Multi-Objective Optimization and Analytical Hierarchical Process for Sustainable Power Generation Alternatives in the High Mountain Region of Santurbán: case of Pamplona, Colombia

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ABSTRACT

This study presents an integrated approach combining the Analytic Hierarchy Process (AHP) with a Mixed-Integer Multi-Objective Linear Programming (MOMILP) model to evaluate sustainable power generation alternatives for Pamplona, Colombia. The MOMILP model includes solar, wind, biomass, and diesel technologies, aiming to minimize costs (net present value) and CO_2 emissions while considering design, operational, and budget constraints. The AHP method evaluates multiple criteria such as social acceptance, job creation, technological maturity, and environmental impact. The results show that solar panels are prioritized, with small diesel plants added due to resource limitations. The most sustainable option is a hybrid system with 49% solar, 29% wind, 14% biomass and 8% diesel, generating a net present value of 121,360 USD and 94,720 kg of CO_2 emissions. The proposed methodology can be applied to assess and select the most feasible alternative within a wide range of new projects for the integration of renewable energy systems for the extension of existing power grids.

Keywords: Analytical Hierarchical Process, Multi-objective optimization, Numerical Methods, Renewable and Sustainable Energy, Technoeconomic Analysis.

INTRODUCTION

Energy systems are fundamental for economic and social development; however, around 66% of global energy supply still relies on fossil fuels, contributing to 75% of GHG emissions [1]. Given the continuous population growth and rising energy demand, these percentages are likely to increase in the future [2]. To address this issue, many countries have prioritized the integration of RES into their power distribution systems as a strategy to reduce GHG emissions and mitigate climate change [3]. Colombia, for instance, generates approximately 70% of its electricity from hydropower, significantly decreasing its reliance on fossil fuels [4].

Despite this progress, heavy dependence on hydropower poses a risk, as water resources are highly affected by climate variability [5]. Recognizing the need to diversify its energy mix, Colombia introduced Law 1715 in 2014 to regulate the integration of RES into the SIN. The law includes various incentives, such as income tax deductions, VAT exemptions, import duty exemptions, and accelerated asset depreciation, to promote the adoption of RES [6].

To effectively integrate RES into power grids, several studies have utilized MCDM methods. For example, Arikan et al. (2024) applied AHP and VIKOR to identify the most suitable non-conventional technology for a hotel's power supply, considering technical, economic, and environmental aspects [7]. Similarly, Xu et al. (2023) evaluated a hybrid RES using an optimization model combined with AHP, focusing on technical, economic, and environmental criteria [8]. However, these studies often overlook social factors, which are crucial for the successful design and implementation of hybrid energy systems. Ali et al. (2020) addressed this gap by incorporating social criteria, such as social acceptance and policy impacts, in their

assessment of RES options for a refugee camp in Bangladesh using the AHP method [9]. Despite the extensive body of research on RES integration, there is still a need for more comprehensive studies that consider social criteria and involve direct input from experts. Additionally, existing studies frequently fail to account for specific geographical characteristics of the case study area.

Addressing these gaps, this research employs a MOMILP model and the AHP to evaluate the integration of PV panels, biomass gasifiers, wind turbines, and diesel generators into the SIN to meet the energy demand of Pamplona, Colombia. The MOMILP model is designed with a 16-year planning horizon starting in 2024. It aims to minimize both costs and CO_2 emissions, considering design, operational, and budget constraints. The model also explores the potential for selling surplus electricity, which could contribute to local economic growth and enhance energy independence. To select the most sustainable alternative from the Pareto front, the AHP method is employed, using a comprehensive set of criteria: economic, technical, environmental, and social. It includes sub-criteria reflecting specific geographical aspects and social factors such as social acceptance and job creation. The weighting of these criteria and sub-criteria is determined through expert input, using the Delphi method and Saaty's scale. This integrated approach allows for a more holistic evaluation of RES integration strategies, ensuring that both technical and socio-economic factors are considered in the decision-making process.

