similar constraints appear in national applications. Karbasioun et al. [30] analyse transitions in fossil-fuel-rich countries using system dynamics and assess the techno-economic and environmental impacts of alternative policies. Although they disaggregate energy demand by sector, electricity demand projections rely on statistical and regression methods based on fossil-fuel and demographic variables, with transport electricity demand estimated separately. This structure limits the endogenous representation of substitution dynamics across sectors.

System dynamics has also been applied to developing-country transitions, including Indonesia [3], Vietnam [31], and Ethiopia [32], through models linking supply, demand, demographic, economic, and emission modules. These studies identify industry as the main driver of electricity consumption, but they do not capture how electricity demand growth feeds back into GDP, and how economic expansion, in turn, shapes energy use and the pace of transition. As a result, macroeconomic interdependencies – central to policy assessment – remain only partially represented.

In Colombia, Nieves [33] develops an integrated assessment of energy demand and greenhouse gas emissions across residential, transport, industrial, and tertiary sectors, employing LEAP as the modelling framework. LEAP is an accounting-based, end-use-driven tool that calculates energy requirements from sectoral activity levels and the energy intensity of each end-use, whilst incorporating exogenous growth rates. However, the analysis does not explicitly represent cross-sector linkages, nor the feedback and time-delay mechanisms among sectors and the economy, features that are central to evaluating policy effectiveness in complex energy transitions.

Zapata [15] adopts a system dynamics approach to assess the feasibility of achieving 100% renewable penetration in the electricity generation mix, whilst accounting for delays in both transmission and generation infrastructure. To this end, the model represents the intraday electricity dispatch between two interconnected regions of the country via a high-voltage grid. It captures how project delays affect electricity prices, which in turn influence electricity demand, with demand simulated on the basis of UPME demand projections and two elasticities: price elasticity and GDP elasticity of demand.

Castaneda et al. [34], in turn, combines scenario planning and system dynamics to incorporate social acceptance and political willingness as pivotal

dimensions of Colombia's energy transition. In line with Zapata [15], the model seeks to assess the feasibility of achieving a 100% renewable generation mix, whilst treating electricity demand as an exogenous variable. Notwithstanding the methodological contributions of these studies, the two models focus exclusively on the transition within the power generation sector, overlooking the impact of energy policies on other sectors of the economy.

A further dimension of the energy transition concerns electricity access in off-grid areas – both initial provision and the expansion of service hours – alongside the transformation of the generation mix in communities not connected to the national grid. Garces [35] draws on the strengths of system dynamics, notably its capacity to incorporate feedback loops and represent long-term interactions between electricity supply and demand, to propose a model that evaluates strategies to improve electricity access across five sustainability dimensions: environmental, economic, social, technological, and institutional.

Whilst each of these contributions advances the application of system dynamics to Colombia's energy transition [15,34-35], none adopts a fully integrated, cross-sectoral perspective that captures the interdependencies between the power generation sector and the broader economy.

Related work has examined specific policy domains, including electromobility measures, the risks of transition slowdowns arising from weak actor coordination [36], and the impacts of wind power penetration under political, economic, social, and technical conditions [10]. Yet these studies typically remain partial: they do not trace system-wide implications or quantify the aggregate contribution of such measures to national emissions reductions when interactions across end-use sectors are taken into account.

Overall, the review confirms that demand dynamics remain under-analysed. In particular, limited attention has been paid to how energy-use behaviour responds to policy-driven technological substitution across sectors, and how these shifts reshape the energy mix of a developing country. A further omission concerns the feedback between the energy transition and economic growth: changes in energy demand can influence GDP, and economic growth, in turn, can alter energy use, technology uptake, and the pace of the transition.

This article addresses these gaps by analysing how public policies can steer Colombia's energy transition through sectoral electrification. A system dynamics model is used to capture technological change, end-use substitution dynamics, and intersectoral interactions, providing a policy-relevant, system-wide assessment of decarbonisation pathways and their implications for development.

3. Methodology

An integrated, multisectoral system dynamics model is developed to capture cross-sector feedback and the time delays that characterise the system. The model is used to evaluate the impact of alternative public policies on the energy transition in a developing country, and to assess how such interventions may influence final energy use, electricity demand, and long-term emissions trajectories. The framework is applied to the Colombian context, but it is designed to be transferable to other countries.

The model is described from a demand-decision perspective, focusing on the choices that shape energy consumption. Figure 1 summarises the structure linking sectors, the end uses associated with each sector, and the decision-maker responsible for those end uses.

Population growth increases household formation and travel demand, affecting energy consumption in both the residential and transport sectors. Economic growth raises household purchasing power, influencing technology choice for domestic equipment and mobility patterns by altering trip rates and mode choice. Economic growth also affects energy demand in the industrial and tertiary sectors, which in turn feeds back into sectoral economic activity. Ultimately, sectoral technological change and growth jointly shape the national energy configuration and, consequently, national CO_2 emissions. Figure 2 provides a simplified view of the interconnections between model modules.

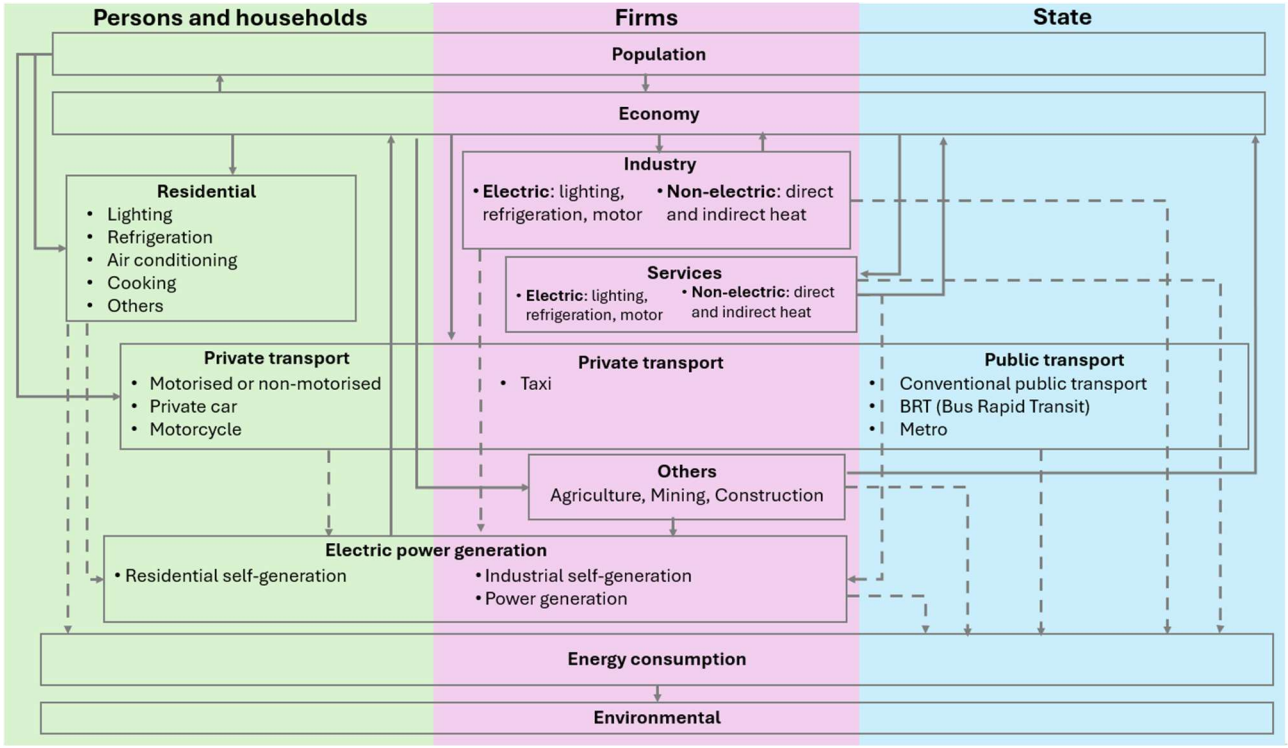


Figure 1: Model structure linking decision-makers, sectors, and end uses.

