Multi-objective and Bi-Level Optimisation Approach Considering Renewable Energy Sources and Hydrogen for Off-Grid Power Systems

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Abstract: Predominantly, hydroelectric power fuels Colombia's electricity. Yet, non-interconnected zones, mainly in the Pacifico, Orinoquia, Amazonia, and insular regions, rely primarily on diesel power plants. This research presents an optimisation model for integrating Renewable Energy Sources (RES) in San Andres Island, Colombia. A bi-level, multi-objective optimisation strategy is employed, developed on MATLAB. Utilizing a particle swarm multi-objective algorithm, the model synergizes planning/design with operational aspects. Solutions are assessed via Key Performance Indicators (KPIs), considering renewable sources such as solar, wind, battery storage, electrolysers, hydrogen storage, and fuel cells. Remarkably, 78 out of 80 results from the four case studies retained diesel generation, battery storage was mainly excluded, and wind emerged as the dominant renewable source.

Keywords: Hydrogen, particle swarm algorithm, key performance indicators, KPIs, bilevel multi-objective optimization

1. Introduction

1.1. Motivation

The electricity and heat sector, reliant on fossil fuels, remains a chief contributor to greenhouse gas emissions. The UN 2030 sustainable development goals emphasise affordable, clean energy [1]. Non-conventional Renewable Energy Sources (NCRES) are pivotal for electricity decarbonisation, with global renewable energy generation accounting for 29% in 2020 [2].

Colombia's NCRES encompasses biomass, solar, wind, tidal, geothermal, and small-scale hydroelectric plants, with policy interventions encouraging NCRES projects in non-interconnected zones [3]. Recently, hydrogen has emerged as a significant contender in climate change mitigation and ensures energy security. Despite the promising potential of hydrogen-related technologies, they warrant further developmental efforts for cost and technical efficacy [4].

Electrolysis serves as a pivotal hydrogen production technique. Electricity derived from renewable sources can yield low-emission hydrogen through electrolysis. The transformation of electricity to gases like hydrogen via processes like Power to Gas (P2G and PtG) underlines this [5, 6]. Fuel cells convert chemical energy directly to electricity and are a prominent decarbonising tool with efficiency rates outstripping internal combustion engines [7].

With freshwater scarcity affecting various regions, seawater electrolysis presents a promising alternative. San Andres and Providencia islands are primed for renewable energy integration, requiring comprehensive feasibility studies that account for economic and technical parameters [8–10].

Microgrid optimisation for isolated and interconnected systems commonly utilises tools like Homer Pro, developed by Nrel [11]. Existing literature showcases optimisation models tailored for island scenarios, with methodologies ranging from machine learning and deep learning to Particle Swarm Optimisation (PSO) algorithms [12–14]. Hybrid and meta-heuristic optimisations suit large, intricate systems, ensuring optimal solutions for singular and multi-faceted objectives [15].

This study delves deep into San Andres Island’s optimisation scenario, blending renewable energy sources, battery storage, and hydrogen, emphasising a bi-level multi-objective approach. In conjunction with KPIs, the PSO algorithm sheds light on the region’s energy landscape.

1.2. State-of-the-Art

The Colombian mining and energy sector’s climate change management plan for 2050 envisions the evolution of energy sector emissions across various scenarios. In oil and gas, predictions indicate a decline in CO_2 emissions by 3.3% annually from 2020 to 2050. By 2050, these emissions will account for merely 13% of the total, attributable to the gradual diminishment of oil production. In stark contrast, emissions from electricity generation are set to rise, accounting for 20% in 2020, burgeoning to 49% in 2030 and an astounding 69% by 2050. This upswing is primarily credited to the proliferation of electric mobility solutions and the growing appetite for electricity [16].

Our research pivots on the energy metamorphosis of San Andres Island. Data collected in 2022, taken from meteorological stations and active power demand measurements, formed the bedrock of our analyses. Our methodological approach comprised four distinct stages:

- Deciphering the energy character of San Andres,
- Unravelling the intricacies of the bi-level and multi-objective model paired with the PSO algorithm,
- Delineating the sources,
- Crafting models grounded in Key Performance Indicators (KPIs).

Characterisation of the Energy Sources of San Andres San Andrés and Providencia are two islands in the Colombian insular region. Ten diesel generators supply electricity with 64,95 MW installed capacity, and three diesel generators produce power in Providencia with 3.55 MW. Table 1 summarises technical data on these islands.

Table 1. San Andres and Providencia Demographic and Energy Data

Description	Value
San Andres area (km2)	26
Providencia area (km2)	18
San Andres Population	79,060
Providencia population	5210
Generation Installed Capacity (MW)	68,5
Electricity generation in 2019 (MWH year)	222,438
Electricity generation in 2020 (MWH year)	176,985
Peak power demand (MW)	29,596
Peak power demand hour	4:00 pm
Fossil fuel demand in San Andres Island in 2021 (MGallons)	Diesel 15 Petrol 4 Jet fuel 4

Note: Information taken from [17–19]

The power demand peak in San Andres is reached at 4:00 pm and 7:00 pm, with values around 30.000 MW, and power consumption is reduced between 1:00 a.m. and 6:00 a.m.; Fig. 1 shows the active power demand hourly per day.

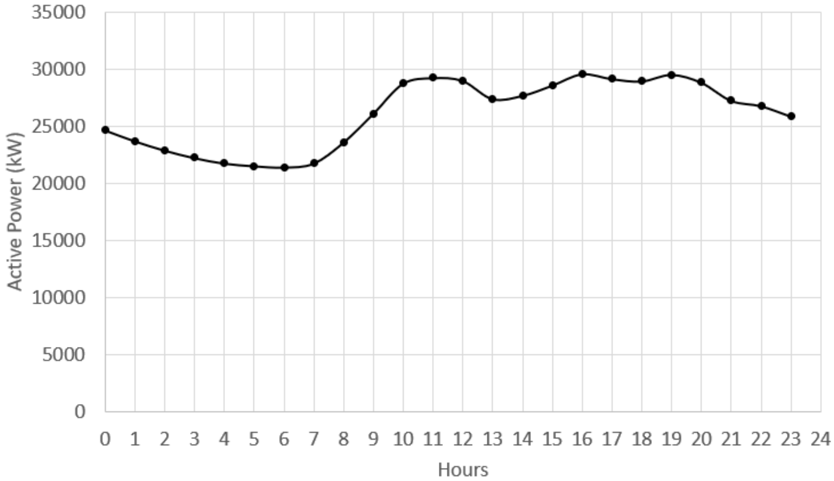

Fig. 1. San Andres Island has an active power demand per day.

Direct hourly measurements spanning nine years, from 2014 to 2022, offered insights into solar irradiation in San Andres. The island basks in sunlight for approximately 12 h daily, with the average irradiation registering at 4.7 kWh/m^2/day. Peak irradiation is typically observed between 11:00 a.m. and 2:00 p.m. February, March, and April emerge as the pinnacle of solar intensity, showcasing the highest mean sun irradiation. Fig. 2 shows the solar irradiation trends in San Andres.

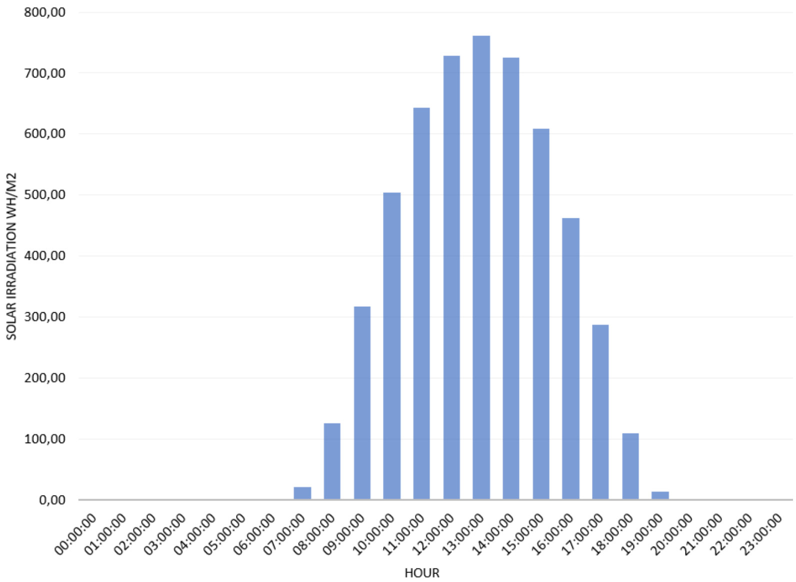

Fig. 2. San Andres average hourly solar irradiation per day.