MATHEMATICAL FORMULATION

In this section, the objective functions and constraints of the MOMILP model are presented.

Objective functions:

The objective functions aim to minimize the total generation system cost (NPV, which is the result of subtracting the energy costs — CAPEX, OPEX, and energy sales to the grid) (Eq. 1) and CO_2 emissions (Eq. 2):

$$NPV=\sum_t \frac{1}{(1+TD)^t}\cdot[\sum_p \widehat{InvCo}_{p,t}\cdot CaA_{p,t}$$

$$+\sum_p \widehat{FixCo}_{p,t}\cdot CaT_{p,t} +\sum_p \widehat{VarCo}_{p,t}\cdot EnG_{p,t} \qquad (1)$$

$$+\sum_p \widehat{FuCo}_{p,t}\cdot FuR_{p,t} -\sum_p \widehat{SellCo}_{p,t}\cdot EnVe_{p,t}]$$

$$CO_2=\sum_t [\sum_p \widehat{Em}_p \cdot EnG_{p,t}] \qquad (2)$$

Operational constraints:

The operational constraints are included to meet the electricity and power demand of the community, as well as to account for energy and power surpluses for sale, ensuring system reliability.

Energy balance: The generated energy must meet the electrical demand, with 5% of the demand allocated for surplus energy sales

$$\sum_p EnG_{p,t} =\widehat{DE}_t+\sum_p EnVe_{p,t} \qquad (3)$$

Reserve margin: To ensure system reliability, a reserve margin of 6% is set over the maximum power demand.

$$\sum_p PoG_{p,t} \geq (1+\rho)\cdot \widehat{DP}_t \qquad (4)$$

Availability factor: The fraction of time during which generation plants operate without forced outages, maintenance, repairs, or climatic variations must be considered.

$$EnG_{p,t}=A_p\cdot DB_t\cdot PoG_{p,t} \qquad (5)$$

Capacity factor: The ratio between the average power generated by the plant and the power that would be generated under ideal conditions.

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

Design constraints:

These constraints ensure that the system is not oversized by considering the capacity limits to be added, the construction time, and the specific consumption of available resources.

Available installed capacity: Existing capacity plus the newly added capacity of the generation plant.

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

Added capacity limits: Limits are set on the added capacity to prevent oversizing and ensure that the capacities added during the planning horizon do not exceed the established maximum capacity.

$$\widehat{Camin}_p\cdot In_{p,t}\leq CaA_{p,t}\leq \widehat{Camax}_p\cdot In_{p,t} \qquad (8)$$

$$\sum_t CaA_{p,t} \leq \widehat{Camax}_p \qquad (9)$$

Installed capacities per period: The amount of plant constructions is limited during specific period

$$\sum_p In_{p,t} \leq 2 \qquad (10)$$

Limits on the specific consumption of available resources: The primary resources used for energy generation must not exceed the available primary resources in the area.

$$\widehat{Rw}_{r,p}\cdot EnG_{p,t}\leq PriT_{r,t} \qquad (9)$$

Specific fossil fuel consumption (diesel plants): The primary resource used in diesel plants is the amount of fossil fuel consumed.

$$\widehat{Rw}_{r,p}\cdot EnG_{p,t}= FuR_{r,t} \qquad (10)$$

Budgetary constraint:

The investment to add new capacities is limited by the budget allocated to the region of interest, as established by the Financial Support Fund for the

Electrification of Interconnected Rural Areas

$$\sum_t \frac{1}{(1+r)^t} \cdot [\sum_p \widehat{InvCo}_{p,t} \cdot CaA_{p,t}] \leq \widehat{BugCo} \qquad (11)$$

The MOMILP model is built in Python using the Pyomo package and solved using the ε-constraint method with the 'GLPK' solver (SIMPLEX method), yielding 10 alternatives in the Pareto chart.

Technical and financial parameters:

The parameters used to solve the MOMILP model are presented in Table 1. In addition, as the model considers later years, the financial parameters were projected with consumer price index (IPC) (Eq. 12):

$$C_n = C_0 * \left(\frac{IPC_n}{IPC_0}\right) \qquad (12)$$

Where C_n is the cost in 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 the IPC of the base year [10].

