

# A Multi-Objective Optimization Model for Integrating Renewable Energy in Distribution System Expansion: a Case Study of Pamplona, Colombia

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This study presents a comprehensive multi-objective optimisation model for expanding the electrical distribution system of Pamplona, Colombia, a municipality located within the Santurbán páramo. The objective of the optimisation model is to integrate renewable energy resources available in the region, such as solar, wind, and biomass, into the local power grid. Additionally, due to the intermittent nature of renewable energy sources and to ensure a continuous electricity supply, diesel power plants are considered as backup. The proposed optimisation model is a Mixed-Integer Multi-Objective Linear Programming (MOMILP) approach that minimises the total system cost (net present value) and CO<sub>2</sub> emissions while accounting for design, operational, and budgetary constraints. Furthermore, the model explores the potential for surplus electricity sales to foster the development of energy communities. The MOMILP promotes the deployment of photovoltaic panels and biomass gasifiers, while including diesel power plants as backup technologies. The Pareto front alternatives indicate that electricity demand can be met exclusively with biomass gasifiers and diesel plants, albeit at the cost of generating the highest CO<sub>2</sub> emissions. Conversely, to minimise CO<sub>2</sub> emissions, electricity generation relies predominantly on photovoltaic panels, supported by biomass gasifiers, diesel plants, and wind turbines. The proposed methodology can be applied to a wide range of new projects implementing integrated renewable energy systems for the expansion of existing power grids.

## 1. Introduction

Climate change mitigation through the reduction of greenhouse gas emissions has been one of the primary challenges outlined in the Sustainable Development Goals (United Nations). The energy sector is one of the largest contributors to climate change, accounting for approximately 75% of greenhouse gas emissions due to the use of fossil fuels to meet energy demands (International Energy Agency, 2023). One method to reduce CO<sub>2</sub> emissions while meeting energy demand is the integration of renewable technologies into energy distribution systems. However, these technologies have the disadvantage of intermittent availability, as their performance is highly dependent on climatic variations (Karmellos and Mavrotas, 2020). This means that implementing a single technology is not technically feasible because it compromises the continuous supply of energy or requires oversized and expensive equipment, which would also make it economically unfeasible. Therefore, to overcome this disadvantage, it is necessary to design a hybrid renewable energy system (HRES) that integrates various renewable energies together with conventional technologies as backup, guaranteeing a continuous and reliable energy supply, as well as contributing to reduce CO<sub>2</sub> emissions (Oyewole O. et al., 2024). Colombia has been a leading country in the integration of renewable technologies into its energy distribution system, supplying approximately 70% of its national electricity demand through hydropower plants. However, this heavy reliance on hydropower poses a risk, as water resources are subject to climatic variability (Pupo-Roncallo et al., 2019). Consequently, Law 1715 of 2014 was enacted in Colombia to regulate the integration of renewable energy sources into the National Interconnected System (SIN). Additionally, the Mining

and Energy Planning Unit (UPME) and the Institute for Planning and Promotion of Energy Solutions (IPSE) have developed indicative plans to expand electricity coverage through the installation of renewable technologies (Congress of Colombia, 2014). Among the indicative plans proposed by the UPME, the development of energy communities, defined as agents of change for sustainable development and that contribute to the strengthening of communities and the generation of new sources of income, stands out (UPME, 2024).

The design and integration of an HRES into the SIN represent a complex task due to the multiple factors that must be considered, such as costs, available resources, energy demands, and efficiencies. The most used method for designing an HRES is the Mixed-Integer Linear Programming (MILP) model (Nozarian et al., 2023). Alhashedi et al. (2023) proposed a MILP optimisation model to integrate renewable energy into the power grids of Dhahran, Saudi Arabia, and Austin, USA. The model minimises costs while incorporating real-world data on load and region-specific costs. Similarly, Lu et al. (2021) examined the maximisation of monetary benefits by integrating photovoltaic, wind, and hydropower plants into the energy distribution system of a region in southwest China. Karmellos and Mavrotas (2019) developed a MILP model to design energy distribution systems that minimise total annual costs and CO<sub>2</sub> emissions. They also compared results based on whether plant capacities were treated as decision variables or fixed parameters. The literature reveals that optimisation models have included a variety of technologies and constraints, differing in robustness and complexity. However, these models typically treat plant capacities as constant parameters rather than decision variables. Additionally, due to high computational demands, robust models are often avoided.