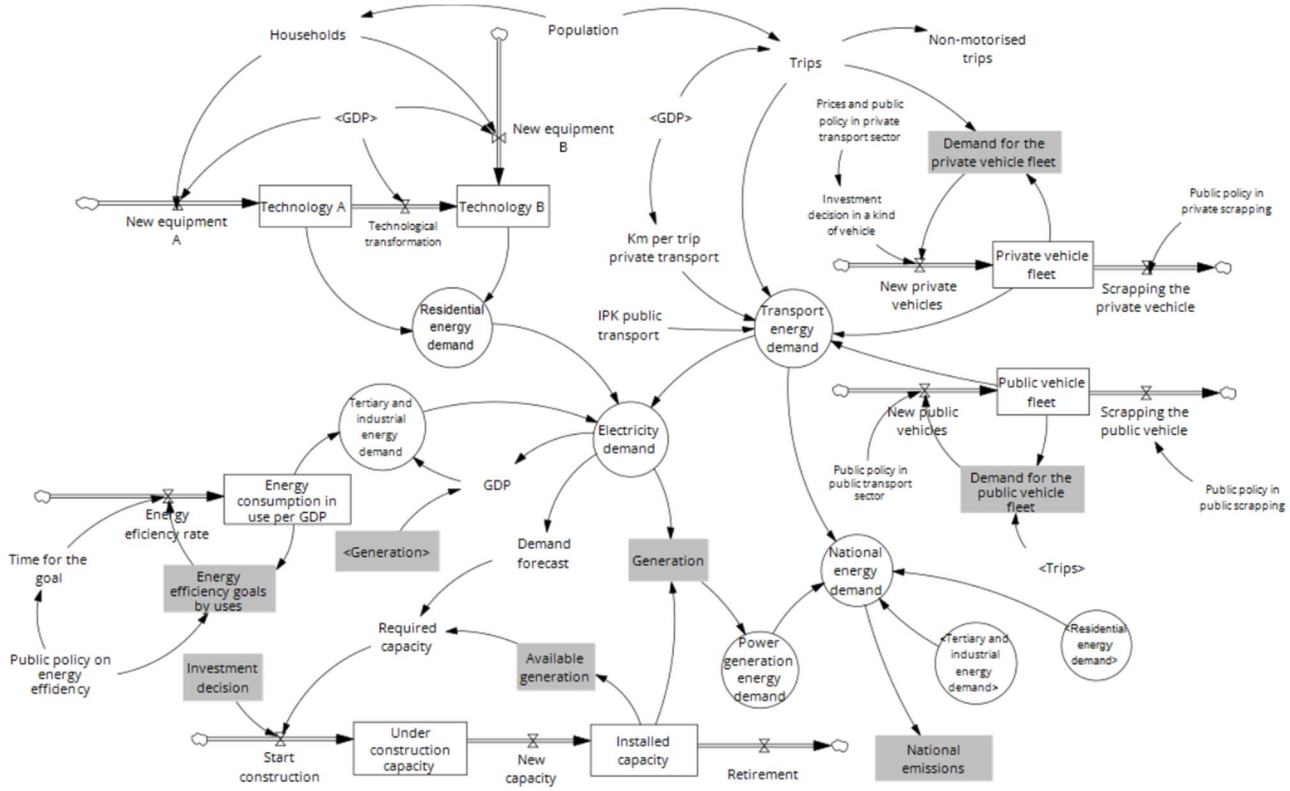


Figure 2: Simplified model structure and sectoral interrelations.

The methodology section concludes with a characterisation of Colombia's energy context and defines the scenarios used for policy assessment.

3.1 Individual and household decision-making on energy consumption

Households shape the energy transition through their end-use choices and the technologies that provide energy services. In the model, household decision-making is represented in three domains: i) basic energy services, ii) mobility choices, and iii) self-generation.

3.1.1 Basic energy services

The residential module represents energy uses for lighting, refrigeration, air conditioning, cooking, and other household end uses. Lighting, refrigeration, and air conditioning are powered by electricity, whereas cooking and miscellaneous uses rely on a mix of electricity, gas, and firewood. For electricity-based end uses, the model first estimates the number of households with electricity access, distinguishing newly electrified households from those already connected, and separating urban and rural areas (Appendix A).

For each end use (lighting, refrigeration, and air conditioning), the model simulates technological transitions amongst equipped households, distinguishing between urban and rural contexts. Lighting diffusion across technology tiers – incandescent, fluorescent, LED, and prospective future technologies – is governed by national R&D investment levels and GDP, with higher investment shortening the time to transfer between successive technologies. Refrigeration follows an approximately 10-year replacement cycle, consistent with equipment turnover patterns in Colombia, with efficiency improvements embedded in new appliances. Air conditioning captures the substitution of fans by air-conditioning units through an exponential function linked to per capita GDP: once this exceeds 20,000 USD, the transition rate reaches 10% in urban areas and 4% in rural areas. These parameters were calibrated through expert elicitation. For both new connections and replacement cycles, appliance efficiency improvements are incorporated. Total household electricity consumption, $C_{h,elect}$, is calculated as a function of the number of appliances $N_{Tech\,X,z}$, unit consumption $W_{Tech\,X,z}$, and utilisation factors $U_{Tech\,X,z}$, as shown in Eq. 1:

$$C_{h,elect}(t) = \sum_{z=1}^{2} \sum_{x}^{A,B,\dots X} HH_{Tech\,X,z}(t) * N_{Tech\,X,z}(t) * W_{Tech\,X,z}(t) * U_{Tech\,X,z}(t) \quad (Eq.1)$$

Where $HH_{Tech\,X,z}$ represents the number of households using Technology X in area z (urban and rural). Cooking is represented by a primary technology choice at the household level (firewood, gas, or electricity). Technological substitution is driven by policy targets that specify the desired shares of cooking fuels over time. Households using firewood may shift to gas or electricity depending on the clean-cooking pathway defined in public policy. Cooking energy demand is calculated by multiplying the number of households using each fuel by the average annual per-stove consumption, accounting for efficiency improvements over time. The module also represents uptake of electric water heating and additional appliances (including smart-home systems) as functions of economic growth and purchasing power.

3.1.2 Decisions related to mobility

Mobility decisions are represented in the transport module to capture how travel behaviour and technology adoption jointly shape the evolution of the transport energy mix. Individuals allocate trips between non-motorised and motorised modes. Motorised travel is distributed across private cars, motorcycles, taxis, conventional public transport, BRT (Bus Rapid Transit), and metro systems, with these choices determining the evolution of the modal fleet over time. In turn, the technological composition of the fleet (shaped by costs and public policy) drives the sector's energy mix.

Trips per person are modelled as a function of GDP per capita, whereby economic growth drives higher daily travel demand across both large and small-to-medium cities. The share of motorised and non-motorised trips varies according to the policy scenario under evaluation and the socio-economic stratum of travellers, and is represented as a proportion of total trips. Once the volume of motorised trips per socio-economic group is established, mode choice is simulated through a multinomial logit specification – widely employed in the literature [37] for representing discrete decision-making, with its parameters calibrated using origin-destination surveys from major Colombian cities [38-40]. For motorised modes, choice is driven by travel time, monetary cost, and perceived comfort, with heterogeneous effects across urban contexts. The model distinguishes large cities from medium and small cities to reflect differences in trip characteristics and available

alternatives. Income segmentation is explicitly represented using Colombian socio-economic strata, distinguishing lower-income (strata 1-3) and higher-income (strata 4-6) groups, which exhibit systematically different mobility patterns and responses to policy. The probability of choosing mode i (car, motorcycle, taxi, public transport, or BRT system) is thus expressed as [37]:

$$T_{i,k} = QMot_k \frac{e^{V_{i,k}}}{e^{\sum V_{i,k}}} \quad \text{(Eq. 2)}$$

$$V_{i,k} = -\mu\left(TT_i * VoT_k + Var_i + Conf_{i,k}\right) \quad \text{(Eq. 3)}$$

Where $T_{i,k}$ denotes the number of trips made using transport mode i by individuals belonging to socio-economic stratum k (lower-income or higher-income groups). $QMot_k$ represents the total number of motorised trips generated by individuals in stratum k. $V_{i,k}$ is the systematic utility associated with transport mode i for individuals in stratum k, while μ is the scale parameter of the multinomial logit model. The utility function is determined by travel time, travel cost, and comfort-related costs. Specifically, TT_i represents the travel time associated with mode i, VoT_k denotes the value of time for individuals in stratum k, Var_i corresponds to the monetary travel cost of mode i, and $Conf_{i,k}$ represents the perceived comfort-related cost associated with using mode i for individuals in stratum k.