MULTI-CRITERIA DECISION-MAKING METHOD (AHP)

AHP approach:

Hierarchy Structure: The problem is decomposed into a hierarchical structure consisting of 4 criteria (C1. Economic, C2. Technical, C3. Environmental, C4. Social), 10 sub-criteria (C2.1 Efficiency, C2.2 Technological Maturity, C2.3 Reliability, C2.4 Access Routes, C3.1 Pollutant Waste, C3.2 Land Requirement, C3.3 Habitat Impact, C3.4 CO2 Emissions, C4.1 Job Creation, C4.2 Social Acceptance), and 10 alternatives (A1:A10) (Figure 1)

Information Collection: The individual weights of the criteria and sub-criteria are obtained through expert opinion collection using the Delphi method and a scale from 1-9 (Saaty scale).

Pairwise Comparison between Criteria and Sub-Criteria: This matrix comparison determines the relative importance of each criterion and sub-criterion compared to the others.

Consistency Ratio (C.R.): Consistency between the comparisons is verified through the consistency ratio (C.R.). If C.R. is less than 0.1, the comparisons are consistent.

Evaluation of Alternatives: The priority of each alternative is determined through pairwise comparisons, considering the relative importance (weights) of each criterion and sub-criterion.
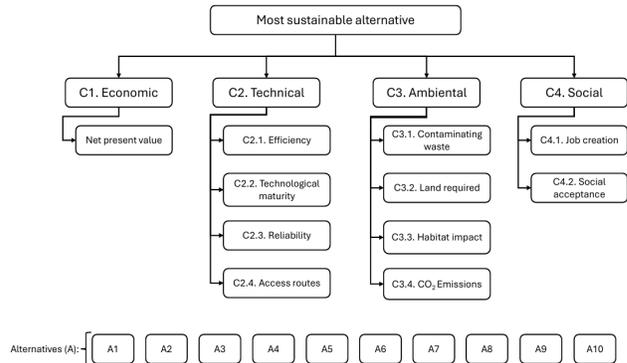
Figure 1. Hierarchical levels of the AHP method.

Case study description

The MOMILP model was applied to the municipality of Pamplona, Colombia, due to its proximity to the high mountain region of the Santurbán páramo, which supplies water to around 2.5 million people and supports rich biodiversity. This municipality is connected to the National Interconnected System (SIN) and has an approximate population of 56,894 people [12] with an electricity demand of 699 MWh [13].

RESULTS AND ANALYSIS

The 10 alternatives obtained on the Pareto front for the objective functions of net present value (NPV) and CO_2 emissions are shown in Table 2. The values of the NPV refer to the net gains up to the year 2040 resulting from the sale of excess electricity generated (5% of the electrical demand). The objective functions have a direct relationship, meaning that if the gains increase, CO_2 emissions also rise, and vice versa. Therefore, alternative A1 achieves the greatest profits, with a value of 159,470 USD, and the highest CO2 emissions, reaching 245.88 tons. Conversely, alternative A10 yields the smallest profits, amounting to 121,360 USD, and the lowest CO2

Parameters	PV panel	Wind turbine	Biomass gasifier	Diesel plants
Availability factor	0.21	0.74	0.58	0.98
Capacity factor	0.25	0.25	0.8	0.5
Emissions factor (kgCO$_2$/kWh)	0.0	0.0	0.68	0.79
Construction time (years)	1.0	2.0	3.0	2.0
Investment cost (USD/kW)	758.00	1,160.00	1,800.00	448.00
Unit fixed O&M costs (USD/kW)	0.02	0.01	0.09	4.74
Unit variable O&M costs (USD/kW)	0.0	0.0	0.0001	0.004
Fuel cost (USD/unit fuel)	0.0	0.0	0.0	1.91