Considering the above, this study proposes a robust MILP optimisation model with a 16-year planning horizon to integrate renewable technologies such as photovoltaics, wind, and biomass into the SIN to design for the first time a renewable hybrid system that meet the electricity demand to the municipality of Pamplona, Colombia. Moreover, given the intermittent nature of renewable resources, diesel power plants are included to ensure a continuous electricity supply. The model minimises the objective functions of net present value and CO<sub>2</sub> emissions while accounting for design, operational, and budgetary constraints, where plant capacities are treated as decision variables. Furthermore, the model incorporates surplus electricity sales to promote the development of energy communities considering the marginal energy limits as defined by Decree 1043 of 2024 of the Republic of Colombia.

## 2. Mathematical Formulation

This section presents the MOMILP model, including the objective functions and the design, operational, and budgetary constraints.

### 2.1 Objective Functions

The objective functions aim to minimize the Net Present Value (NPV) and CO<sub>2</sub> emissions. The NPV comprises the summation of the total capital cost of each technology used, fixed and variable operation and maintenance costs, fossil fuel costs, and the revenue from electricity sold to the grid (Eq. (1)). CO<sub>2</sub> emissions account for those generated by fuel-based technologies (biomass gasifiers and diesel plants) (Eq. (2)):

$$\text{NPV} = \sum_t \frac{1}{(1+TD)^t} [\sum_p \widehat{\text{InV}}_{\text{Co}_p,t} \cdot \text{CaA}_{p,t} + \sum_p \widehat{\text{Fix}}_{\text{Co}_p,t} \cdot \text{CaT}_{p,t} + \sum_p \widehat{\text{Var}}_{\text{Co}_p,t} \cdot \text{EnG}_{p,t} + \sum_p \widehat{\text{Fu}}_{\text{Co}_p,t} \cdot \text{FuR}_{p,t} - \sum_p \widehat{\text{Sell}}_{\text{Co}_p,t} \cdot \text{EnVe}_{p,t}] \quad (1)$$

$$\text{CO}_2 = \sum_t [\sum_p \widehat{\text{Em}}_p \cdot \text{EnG}_{p,t}] \quad (2)$$

### 2.2 Constraints

The model constraints are categorized in operational, design, and budgetary constraints for power plants.

#### 2.2.1 Operational Constraints

The operational constraints ensure the completion of energy demands and the generation of excess electricity.

**Energy Balance:** The electricity generated must meet the energy demand and generate a 5% surplus of electricity.

$$\sum_p \text{EnG}_{p,t} = \widehat{\text{DE}}_t + \sum_p \text{EnVe}_{p,t} \quad (3)$$

**Reserve Margin:** To ensure the achievement of demand in the event of unforeseen circumstances that affect electricity generation, a reserve margin of 6% is established over the maximum power demand.

$$\sum_p \text{PoG}_{p,t} \geq (1+\rho) \cdot \widehat{\text{DP}}_t \quad (4)$$

**Availability Factor:** The electricity generation time of a plant relative to the total considered time, including failures, forced outages, maintenance periods, or climatic variations.

$$\text{EnG}_{p,t} = A_p \cdot \text{DB}_t \cdot \text{PoG}_{p,t} \quad (5)$$

**Capacity Factor:** The efficiency of a power plant, calculated by comparing the average power generated over a year with the maximum power that would be generated under ideal conditions.

$$PoG_{p,t} \leq F_p \cdot CaT_{p,t} \quad (6)$$

### 2.2.2 Design Constraints

These constraints consider the installed capacities as decision variables, including available resources, construction times, and limits on the number of plants to be installed per year, as well as the additional capacity to avoid oversizing.

**Available Installed Capacity:** The previously installed capacity plus the newly added capacity.

$$CaT_{p,t} = ICa_{p,t} \cdot Op_{p,t} + \sum_{v \leq t - T_p} CaA_{p,t} \quad (7)$$

**Added Capacity Limits:** Limits are set for the added capacity (Eq(8)), ensuring that these do not exceed the maximum capacity throughout the entire planning horizon (Eq(9)). These added capacities determine the areas required by the equipment.

$$Ca_{min_p} \cdot ln_{p,t} \leq CaA_{p,t} \leq Ca_{max_p} \cdot ln_{p,t} \quad (8)$$

$$\sum_t CaA_{p,t} \leq Ca_{max_p} \quad (9)$$

**Installed Capacities per Period:** The amount of plant construction is limited during a specific period.

$$\sum_p ln_{p,t} \leq 2 \quad (10)$$

**Specific Consumption of Available Resources:** The primary sources used for electricity generation must not exceed the available number of resources.

