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Multi-Objective Optimization Model for Generation Expansion Planning in Industrial Power Systems: A Case Study of Kolwezi, DRC

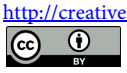
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Abstract

The energy transition and rapid growth in electricity demand in African mining regions, such as Kolwezi (Democratic Republic of the Congo), require a redesign of industrial power systems currently dependent on costly and polluting diesel generators. This work proposes a multi-objective optimization model based on mixed-integer linear programming (MILP) for generation expansion planning, integrating photovoltaic plants, battery energy storage systems (BESS), and demand response (DR) programs. Three objectives are simultaneously minimized: total annualized cost, CO_2 emissions, and energy not supplied. The ε-constraint method is used to generate the Pareto front, and the best compromise solution is identified using the TOPSIS method. Applied to the Kolwezi industrial power system, the model shows that integrated planning can reduce total operating costs by more than 20%, CO_2 emissions by approximately 49%, and energy not supplied by more than 80% compared to the reference scenario, while increasing the share of renewables to over 55% of the energy mix. Sensitivity analysis shows that both the battery investment cost and the diesel price are the most influential parameters: a 50% reduction in battery costs increases the optimal BESS capacity by 6% and improves system profitability, while a 30% increase in battery costs would further improve system profitability. This model constitutes a robust decision-support tool to support the energy transition of African mining basins.

Keywords

Generation Expansion Planning, Multi-Objective Optimization, MILP, Renewable Energy, Battery Storage, Demand Response, Industrial Power System, Kolwezi, DRC

1. Introduction

The global energy transition, driven by decarbonization objectives and the continuous growth in electricity demand, is reshaping the planning and operation of power systems worldwide [1] [2]. In mining regions such as Kolwezi, in the Democratic Republic of the Congo (DRC), electricity supply reliability is particularly important because mining and mineral-processing operations require a continuous and dependable power supply. Interruptions can disrupt production processes, increase operating costs, and compromise industrial productivity. Consequently, generation expansion planning must account not only for economic performance but also for supply reliability and environmental sustainability.

The DRC has substantial energy resources, particularly hydropower, as well as considerable potential for solar photovoltaic generation. However, the availability of these resources does not automatically translate into reliable and sufficient electricity supply. Electricity infrastructure constraints and the mismatch between available generation capacity and growing demand continue to challenge industrial and economic development. These challenges highlight the need for integrated planning approaches that can identify cost-effective investment strategies while improving electricity access, system reliability, and environmental performance [3].

Kolwezi, the capital of Lualaba Province, is one of the major copper- and cobalt producing centres in the DRC. These minerals are essential to several technologies associated with the energy transition, including batteries and electric vehicles. As mining activities expand, electricity demand increases, placing additional pressure on existing supply infrastructure. Where grid electricity is insufficient or unreliable, mining operations may rely on diesel generators as backup sources, potentially increasing fuel expenditure and operational greenhouse gas emissions. The integration of renewable generation and energy storage therefore represents a promising approach to reducing diesel dependence while improving the flexibility and resilience of industrial power systems [4] [5]. Nevertheless, the effective integration of photovoltaic generation and battery energy storage requires careful coordination of investment and operational decisions. Mixed-integer linear programming (MILP) provides a suitable framework for representing discrete investment decisions and operational constraints, while multi-objective optimization enables decision-makers to examine trade-offs among system cost, emissions, and electricity supply reliability [4] [6]. Accordingly, this study develops a multi-objective MILP model for generation expansion planning in the industrial power system of Kolwezi, integrating photovoltaic generation, battery energy storage systems (BESS), and demand response (DR) [5]. The model aims to identify compromise solutions that reduce annualized system costs and CO_2 emissions while improving electricity supply reliability.

2. State of the Art

2.1. Generation Expansion Planning (GEP)

Generation Expansion Planning (GEP) aims to determine optimal investments to

meet future demand at the lowest cost while respecting the technical constraints of the power system. Mixed-Integer Linear Programming (MILP) models are now widely used for their ability to simultaneously represent investment decisions (binary variables) and operational constraints (continuous variables). This approach has been formalized and validated by numerous works, notably those of [6] on nonlinear and mixed-integer programming techniques, and [2] on the optimal response of thermal units to electricity spot markets.

GEP models have evolved toward multi-period and multi-objective formulations. This study proposed an approach integrating Monte-Carlo simulation to account for the random availability of components and demand uncertainties, thereby demonstrating the value of stochastic MILP formulations for capturing trade-offs between cost and environmental impact [7] extended this approach by explicitly considering power system adequacy within a multiobjective framework. More recently, [8] applied a GEP model integrating renewable energy and optimal unit commitment to a real case study in Afghanistan, confirming the relevance of such approaches for developing systems. Koltsaklis and Knäpek explored the challenges and opportunities of generation expansion planning for 100% renewable energy systems, while [9] developed a multi-objective model under uncertainties to achieve renewable energy policy objectives. These works confirm that GEP is a mature field, but its application to isolated or weakly connected industrial systems remains limited.

2.2. Integration of Renewable Energy and Storage

The integration of renewable energies, particularly photovoltaics, improves the sustainability of power systems but introduces intermittent production. Battery energy storage systems (BESS) can compensate for this variability by storing surplus energy and releasing it during periods of high demand. [10] provided an overview of different optimization approaches for the design of hybrid renewable energy systems, while [11] analyzed the use of HOMER software for planning such systems. [12] reviewed modeling and optimization techniques for hybrid systems in off-grid applications, and proposed a state of the art review of optimal design methods for hybrid renewable energy systems. Demand response (DR) programs also enhance grid flexibility by adapting consumption to production conditions [12] analyzed the key functionalities of BESS in renewable-integrated power systems, and [5] proposed a quantitative framework to analyze the actual duty profiles of grid-connected BESS. More recently, [13] and [14] respectively reviewed renewable integration and storage management in power systems, and optimization approaches for hybrid systems, confirming the growing importance of storage and demand-side flexibility in modern power systems.

2.3. Multi-Objective Approaches

Multi-objective approaches allow for the simultaneous optimization of several criteria, including:

1) Total system cost;
2) CO_2 emissions;
3) Supply reliability;
4) Renewable energy penetration.

The most commonly used methods are the weighted sum method, the ε-constraint method, and evolutionary algorithms such as NSGA-II. The ε-constraint method is particularly well-suited to MILP models, as it allows secondary objectives to be transformed into parametrized constraints while preserving the linearity of the problem. [14] proposed a multi-period multi-objective GEP model using Monte-Carlo simulation, while [7] extended this approach by explicitly considering power system adequacy within a multi -objective framework. More recently [15] proposed a recuperation-based multi-objective generation expansion planning method for a real-world power system, confirming the relevance of multi -objective approaches for balancing economic, environmental, and reliability criteria. [9] also developed a multi-objective GEP model under uncertainties to achieve renewable energy policy objectives. These works confirm that combining MILP with the ε-constraint method is a robust approach for exploring trade-offs between cost, emissions, and reliability.