The same behavioural structure is applied across city types. As motorised travel demand increases, demand for the corresponding vehicle fleets rises accordingly. Within each mode, vehicles can adopt alternative technologies, including petrol, compressed natural gas (CNG), diesel (ACPM), battery-electric, hybrid, and hydrogen. Technology choice is modelled using a logit structure in which utility reflects both user constraints and policy signals, captured through attributes such as driving range, mobility restrictions, purchase cost, and operating and maintenance costs.

Transport energy use is endogenously derived from mobility patterns and technology choices. Trips are allocated across technologies according to fleet composition and converted into vehicle-kilometres travelled using average trip distances by mode. Energy demand is then calculated by applying technology-specific efficiencies to these vehicle-kilometres, yielding consumption by energy carrier (Appendix A, Eqs. A7-A8).

3.1.3 Decisions related to self-generation:

Households either rely on grid electricity or adopt rooftop solar, which reduces grid-supplied residential demand and affects long-term generation planning. In the model, self-generation is treated as a scenario assumption within the electricity generation module. Under the energy transition scenario, residential self-generation supplies 20% of residential electricity consumption by 2040 and remains at that level until 2050. This share is netted from grid demand, reflecting the reduction in system load and its implications for capacity planning.

3.2 Firm-level decision-making

Firm-level decisions shape sectoral energy demand and, consequently, energy transition pathways. The model represents four decision domains: i) energy use linked to production in industrial, tertiary, and other sectors; ii) efficient energy management in industrial and services; iii) private taxi fleet expansion and its energy use, and iv) electricity generation. These dynamics are implemented through the Industrial, Tertiary, Other Sectors, Transport, and Electricity Generation modules.

3.2.1 Energy use linked to production:

In the industrial and tertiary sectors, energy consumption is driven by subsector output and energy intensity. Output is represented by subsector Gross Domestic Product (GDP), endogenised through Electric GDP and sectoral energy demand, capturing feedback between economic activity and the energy system. Base-year energy intensities are calibrated using Colombia's First Useful Energy Balance [41] and the National Energy Balance (BECO) [42].

Energy demand is disaggregated by end use – lighting, air conditioning, refrigeration, motive power, direct heat, indirect heat, and other uses – to support targeted electrification strategies. Given sectoral heterogeneity, the model prioritises subsectors with high dependence on coal, fuel oil, and natural gas, where substitution towards electricity – and hydrogen, where relevant – is most feasible. For each energy carrier, consumption is computed from activity levels, end-use intensities, and technology shares:

$$C_{sec,j}(t) = \sum_{s \in S_{sec}} \sum_{u \in U} EI_{s,u,j}(t) * GDP_s(t) * \theta_{s,u,j}(t) \quad \text{(Eq. 4)}$$

Where $C_{sec,j}$ denotes the final energy consumption of sector s for energy carrier j; $EI_{s,u,j}$ is the energy intensity of end-use u per unit of economic activity associated with carrier j; GDP_s is the Gross Domestic Product of sector s, used as a proxy for activity level; and $\theta_{s,u,j}$ is the share of energy carrier j in end-use u, determined by the prevailing technological mix.

Sectoral GDP is estimated as a level variable, accumulating as a function of the growth in electricity demand within that sector and the GDP of the electricity sector (Eqs. 5-6). An increase in energy demand reflects gains in sectoral productivity and is accordingly associated with growth in sectoral GDP. Likewise, growth in the electricity sector's GDP exerts an influence across all economic sectors, insofar as greater expansion yields more competitive energy prices that stimulate broader economic activity:

$$GDP_s(t) = A * \left(ED_s(t)\right)^{\alpha} * \left(GDP_{elect}(t)\right)^{\beta} \quad \text{(Eq. 5)}$$

$$GDP_{elect}(t) = GDP_{elect}(t-1) * (1 + \alpha * \gamma_{elect\ dem}) \quad \text{(Eq. 6)}$$

Where ED_s is the electricity demand of sector s, GDP_{elect} is the Gross Domestic Product of the electricity sector; and α, β are the elasticities of consumption and GDP, respectively. The computation of GDP_{elect} depends on the annual growth or decline rate of national electricity demand ($\gamma_{elect\ dem}$). The elasticities were estimated from historical series of energy consumption, sectoral GDP, and electricity-sector GDP, employing a non-linear regression technique; their values are reported in Table A1 in Appendix A.

The endogenisation of GDP within the model is made possible by the inherent capacity of system dynamics to explicitly represent interdependencies and feedback relationships. By construction, stock variables – such as sectoral GDP – retain their value from the preceding integration step, so that all auxiliary variables and flows are evaluated against a fully determined system state at each time step. Consequently, the feedback between electricity demand and GDP is resolved dynamically over time rather than algebraically within the same time step, which distinguishes the present approach from static frameworks.

Industrial subsectors include Food Processing, Paper and Cardboard, Coking and Refining, Non-Metallic Minerals, and Other Industries, collectively accounting for over 75% of industrial energy use in Colombia. In the tertiary sector, the analysis considers Hotels and Restaurants, Financial Institutions, Health, Education and Culture, Commerce, and Other Services, selected for their high electrification potential. In these activities, both direct and indirect heat uses offer significant opportunities for transition, particularly where technological advancements allow for the substitution of natural gas with electricity or hydrogen. Finally, other sectors are included to ensure consistency of economy-wide energy demand.

3.2.2 Efficient energy management:

Firm-level efficiency improvements are represented through sector-specific targets and onsite solar self-generation. Efficiency targets follow a goal-seeking structure (Figure 2) and are implemented by adjusting end-use energy intensities, reflecting gradual equipment upgrades and process changes over a 20-year horizon (Appendix A, Eqs. A9-A10).

Onsite solar self-generation is represented for the tertiary sector in the Electricity Generation module, in line with the scenario assumptions. By 2050, commerce, hotels, and restaurants are expected to reach around 25% self-supply, while health services are expected to reach approximately 10%.

3.2.3 Expansion of the private taxi fleet:

The expansion of the private taxi fleet is represented as a firm-level decision within the transport sector. The number of authorised operating licences grows in proportion to population, reflecting the market-driven expansion of the service. The gap between authorised taxis and user demand is interpreted as an indicator of informal or unauthorised public transport activity.

As taxi trip demand increases – driven by the dynamics described in Section 3.1.2 – the model estimates the desired fleet size based on average daily trips per taxi in Colombia and the number of existing licences. The difference between the desired and current fleet determines new entries. New taxis may operate on petrol, CNG, diesel, electricity, hybrid technologies, or hydrogen. Technology choice follows the logit model described in the travel-demand section, with utility shaped by vehicle range, mobility restrictions, acquisition cost, and operating and maintenance costs.

Energy consumption in this mode is derived from total taxi trips, fleet composition, and average trip distance,

linking demand dynamics directly to energy use.

3.2.4 Electricity generation activities:

Capacity expansion in Colombia's electricity generation sector is represented as a firm-level investment decision driven by the margin between electricity supply and demand, and by technology-specific levelised costs of energy (LCOE). Investments are subject to development and construction lead times that vary by technology and are calibrated using historical national averages.

As installed capacity expands, the electricity supply is adjusted using average capacity factors by technology, which reflect the availability of each energy resource in Colombia. Total electricity demand is computed as the sum of demands across all economic sectors. The model maintains a reserve margin of 20% above electricity demand, consistent with Colombia's historical operating conditions; the energy required to meet this target margin is translated into new investment signals.

It is worth noting that the model operates on an annual regulatory basis, so that demand, available energy, and investment decisions are all resolved at yearly intervals.