$$\widehat{Rw}_{r,p} \cdot EnG_{p,t} \leq PriT_{r,t} \quad (11)$$

**Specific Consumption of Fossil Fuels:** The primary resource used in diesel plants is fossil fuel.

$$\widehat{Rw}_{r,p} \cdot EnG_{p,t} = FuR_{r,t} \quad (12)$$

### 2.2.3 Budgetary Constraint

The total cost of the hybrid system to be installed is limited by the financial support allocated for the expansion of electricity coverage in interconnected areas.

$$\sum_t \frac{1}{(1+r)^t} \cdot [\sum_p ln_{p,t} \cdot \widehat{Co}_{p,t} \cdot CaA_{p,t}] \leq BugCo \quad (12)$$

## 2.3 Case study

The MOMILP model was applied to the municipality of Pamplona, Colombia, which spans an area of 29,840 hectares, of which 24.2% are classified as páramo zones. These páramo zones are of vital importance due to their rich biodiversity and ability to supply water to approximately 2.5 million people. This municipality is connected to the national interconnected system and meets an electricity demand of 699 MWh for a population of approximately 56,894 people (Villamizar-Villamizar et al., 2024).

### 2.4 Technical and financial parameters

The technical and financial parameters used to solve the MOMILP model are shown in Table 1. In addition, the financial parameters were projected using the Colombian consumer price index (IPC) and the Eq(13)

$$C_n = C_0 * \left( \frac{IPC_n}{IPC_0} \right) \quad (13)$$

Where  $C_n$  is the cost of the year to be projected,  $C_0$  is the base year cost,  $IPC_n$  is the IPC of the year to be projected and  $IPC_0$  is the IPC of the base year (CREG, 2005).

*Table 1. Technical and financial parameters of renewable energy (IRENA, 2023).*

Parameters	Photovoltaic panel (PV)	Wind turbine (WT)	Biomass gasifier (GenBio)
Availability factor	0.21	0.74	0.58
Capacity factor	0.25	0.25	0.8
Emissions factor (kgCO <sub>2</sub> /kWh)	0.0	0.0	0.68
Construction time (years)	1.0	2.0	3.0
Investment cost (USD/kW)	758.00	1,160.00	1,800.00
Unit fixed O&M costs (USD/kW)	0.02	0.01	0.09
Unit variable O&M costs (USD/kW)	0.0	0.0	0.0001
Fuel cost (USD/kW)	0.0	0.0	2.33

### 3. Results and Analysis

The MOMILP model was built in Python using the Pyomo package and solved using the  $\epsilon$ -constraint method with the 'GLPK' solver (SIMPLEX method). Since the model considers two objective functions, there is no single solution that simultaneously optimizes both objectives. Therefore, in the multi-objective model, a Pareto front is obtained, which shows the different trade-offs between the objectives (alternatives). The 10 alternatives obtained on the Pareto front between Net Present Value (NPV) and CO<sub>2</sub> emissions are shown in Figure 1. The negative sign of the NPV refers to the profits from the sale of surplus electricity generated. The Pareto front indicates that if capital recovery is maximised, CO<sub>2</sub> emissions must be increased. An example of this is alternative A1, which generates the highest profits of -159,470 USD but produces the highest CO<sub>2</sub> emissions, at 245.88 t. Conversely, alternative A10 generates the lowest profits of -121,360 USD and produces the lowest CO<sub>2</sub> emissions, at 94.72 t. This variation in costs and emissions is due to the different capacities of plants considered for installation in each alternative (Figure 2).

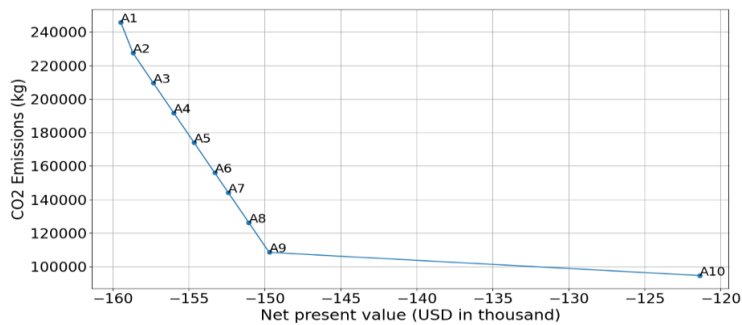


Figure 1. Pareto chart

Figure 2 shows that due to the constraints on the installation of two plants in a specific period and the intermittent nature of photovoltaic energy, it is necessary to install diesel plants and biomass gasifiers in the initial years to meet electricity demand. Furthermore, as CO<sub>2</sub> emissions are minimized, the installed capacities of solar panels increase. Notably, Alternative 10 proposes the installation of solar panels, wind turbines, biomass gasifiers, and diesel plants with capacities of 25 kW, 15 kW, 7 kW, and 4 kW, respectively.