2.4. Gaps for African Industrial Systems: The Case of Kolwezi

Studies on African industrial power systems remain limited, particularly for mining regions. In Kolwezi, the growth in electricity demand, dependence on diesel generators, and grid constraints require tailored solutions. In this context, this work proposes a multi-objective MILP model integrating expansion planning, photovoltaic plants, batteries (BESS), demand response (DR), and technical grid constraints to minimize costs, reduce CO_2 emissions, and improve supply reliability.

3. Methodology and Mathematical Formulation

3.1. System Architecture

Figure 1 presents the architecture of the studied hybrid energy system. The system includes production sources (SNEL grid, photovoltaic plant, and diesel generators), a battery energy storage system (BESS), mining loads, and a demand response (DR) program. The whole is managed by a multi-objective optimization model based on mixed-integer linear programming (MILP), aiming to minimize total cost, CO_2 emissions, and energy not supplied while respecting system technical constraints. This architecture is consistent with the hybrid renewable energy system configurations reviewed in the literature [16] which emphasize the integration of multiple generation sources with storage and demand-side management to improve reliability and sustainability.

3.2. Nomenclatures and Sets

Before the mathematical formulation, the sets and main decision variables are defined as follows.

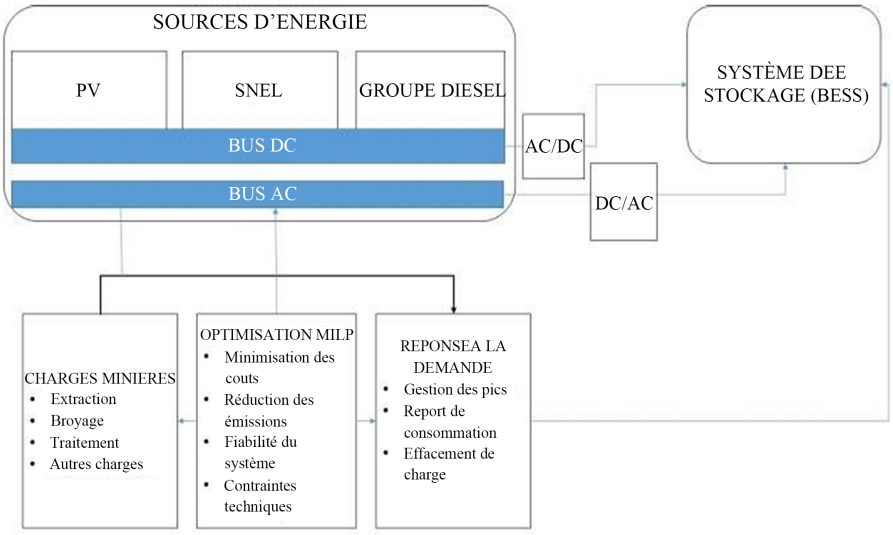


Figure 1. Architecture of the proposed hybrid energy system for generation expansion planning in the Kolwezi industrial grid.

Sets:

- L : Set of production technologies.
- $I_{news} \subseteq I$: Technologies eligible for new investment (PV, BESS, Diesel).
- $I_{existing} \subseteq L$: Already installed technologies (Hydropower).
- $I_{diesel} \subseteq L$: Diesel generator sets subject to ramping constraints.
- T : Time horizon, with $t = 1, \cdots, 8760$ hours.

Decision Variables:

- $y_i \in \{0,1\}$: {0, 1}: Binary variable indicating investment in technology i.
- $u_{i;t} \in \{0,1\}$: Operating state of unit i at time t.
- $P_{i;t} \geq 0$: Power produced by technology i at time t (MW).
- SOC_t : State of charge of the storage system (MWh).
- $P_{BESSch,t}$: BESS charging power (MW).
- $P_{BESSdech,t}$: BESS discharging power (MW).
- $ENS(t) \geq 0$: Energy not supplied at time t (MWh).

Main Parameters:

- $CAPEX_i$: Investment cost of technology i (\$/MW).
- $OPEX_i^{fix}$ Fixed operating cost (\$/MW/year).
- $OPEX_i^{var}$: Variable operating cost (\$/MWh).
- EF_i : CO_2 emission factor (tCO_2/MWh).
- P_i^{min}, P_i^{max} : Minimum and maximum power (MW).
- $RampUp_i, RampDown_i$: Ramp-up and ramp-down limits (MW/h).
- $VOLL$: Value of lost loads (\$/MWh).
- η_{ch}, η_{dech} : BESS charging and discharging efficiencies.

3.3. Objectives Functions

The problem is formulated as a multi-objective optimization aiming to simultaneously minimize the total annualized cost, CO_2 emissions, and energy not sup-

plied. This three-objective formulation is consistent with the multi-objective GEP approaches proposed by [7] [9] which jointly consider economic, environmental, and reliability criteria.

3.3.1. Objective 1: Minimization of CO_2 Emissions

$$\text{Minimize } z_1 = \sum_i \sum_t EF_i \times P_{i,t} \tag{1}$$

where EF_i represents the emission factor (tCO_2/MWh) of technology ii. This formulation follows the environmental objective adopted in multi-objective GEP studies and uses emission factors consistent with the IPCC guidelines [8].

3.3.2. Objective 2: Minimization of Total Annualized Cost

$$\begin{aligned}\text{Minimize } Z_1 = &\sum_{i\in I} FCF \times CAPEX_i \times y_i + \sum_{i\in I}\sum_{t\in T} OPEX_i^{fix} \times u_{i,t} \\ &+ \sum_{i\in I}\sum_{t\in T} OPEX_i^{var} \times P_{i,t} + \sum_{t\in T} VOLL \times ENS_t\end{aligned} \tag{2}$$

where:

- FCF is the annuity factor;
- $CAPEX_i$ is the investment cost ($/MW);
- $OPEX_i^{fix}$ is the fixed operating cost;
- $OPEX_i^{var}$ is the variable operating cost;
- $VOLL$ is the value of lost load ($/MWh).

This cost function includes the annualized investment costs (via the fixed charge factor, *FCF*), fixed and variable operating costs, the value of lost load (*VOLL*) associated with energy not supplied, and the incentive costs for demand response. The *VOLL* parameter is a standard economic measure of supply reliability, as discussed in [14].