Table 1: Technical and financial parameters of renewable energies [11].
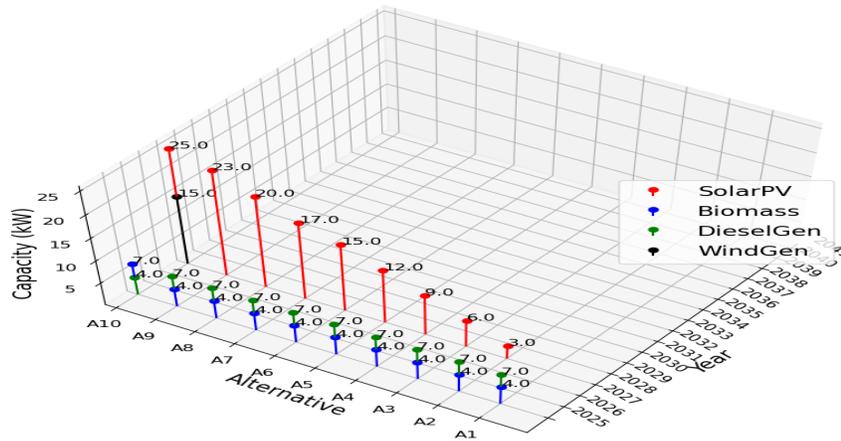
Figure 2: Added capacities in each alternative.

emissions, producing 94.72 tons.

Table 2: Pareto front alternatives.

Alternative	NPV (USD)	CO_2 emissions (Ton)
A1	159,470	245.88
A2	158,670	227.57
A3	157,330	209.70
A4	155,990	191.84
A5	154,640	173.98
A6	153,290	156.13
A7	152,390	144.22
A8	151,050	126.36
A9	149,700	108.51
A10	121,360	94.72

Each alternative considers adding different generation plant capacities (Figure 2). The obtained alternatives favour the addition of solar plants, biomass gasifiers, and diesel plants. Although diesel plants produce the highest CO_2 emissions, the available resources in the area lead to their inclusion to meet the electricity demand. Alternative A1 generates the highest profits but does not consider CO_2 emissions reduction. This alternative considers including only diesel plants and biomass gasifiers with proportions of 64% and 36%, respectively.

In contrast, alternative A10, while generating the lowest profits, seeks to minimize CO_2 emissions as much as possible, promoting the construction of solar plants, wind turbines, biomass gasifiers and diesel generators with proportions of 49%, 29%, 14% and 8%, respectively. This last alternative is the only one that includes wind generation, as the area's wind speeds are not strong enough to install plants with capacities greater than 1 kW.

The energies generated by the added capacities are shown in Table 3. Biomass gasifiers predominate as the main technology up to alternative A8, since they guarantee energy supply and produce less CO_2 emissions compared to diesel plants. From alternative A9 onwards, photovoltaic panels stand out as the main source of electricity generation. It should be noted that, in alternative A10, wind energy contributes a small proportion of the total electricity generation, which contributes to this alternative having the lowest emissions. Furthermore, due to the high CO_2 emissions produced by diesel plants, these are used only as backup sources to ensure a continuous and reliable electricity supply.

Applying the AHP method to the expert opinions

	Total energy generated by installed plants (kWh) (percentage)			
Alternative	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 3: Total energy generated by installed plants.

Power plant	C1	C2.1	C2.2	C2.3	C2.4	C3.1	C3.2	C3.3	C3.4	C4.1	C4.2	Total
Solar	0.086	0.02	0.005	0.004	0.002	0.056	0.015	0.008	0.042	0.006	0.074	0.302
Biomass	0.014	0.008	0.004	0.008	0.002	0.011	0.004	0.017	0.020	0.053	0.027	0.167
Diesel	0.183	0.010	0.018	0.017	0.002	0.005	0.002	0.053	0.004	0.025	0.012	0.331
Wind	0.026	0.008	0.012	0.002	0.002	0.056	0.015	0.005	0.009	0.019	0.045	0.200
Total	0.308	0.029	0.039	0.030	0.010	0.128	0.037	0.082	0.076	0.103	0.158	1.000