San Andres' wind potential was rigorously assessed using data collected and examined between 2004 and 2014. The hourly wind speed consistently surpasses the threshold of 3 m/s, acknowledged as the cut-in speed for turbines. January stands out of all months, consistently recording the highest wind speeds when evaluating mean and median values over the ten years under study. Fig. 3 clearly shows the wind speed trends.

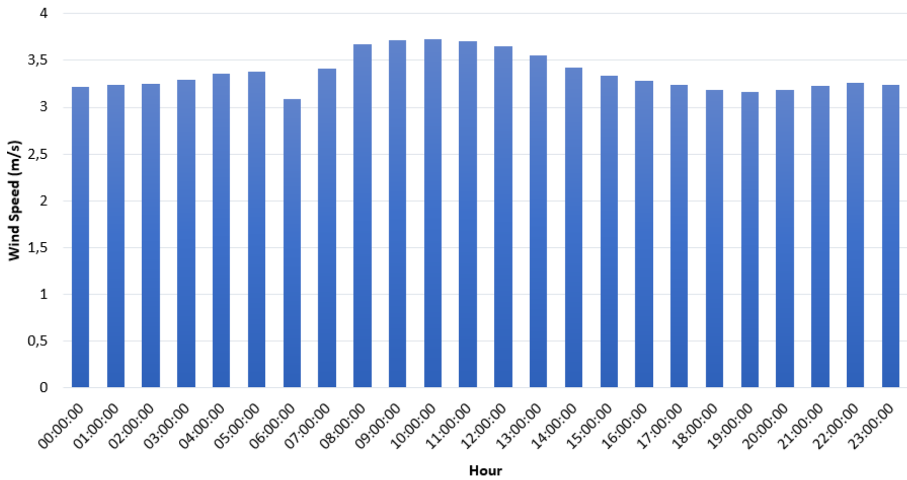

Fig. 3. San Andres average hourly wind speed per day.

The crucial point of this study is to identify optimal solutions that seamlessly integrate Renewable Energy Sources (RES) to address San Andres's load demand. Fig. 4 shows the comprehensive integration and its implications.

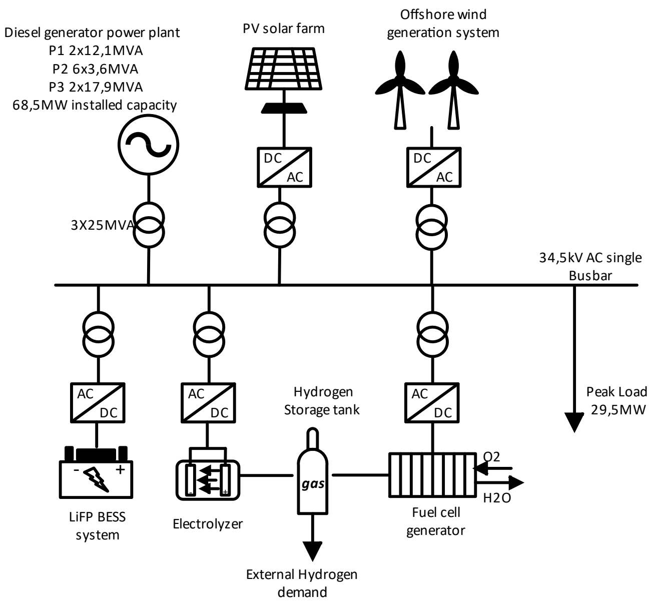

Fig. 4. San Andres optimisation case.

1.3. Bi-Level and Multi-objective Optimisation Model and PSO Algorithm

Two-level decision techniques (bi-level) are commonly used in microgrid studies in which it is necessary to consider planning and operation in a coordinated manner. In these models, decision makers try to optimize their objective functions independently, but decisions are affected in the decision space of the other level. Planning is the leader or the upper-level problem, and operation is the follower or the lower-level problem. The execution of decisions is sequential, from upper to lower levels, consistent with the logical relationship between planning and operation. Another aspect to consider is the time scales between long-term planning and short-term operation; a bi-level decision model can enable their interaction and optimal modelling [20].

PSO is intrinsically a metaheuristic inspired by the collective behaviour observed in nature, such as the flocking patterns of birds and the schooling dynamics of fish [21]. In various scientific disciplines, including the energy sector, this algorithm has successfully addressed intricate challenges characterised by multiple objectives [22]. The structural underpinning of the proposed algorithm is consistent with the scheme proposed in [23], tailored explicitly for bi-level multi-objective optimisation problems.

This study focuses on the use of Key Performance Indicators (KPIs) that are directly aligned with key strategic objectives. These KPIs were carefully selected to address critical business questions within a specific optimization framework. For decision-making, the study uses qualitative methods to adjust the importance of each KPI accurately.

This work considers a new systemic approach (System of Systems) to model the bi-level optimisation problem. This allows for a conceptual overview and describes each development's stages and tasks. As shown in Fig. 5, the model considers three phases of the life cycle of a system: Definition of the technical process, planning/design (Upper decision unit) and operation (Lower decision unit), and a three-step final decision process using a Hierarchical Analytical Process (AHP) [20].

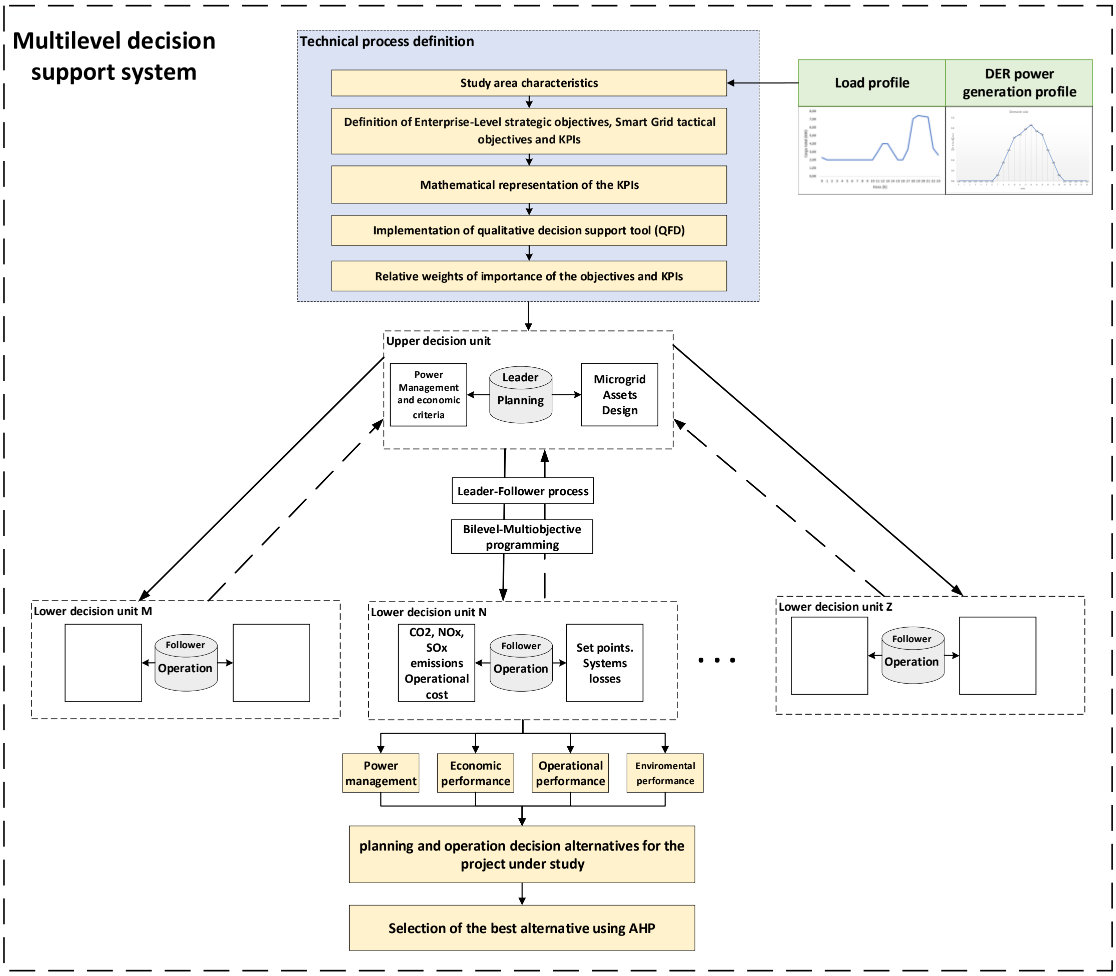

Fig. 5. Decision-making process [20].