3.3.3. Objective 3: Minimization of Energy Not Supplied

$$\text{Minimize } z_1 = \sum_{t\in T} ENS_t \tag{3}$$

This function aims to improve the reliability of the power system by reducing the amount of energy not supplied to consumers.

3.4. Model Constraints

The model is subject to the technical constraints described below.

3.4.1. Investment Constraint

Production from a new technology is allowed only if it is installed:

$$P_{i,t} \le y_i P_i^{max}, \forall i \in I_{new}, \forall t \in T \tag{4}$$

where y_i is the binary investment variable and P_i^{max} is the installed capacity.

3.4.2. Supply-Demand Balance

At each period, the power produced, adjusted by BESS exchanges, must satisfy demand:

$$\sum P_{i,t} + P_{bess,dech,t} + ENS_t = D_t, \quad \forall t \in T \tag{5}$$

where D_t is the electricity demand and ENS_t the energy not supplied. This balance equation ensures that generation, storage discharge, and energy not supplied meet the net demand after demand response actions. It is consistent with the balance formulations used in hybrid system models [17].

3.4.3. Production Limits

Each unit operates within its admissible range:

$$P_i^{min} u_{i,t} \le P_{i,t} \le P_i^{max} u_{i,t}, \forall i \in I, \forall t \in T \tag{6}$$

where $U_{i,t}$ is the binary variable indicating the unit's operating state. This constraint is standard in unit commitment and GEP models [2] [8].

3.4.4. Ramping Constraints

Power variations of diesel generators are limited to respect their dynamic characteristics:

$$P_{i,t} - P_{i,t-1} \le RampUp_i u_{i,t-1} + P_i^{max}\left(1-u_{i,t-1}\right), \forall i \in I_{diesel}, t>1 \tag{7}$$

$$P_{i,t} - P_{i,t-1} \le RampDown_i u_{i,t-1} + P_i^{max}\left(1-u_{i,1}\right), \forall i \in I_{diesel}, t>1 \tag{8}$$

The term $P_i^{max}\left(1-u\right)$ corresponds to the Big-M parameter that deactivates the constraint when the unit is off.

3.4.5. Minimum up Time

A started unit must remain in operation for a minimum duration:

$$\sum_{k=t}^{t+T_{on}^{min}-1} U_{i,k} \ge T_{on}^{min}\left(u_{i,t} - u_{i,t-1}\right), \forall i \in I_{diesel}, t>1 \tag{9}$$

3.4.6. Minimum down Time

A stopped unit must respect a minimum duration before a new start:

$$\sum_{k=t}^{t+T_{off}^{min}-1}\left(1-U_{i,k}\right) \ge T_{off}^{min}\left(u_{i,t-1} - u_{i,t}\right), \forall i \in I_{diesel}, t>1 \tag{10}$$

3.5. Battery Energy Storage System (BESS) Constraints

The evolution of the state of charge is given by:

$$SOC_t = SOC_{t-1} + \eta_{ch} P_{BESS,ch,t} - \frac{P_{BESS,dech,t}}{\eta_{dech}}, \forall t \in T \tag{11}$$

with power limits:

$$0 \le P_{BESS,ch,t} \le P_{BESS}^{max} u_{ch,t} \tag{12}$$

$$0 \le P_{BESS,dech,t} \le P_{BESS}^{max} u_{dech,t} \tag{13}$$

Simultaneous charging and discharging are prohibited:

$$u_{ch,t} + u_{dech,t} \le 1, \forall t \in T \tag{14}$$

Finally, the state of charge must remain within admissible limits:

$$SOC^{min} \le SOC_t + SOC^{min}, \forall t \in T \tag{15}$$

3.6. Multi-Objective Resolution Method

The generation expansion planning problem is formulated as a multi-objective mixed-integer linear programming (MILP) problem. To obtain a set of compromise solutions among economic, environmental, and reliability objectives, the ε-constraint method is adopted. In this approach, the economic objective function Z_1 is minimized, while CO_2 emissions (Z_2) and energy not supplied (Z_3) are transformed into parametrized constraints:

$$\min Z_1$$

subject to:

$$Z_2 = \varepsilon_2$$

$$Z_3 = \varepsilon_3$$

where ε_2 and ε_3 represent the allowable thresholds for CO_2 emissions and energy not supplied, respectively.

The resolution procedure includes the following steps:

1) Independent resolution of each of the three objectives to obtain individual optimal values (Z_1^* , Z_2^* , Z_3^*)

2) Determination of the variation intervals for parameters ε_2 and ε_3;

3) Iterative resolution of the MILP model for different combinations of ε_2 and ε_3;

4) Construction of the Pareto front from the obtained non-dominated solutions;

5) Selection of the best compromise solution using the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution).

This approach enables the analysis of trade-offs among total annualized cost, CO_2 emissions, and power supply reliability, while guaranteeing optimal solutions for each studied scenario.

3.7. Model Implementation, Data and Reproducibility

The hourly demand and hydropower production data come from SNEL (Société Nationale d'Électricité) for the year 2023. They were anonymized, cleaned (removal of outliers, interpolation of missing data), and normalized. The complete hourly profiles are provided in supplementary material. Confidential data are not disclosed.

The techno-economic parameters are taken from [13], and local quotes. **Table 3**. Impact of diesel price variation on key indicators (Scenario D).23. in the **appendix** provides the numerical values used.

4. Case Study: Industrial Power System of Kolwezi

This study is applied to the industrial power system of the city of Kolwezi, located in Lualaba province, in the southeast of the Democratic Republic of the Congo (DRC). Kolwezi is today one of the world's most important mining basins for cop-

per and cobalt production, two strategic minerals essential for the manufacturing of lithium-ion batteries, electric vehicles, and energy transition technologies.

The rapid expansion of mining activities over the last decade has led to a significant increase in electricity demand. Despite the existence of significant hydroelectric resources in the Katanga region, the currently available capacities remain insufficient to meet the growing needs of mining operations. Power interruptions are frequently compensated by diesel generator sets, which considerably increases operating costs as well as greenhouse gas emissions.

4.1. Description of the Studied System

The considered power system includes the following components:

- The existing hydroelectric grid supplied by SNEL;
- Several diesel generator sets used as backup means;
- A large-scale photovoltaic plant;
- A battery energy storage system (BESS);
- An active demand management program (Demand Response).

Figure 2 shows the location of Kolwezi in the DRC, at the heart of the African Copperbelt, a region rich in copper and cobalt. Kolwezi is located in the south-eastern part of the Democratic Republic of the Congo, in Lualaba Province, approximately 1400 km from Kinshasa, the national capital. The city lies close to the borders with Zambia to the south and Angola to the south-west, which explains its strategic position as a regional mining and trading hub.