Table 4: Weights of the criteria, subcriteria, and power plants.

collected through the Delphi method, the prioritization scores for the criteria, subcriteria, and generation plants are shown in Table 4. The most important criterion is environmental, followed by economic, social, and technical. Social acceptance (C4.2) is considered by the experts as the second most important criterion for evaluating the alternatives, as it ensures that the beneficiary region or community makes the most of these sustainable technologies and contributes to their care. In addition, the job creation sub-criterion (C4.1) has a high weight due to its relevance for the socio-economic development of the region. As a result, in the AHP evaluation, conventional technologies can be given more weight in the prioritisation of alternatives. Although the diesel power plant produces the highest CO_2 emissions, it has the lowest habitat impact, the lowest investment cost, and the best technological aspects. These characteristics make the diesel plant the highest prioritized. Furthermore, since the alternatives obtained through MOMILP consider a mix of generation plants, the best alternative was selected based on the individual criterion and the percentage of energy generated by each plant throughout the planning horizon (Table 5).

Table 5: Percentage of alternatives prioritization.

Alternative	Prioritization weight	Ranking
A1	0.1848	10
A2	0.1930	9
A3	0.2028	8
A4	0.2126	7
A5	0.2224	6
A6	0.2322	5
A7	0.2388	4
A8	0.2486	3
A9	0.2584	2
A10	0.2601	1

Since electricity generation from diesel plants is similar across all alternatives, the prioritization is influenced by the installation of photovoltaic panels. Consequently, Alternative A10, with a score of 0.1848, turns out to be the least favourable option, as it does not include the implementation of any PV capacity. Similarly, the alternative A10, with a score of 0.268, is the preferred option to meet Pamplona's energy demand while simultaneously reducing CO_2 emissions.

CONCLUSIONS

A Mixed-Integer Linear Multi-Objective Optimization model was implemented to evaluate the Pareto front alternatives that integrate solar, wind, biomass, and diesel power plants into the National Interconnected System, in order to meet the electricity demand of the municipality of Pamplona, Colombia. The alternatives promoted the construction of solar plants, aiming to minimize CO_2 emissions. Additionally, due to the limitation of available resources, diesel plants were required to generate energy to meet demand and sell to energy distributors. The most sustainable alternative was determined by collecting expert opinions using the Delphi method and the AHP method, which considered economic, technical, environmental, and social criteria, and included 10 subcriteria. The most important criterion was environmental, followed by economic, social, and technical. Among the power plants, the diesel plant is preferred due to its higher efficiency and lower impact on habitats. The evaluation of the alternatives determined that alternative A10 is the highest priority, which consists of implementing solar plants, wind turbines, biomass gasifiers and diesel generators with proportions of 49%, 29%, 14% and 8%, respectively. The proposed methodology can be applied to assess and select the most feasible alternative within a wide range of new projects for the integration of renewable energy systems for the extension of existing power grids.

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)

$\widehat{Em}_p$: CO2 emission factor (kgCO2/kWh)

$\widehat{DE}_t$: Energy demand (kWh)

ρ : Reserve margin (kW)

$\widehat{DP}_t$: Peak demand (kW)

A_p : Availability factor

DB_t : Block duration
F_p : Capacity factor
$\widehat{Camin}_p$: Minimum capacity (kW)
$\widehat{Camax}_p$: Maximum capacity (kW)
$\widehat{Rw}_{r,p}$: Consumption factor of primary resources (primary resource units/kWh)
$\widehat{BugCo}$: Total budget (USD)

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)
$FuR_{r,t}$: Fossil fuel unit
$EnVe_{p,t}$: Surplus energy sold (kWh)
$PoG_{p,t}$: Power generated (kW)

Decision binary variables

$Op_{p,t}$: If the installed capacity is operational
$In_{p,t}$: If new capacity is to be installed

Abbreviations

RES : Renewable Energy System
SIN : National Interconnected System
IPC : Consumer price index

ACKNOWLEDGEMENTS

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