The main contribution of this work is the following: A proposal for a multi-objective bi-level particle swarm optimisation strategy considering several RES and traditional energy sources for San Andres Island electricity demand was developed and implemented by an islanded power system study case.

This article is organised as follows: Section 2 introduces our primary model and explains the math behind the assets and KPIs. Section 3 provides a real-world example to showcase how our model works. Finally, Section 4 presents our main findings and conclusions.

2. Proposed General Model

PV systems were modelled based on Eq. (1); the decision variable is the number of *PV* power plants N_{pv}

$$P_{PV} = N_{PV} \times Y_{PV} \times f_{PV} \times \frac{\overline{G}_T}{\overline{G}_{T,STC}} \tag{1}$$

Wind power plants were modelled based on Eq. (2); the decision variable is the number of wind plants.

$$\begin{gathered} P_{WT} = N_{wt}\left(\frac{\rho}{\rho_0}\right) \times P_{WTG,STC} \\ U_{hub} = U_{anem}\left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \end{gathered} \tag{2}$$

Electrolyzer hydrogen production was modelled based on Eq. (3); the decision variable is the number of electrolysis.

$$R_{h2el}[kgH_2] = N_{el} \times \left(\frac{P_{el} \times 1h}{\eta_{el}}\right) \tag{3}$$

The fuel cell model is based on hydrogen fuel consumption considering commercial equipment standard values (see Eq. (4)).

$$P_{fc}[kW] = N_{fc} \times \left(\frac{R_{h2fc} \times 1h}{\eta_{fc}}\right) \tag{4}$$

The amount of hydrogen stored inside the tank depends on electrolyser hydrogen generation, fuel cell hydrogen consumption, and external hydrogen demand; Eq. (5) represents the hydrogen tank model. The hydrogen state of charge (SOC_{th2}) was modelled considering an hourly-based cyclic behaviour when the SOC_{th2} at $t = i$ depends on the previous state $t = i{-}1$.

$$\begin{gathered} SOC_{th2\ t=i+1} = SOC_{th2\ t=i} + R_{h2fc\ t=i} - R_{h2el\ t=i} \\ SOC_{th2\ t=0} = SOC_{th2\ t=23} + R_{h2fc\ t=23} - R_{h2el\ t=23} \\ SOC_{th2min} = 0\ kgH_2 \\ SOC_{th2max} = 1\ kgH_2 \times N_{th2} \\ SOC_{th2min} < SOC_{th2} < SOC_{th2max} \end{gathered} \tag{5}$$

The battery storage system model is represented by Eq. (6), considering battery efficiency, deep discharge, number of batteries, and minimum and maximum charge levels.

$$C_{bat}(t) = C_{bat}(t-1) + \begin{cases} P_{bat}(t) \times \eta_{Bat} & P_{bat}(t) \le 0 \\ \dfrac{P_{bat}(t)}{\eta_{Bat}} & P_{bat}(t) > 0 \end{cases} \tag{6}$$

$$\begin{gathered} P_{bat}(t) \le N_{bat} \times P_{bat\_max} \\ N_{bat} \times C_{bat\ min} \le C_{bat}(t) \le N_{bat} \times C_{bat\ max} \\ C_{bat\ min} = (1 - DOD) \times C_{bat\ max} \end{gathered}$$

The diesel power plant is modelled based on Eq. (7)

$$P_{dsl} = N_{dsl} \times \eta_{dsl} \times P_{max-dsl} \tag{7}$$

2.1. Key Performance Indicators (KPIs) Model

Six KPIs were defined based on the project objectives and measurable metrics for RES projects (see Fig. 6). Eq. (8) through Eq. (14) describe KPIs.

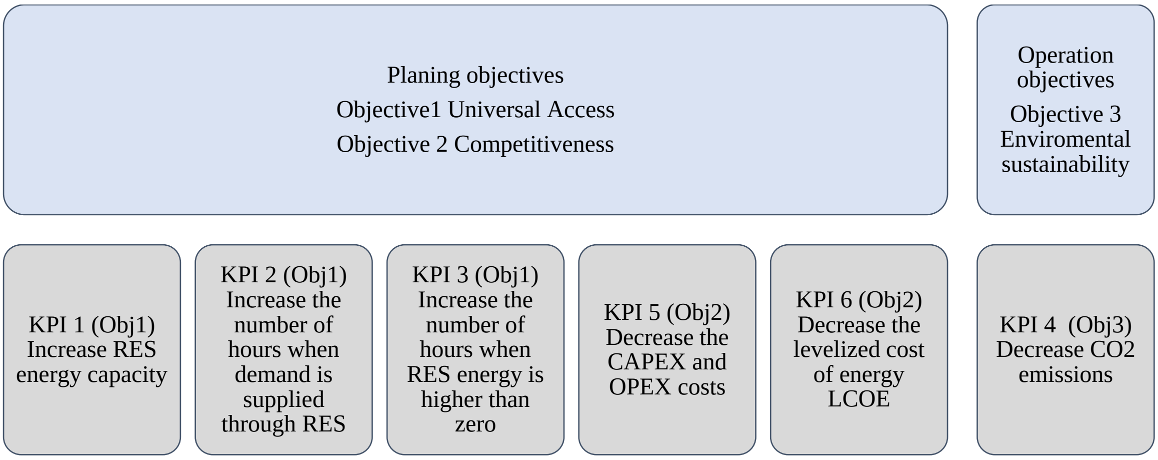

Fig. 6. KPIs and objectives defined for RES optimisation study case.

Increase RES energy capacity.

$$KPI_1 = \gamma_{re} = \frac{P_{wt}^{M} \times N_{WT} + P_{PV}^{M} \times N_{PV} + P_{cc}^{M} \times N_{cc}}{P_{wt}^{M} \times N_{WT} + P_{PV}^{M} \times N_{PV} + P_{cc}^{M} \times N_{cc} + P_{Gi} \times N_{Diesel}} \quad (8)$$

Increase the number of hours when demand is supplied through RES.

$$KPI_2 = LPS = \frac{\sum_{t=1}^{N} LPS(t)}{N} \qquad N = 24 \quad (9)$$

$$LPS = \begin{cases} P_R \geq P_L & 1 \\ P_R < P_L & 0 \end{cases} \quad (10)$$

Increase the number of hours when RES energy is higher than zero.

$$KPI_3 = \frac{\sum_{t=1}^{N} X}{N}, \quad N = 24$$
$$X = \begin{cases} P_R > 0 & 1 \\ P_R \leq 0 & 0 \end{cases} \quad (11)$$

Decrease CO_2 emissions.

$$KPI_4 = N_{PV} \times P_{PV}^{M} \times E_C^{PV} + N_{wt} \times P_{wt}^{M} \times E_c^{wt} + N_{bat} \times S_{bat} \times E_C^{bat} + 365 \times 25 \times \left[\sum_{t=1}^{24} E_{op}^{Diesel} \times PDSL(t) \right] + N_{cc} \times P_{cc}^{M} \times E_c^{cc} + N_{el} \times P_{el}^{M} \times E_c^{el} + N_{th2} \times E_c^{th} \quad (12)$$

Decrease the CAPEX and OPEX costs.

$$KPI_5 = C_T = C_{caex} + C_{opex} \quad (13)$$

$$C_{caex} = C_{PV}N_{PV} + C_{wt}N_{wt} + C_{fc}N_{fc} + C_{el}N_{el} + C_{bat}N_{bat} + C_{th2}N_{th2} + C_{dsl}N_{dsl}$$

$$C_{opex} = \sum_{n=1}^{25} \frac{C_{opPV}N_{PV} + C_{opwt}N_{wt} + C_{opfc}N_{fc} + C_{opel}N_{el} + C_{opbat}N_{bat} + C_{opth2}N_{th2} + C_{opdsl}N_{dsl}}{(1+i)^t}$$

Decrease the levelized cost of energy LCOE.

$$\boldsymbol{LCOE} = \frac{I_o + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}} = \frac{KPI_5}{365 \times 25 \times \textit{daily total generation}} \tag{14}$$

2.2. Model parameters

Variable values were taken from bibliographic references (see Tables 2–9).