Figure 2. Geographical location of the city of Kolwezi in the DR Congo.

4.2. Electricity Demand Profile

Electricity consumption is mainly dominated by industrial processes related to Figure 3 The KCC mining site.

- Ore crushing;
- Grinding;
- Flotation;
- Hydrometallurgical units;
- Maintenance workshops.

The daily profile generally presents two periods of high consumption:

1) between 08:00 and 12:00;

2) between 18:00 and 21:00.

These peaks correspond to the full production periods of mining facilities.



Figure 3. Picture of KCC mine.

4.3. Solar Potential

Kolwezi benefits from an excellent photovoltaic potential. The average annual solar irradiation is between:

✓ 5.0 - 5.8 kWh/m^2/day

according to PVGIS data.

This resource allows for a high penetration of photovoltaic systems while reducing diesel generator fuel consumption.

Figure 4 compares renewable generation with hourly demand, confirming the importance of battery storage for covering the evening peak and improving system flexibility [12].

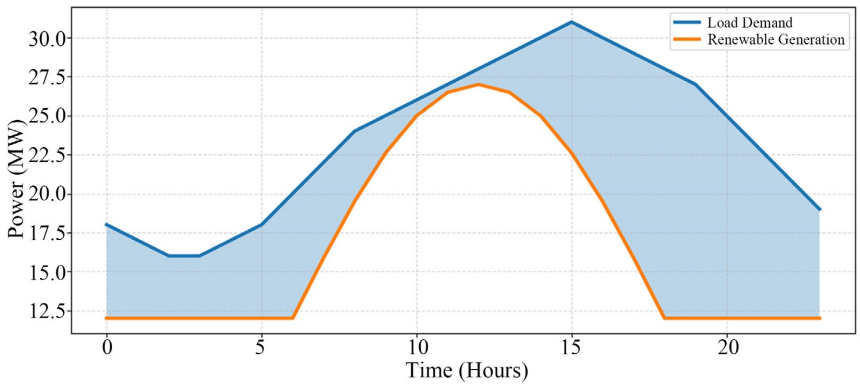


Figure 4. Renewable generation vs load demand.

Figure 5 shows the daily generation profile, where hydropower provides a stable baseload, PV output follows the daytime solar cycle, and diesel generators operate mainly during periods of low renewable production. This complementary behavior is consistent with previous studies on hybrid hydrosolar systems [13] [18].

Figure 6 the optimal dispatch strategy, where the MILP model prioritizes hydropower and PV, uses batteries to store excess solar energy, and limits diesel generation to periods of necessity [15].

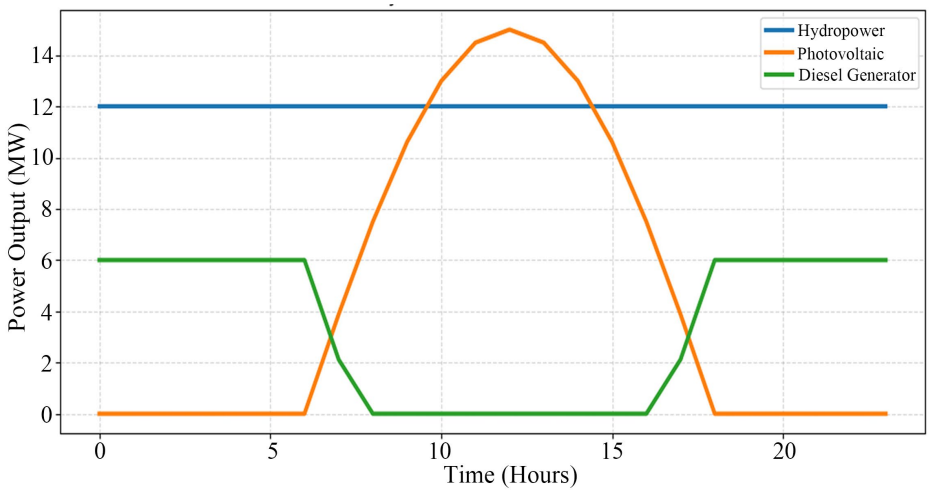


Figure 5. Daily power generation profile.

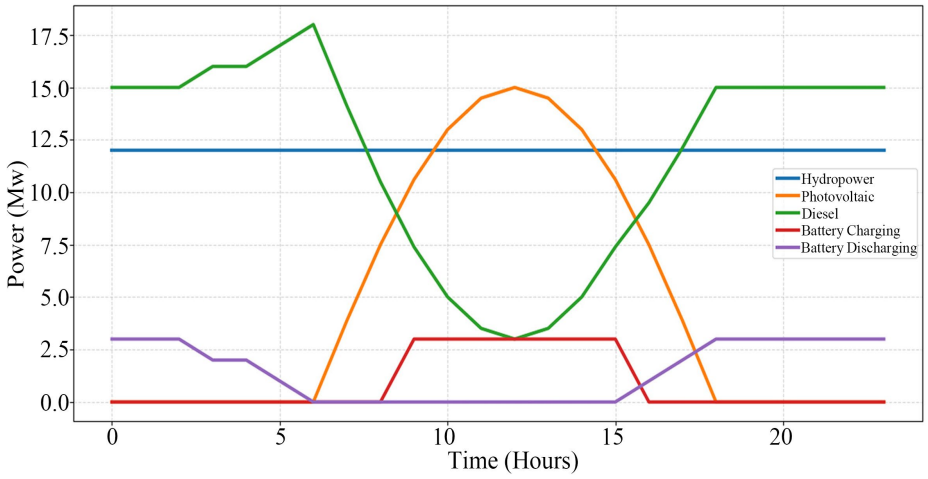


Figure 6. Optimal dispatch of hybrid system.

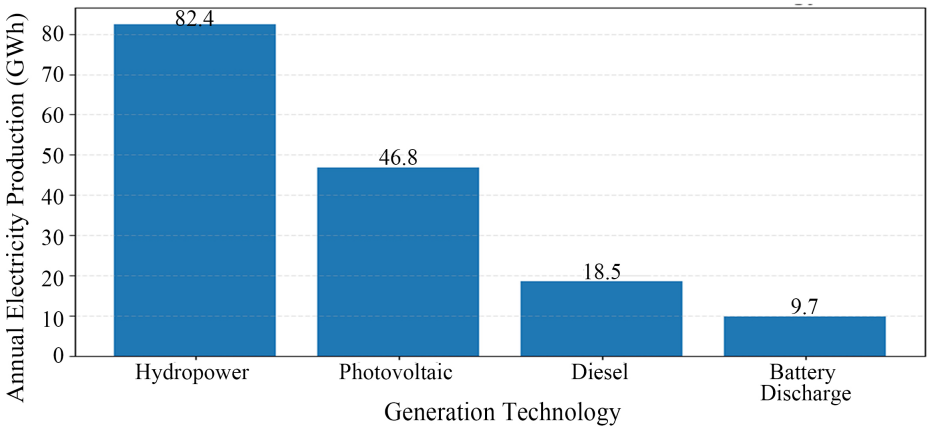


Figure 7. Annual electricity production by generation technology.