The module simulates an aggregated merit-order dispatch, under the assumption that variable renewable energy sources are called upon first to meet demand, followed by dispatchable technologies such as reservoir hydropower, coal, natural gas, and fuel oil. Dispatch outcomes determine the average annualised consumption of each energy carrier through to 2050.

Given its annual resolution, the model does not capture daily or intra-hourly variability in resource availability; nonetheless, the capacity factor incorporates the average availability of each resource over the period. Transmission network constraints are assumed to be addressed through new investment in grid expansion; however, quantifying the investment requirements associated with the energy transition falls outside the scope of this study and is therefore not modelled explicitly.

Technology selection follows a cost-based rule, favouring lower-LCOE options. As renewable technologies gain share in the generation mix, the need for gas, coal, and fuel oil decreases progressively, reducing fossil fuel use in power generation and reinforcing the energy transition.

The dynamics of capacity expansion for each technology X are represented as (see Appendix A for variable definitions):

$$IC_{Tech\,X}(t) = \int_{t=0}^{t} [NCap_x(s) - RCap_x(s)]ds + IC_{Tech\,X}(t0) \qquad \text{(Eq. 7)}$$

Where $IC_{Tech\,X}$ represents the installed capacity of technology X (hydropower, gas, coal, fuel oil, small hydro, wind, solar, biomass, geothermal and other sources); $NCap_x$ is the new capacity becoming operational upon completion of the construction phase; and $RCap_x$ is the capacity retired from the generation mix due to public policy measures.

Whilst the model's annual resolution and stylised dispatch logic preclude a full representation of real-time system operation, the results are intended to provide long-run structural insights into the evolution of the generation mix and fossil fuel displacement under alternative transition pathways. System adequacy is proxied through the 20% reserve margin, and variability constraints are implicitly embedded in technology-specific capacity factors. Integration challenges – including grid flexibility, storage requirements, and intra-day balancing – are acknowledged as boundary conditions of the present framework, and results should accordingly be interpreted as indicative of transition trajectories rather than operationally optimised outcomes.

3.3 State-led decision-making on energy consumption

The model captures state interventions through decisions on: i) public transport provision and ii) energy policy design. This section explains how these elements are represented within the system dynamics framework:

3.3.1 Expansion of the public transport fleet:

The number of buses and BRT units required each year is determined by total trips by mode and average daily passenger occupancy per vehicle. The gap between the required and existing fleets determines the number of new vehicle entries. Vehicle acquisition is subject to time lags, reflecting administrative procurement processes, while technology choice is primarily driven by public policy.

The model allows for accelerated scrappage and strategic replacement programmes to promote cleaner technologies, including hybrid, electric, and hydrogen-powered buses, in line with targeted fleet composition.

Energy consumption for buses and BRT systems follows the same logic applied to private mobility, as described

in Section 3.1 ii).
For metro systems, fleet requirements are estimated from daily trips and the number of vehicles in operation, enabling simulation of system expansion. Daily kilometres travelled are calculated from the number of cars and the average distance per car, while energy consumption is derived from the average electricity use per kilometre.

3.3.2 Energy policy design:
Policy interventions are represented at the sectoral level, allowing a differentiated assessment of their effects on energy demand and system structure. The model includes measures to promote non-motorised travel, vehicle fleet renewal, interventions in private and public transport, energy efficiency in residential, industrial, and tertiary sectors, targets to eliminate firewood use for cooking, and self-generation scenarios.
The following section outlines the specific policies for each scenario.

3.4 Characterisation of energy consumption in Colombia

Before addressing the simulated scenarios, it is essential to characterise Colombia's current energy consumption and CO_2 emissions. This characterisation provides a solid foundation for designing public policies tailored to the national context.

All scenarios share the same demographic projection, ensuring consistency in comparative analysis. Colombia's population is projected to increase from 52.7 million in 2024 to 57.7 million by 2050. In contrast, aggregate and sectoral GDP evolve endogenously within the model, reflecting the dynamics induced by each energy transition scenario.

In 2023, focusing only on emissions from energy consumption and on land-based passenger transport, the transport sector (36%), industrial (25%), and residential (24%) sectors together accounted for 85% of CO_2 emissions. Transport represented approximately 34% of national energy demand, with private vehicles responsible for over half of this consumption. In the industrial sector, energy use was dominated by direct and indirect heat, accounting for more than 70% of total demand, while in the residential sector, cooking represented over half of energy consumption.

At the national level, gasoline was the most consumed energy carrier (27%), followed by electricity (26%) and natural gas (21%).

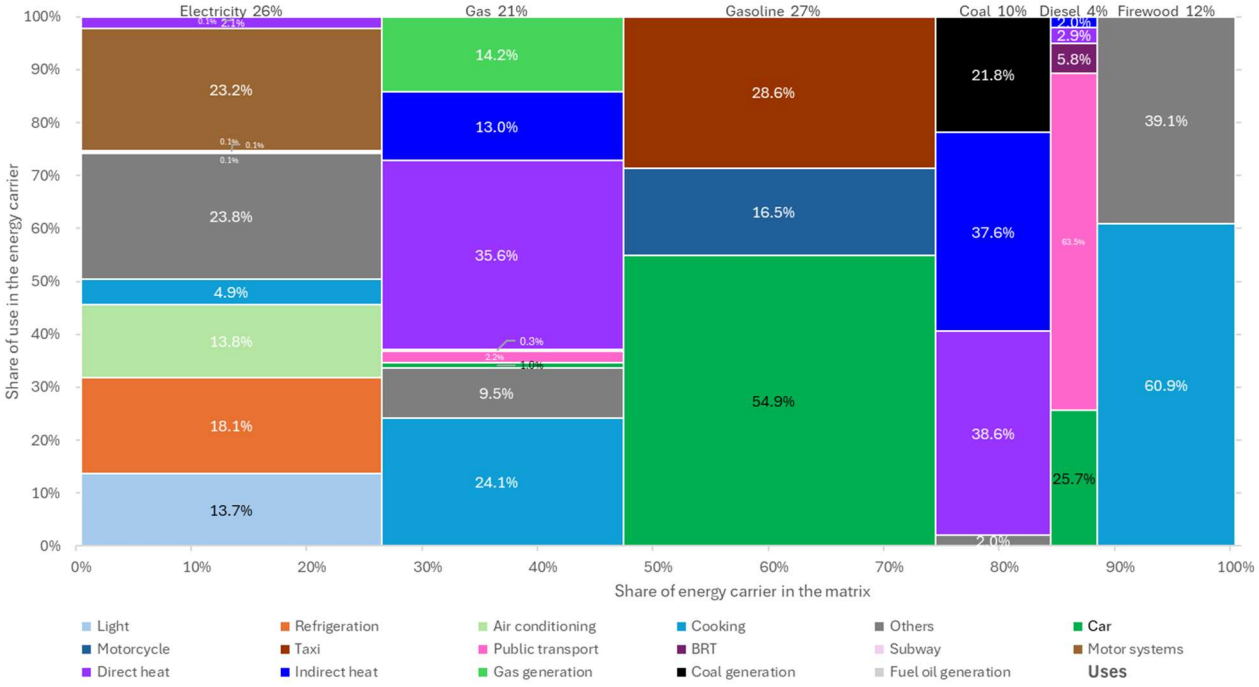


Figure 3: Final energy consumption by end use in Colombia, 2023.