Table 2. PV Power Plant Model Values

Abbreviation	Variable description	Value	Units	Reference
P_{PV}	PV plant's power output	OV	kW	
N_{PV}	Number of PV power plants	OV		
Y_{PV}	PV plant's standard condition-rated power	500	kW	
f_{PV}	PV derating factor	0.722	%	[24]
$\overline{G}_T$	Incident sun radiation	(*)	kW/m²	
$\overline{G}_{T,STC}$	Standard condition sun radiation	1	kW/m²	
E_C^{PV}	Lifetime CO_2 emissions from PV power plants	57	gCO_2e/kW	[25]
C_{pv}	PV power plant's capital expenditures	1930	USD/kWp	[26]
C_{opPV}	PV power plant's operational and maintenance costs	18.03	USD/kWp-year	[26]
T_{PV}	Operational lifetime	10	years	

(*) Taken from the San Andres sun radiation curve

Table 3. Wind Power Plant Model Values

Abbreviation	Variable description	Value	Units	Reference
P_{WTG}	Wind turbine power plants' output	OV	kW	
N_{wind_plants}	Number of wind power plants	OV		
$\left(\frac{\rho}{\rho_0}\right)$	Air density derating factor	1		
$P_{WTG,STC}$	Wind turbine standard output power	2,3	kW	[27]
U_{hub}	Wind speed at turbine hub height	CV	m/s	
U_{anem}	Wind speed at anemometer height	(*)	m/s	
Z_{hub}	Turbine hub height	101	m	[27]
Z_{anem}	Anemometer height	1	m	
α	Power law exponent	0.233		[28]
E_C^{wt}	Lifetime CO_2 emissions from wind power plants	13	gCO_2e/kWh	[25]
C_{wt}	Wind power plant's capital expenditures	5329	USD/kW	[29]
C_{opwt}	Wind power plant's operational and maintenance costs	130	USD/kWp-year	[29]
T_{wt}	Operational lifetime	20	years	

(*) Taken from historical San Andres wind speed measurements

Table 4. Electrolyzer Model Values: Manufacturer ITM Hgas 1SP PEM Technology

Abbreviation	Variable description	Value	Units	Reference
N_{el}	Number of electrolysers	OV		
P_{el}	Electrolyzer input power	OV	kW	
R_{H^2el}	Electrolyzer hydrogen production	CV	kgH2	
η_{el}	Electrolyzer efficiency	63,3	kWh/kgH2	[30]
$R_{H^2std-el}$	Electrolyzer rated hydrogen production	11	kgH2/h	
C_{water}	Water consumption	25	L/kgH2	[30]
E_C^{el}	Lifetime CO_2 emissions from electrolyzer hydrogen plants	0	gCO2e/kWh	
C_{el}	Electrolyzer plant's capital expenditures	400	USD/kW	[31]
C_{opel}	Electrolyzer plant's operational and maintenance costs	1%* Cel	USD/year	[32]
T_{opel}	Operational lifetime	50,000	Hours	

Table 5. Fuel Cell Model Values Manufacturer: Fuel Cell Energy Technology Solid Oxide 250 kW

Abbreviation	Variable description	Value	Units	Reference
N_{fc}	Number of fuel cells	OV		
P_{fc}	Fuel cell power	OV	kW	
R_{H^2fc}	Fuel cell hydrogen consumption	CV	kgH2	
η_{fc}	Fuel cell efficiency	0.06	kgH2/kWh	[33]
R_{H^2stdfc}	Rated fuel cell hydrogen consumption	129 11.59	Nm3/h kg/h	[33]
$V_{out\ fc}$	Fuel cell output voltage	480 V 60 Hz	V	[33]
P_{fcstd}	Reference fuel cell power	250	kW	[33]
Q_{fcstd}	Water production	26	Gallons/h	[33]
E_C^{fc}	Lifetime CO_2 emissions from fuel cell power plant	0	gCO_2e/kWh	
C_{fc}	Fuel cell plant's capital expenditures	2400	USD/kWh	[32]
C_{opexfc}	Fuel cell plant's operational and maintenance Costs	1% Cfc	USD/year	[32]
T_{opexfc}	Operational lifetime	90,000	Hours	

Table 6. Battery System Model Values: Manufacturer Narada Model 76880135 160A-H 135kWH

Abbreviation	Variable description	Value	Units	Reference
N_{bat}	Number of battery storage systems	OV		
P_{bat}	Battery system output power	OV	kW	
η_{bat}	Battery system efficiency	93	%	
SOC_{max}	Maximum state of charge SOC	95	%	[34]
SOC_{min}	Minimum state of charge SOC	5	%	[34]
$E_{bat-std}$	Standard energy battery capacity	135	kWh	[34]
E_C^{bat}	Lifetime CO_2 emissions from fuel cell power plant	32.9	gCO_2e/kWh	[25]
C_{bat}	Battery system's capital expenditures	3000	USD/kWh	[35]
C_{opbat}	Battery system's operational and maintenance costs	75	USD/kWh-year	[35]
T_{bat}	Battery system's operational lifetime	2000	Cycles over 10 years	

Table 7. Hydrogen Storage Tank Model Values

Abbreviation	Variable description	Value	Units	Reference
N_{th2}	Number of hydrogen tanks	OV		
$SOC_{th2\ i}$	Hydrogen tank state of charge at t=i	OV		
SOC_{th2max}	Maximum state of charge of hydrogen tank	1		
SOC_{th2min}	Minimum state of charge of hydrogen tank	0		
SOC_{th2ini}	Initial state of charge of hydrogen tank	0		
E_C^{th2}	Lifetime CO_2 emissions from hydrogen storage system	0.63	$TONCO_2e$	[25]
C_{th2}	Hydrogen storage system's capital expenditures	1300	USD/kgH2	
$C_{op\ th2}$	Hydrogen storage system's operational and maintenance costs	10	USD/kWh-year	
T_{th2}	Hydrogen storage system's operational lifetime	15	Years	

Table 8. Diesel Power Plant Model Values

Abbreviation	Variable description	Value	Units	Reference
N_{dsl}	Number of diesel power plants			
P_{dsl}	Diesel power plant electric output power		kW	
η_{dsl}	Diesel system efficiency	90	%	
$P_{dsl\ std}$	Standard diesel plant power		kW	
E_C^{dsl}	Lifetime CO_2 emissions from diesel power plant	0.0017	$TONCO_2$/kWh	
Cdsl	Diesel power plants' capital expenditures	800	USD/kWh	[36]
OPdsl	Diesel power plants' operational and maintenance costs	35	USD/kWh-year	[36]
Tdsl	Diesel power plants' operational lifetime	20,000	hours	

Table 9. Financial Model Values

Abbreviation	Variable description	Value	Units
i	Interest rate	13	%
t_{proj}	Project lifetime	25	Years

3. Case Study

In this research was developed an optimisation algorithm to model four scenarios classified as follows:

FULL RES: Demand is supplied by renewable energy sources, including diesel generation, without restrictions.

WTLIM: Demand is supplied by renewable energy sources, with a limit on the number of wind turbines and diesel generation.

H2WTLIM: Demand supplied by renewable energy sources with a limit in the quantity of wind turbines, including Diesel generation and hydrogen.

RESH2: Demand supplied by renewable energy sources, including Diesel generation and hydrogen, without restrictions.

The optimisation algorithm implemented in this project is presented in Fig. 7.

Fig. 7. Flow diagram of the Bi-Level Multi-objective Particle Swarm Optimisation (BLMOPSO) algorithm.

Twenty different solutions were identified for each model. The FULL RES scenario consistently showed the most environmentally efficient solutions with the lowest emissions among the eighty results. On the other hand, the most cost-effective solution, obtained with the Levelized Cost of Electricity (LCOE), was the first result in the WTLIM model. It is worth noting that the initial results for H2WTLIM and RESH2 displayed the peak emissions of all eighty results.