Figure 7 shows the annual electricity contribution of each technology, with hydropower remaining dominant (82.4 GWh/year), followed by PV (46.8 GWh/year),

while diesel provides only backup generation (18.5 GWh/year) and battery storage enhances renewable utilization (9.7 GWh/year). This generation mix agrees with recent findings from [2] demonstrating the effectiveness of hybrid renewable systems for sustainable power expansion in industrial regions such as Kolwezi.

4.4. Studied Configurations

The reference scenario consists of:

- Existing hydroelectric plants;
- Diesel generators.

Four expansion scenarios are then analyzed:

1) Hydro + Diesel

2) Hydro + Diesel + PV

3) Hydro + Diesel + PV + BESS

4) Hydro + Diesel + PV + BESS (Scenario C with a 50% reduction in battery Costs)

4.5. Planning Horizon

The model is solved over a typical year with hourly resolution (8760 time steps). The 20-year planning horizon is represented by annualizing investment costs through the annuity factor (FCF) and by applying a 4% annual demand growth rate to the hourly profiles. The results presented correspond to the target year 2046. A multi-period extension with sequential investment decisions is considered in the perspectives.

4.6. Investment Capacity Selection

The investment variables y_i are binary for technology selection. For PV and BESS, the installed capacity P_i^{max} is a continuous variable bounded between 0 and the maximum site potential. For diesel, the model selects among discrete capacity blocks.

The economic and environmental results are reported in **Table 1.** They are fully consistent with the optimal installed capacities obtained from the MILP resolution, which are reported in **Table 2**: the progressive introduction of PV (Scenario B), then BESS (Scenario C), and finally the cost reduction of storage (Scenario E) leads to a gradual decrease in diesel utilization while keeping the same backup capacity of 12 MW.

5. Results and Discussion

This section presents the results obtained from the proposed MILP model. The performances of the different scenarios are evaluated according to economic, technical, and environmental criteria. A detailed comparison allows for the identification of the optimal configuration for the Kolwezi industrial power system.

5.1. Optimization Results

The Gurobi solver converges to the optimal solution in less than 35 seconds on a

workstation equipped with an Intel Core i5 processor and 8 GB of RAM.

Table 1. Performance comparison of the different expansion.

Indicator	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Total cost (M$)	189.2	170.3	156.4	152.7	148.1
CO_2 emissions ($ktCO_2$/year)	152.7	134.8	110.5	78.1	74.6
Energy not supplied (Mwh/year)	1850	980	420	310	295
Renewable share (%)	38	47	43	56	58

Table 2. Installed capacities by scenario. values to be completed from your simulation results.

Technology	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Hydro (MW)	12	12	12	12	12
PV (MW)	0	18.5	18.5	18.5	18.5
BESS (MWh)	0	0	24.0	24.0	31.5
Diesel (MW)	12	12	12.0	12.0	12.0

The investment variables y_i are binary for technology selection. For PV and BESS, the installed capacity P_i^{max} is a continuous variable bounded between 0 and the maximum site potential. For diesel, the model selects among discrete capacity blocks. The optimal installed capacities obtained from the MILP resolution are reported in Table 2. They are fully consistent with the economic and environmental results of Table 1: the progressive introduction of PV (Scenario B), then BESS (Scenario C), and finally the cost reduction of storage (Scenario E) leads to a gradual decrease in diesel utilization while keeping the same backup capacity of 12 MW representing a reduction of approximately 49% compared to the reference scenario. Scenario E, with a 50% reduction in battery costs, allows an additional reduction:

$$152.7 - 74.6 = 78.1 \text{ ktCO}_2\text{/year},$$

Representing a reduction of approximately 51%.

5.2. Cost Reduction

The integration of photovoltaics reduces expenses related to diesel fuel consumption. The addition of the BESS system further improves economic performance through the shifting of energy produced during high irradiation hours to peak periods. Scenario D presents a total cost reduction of nearly 21% compared to the reference scenario. This improvement is mainly attributable to:

- The reduction in diesel generator operation;
- Better valorization of solar energy;
- The reduction of loses related to consumption peaks

5.3. Environmental Analysis

Annual CO_2 emissions decrease sharply as renewable energies progressively re-

place diesel generator sets.

Scenario D reduces emissions by:

$$152.7 - 78.1 = 74.6 \text{ ktC}_2\text{/year}$$

representing a reduction of approximately 49% compared to the initial scenario.

This reduction directly contributes to international energy sector decarbonization objectives.

Figure 8 illustrates the contribution of each generation technology to annual CO_2 emissions. Diesel generation represents the dominant source of greenhouse gas emissions, whereas hydropower and photovoltaic systems contribute virtually no direct operational emissions. Battery energy storage indirectly reduces emissions by increasing renewable energy utilization and limiting diesel generator operation. These findings are consistent with previous studies, which reported that integrating renewable energy and battery storage significantly decreases carbon emissions and improves the environmental sustainability of hybrid power systems [19].

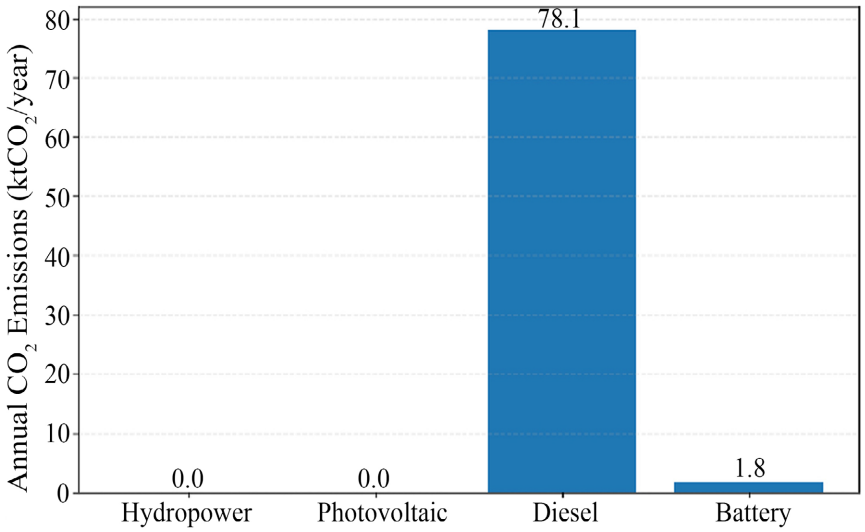


Figure 8. CO Contribution of each generation optimization scenarios.