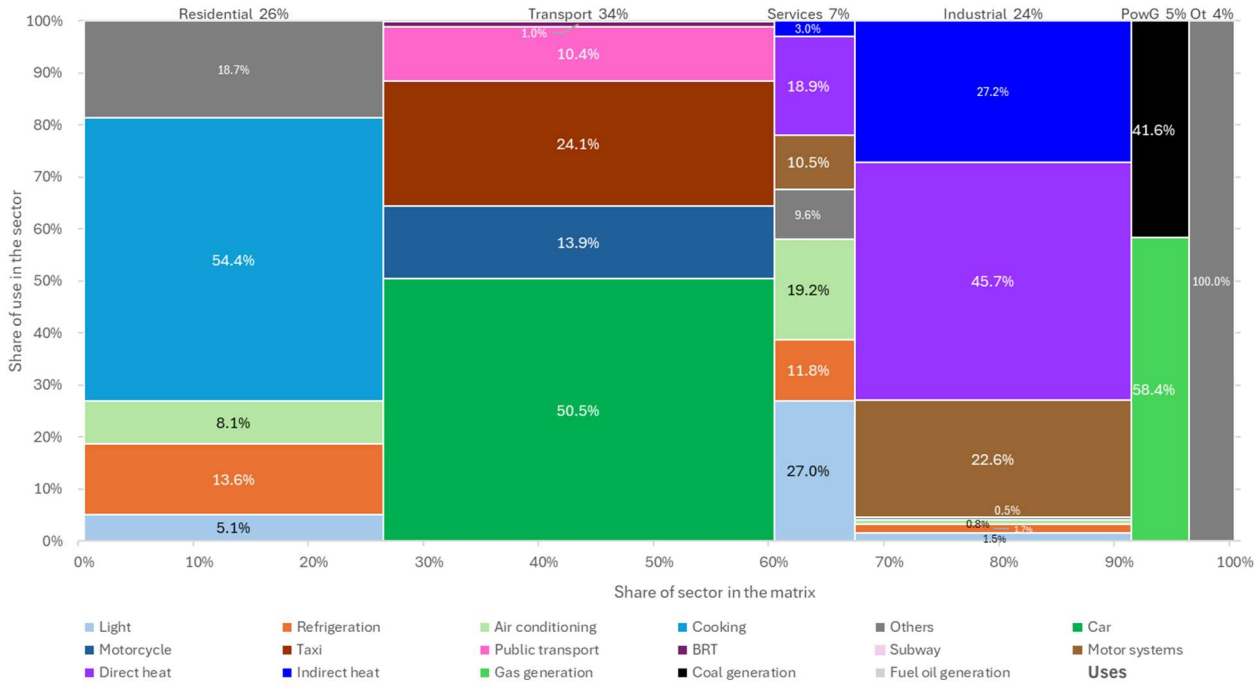


Figure 4: Final energy consumption by sector and end use in Colombia, 2023.

Figures 3 and 4 show that gasoline is mainly used in private vehicles such as cars, motorcycles, and taxis. Natural gas is largely consumed for direct and indirect heating, with the industrial sector as the main user, while residential and tertiary consumption is primarily for cooking. Coal use is concentrated in industrial heat applications, while firewood is mainly used for cooking in rural areas.

Electricity generation in Colombia is predominantly renewable, with around 70% of installed capacity from renewable sources. The sector shows significant growth potential, particularly in solar and wind technologies, supported by resource availability and declining costs.

Based on this characterisation, it is essential to evaluate public policies that promote sectoral electrification while accounting for demand behaviour and the expansion of renewable energy generation capacity.

The sectoral characterisation presented above – expressed in relative terms across energy carriers, end uses, and productive sectors – serves to contextualise Colombia's energy system and does not directly constitute the model's starting point. The initial conditions of the model are defined in physical and economic stock units, including the number of households with access to electricity and gas, households equipped with refrigeration, vehicles by technology type, installed generation capacity, and the energy intensity of the commercial and industrial sectors, expressed per unit of GDP, among other variables. These values were derived through a calibration process that drew on the 2023 BECO alongside complementary sources, notably DANE national statistics, to ensure consistency between the structural composition of the energy system and the operational quantities required as model inputs.

3.5 Scenario description

To construct the scenarios, two sets of public policies are defined, informed by a structured expert workshop with representatives from the Colombian energy sector. The first reflects the continuation of current trends and policy orientations (Business as Usual, BAU). The second represents a coordinated energy transition strategy (ET), in which efficiency, fuel switching, and electrification reshape decisions by households, firms, and the State. The scenarios differ not only in policy ambition but also in how these decisions jointly transform energy demand and technology adoption across sectors.

The following tables describe each scenario from the perspective of the decision-making agents:

Table 1: Public polices shaping individual and household energy decisions.

Category	Business as usual (BAU) scenario	Energy transition (ET) scenario
Residential sector		
Refrigeration	25% efficiency gain by 2050. Refrigerator replacement cycles remain stable at 20 years.	34% efficiency gain by 2050. Refrigerator replacement cycles will be shortened to 12 years by 2050.
Air conditioning	21% efficiency gain by 2050. 20% probability of adoption compared with fans.	27% efficiency gain by 2050. Active promotion of efficient, competitively priced units; 70% adoption probability compared with fans.
Cooking	Gradual replacement of firewood with gas over 15 years.	Accelerated firewood phase-out; maximum lifespan reduced to 8 years by 2040, with substitution directed towards electricity.
Other home appliances	3% growth in consumption driven by home automation. 20% uptake of electric water heaters.	5% growth in consumption driven by home automation. Active promotion of electric water heaters; 35% uptake rate.
Transport sector		
Non-motorised transport	Modal share is stable at 32% (lower-income) and 19% (higher-income).	Modal share increases to 38% (lower-income) and 33% (higher-income).
Vehicle scrappage	Gradual reduction in maximum permitted vehicle lifespan to 37 years by 2035.	Aggressive scrappage policy; maximum permitted vehicle lifespan reduced from 40 years to 7 years by 2035 (This applies only to the Transport + scenario).
Fuel vehicle operating costs	Operating costs of petrol and diesel vehicles increase to 1.5 times their 2024 level by 2040 and to 2.1 times their 2024 level by 2050.	Operating costs of petrol and diesel vehicles increase to 2.4 times their 2024 level by 2040 and to 3.7 times their 2024 level by 2050, driven by fuel cost escalation.
Mobility restrictions	Partial restrictions on petrol and diesel vehicles, taxis, and motorcycles; technology use restriction index of 0.5 by 2040.	Stringent mobility restrictions on petrol and diesel vehicles, taxis, and motorcycles; technology use restriction index of 0.7 by 2040.
Electric vehicle costs	Electric vehicle purchase costs decline by 20% by 2040 without targeted subsidies or significant cost-reduction measures.	Active promotion of electric vehicle adoption through subsidies and cost reduction measures; purchase costs decline by 70% by 2040.
Generation power sector		
Electricity generation	Gradual increase in adoption of self-generation, reaching 10% of households by 2050.	Self-generation is actively promoted, with household uptake reaching 20% by 2050.

Table 2: Public policies influencing corporate energy and production decisions.

Category	BAU scenario	ET scenario
Tertiary sector		
Energy efficiency	Both scenarios apply modest energy efficiency targets across end-uses: lighting (4%), air conditioning (6%), refrigeration (4%), motive power (4%), direct heat (5%), and indirect heat (3%).	
Self-generation	Gradual uptake of self-generation, reaching 20% in selected tertiary subsectors by 2050.	Active promotion of self-generation, reaching 30% in selected tertiary subsectors by 2050.
Heat processes	Natural gas retains a dominant role in direct and indirect heat processes across tertiary subsectors.	Electricity progressively substitutes natural gas in direct and indirect heat processes across tertiary subsectors.

Industrial sector		
Energy efficiency	Both scenarios apply modest energy efficiency targets across end-uses: lighting (4%), air conditioning (5%), refrigeration (3%), motive power (3%), direct heat (4%), and indirect heat (2%).	
Heat processes	No policies to encourage the adoption of low-emission technologies for thermal processes.	Reliance on coal and diesel for direct and indirect heat is progressively reduced, with targeted substitution by natural gas and electricity in specific subsectors. For direct heat in selected industries, a further transition towards hydrogen and electricity is assumed to replace natural gas.
Electric generation sector		
Plant retirement policy	No retirement of gas, coal, or diesel plants.	Policy is enacted to retire coal and diesel plants before 2035. Gas plants are gradually retired with a complete phase-out before 2035.

Table 3: Public policies guiding governmental energy demand and sectoral interventions.

Category	BAU scenario	ET scenario
Transport sector		
Public transport fleet policy	- Diesel-powered TPC (Spanish acronym for public collective transport) and BRT buses continue to be purchased. 50% of new TPC buses are targeted to be electric by 2050. Natural gas buses continue to be purchased through 2050.	The number of refuelling stations is progressively reduced, constraining the autonomy index of conventional fuel vehicles. Starting in 2030, no new diesel TPC or BRT buses will be acquired. 80% of new TPC buses are targeted to be electric by 2050. Hydrogen buses are introduced beginning in 2035, reaching 10% of new bus purchases by 2050. Natural gas bus purchases are gradually reduced starting in 2035.