The algorithm operated with maximum flexibility without constraints or restrictions in the FULL RES scenario.

In the case of WTLIM, a restriction related to a maximum number of wind turbines Nwt=10000 was introduced. In the case of H2 WTLIM, a hydrogen demand of 100 kgH2 and a maximum number of wind turbines Nwt = 10,000 were introduced. In the RES H2 case, only a hydrogen demand of 100 kgH2 was introduced. Solutions were highlighted with colours for each model case; Table 10 shows the conventions.

Table 10. Colour conventions for optimisation results

Yellow	Red	Green	Grey
Lowest LCOE solution	Highest LCOE solution	Lowest CO_2 emissions solution	Highest CO_2 emissions solution

3.1. Model Case 1 FULL RES

Table 11 and Figs. 8 and 9 summarise the results of the optimisation model, which predominantly leveraged wind energy combined with diesel generation to cater to electricity needs. The second solution is the most eco-friendly alternative, with only 97.6 tons of CO_2 emissions over the project's lifespan. While Solution No. 10 boasts the most attractive Levelized Cost of Electricity (LCOE), unfortunately, it is also the most carbon-intensive over the project's lifespan.

Interestingly, battery storage systems did not appear in the model's optimal solutions. This pattern is likely due to the prohibitive costs associated with battery storage, juxtaposed with San Andres' abundant wind resources, which seem sufficient to meet the electricity demand independently.

Table 11. Optimisation Model Results Case FULL RES

No.	PV (kWh Day)	WT (kWh Day)	Dsl (kWh Day)	EL (kWh Day)	FC (kWh Day)	BATT (kWh Day)	Capex MUSD	Opex MUSD	LCOE (USD/kWh)	Total CO_2e TON CO_2 25 years
1	0.000	698753.6	21750.4	−10887.6	2866.7	0.0	$ 252.2	$ 6.1	$ 0.097	333543.9
2	0.000	832959.8	0.0	−4523.8	1191.1	0.0	$ 289.6	$ 7.0	$ 0.110	97.6
3	0.000	868024.6	0.0	0.0	0.0	0.0	$ 297.2	$ 7.2	$ 0.113	102.1
4	1923.009	653946.5	37440.5	−13509.9	3557.1	0.0	$ 241.3	$ 5.9	$ 0.096	1148026.8
5	3846.019	709677.7	17874.3	−10381.2	2733.3	0.0	$ 256.7	$ 6.2	$ 0.098	274118.2
6	9615.047	526223.1	100038.4	−10259.3	2701.2	0.0	$ 201.8	$ 4.9	$ 0.085	3067275.0
7	11538.056	624469.1	46060.1	−17839.5	4697.1	0.0	$ 236.7	$ 5.8	$ 0.095	1412311.4
8	19230.094	714763.8	13950.0	−10824.3	2850.0	0.0	$ 265.6	$ 6.3	$ 0.101	213963.0
9	19230.094	769384.7	4307.5	−10824.3	2850.0	−17.7	$ 284.4	$ 6.8	$ 0.108	66143.9
10	24999.122	19054.6	582581.7	0.0	0.0	0.0	$ 42.9	$ 1.3	$ 0.053	44654895.1
11	26922.131	571352.5	67245.3	−14648.2	3856.8	0.0	$ 227.7	$ 5.4	$ 0.092	2061844.0
12	26922.131	752586.5	6157.8	−10697.7	2816.7	0.0	$ 283.0	$ 6.7	$ 0.106	94507.0
13	36537.178	530449.5	85928.7	−12472.1	3283.9	0.0	$ 219.2	$ 5.1	$ 0.089	2634690.0
14	38460.188	719599.0	12669.3	−4557.6	1200.0	0.0	$ 273.2	$ 6.4	$ 0.103	194266.5
15	49998.244	17084.7	559552.6	0.0	0.0	0.0	$ 54.3	$ 1.4	$ 0.058	42889708.2
16	76920.375	24606.3	525108.9	0.0	0.0	0.0	$ 70.4	$ 1.6	$ 0.064	40249601.0
17	113457.554	20021.7	493156.3	0.0	0.0	0.0	$ 87.2	$ 1.7	$ 0.070	37800431.3
18	151917.741	26361.3	448356.5	0.0	0.0	0.0	$ 109.0	$ 2.0	$ 0.077	34366528.9
19	192300.938	0.0	434381.6	−63.9	16.8	0.0	$ 121.1	$ 1.9	$ 0.082	33295512.0
20	215377.051	35.8	415214.0	−5417.9	1426.5	0.0	$ 138.0	$ 2.1	$ 0.083	31826314.9

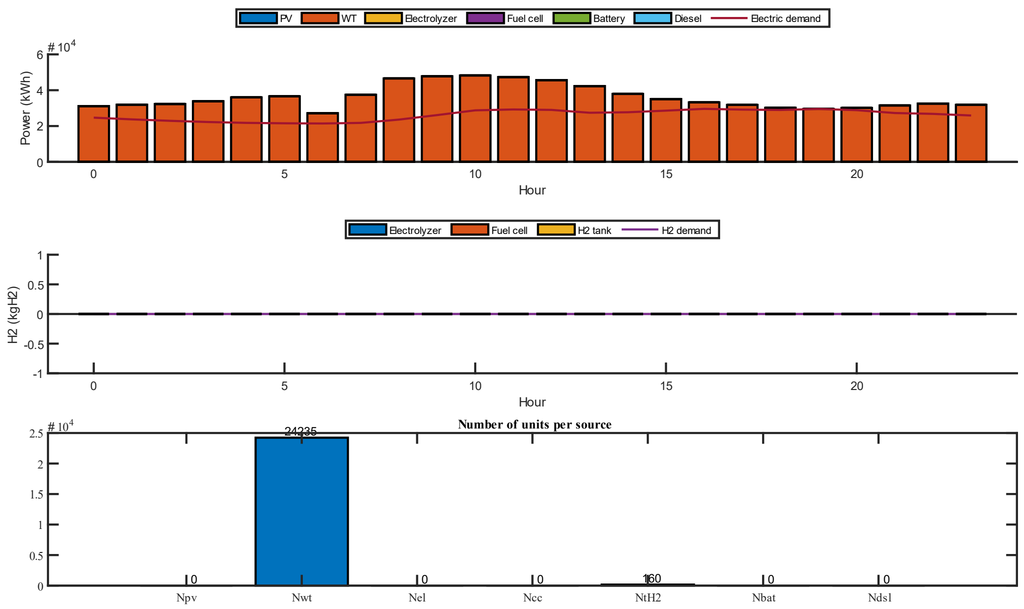

Fig. 8. Results of Solution 3rd in FULL RES cases.

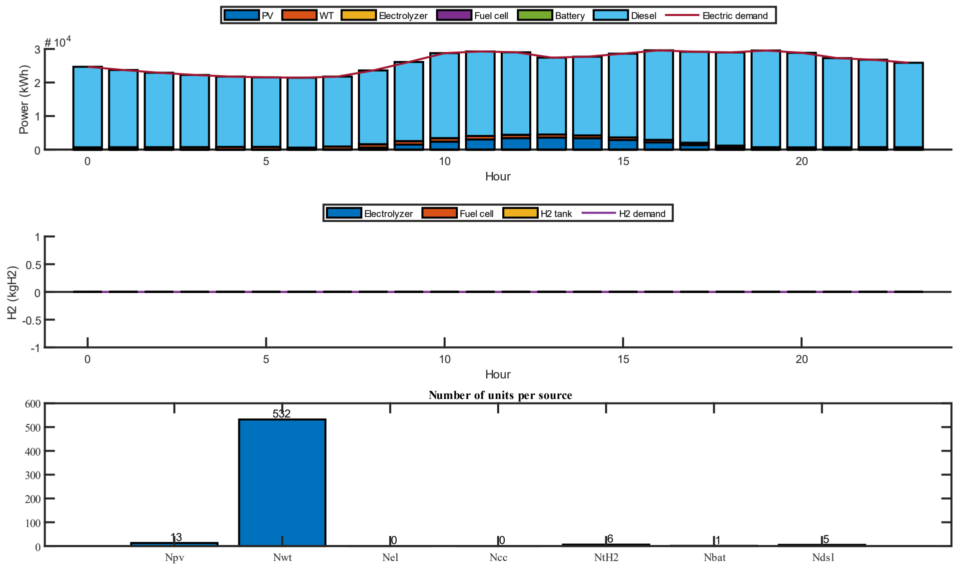

Fig. 9. Results of Solution 10th in FULL RES cases.