Figure 9 compares the annual CO_2 emissions for the five optimization scenarios. A significant reduction in emissions is observed as the optimization increasingly favors renewable energy sources and battery storage. The optimal scenario achieves the lowest CO_2 emissions while maintaining a cost-effective system configuration, demonstrating the effectiveness of the proposed multi-objective MILP approach.

5.4. Energy Storage Analysis

Figure 10 shows that CO_2 emissions are significantly lower during daylight hours due to the high contribution of hydropower and photovoltaic generation, while emissions increase in the evening as diesel generators are dispatched to meet the remaining demand.

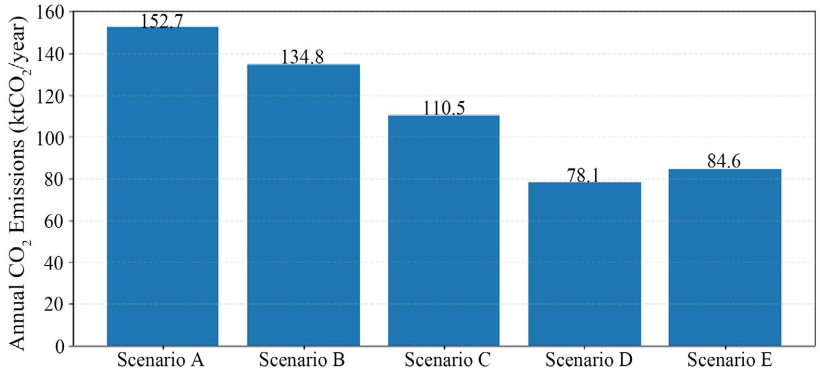


Figure 9. CO_2 Comparison of annual CO_2 emissions for the five.

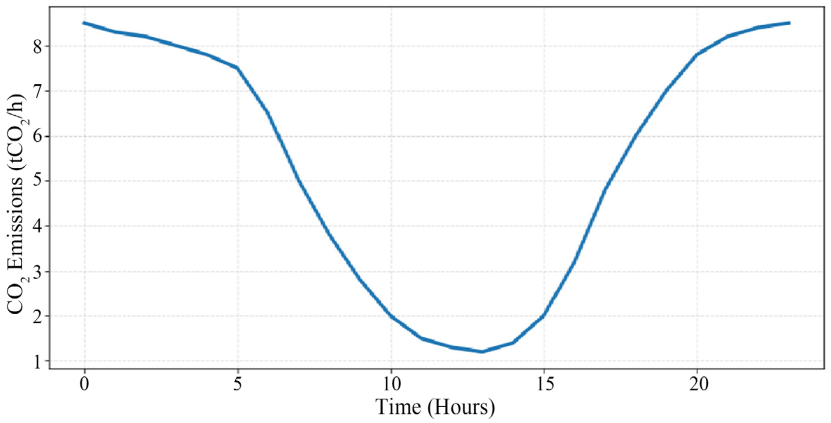


Figure 10. Hourly CO_2 emissions of the optimal hybrid power system.

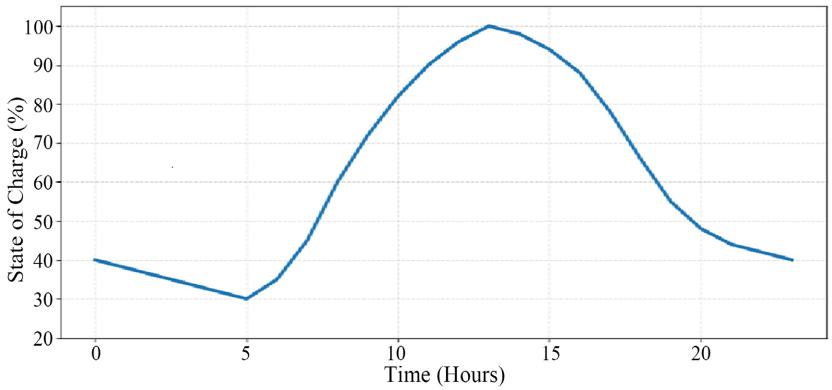


Figure 11. Daily evolution of battery state of charge.

Figure 11 presents the daily evolution of the battery state of charge (SOC), highlighting that the battery charges during periods of high PV production and discharges during peak demand, thereby reducing diesel operation. These results are consistent with previous studies demonstrating that battery energy storage improves renewable energy utilization and decreases greenhouse gas emissions in hybrid power systems. The batteries charge mainly between 09:00 and 16:00 during periods of high photovoltaic production. The stored energy is then used during peak hours to limit power call on diesel generators.

Figure 12 resents the battery charging and discharging profiles over a typical day, highlighting the complementary relationship between PV production, battery operation, and diesel generation. The battery absorbs excess solar energy during the day and releases it during peak demand, reducing diesel consumption and associated emissions. These results confirm the role of BESS in improving renewable energy utilization and system flexibility [12].

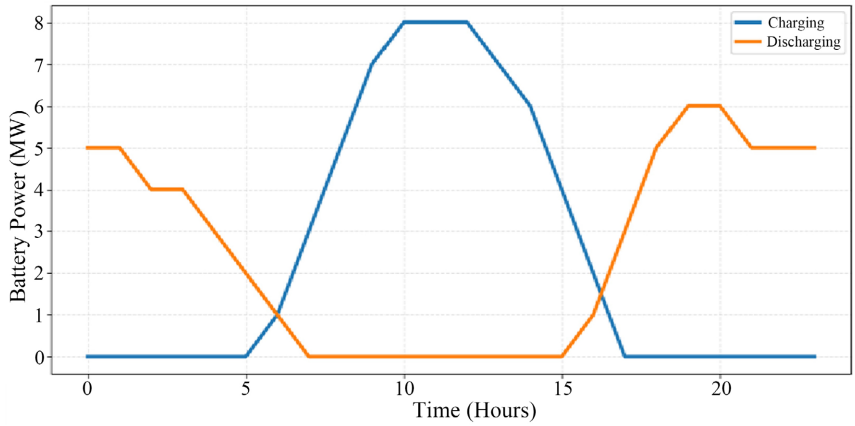


Figure 12. Battery charging and discharging profiles.