4. Results and discussion

This section reports the simulation results of the energy transition scenarios. It first analyses the effects of coordinated policies across sectors on energy use, technology adoption, and emissions, and then examines sector-specific interventions to assess their individual contributions and constraints.

4.1 Energy transition in the sectors

Under current policies (BAU), the residential sector is projected to constrain energy consumption by 2050; however, no substantial energy transition in fuel use occurs (Figure 5). Under the ET scenario, which incorporates the policies described in Table 1, Table 2 and Table 3, a shift in the energy mix becomes evident from 2035 onwards, with electricity consumption potentially exceeding 210 PJ. In this scenario, policies promoting the transition from firewood and gas to electricity for cooking (Table 1) play a central role. By 2050, the residential sector could reach an electrification rate above 92%, up from 47% in 2024, and electricity consumption could exceed 340 PJ.

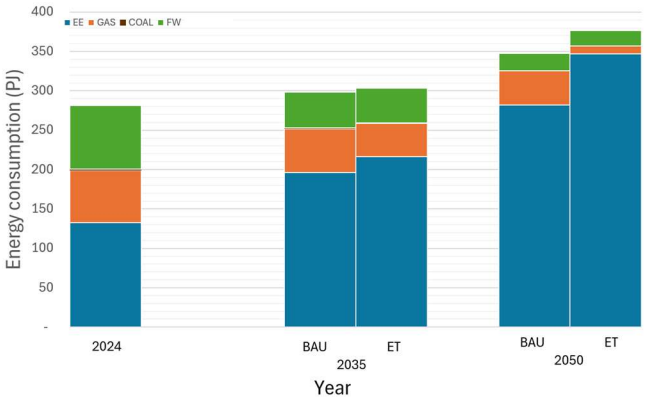


Figure 5: Comparison of energy consumption in the residential sector under BAU and ET scenarios. EE= electricity; FW= firewood.

In the tertiary sector, under the BAU scenario,

energy consumption is projected to double by 2050, exceeding 200 PJ, with electricity maintaining the largest share of the sector's energy mix (Figure 6). Under the energy transition scenario, energy consumption is projected to grow exponentially from 2035 onwards. This growth reflects not only the electrification of processes within the tertiary sector, but also economy-wide electrification dynamics, whereby rising electricity demand across all sectors propagates through the economy and translates into higher tertiary-sector output. In this scenario, total energy demand could reach 400 PJ, with electricity accounting for 88% of the energy mix.

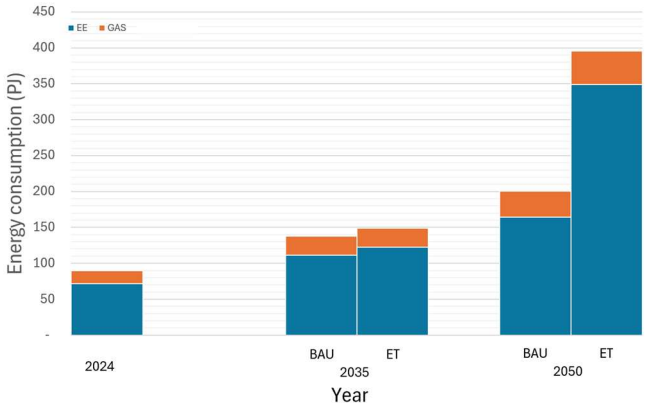


Figure 6. Comparison of energy consumption in the tertiary sector under BAU and ET scenarios. EE= electricity.

In the transport sector (Figures 7 and 8), the analysis focuses on the road vehicle fleet, given its relevance in the Colombian context. No structural shift is expected in the freight transport energy mix due to the high costs of alternative technologies in a market such as Colombia. Under BAU policies (Table 1), only around 10% of the vehicle fleet is projected to be clean by 2050, whereas under the energy transition scenario, the share exceeds 80%.

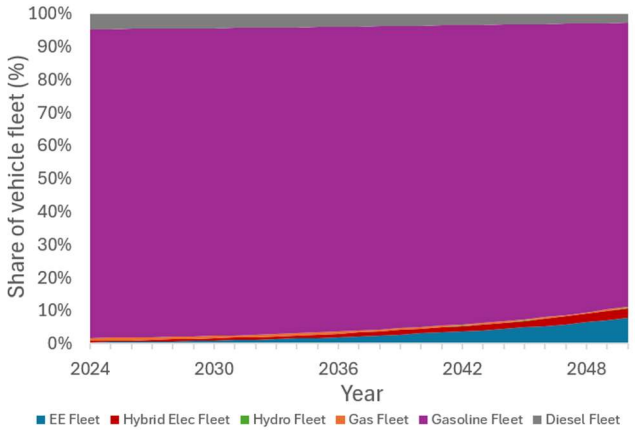


Figure 7. Distribution of the vehicle fleet by technology under the BAU scenario.

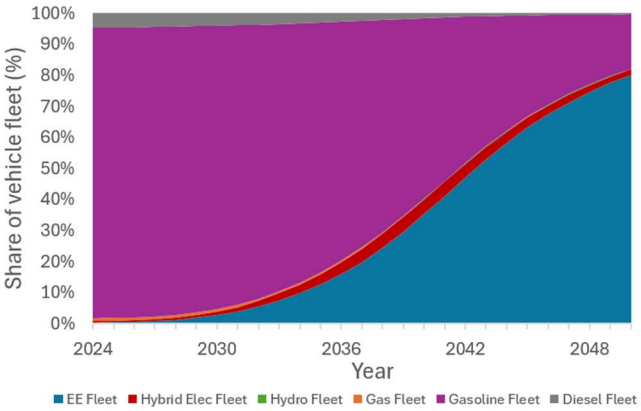


Figure 8. Distribution of the vehicle fleet by technology under the ET scenario.

This transformation of the vehicle fleet results in a 70% reduction in transport-sector emissions relative to 2024 levels (Figure 9). By contrast, despite efforts under the BAU scenario, emissions would grow slightly, resulting in a 14% increase by 2050 compared to 2024.

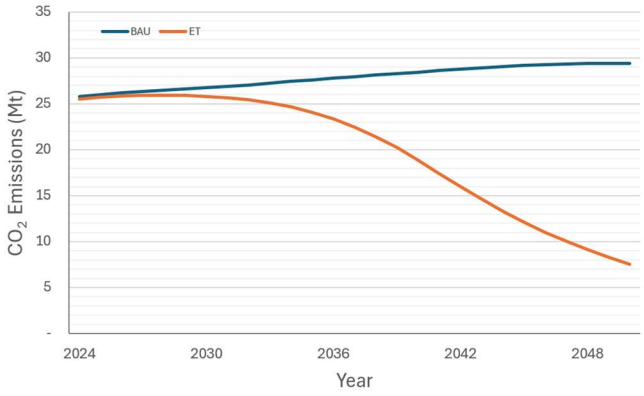


Figure 9. Emissions in the transport sector.

In the industrial sector, total energy consumption is projected to double by 2050 under the energy transition scenario; however, the share of fossil fuels is only reduced from 70% to 50%. This outcome reflects the incipient role of hydrogen in industrial processes and the partial electrification of certain activities. The limited reduction in fossil fuel use is explained by the absence of an early, large-scale technological transition capable of replacing coal and gas with hydrogen in industrial processes, due to high technological costs and their implications for the national market.

As a result, national electricity consumption is projected to increase by 3.5 times relative to 2024, reaching 281 TWh by 2050. This growth requires a substantial expansion of the power generation fleet, reaching 85 GW of installed capacity – equivalent to a 4.3-fold increase from 2024 – based on a fully renewable generation mix. Total final energy consumption is 1479 PJ, and the share of clean energy in the national energy mix increases from 28% in 2024 to 71% in 2050, indicating a successful energy transition, as shown in Figure 10.