3.2. Model Case 2 WTLIM

In this model, the LCOE ranges from 0.041 USD/kWh to 0.142 USD/kWh. The lowest LCOE appears when the demand is met by diesel generators; all model solutions for this case use diesel generation. For WTLIM model results, the optimisation algorithm prioritises hydrogen generation and fuel cell electricity generation over lithium battery storage system operation (see Table 12).

Table 12. Results of the Optimisation Model for WTLIM Cases

No.	PV (kWh Day)	WT (kWh Day)	Dsl (kWh Day)	EL (kWh Day)	FC (kWh Day)	BATT (kWh Day)	Capex MUSD	Opex MUSD	LCOE (USD/kWh)	Total CO_2e TON CO_2 25 years
1	19230.1	10852.5	596552.9	0.0	0.0	0.0	$ 36.8	$ 1.2	$ 0.051	45725778.6
2	49998.2	4763.7	571873.6	0.0	0.0	0.0	$ 50.1	$ 1.3	$ 0.056	43834112.3
3	107688.5	2578.8	516368.2	0.0	0.0	0.0	$ 78.3	$ 1.6	$ 0.066	39579620.8
4	128841.6	343592.3	181373.5	−506.4	133.3	0.0	$ 197.2	$ 4.1	$ 0.089	8341376.1
5	144225.7	1862.5	480547.3	0.0	0.0	0.0	$ 96.4	$ 1.7	$ 0.073	36833955.9
6	148071.7	343520.7	177637.8	−633.0	166.7	0.0	$ 206.8	$ 4.2	$ 0.092	8169572.7
7	167301.8	1683.4	457650.3	0.0	0.0	0.0	$ 107.9	$ 1.8	$ 0.077	35078897.8
8	190377.9	35.8	436221.8	0.0	0.0	0.0	$ 118.9	$ 1.9	$ 0.081	33436400.6
9	190377.9	340547.9	171337.9	−569.7	150.0	0.0	$ 227.0	$ 4.4	$ 0.100	7879840.7
10	209608.0	336035.0	172123.8	−63.3	16.7	0.0	$ 235.1	$ 4.4	$ 0.102	7915976.2
11	213454.0	0.0	417778.0	−63.3	16.7	0.0	$ 131.4	$ 2.0	$ 0.081	32022684.4
12	219223.1	350182.7	162748.8	−253.2	66.7	0.0	$ 244.8	$ 4.6	$ 0.104	7484822.3
13	224992.1	1182.0	410026.3	−63.3	16.7	0.0	$ 137.6	$ 2.1	$ 0.083	31428520.4
14	249991.2	895.4	396488.7	−696.3	183.3	0.0	$ 150.0	$ 2.2	$ 0.084	30390869.4
15	261529.3	967.1	392452.4	−506.4	133.3	0.0	$ 155.9	$ 2.3	$ 0.086	30081482.5
16	269221.3	338148.2	165170.7	−506.4	133.3	0.0	$ 265.7	$ 4.7	$ 0.111	7596208.1
17	317296.5	327582.1	167119.5	−63.3	16.7	0.0	$ 286.2	$ 4.8	$ 0.118	7685829.4
18	328834.6	330984.8	164947.3	0.0	0.0	0.0	$ 292.3	$ 4.9	$ 0.121	7585931.5
19	384601.9	339437.6	158658.3	−696.3	183.3	0.0	$ 324.1	$ 5.3	$ 0.132	7296706.1
20	384601.9	358169.9	140816.5	−31396.8	8266.7	0.0	$ 357.3	$ 5.7	$ 0.142	6476472.0

Figs. 10 and 11 present the results of the 1st (more pollutant and less expensive solution) and 20th (less pollutant and more costly solution) solutions for the WTLIM cases.

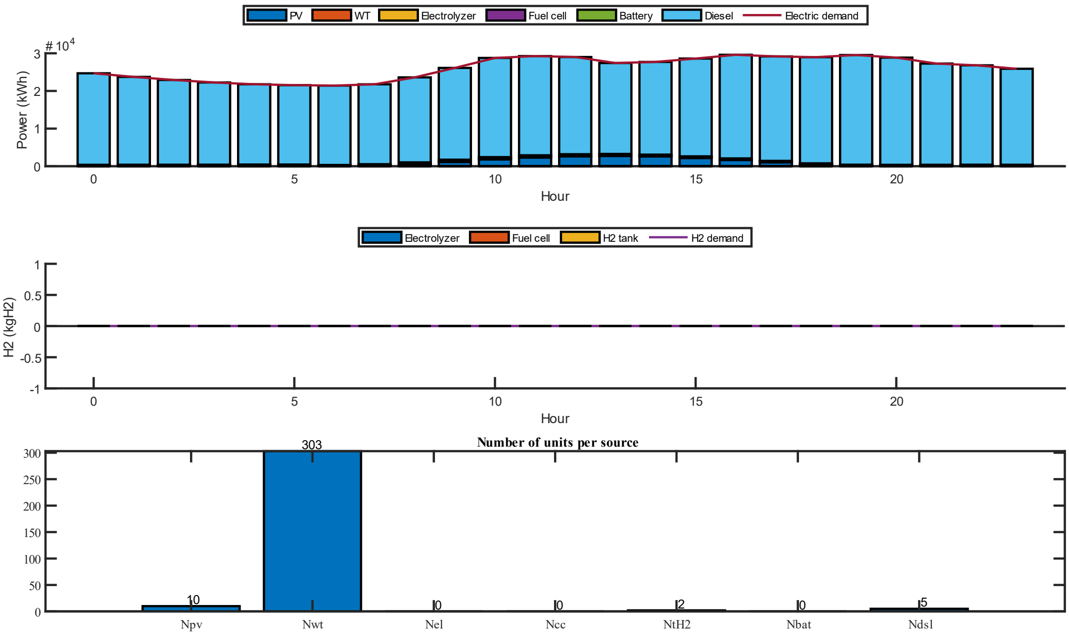

Fig. 10. Results of Solution 1st in WTLIM case.

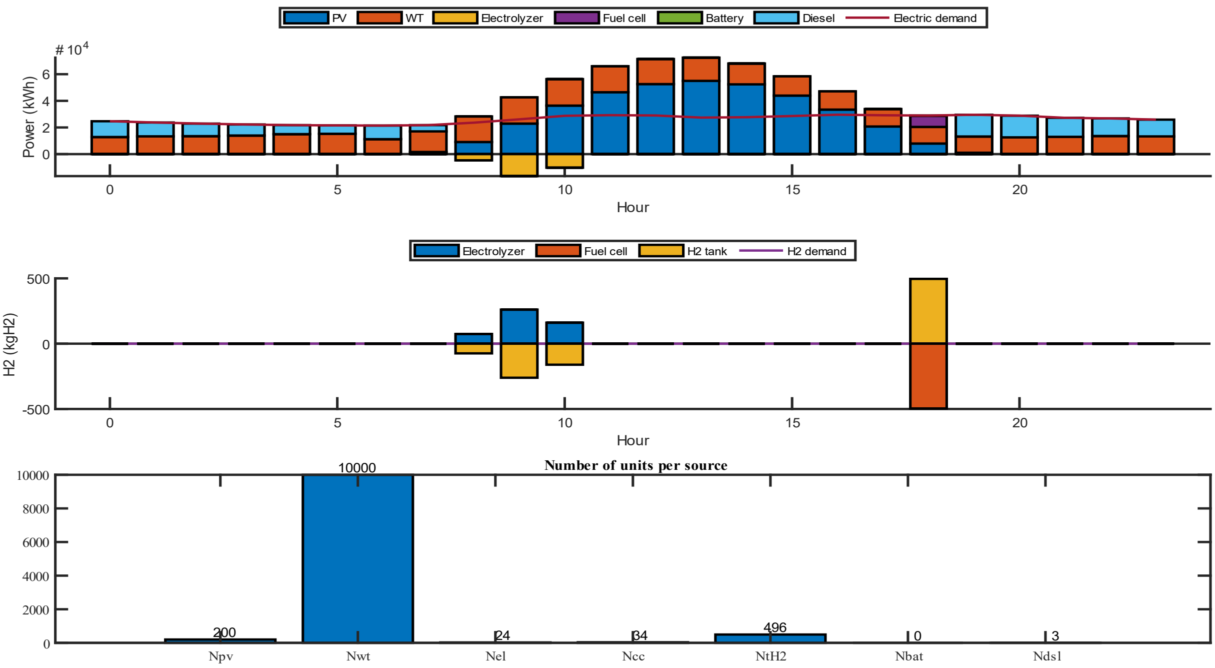

Fig. 11. Results of Solution 20th in WTLIM case.