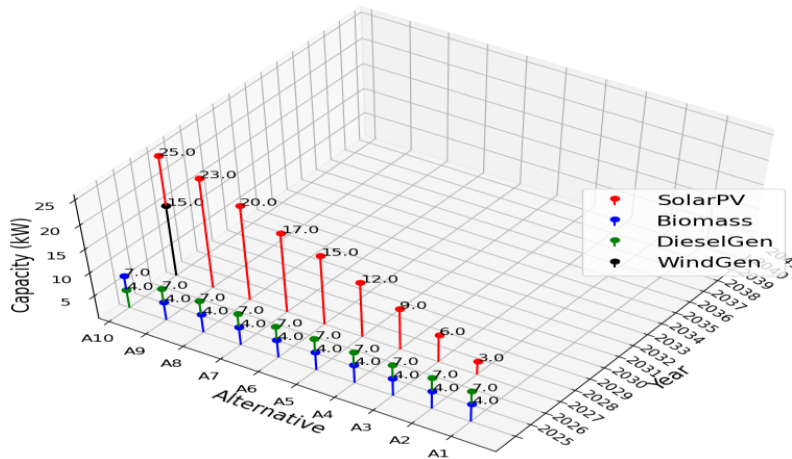


Figure 2. Added capacities for each alternative over the planning horizon.

Additionally, Figure 2 demonstrates the linear behaviour of the Pareto front between alternatives A1:A9, which differ by the increase in the installed photovoltaic technology capacity. Alternative A10 does not follow this same linear pattern as it considers installing the minimum capacity of wind turbines allowed by wind speeds, leading to a significant increase in the total system cost.

The energies generated by the added capacities are shown in Table 2. Biomass gasification plants generate the most energy up to alternative A8, as they ensure a constant energy supply and lower CO<sub>2</sub> emissions compared to diesel plants. Diesel plants have a low share in energy generation due to their high CO<sub>2</sub> emissions and are mainly installed to ensure energy supply during unforeseen interruptions in the electrical grid. The MOMILP model promotes the construction of photovoltaic panels as the goal is to reduce CO<sub>2</sub> emissions. In alternatives A8 and A9, photovoltaic technology covers over 50% of the electrical demand, generating 200,976.3

kWh and 218,452.5 kWh, respectively. Additionally, in alternative A10, due to the low wind speeds in the area, the energy generated by the wind resource is only 839.45 kWh.

*Table 2. Total energy generated by installed plants*

Alternative	Total energy generated by installed plants (kWh) (percentage)			
	Photovoltaic	Eolic	Biomass	Diesel
A1	0 (0 %)	0 (0 %)	324,480.81 (91.16 %)	31,482.24 (8.84 %)
A2	26,214.3 (7.36 %)	0 (0 %)	302,465.45 (84.97 %)	27,283.31 (7.66 %)
A3	52,428.6 (14.73 %)	0 (0 %)	276,363.69 (77.64 %)	27,170.77 (7.63 %)
A4	78,642.9 (22.09 %)	0 (0 %)	250,149.39 (70.27 %)	27,170.77 (7.63 %)
A5	104,857.2 (29.46 %)	0 (0 %)	223,935.09 (62.91 %)	27,170.77 (7.63 %)
A6	131,071.5 (36.82 %)	0 (0 %)	197,720.79 (55.55 %)	27,170.77 (7.63 %)
A7	148,547.7 (41.73 %)	0 (0 %)	180,244.59 (50.64 %)	27,170.77 (7.63 %)
A8	174,762.0 (49.10 %)	0 (0 %)	154,030.29 (43.27 %)	27,170.77 (7.63 %)
A9	200,976.3 (56.46 %)	0 (0 %)	127,815.99 (35.91 %)	27,170.77 (7.63 %)
A10	218,452.5 (61.37 %)	839.45 (0.24 %)	121,694.26 (34.19 %)	14,976.85 (4.21 %)

Table 2 shows that due to the low wind speeds and an average radiation of 7 kWh/m<sup>2</sup> in the municipality of Pamplona, Colombia, the integration of renewable energy into the energy distribution system does not fully reduce CO<sub>2</sub> emissions, as a high percentage of biomass gasifiers is required. Therefore, future research should explore the possibility of integrating renewable technologies such as batteries, small hydroelectric plants, cogeneration (CHP) plants, and hydrogen cells. Additionally, among the alternatives obtained in the Pareto front, it is necessary to select the most sustainable option using multicriteria selection methods, considering the opinions of experts influencing the region of interest.