The 2050 energy mix reflects a marked shift away from traditional and fossil fuels. Firewood, diesel, and gasoline consumption decline substantially, whilst natural gas, despite reducing its share in the residential and tertiary sectors, retains a presence in industry, where it serves as the preferred substitute for coal. Hydrogen begins to enter the mix from 2035 onwards, gaining a modest but growing share in selected industrial subsectors.

With the implementation of policies under the ET scenario, emissions could be reduced by more than 45% by 2050 compared to current policy outcomes.

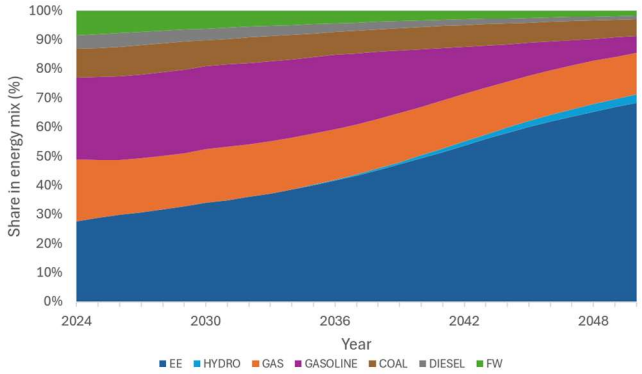


Figure 10. National energy use distribution under the ET scenario. EE= electricity; Hydro= hydrogen; FW= firewood.

4.2 Sector-specific policy effects

Recognising that Colombia is a developing country with fiscal limitations, additional scenarios are defined in which transition policies (described in Section 3.5) are applied to a single sector at a time – transport, residential, tertiary, industrial, or power generation – whilst the remaining sectors retain their BAU assumptions. For the transport sector, an additional scenario (Transport+) is introduced, which differs from the Transport scenario by incorporating accelerated vehicle scrappage (Table 1). This policy requires substantial financing to retire the fleet of vehicles operating on fossil fuels. In the five single-sector scenarios (plus the Transport+ variant), the power generation sector follows the Energy Transition pathway, except for self-generation targets, which are considered exclusively in the Generation scenario.

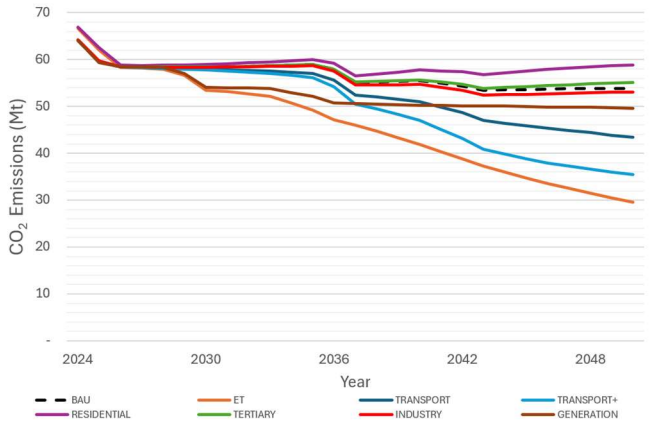


Figure 11. National emissions by scenario.

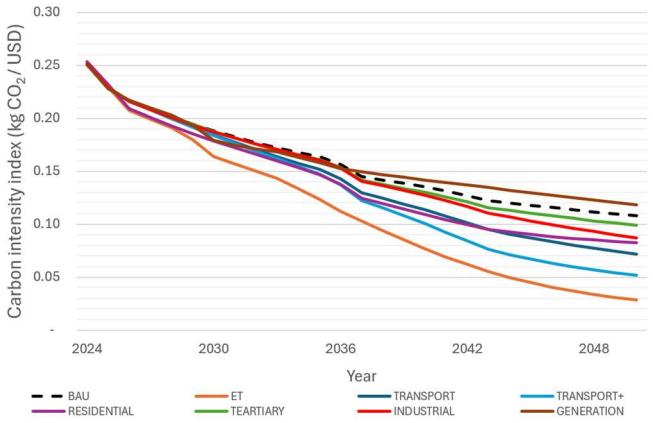


Figure 12. Evolution of GDP carbon intensity under different energy policy scenarios.

Figure 11 shows that when transition policies are

applied exclusively to the power generation sector, emissions are reduced by only 8% relative to the BAU scenario by 2050. Moreover, emissions per unit of GDP remain higher than under the BAU scenario (Figure 12). This outcome reflects the limited macroeconomic impact of supply-side decarbonisation in the absence of economy-wide electrification. Without demand-side electrification, low-carbon electricity generation contributes only marginally to GDP growth, as electricity demand remains relatively constrained (Figure 13).

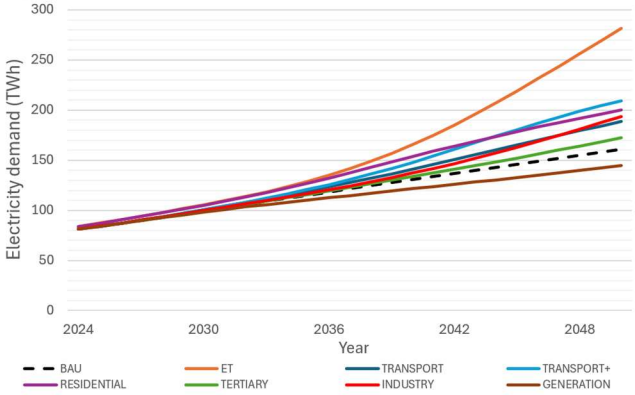


Figure 13. Evolution of electricity demand under different energy policy scenarios.

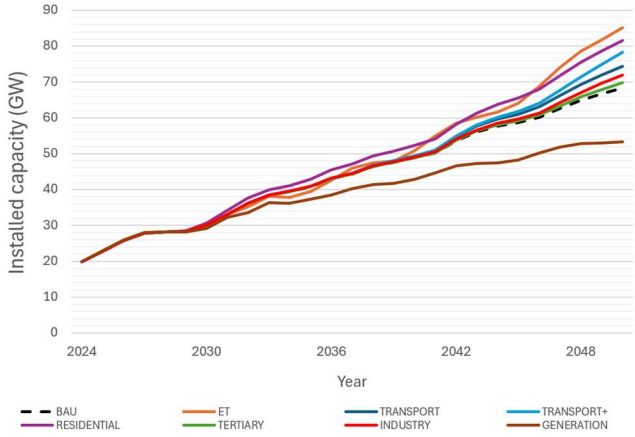


Figure 14. Installed capacity in the electricity generation sector.

Among the isolated sectoral policy scenarios, transport-sector measures deliver the largest contribution to emissions reductions, both in absolute terms and per unit of GDP. By 2050, emissions decline by 45% relative to 2024 when vehicle scrappage policies are implemented, and by approximately 32% even in the absence of this measure (Figure 11).

Implementing measures exclusively in the residential sector generates markedly different long-term effects. While residential electrification stimulates national electricity demand (Figure 13) and positively affects GDP growth, emissions increase in the long term if complementary transition measures are not adopted in other sectors. As a result, by 2050, emissions exceed BAU levels by 9% (Figure 11). This effect is driven by macroeconomic spillovers: rising electricity demand fuels the expansion of the industrial, tertiary, and transport sectors, which remain primarily dependent on fossil fuels.

Figure 11 shows that in the long term, transport-sector measures are the ones that most strongly differentiate outcomes relative to the BAU scenario. In contrast, the residential and tertiary scenarios result in higher emissions by 2050 when policies are implemented independently in each sector.

Meeting electricity demand under the ET scenario requires investments to expand installed generation capacity from approximately 20 GW to 85 GW by 2050 (Figure 14). In the Transport+ scenario, additional capacity requirements 58 GW, implying a more than 3.9-fold increase in the current generation fleet. These results highlight the importance of coordinated planning between demand-side electrification and the expansion of generation capacity to achieve sustained emissions reductions while supporting economic growth.

5. Conclusions and policy implications

The results of this study demonstrate that the energy transition cannot be addressed exclusively through supply-side decarbonisation. Although diversifying the electricity mix toward clean energy sources is a necessary condition, it is not sufficient to achieve long-term emissions reductions. The simulations show that pursuing a strategy focused solely on decarbonising the power generation mix, without simultaneously electrifying energy demand, may even lead to increased emissions in the long run.