3.3. Model case 3 H2WTLIM

This model considers a constant H2 demand per hour of 100 kgH2 and the number of wind power units limited to a maximum value of Nwt = 10,000. Hydrogen demand could be used as an energy to power mobility solutions. Results 19 and 20 incorporate PV, wind, diesel, electrolyser, fuel cell, and battery storage systems; these results were the least polluted but appeared as the highest LCOE for H2WTLIM cases. In results 19 and 20, the battery system stores energy between 10 am and 11 am and delivers power at 6 pm and 7 pm; hours without sun radiation were compensated with diesel generation and wind. Table 13 shows the case solutions.

Table 13. Results of the Optimisation Model in H2WTLIM Cases

No.	PV (kWh Day)	WT (kWh Day)	Dsl (kWh Day)	EL (kWh Day)	FC (kWh Day)	BATT (kWh Day)	Capex MUSD	Opex MUSD	LCOE (USD/kWh)	Total CO_2e TON CO_2 25 years
1	0.0	0.0	775550.5	−151920.0	0.0	0.0	30.9	1.3	0.058	71335131.8
2	5769.0	573.1	770984.1	−151920.0	0.0	0.0	34.3	1.3	0.059	70915121.7
3	40383.2	1289.4	736239.4	−151920.0	0.0	0.0	51.6	1.5	0.066	67719296.4
4	80766.4	2578.8	694744.2	−151920.0	0.0	0.0	74.6	1.7	0.074	63902573.9
5	149994.7	3975.7	624353.9	−151920.0	0.0	0.0	107.5	2.0	0.086	57428078.0
6	192300.9	0.0	585997.6	−151920.0	0.0	0.0	127.4	2.2	0.093	53900066.0
7	199993.0	351901.9	271247.2	−152236.5	83.3	0.0	242.9	4.7	0.115	16632883.6
8	203839.0	0.0	574495.7	−151920.0	0.0	0.0	133.2	2.2	0.095	52842115.7
9	213454.0	0.0	564906.8	−151920.0	0.0	0.0	138.4	2.3	0.097	51960130.8
10	228838.1	1074.5	548619.7	−152046.6	33.3	0.0	147.8	2.4	0.100	50462045.2
11	259606.3	465.6	523401.5	−152046.6	33.3	0.0	161.9	2.5	0.100	48142478.9
12	296143.4	3760.8	499589.0	−151920.0	0.0	0.0	180.8	2.7	0.107	45952197.2
13	307681.5	343341.6	258776.6	−152489.7	150.0	0.0	294.0	5.2	0.130	15868189.1
14	321142.6	342589.5	257688.4	−152363.1	116.7	0.0	300.5	5.2	0.133	15801463.9
15	334603.6	10494.4	480096.5	−151920.0	0.0	0.0	202.4	2.9	0.110	44159280.6
16	344218.7	16977.3	471858.2	−151983.3	16.7	0.0	210.0	3.0	0.113	43401525.8
17	374986.8	346744.2	249004.2	−151920.0	0.0	0.0	328.3	5.5	0.143	15268945.2
18	384601.9	358169.9	243741.6	−183316.8	8266.7	0.0	364.5	5.9	0.156	14946556.4
19	384601.9	358169.9	241787.4	−183443.4	8300.0	−300.1	371.1	6.1	0.179	14826723.2
20	384601.9	358169.9	219155.0	−183570.0	8333.3	−3830.1	448.0	8.0	0.446	13438910.7

Figs. 12 and 13 show the results of the 1st (more pollutant and less expensive solution) and 20th solutions (less pollutant and more expensive solution) for the H2WTLIM cases.

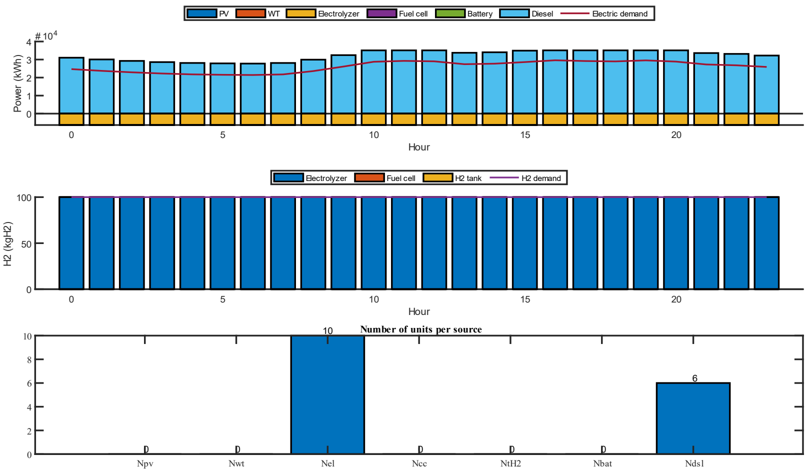

Fig. 12. Results of Solution 1st in H2WTLIM cases.

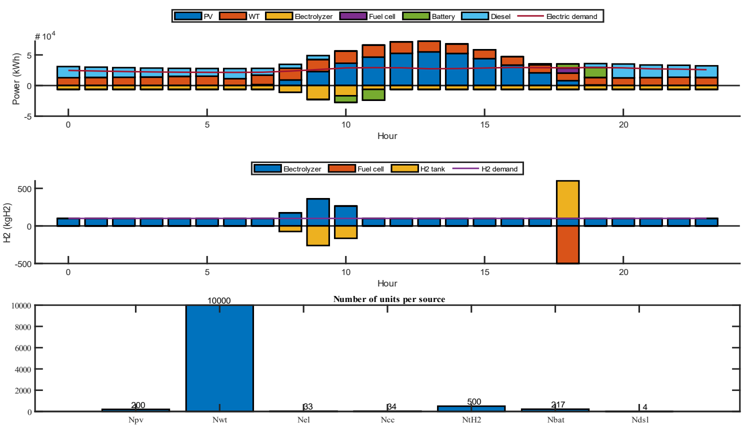

Fig. 13. Results of Solution 20th in H2WTLIM cases.

3.4. Model Case 4 RES H2

The results of RES H2 cases show a mix of diesel, PV, and wind electricity generation; the battery is not included in the optimisation algorithm modelling. Wind electricity, PV, and diesel mix represent the less polluting solution for these cases (see Result No. 15 in Table 14).