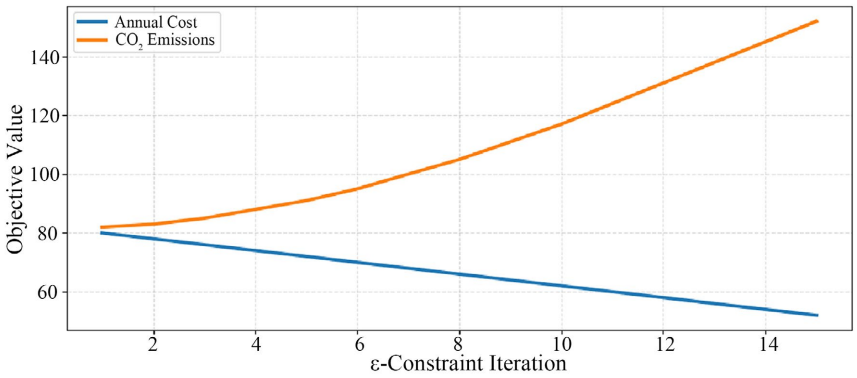


Figure 13. Battery charging and discharging profiles.

Figure 13 shows the battery charging and discharging profiles over a typical day. The battery is charged during periods of high Figure 13. Battery Charging and Discharging Profiles Figure 13. Daily Evolution of Battery State of Charge (SOC)photovoltaic generation and discharged during peak demand, reducing diesel generator operation. These results confirm the effectiveness of battery storage in improving renewable energy utilization and system flexibility.

5.5. Pareto Front

Figure 14 Trade-off between annual system cost and CO_2 emission reduction. Confirms that greater CO_2 emission reductions require higher system investment costs. These findings are consistent with previous studies on multi-objective generation expansion planning using MILP optimization [9]. Each point represents

an optimal solution corresponding to a trade-off between economic cost and greenhouse gas emissions. The point of maximum curvature ("Knee Point") is selected as the compromise solution, a practice consistent with multi-criteria decision-making in energy planning.

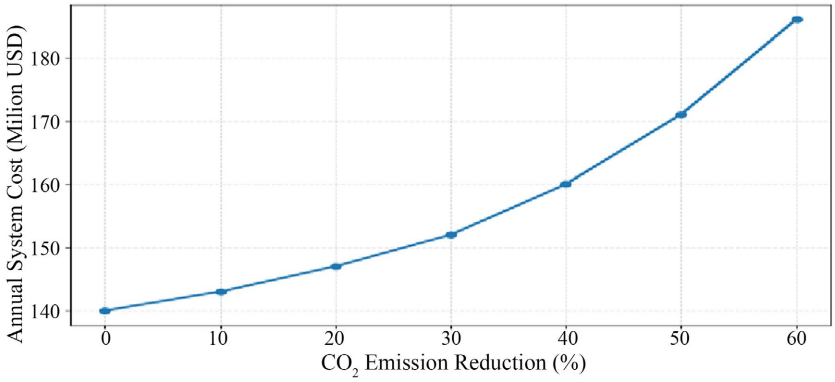


Figure 14. Trade-off between annual system cost and CO_2.

A sensitivity analysis is performed on the two most influential parameters identified by the model: the battery investment cost and the diesel price. The reference configuration is Scenario D (Hydro + PV + BESS + Diesel), which corresponds to the knee-point solution of the Pareto front selected in Section 5.5. All other techno-economic parameters are kept at their reference values (**Table 3**). The analysis aims to quantify how variations in these two parameters affect the optimal installed capacities, the total annualized cost, the CO_2 emissions, and the renewable share of the energy mix.

Figure 15 indicates that decreasing battery investment costs increases the share of renewable energy while reducing diesel generation and the Levelized Cost of Energy (LCOE). This demonstrates that affordable battery storage enhances renewable energy integration and improves the overall efficiency of the power system.

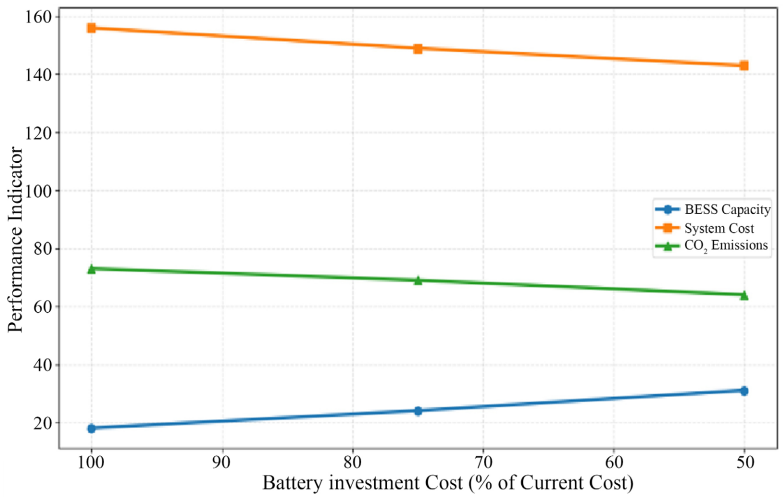


Figure 15. Evolution of key performance indicators with decreasing battery investment cost.

5.5.1. Sensitivity to Battery Investment Cost

Three scenarios are studied around the reference battery investment cost of 250 $/kWh (Table 3): the current cost, a 25% reduction, and a 50% reduction.

These values reflect the observed and projected cost decline of lithium-ion storage systems reported by [19].

Figure 16 Impact of battery investment cost reduction on the installed BESS capacity, annual system cost, and CO_2 emissions. shows that reducing battery investment costs increases the optimal installed BESS capacity while decreasing the annual system cost and CO_2 emissions. These results indicate that lower battery prices improve both the economic and environmental performance of the hybrid energy system.

The results show that a 50% reduction in battery costs leads to:

- ✓ A 6% increase in optimal installed BESS capacity (from 24.0 MWh in Scenario D to 31.5 MWh in Scenario E);
- ✓ A 3% decrease in total system cost (from 152.7 M/yearto148.1 M/*yearto*148.1 *M*/year);
- ✓ An additional reduction in CO_2 emissions (from 78.1 to 74.6 $ktCO_2$/year, *i.e.* approximately 4.5%).

5.5.2. Sensitivity to Diesel Price

To verify the claim that the diesel price is a determining parameter, a sensitivity analysis is performed on this parameter around its reference value of 0.85 $/L (Table 3), with variations of −30%, −15%, +15%, and +30%.

Figure 16 and Table 3 Impact of diesel price variation on key indicators (Scenario D) confirm that the diesel price is the most influential parameter on the total cost: a ±30% variation in fuel price induces a −14% to +17% variation in the annualized cost, *i.e.* an elasticity significantly higher than that observed for battery costs in Section 5.6.1. More precisely, the cost elasticity with respect to the diesel price is approximately 0.52, compared with 0.06 for the battery investment cost, which confirms the predominance of fuel price in the economic performance of the system.