In this context, the model developed in this study constitutes a relevant tool for public policy design in developing countries, as it enables an integrated assessment of the long-term impacts of different policy combinations, explicitly incorporating consumption dynamics, intersectoral interactions, and feedback mechanisms.

For Colombia, the transport sector plays a central role in the country's energy transition. Policies aimed at vehicle scrappage and technological renewal of the

vehicle fleet generate significant emissions reductions, achieving decreases of more than 45% relative to 2024. However, these policies also exert substantial pressure on the electricity system, requiring an expansion of generation capacity to more than 3.9 times the current installed capacity, as well as coordinated infrastructure planning.

Complementarily, policies promoting the electrification of cooking in the residential sector have a significant impact on electricity demand; however, when implemented in isolation, they may produce counterproductive effects on emissions. This finding highlights that the energy transition also affects economic growth and, consequently, the trajectory and composition of energy consumption in other sectors, potentially increasing their emissions if they remain highly dependent on fossil fuels.

Colombia's energy transition can be achieved by prioritising demand-side electrification in the transport, residential, and tertiary sectors, requiring a 4.3-fold expansion of fully renewable power generation capacity.

From an academic perspective, this study contributes to the energy transition literature by shifting the analytical focus from supply to demand, explicitly modelling how public policies influence final energy use and emissions. Unlike conventional approaches, the proposed model integrates multiple sectors and captures dynamic feedback between electrification, power system expansion, economic growth, and environmental performance, thereby enabling an ex-ante evaluation of the systemic effects of alternative policy portfolios.

As a direction for future research, this study proposes endogenising energy price formation within the model by incorporating the effects of the energy transition on energy costs and their influence on demand-side decisions, thereby strengthening public policy analysis from a dynamic, realistic perspective. In addition, future work should assess the role of hydrogen as an energy carrier, provided it demonstrates technical and economic viability for deployment in the transport and industrial sectors.

Appendix A. Variable definitions and explanatory formulas

Variable	Definition
$C_{h,elect}$	electricity consumption by households
C_{ij}	energy consumption j by mode i
$C_{sec,j}$	consumption of energy carrier j in sector sec (industrial or tertiary) at time t
$Conf_{i,k}$	comfort cost of mode i for stratum k households
ED_s	electricity demand of sector s
$EE_{u,s}$	achieved energy efficiency for end-use u in sector s, expressed in terms of energy consumption per unit of sectoral GDP
$EI_{j,u}$	energy intensity of end-use *u* associated with energy carrier *j* at time *t*
$EI_{s,u,j}^{targ}$	target energy intensity of energy carrier j for end-use u in sector s
EpK_{ij}	energy consumption per km of energy j by mode i
GDP_{elect}	Gross Domestic Product of the electricity sector
GDP_s	Gross Domestic Product of sector s
Goal time	required time to reach the target level
$HH_{elec,z}$	electrified households in area z
$HH_{Tech\ A,z}$	households using technology A in area z
$HH_z(t)$	households in area z
i	[1,…,5] 1= Car; 2= Motorcycle; 3= Taxi; 4= Public Transport; 5= BRT System
$IC_{Tech\ X}$	installed capacity of technology X (hydropower, gas, coal, fuel oil, small hydro plant, wind, solar, biomass, geothermal, and other sources)
j	[1,…,5] 1= Gasoline; 2= Diesel; 3= NGV; 4= Hydrogen; 5= Electric Energy
k	[1,2] 1= Stratum 1,2,3; 2= Stratum 4,5,6
KpT_i	km per trip in mode i
$N_{Tech\ X,z}$	number of appliances of technology X in area z by households
$NCap_x$	new capacity becoming operational after the construction phase is completed
$NHH_{elec,z}$	newly electrified households in area z
$NHH_{Tech\ A,z}$	new households adopting technology A in area z
$QMot_k$	motorised trips by stratum k households
$RCap_x$	capacity retired from the generation matrix

	due to public policy measures
$RHH_{Tech\ A,z}$	households replacing technology A with another technology in area z
$RHH_{Tech\ XtoA,}$	households replacing technology X with technology A in area z
$r_{Tech\ AtoB,z}$	probability curve of replacing technology A with technology B, depending on GDP per capita in area z
$S_{Tech\ A,z}$	share of technology A among new households in area z
sec	$\in \{industrial, tertiary\}$
S_{sec}	set of subsectors within each sector: S_ind= {1,…,5} for the industrial sector; S_tert= {1,…,6} for the tertiary sector
$t_{cov,z}$	time to reach the target in area z
T_i	trips in mode i
T_{ij}	trips in mode i with energy j
$T_{i,k}$	trips in mode i for stratum k households
TT_i	travel time in mode i
U	{1, … ,7} 1= lighting; 2= air conditioning; 3= refrigeration; 4= motive power; 5= direct heat; 6= indirect heat; 7= other uses
$U_{Tech\ X,z}$	utilisation factor of technology X in area z
$V_{i,k}$	travel utility of mode i for stratum k households
Var_i	travel cost of mode i
Veh_{ij}	energy j mode i vehicle
VoT_k	value of time for stratum k households
$W_{Tech\ X,z}$	unit consumption of technology X in area z
Z	1,2 (1: Urban, 2: Rural)
α, β	elasticities of consumption and GDP, respectively
μ	scale factor
$\theta_{s,u,j}$	share of energy carrier j in end-use u, determined by the technological mix
$\gamma_{elect\ dem}$	annual growth/decline rate of national electricity demand

Access to electricity.

$$HH_{elec,z}(t) = HH_{elec,z}(t-1) + NHH_{elec,z}(t) \quad (Eq.A1)$$

$$NHH_{elec,z}(t) = \frac{HH_z(t) - HH_{elec,z}(t-1)}{t_{cov,z}} \quad (Eq.A2)$$

Technology acquisition in the residential sector.

$$HH_{Tec\ \ A,z}(t) = HH_{Tech\ A,z}(t-1) + NHH_{Tech\ A,z}(t) - RHH_{Tech\ A,z}(t) \quad (Eq.A3)$$

$$NHH_{Tech\ A,z}(t) = NHH_{elec,z}(t) * S_{Tech\ A,z} + RHH_{Te\ \ XtoA,z}(t) \quad (Eq.A4)$$

$$RHH_{Tech\ A,z}(t) = HH_{Tech\ A,z}(t-1) * r_{Tech\ AtoB,z} \quad (Eq.A5)$$

$$r_{Tech\ AtoB,z} = f_z(GDP_{pc}) \quad (Eq.A6)$$

Energy consumption in the transport sector.

$$C_{ij} = T_{ij} * KpT_i * EpK_{ij} \quad (Eq.A7)$$

$$T_{ij} = T_i * \frac{Veh_{ij}}{\sum_{j=1}^{J} Veh_{ij}} \quad (Eq.A8)$$

Energy intensity associated with each use in the industrial or tertiary sector.

$$EI_{s,u,j}(t) = \int_{to}^{t} [EE_{u,s}(s)]ds + EI_{s,u,j}(t0) \quad (Eq.A9)$$

$$EE_{u,s}(t) = \frac{EI_{s,u,j}^{targ} - EI_{s,u,j}(t)}{Goal\ time} \quad (Eq.A10)$$

Table A1. Parameters estimated in each sector.

Sector	A	α	β	R^2
Hotels and Restaurants	0.14	0.346878	0.997059	0.994798
Financial Institutions	0.00	0.557125	1.671015	0.987471
Health	0.94	0.014531	1.042175	0.962207
Education and Culture	20.43	0.219396	0.622288	0.991107
Commerce	0.13	0.178505	1.165496	0.978756
Other Services	0.43	0.062781	1.297965	0.992109
Food	36.03	0.171280	0.541764	0.959830
Paper and Cardboard	14.43	-0.046920	0.652607	0.795184
Coking and Refining	13.34	0.010971	0.704173	0.839883
Non-metallic Minerals	7.53	0.035844	0.652084	0.832350
Other Industries	266.06	0.143821	0.398596	0.492738

Additional Sector	475.40	0.351706	0.282388	0.708180

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