#### 4. Conclusions

The application of the Mixed Integer Multi-Objective Linear Optimization (MOMILP) model allowed to assess the integration of electricity generation plants, such as photovoltaic panels, wind turbines, biomass gasifiers and diesel plants, to the electrical grid of the municipality of Pamplona, Colombia.

The resulting Pareto front shows that the alternative with the highest benefit, -\$159,470, is also the one that generates the highest CO<sub>2</sub> emissions, totalling 245.88 tons. In contrast, the alternative with the lowest benefit, -\$121,370, produces lower CO<sub>2</sub> emissions, totalling 94.72 tons. Alternative A1 generates the highest amount of CO<sub>2</sub> emissions because the electricity demand can only be met by installing biomass gasifiers and diesel plants, which supply 324,480 kWh and 31,482 kWh of energy, respectively. To reduce CO<sub>2</sub> emissions, the model promotes the construction of photovoltaic plants, which become the dominant technology in alternative A10, with an electricity production of 218,452 kWh, supported by biomass gasifiers, diesel generators and wind turbines, producing 121,694 kWh, 14,976 kWh and 839.45 kWh respectively.

The optimization model implemented in the municipality of Pamplona demonstrates that it is possible to satisfy the energy demand of the population through a hybrid system of renewable energies, such as solar, wind and biomass. The alternatives obtained in the Pareto front allow stakeholders and others interested in integrating a hybrid system to the Pamplona power grid, to apply a Multi-Criteria Decision Method to select the alternative that best fits their needs and priorities, considering aspects such as investment, profitability and CO<sub>2</sub> emissions. Furthermore, by proposing a robust optimization model that integrates wide technical and financial characteristics, this methodology can be adapted to other regions to assess the integration of renewable energies in their respective electricity grids, thus contributing to the sustainable expansion of these systems.

#### Nomenclature

##### Model parameters

TD – Discount rate, -

$\widehat{InvCo}_{p,t}$  – Unit investment costs, USD/kW

$\widehat{FixCo}_{p,t}$  – Unit fixed costs, USD/kW

$\widehat{VarCo}_{p,t}$  – Unit variable costs, USD/kW

$\widehat{FuCo}_{p,t}$  – Unit cost of fossil fuel, USD/fossil fuel unit

$\widehat{SellCo}_{p,t}$  – Unit Price of electricity, USD/kW

$\widehat{Em}_p$  – CO<sub>2</sub> emission factor, kgCO<sub>2</sub>/kWh

$\widehat{DE}_t$  – Energy demand, kWh

$\rho$  – Reserve margin, kW

$\widehat{DP}_t$  – Peak demand, kW

$ICa_{p,t}$  – Initial capacity available, -

$PriT_{r,t}$  – Total primary resources available, -

##### Sets

p – power generation plants, -

r – primary resources, -

t,v – Time period, 2024-2040

Tp – construction time, -

##### Decision variables

$CaA_{p,t}$  – Capacity to be added, kW

$CaT_{p,t}$  – Total available capacity, kW

$EnG_{p,t}$  – Energy generated, kWh

$A_p$ – Availability factor, -	$FuR_{p,t}$ – fossil fuel unit, -
$DB_t$ – Block duration, -	$EnVe_{p,t}$ – Surplus energy sold, kWh
$F_p$ – Capacity factor, -	$PoG_{p,t}$ – Power generated, kW
$\widehat{C}_{min_p}$ – minimum capacity, kW	<b>Decision binary variables</b>
$\widehat{C}_{max_p}$ – maximum capacity, kW	$Op_{p,t}$ – If the installed capacity is operational, -
$\widehat{R}w_{r,p}$ – Consumption factor of primary resources, primary resource units/kWh	$In_{p,t}$ – If new capacity is to be installed, -
$\widehat{BugCo}$ – Total budget, USD	

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