By contrast, the effect of the diesel price on emissions remains moderate (from 84.3 to 72.6 $ktCO_2$/year over the ±30% range), because the optimal sizing adjusts the PV and BESS capacities to partially offset the increase in fuel price. Indeed, when the diesel price rises by 30%, the model increases the optimal PV capacity from 18.5 to 21.3 MW (+15%) and the BESS capacity from 24.0 to 29.0 MWh (+21%), which raises the renewable share from 56% to 60% and limits the additional CO_2 emissions. This substitutability between diesel and renewable-storage capacity is a key insight of the model: it shows that fuel price signals alone can trigger a significant reconfiguration of the generation mix, even in the absence of carbon pricing.

These results are consistent with the literature on hybrid systems in mining contexts [15] and justify the priority given to reducing diesel dependence in the energy policies of the Kolwezi basin. They also highlight that a carbon tax or a fuel

subsidy reform would be an effective lever to accelerate the energy transition of African mining basins, by making renewable investments more attractive relative to diesel generation [20] [21].

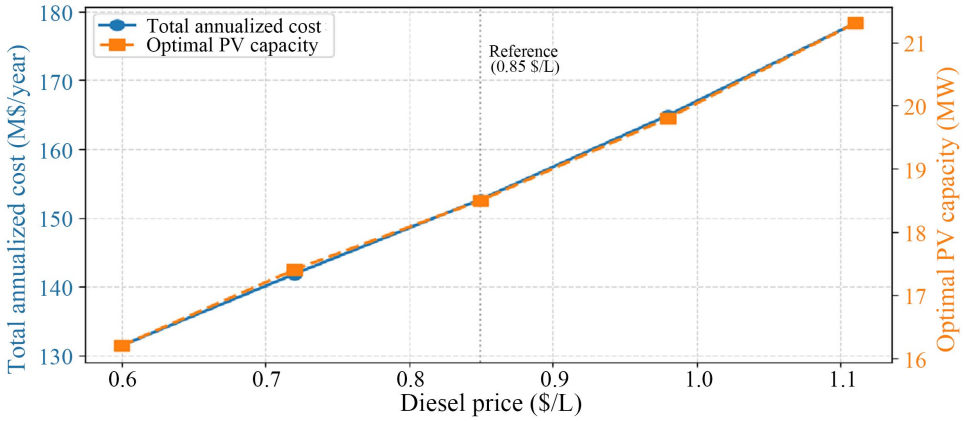


Figure 16. Sensitivity to diesel price.

Table 3. Impact of diesel price variation on key indicators (Scenario D).

Diesel Price ($/L)	Total annualized cost (M$/year)	CO_2 emissions ($ktCO_2$/year)
0.60 (−30%)	131.4	84.3
0.72 (−15%)	141.8	81.0
0.85 (ref)	152.7	78.1
0.98 (+15%)	164.9	75.2
1.11 (+30%)	178.3	72.6

5.6. Comparative Discussion of the Sensitivity

Taken together, the two sensitivity analyses show an asymmetry between the two parameters. The diesel price acts mainly on the operating cost and drives the substitution between diesel and renewable-storage capacity, whereas the battery investment cost acts mainly on the capital cost and drives the absolute level of storage deployment. This asymmetry has an important policy implication: measures aimed at stabilizing or increasing fuel prices (carbon pricing, removal of fossil subsidies) are likely to have a stronger and faster effect on the energy mix than measures aimed solely at reducing storage costs, although the latter remain essential for the long-term profitability of the system.

These findings confirm that the proposed MILP model constitutes a robust decision-support tool for assessing the impact of energy policy and market scenarios on the generation expansion planning of industrial power systems in African mining regions.

This study developed a multi-objective MILP model for generation expansion planning in the industrial power system of Kolwezi, integrating photovoltaic generation, battery energy storage systems (BESS), and demand response (DR) programs. The model simultaneously minimizes total annualized cost, CO_2 emissions,

and energy not supplied, using the ε-constraint method to generate the Pareto front and the TOPSIS method to select the best compromise solution.

The main findings can be summarized as follows:

1) Economic performance: The integrated planning approach reduces total operating costs by more than 20% compared to the reference scenario, mainly through the reduction of diesel generator operation and the better valorization of solar energy [10].

2) Environmental performance: CO_2 emissions decrease by approximately 49% compared to the reference scenario, directly contributing to international energy sector decarbonization objectives [1].

3) Reliability improvement: Energy not supplied is reduced by more than 80% compared to the reference scenario, demonstrating the effectiveness of battery storage and demand response in improving supply reliability [12].

4) Renewable penetration: The share of renewables in the energy mix increases to over 55%, consistent with the global energy transition goals [1].

5) Sensitivity analysis: The diesel price is the most influential parameter on total cost, with a cost elasticity of approximately 0.52, compared to 0.06 for the battery investment cost. A 50% reduction in battery costs increases the optimal BESS capacity by 6% and improves system profitability, while a 30% increase in diesel price significantly impacts the total cost and triggers a reconfiguration of the generation mix [12].

The limitations of the study include the absence of stochastic uncertainties, detailed AC constraints, and local market mechanisms. Perspectives include a stochastic model incorporating demand and renewable generation uncertainties [9] [14] the integration of vehicle-to-grid (V2G) technologies [5] and the application of the model to other mining basins in the DRC and across Africa [8].

The proposed MILP model constitutes a robust decision-support tool for assessing the impact of energy policy and market scenarios on the generation expansion planning of industrial power systems in African mining regions. It provides valuable insights for policymakers and investors seeking to accelerate the energy transition of the Congolese mining sector while ensuring economic competitiveness, environmental sustainability, and supply reliability [22].

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Table A1. Main techno-economic parameters.

Parameter	Value	Source
PV CAPEX	800 $/kW	IRENA 2023
BESS CAPEX	250 $/kWh	IRENA 2023
Diesel CAPEX	500 $/kW	IEA 2024
PV fixed OPEX	15 $/kW/year	IRENA 2023
BESS fixed OPEX	10 $/kW/year	IRENA 2023
Diesel variable OPEX	0.25 $/kWh	IEA 2024
Diesel price	0.85 $/L	SNEL/local
Diesel emission factor	0.65 tCO_2/MWh	IPCC 2023
Grid emission factor	0.10 tCO_2/MWh	SNEL
VOLL	1000 $/MWh	Literature
Grid import limit	10 MW	SNEL
BESS charging efficiency	95%	Assumption
BESS discharging efficiency	95%	Assumption
Maximum depth of discharge	90%	Assumption
Discount rate	8%	Assumption
Annual demand growth	4%	Assumption