Table 14. Results of the Optimisation Model in RES H2 Cases

No.	PV (kWh Day)	WT (kWh Day)	Dsl (kWh Day)	EL (kWh Day)	FC (kWh Day)	BATT (kWh Day)	Capex MUSD	Opex MUSD	LCOE (USD/kWh)	Total CO_2e TON CO_2 25 years
1	0.0	0.0	775550.5	−151920.0	0.0	0.0	$ 30.9	$ 1.3	$ 0.058	71335131.8
2	7692.0	538221.8	232828.2	−152173.2	66.7	0.0	$ 205.5	$ 5.2	$ 0.102	10707769.2
3	15384.1	539582.9	223681.8	−152046.6	33.3	0.0	$ 209.8	$ 5.2	$ 0.104	10287128.1
4	15384.1	725293.9	84806.1	−151983.3	16.7	0.0	$ 268.7	$ 6.6	$ 0.112	2600157.4
5	17307.1	0.0	760444.1	−151920.0	0.0	0.0	$ 39.6	$ 1.3	$ 0.061	69945648.0
6	24999.1	623466.3	141975.7	−151920.0	0.0	0.0	$ 242.7	$ 6.0	$ 0.111	6529462.5
7	26922.1	889765.5	16396.1	−151920.0	0.0	0.0	$ 325.5	$ 7.8	$ 0.126	251353.7
8	28845.1	3975.7	745175.5	−151920.0	0.0	0.0	$ 46.7	$ 1.4	$ 0.064	68541249.9
9	28845.1	734033.3	76320.3	−151920.0	0.0	0.0	$ 277.8	$ 6.7	$ 0.114	2339982.1
10	53844.3	755917.5	60816.8	−151983.3	16.7	0.0	$ 298.4	$ 7.0	$ 0.121	1864643.7
11	55767.3	552333.7	177549.9	−152173.2	66.7	0.0	$ 234.4	$ 5.5	$ 0.108	8165521.5
12	59613.3	534962.5	187645.5	−152046.6	33.3	0.0	$ 230.4	$ 5.4	$ 0.106	8629817.0
13	69228.3	890087.9	13891.8	−151920.0	0.0	0.0	$ 346.8	$ 8.0	$ 0.133	212962.5
14	73074.4	11389.8	693904.3	−151920.0	0.0	0.0	$ 71.8	$ 1.7	$ 0.073	63825319.7
15	94227.5	916520.8	9602.2	−151920.0	0.0	0.0	$ 368.4	$ 8.3	$ 0.141	147203.6
16	111534.5	7593.2	659215.6	−151920.0	0.0	0.0	$ 89.4	$ 1.8	$ 0.079	60634654.6
17	173070.8	5229.3	600129.4	−151920.0	0.0	0.0	$ 120.3	$ 2.1	$ 0.090	55199902.9
18	201916.0	0.0	576459.3	−151983.3	16.7	0.0	$ 133.6	$ 2.2	$ 0.095	53022730.7
19	207685.0	7879.7	562990.8	−151920.0	0.0	0.0	$ 137.8	$ 2.3	$ 0.097	51783892.7
20	263452.3	3832.4	518236.6	−151920.0	0.0	0.0	$ 164.4	$ 2.5	$ 0.101	47667402.3

Figs. 14 and 15 present the results of the 1st (more pollutant and less expensive solution) and 15th (less pollutant and more costly solution) solutions for the RES H2 cases.

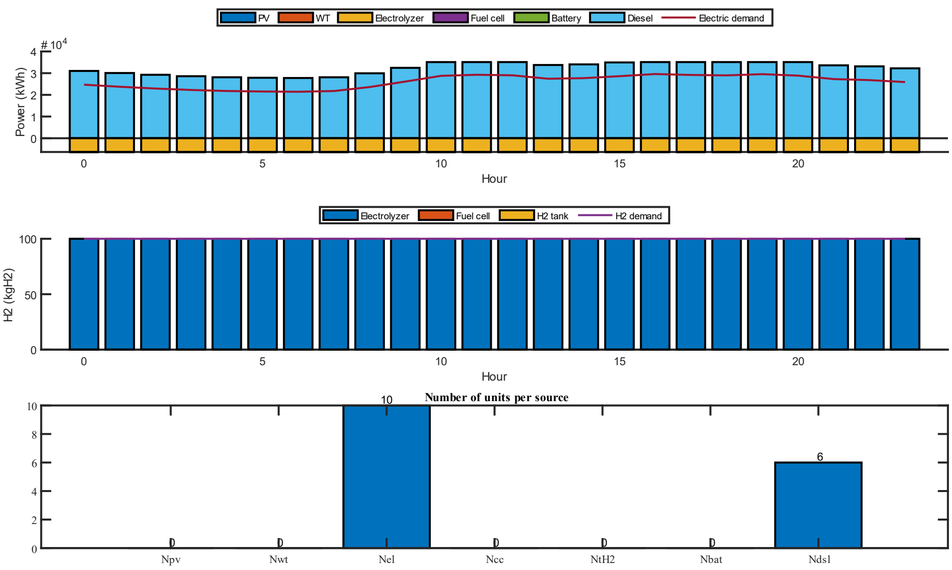

Fig. 14. Results of Solution 1st in RES H2 cases.

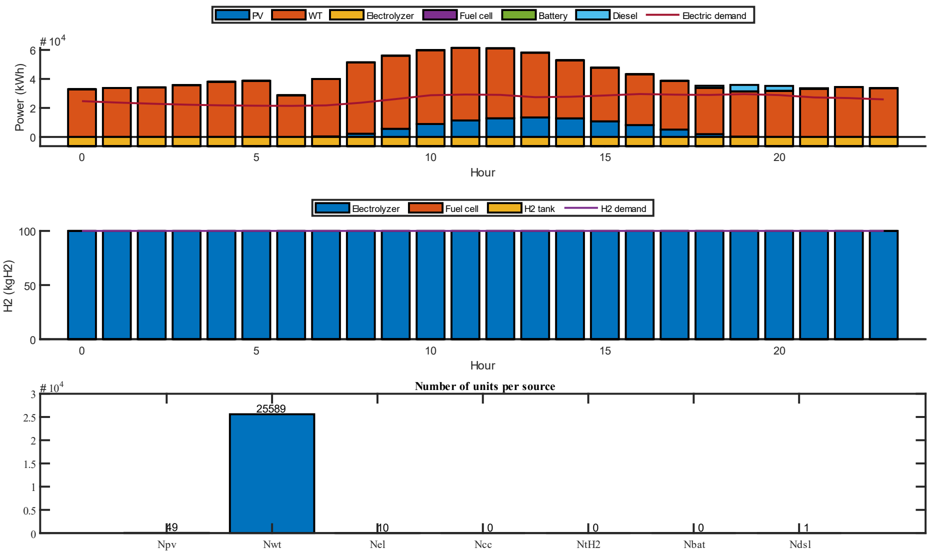

Fig. 15. Results of Solution 15th in RES H2 cases.

4. Conclusions

A comprehensive multi-objective, bi-level Particle Swarm Optimisation (PSO) model was implemented to delineate a sustainable and cost-efficient energy roadmap for San Andres Island. This state-of-the-art analytical tool evaluated the island's electrical demand's intricacies using Renewable Energy Sources (RES) and conventional energy.

Prevalence of diesel generation: Contrary to the global shift towards cleaner energy solutions, our findings reveal a strong preference for diesel. Of the 80 optimised solutions drawn across four scenarios, diesel was the dominant choice 78. Such results underscore the pragmatic constraints and potential advantages diesel might offer in San Andres Island's unique energy landscape.

Battery storage—an overlooked asset: One notable finding from the model was the marginalisation of lithium battery storage systems. Their omission is likely due to their substantial capital expenditure (capex) and the comparative edge wind energy has over photovoltaic energy. The latter could be attributed to the island's abundant availability of wind resources and the associated lower CO_2 emission metrics per kWh in contrast with PV-derived power.

Economic-environmental dilemma: A critical observation encapsulates the inverse correlation between environmental sustainability and the Levelized Cost of Electricity (LCOE). In contrast, greener solutions had a higher cost paradigm, and the more economically viable solutions involved pronounced environmental footprints. Even with the global trend of decreasing renewable energy costs, the economic appeal of diesel-generated electricity remains resilient, especially within the confines of San Andres.

Future Research Avenues:

A more comprehensive optimisation model is imperative, integrating variables such as desalination processes, wastewater treatment operations, and the intriguing realm of hydrogen-based multifunctional energy systems.

A granular, non-subsidized analysis of the operational expenditures associated with diesel power plants on San Andres and Providencia Islands is crucial. That evaluation will facilitate a balanced and equitable comparison of different energy sources and provide policymakers with comprehensive data for informed decision-making.

Our study reveals the complex interaction of economic, environmental, and technical factors in developing an optimal energy strategy for places like San Andres Island. The results emphasize the need for customized strategies rather than broad, one-size-fits-all approaches.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Javier Rosero: Conceptualized the initial study focused on optimizing renewable energy resources for isolated power systems, led the project administration, ensured adherence to objectives and timelines, and supervised the entire research process to ensure compliance with academic and technical standards.

Ricardo Echeverri: Developed the study model's core multi-objective and bi-level optimization algorithm, defined and implemented the methodology for integrating and analyzing energy data, and managed the computational and software resources necessary for simulation and data analysis.

Andrés Zúñiga: Validated the computational model results by comparing them to key performance indicators, conducted formal data analysis to interpret the study results, and significantly contributed to the writing and editing of the manuscript, ensuring that the data interpretation and conclusions were clear and evidence-based.

All authors critically reviewed the manuscript, made significant intellectual contributions, and approved the final version of the article

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