Feasibility Study of Hybrid Solar-Wind Energy Systems for Sustainable Airport Operations for Islands: A Case of San Andrés and Providencia

Master of Science in Aerospace Engineering
Control & Operation
Sustainability in Air Transportation (SAT)

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by

Francy Lorena Martinez Clavijo

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I am deeply grateful to my parents for their unconditional love and unwavering belief in me, a foundation that has carried me through every challenge. I sincerely thank my partner, Jeff, for his constant encouragement, patience, and strength, which have been a constant support and inspiration throughout this journey.

I want to dedicate this thesis to my son Keanu, who is growing in my belly as I write these words. My greatest hope is that you always follow your dreams and never give up, even when others or circumstances try to discourage you. The things that are most worth having in life often require love, time, effort, and perseverance.

Pursuing this master's program and chasing my dream has not been easy. I have faced health challenges, doubts about my age, and unexpected turns in life. Now, I am also blessed to be pregnant with you. Despite these challenges, I never gave up. What kept me going was the support of the kind people around me and my belief that I could learn and overcome from every obstacle.

Remember this: do not make excuses. Confront your fears, and dont let them hold you back. Keep moving forward, no matter how challenging the path may seem. Fight for your dreams, because you can truly achieve anything you set your heart on.

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Lorena Martinez
Delft, July 2025

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List of Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
APU	Auxiliary Power Unit
ARFF	Aircraft Rescue and Firefighting
BESS	Battery Energy Storage System
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DER	Distributed Energy Resource
DIAL	Delhi International Airport Limited
DME	Distance Measuring Equipment
DP	Dynamic Programming
EMA	Estación Meteorológica Automática (Automatic Meteorological Station)
GA	Genetic Algorithm
GPU	Ground Power Unit
GW	Gigawatt
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid Renewable Energy System
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
kWh	Kilowatt-hour
LCC	Life Cycle Cost
LCCA	Life-Cycle Cost Analysis
LCOE	Levelised Cost of Electricity
LP	Linear Programming
MASL	Meters Above Sea Level
MILP	Mixed Integer Linear Programming

MW	Megawatt
MWp	Megawatt-peak
NDC	Nationally Determined Contribution
OLS	Obstacle Limitation Surfaces
PBP	Payback Period
PCA	Pre-Conditioned Air
PCN	Pavement Classification Number
PICT	Pacific Island Countries and Territories
PSO	Particle Swarm Optimization
PV	Photovoltaic
RETScreen	Renewable Energy Technology Screen
SA	Simulated Annealing
SCADTA	Sociedad Colombo Alemana de Transportes Aéreos
SIDS	Small Island Developing States
SLO	Surface Limiting Obstacles
SMR	Steam Methane Reforming
TRNSYS	Transient System Simulation Tool
UAEAC	Unidad Administrativa Especial de Aeronáutica Civil
UN	United Nations
VCCS	Voice Communication Control System
VFR	Visual Flight Rules
VOR	VHF Omnidirectional Range
VPP	Virtual Power Plant

Introduction

I left my home country of Colombia in 2011 with the goal of pursuing a masters degree in Control and Operations. Although I was unable to start the program as planned in 2013, I began my professional journey in the Netherlands as a design engineer. Over the years, my career took me to Spain, where I worked as a project manager. This role allowed me to travel extensively around the world, leading and supporting various international engineering projects.

During my travels, especially to the Caribbean islands, I became increasingly aware of the region's heavy reliance on diesel generators to power critical infrastructure, such as airports. This realization struck me as both surprising and concerning, considering the islands abundant potential for harnessing renewable energy sources like solar and wind. One trip, in particular, to San Andrés Island in Colombia, left a lasting impression on me. Conversations with local residents fueled my curiosity and concern: Why, in a place blessed with natural energy resources, was there so little investment and research in sustainable alternatives?

This experience reignited my motivation to pursue the masters program I had postponed years earlier. When I finally enrolled, I had a clear vision for my thesis project. I aimed to conduct a feasibility study using a real-life scenariospecifically, to explore how a hybrid solar-wind energy system could support airport operations on islands, focusing on the case of San Andrés and Providencia..

With guidance from my supervisor, Paul Roling, I began to shape my idea into a formal research project. As the study progressed, I reached out to various stakeholders, including local authorities and energy companies in Colombia, to gather essential data. Additionally, I contacted manufacturers of solar and wind equipment to obtain the technical specifications needed for modeling the hybrid system. The positive responses and engagement from these organizations not only enhanced the research but also indicated a growing local interest in the future implementation of such a system.

This project focuses on addressing both environmental and societal challenges in a region where infrastructure is fragile and energy sustainability is essential. Its primary contribution is demonstrating the feasibility of transitioning to cleaner energy systems, even in remote island settings. By supporting airport operations, which are crucial for island economies, this study enhances climate resilience, energy security, and long-term sustainability through the use of renewable energy.

This thesis report is structured in three main parts. Part I presents the Scientific Paper, which outlines the core elements of the research, including the applied methodology, analysis of key results, and a discussion on implementation barriers along with proposed strategies to overcome these challenges in the context of the hybrid energy system configuration. Part II comprises the Literature Study, offering the foundation that supports the research. Part III includes Additional Results derived from the case study, providing further insights that complement the main findings.

I

Scientific Paper

Feasibility Study of Hybrid Solar-Wind Energy Systems for Sustainable Airport Operations for Islands: A Case of San Andrés and Providencia

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Abstract

Island airports face unique decarbonization challenges: highly variable electricity demand, limited land, and a costly reliance on diesel. This study quantifies the techno-economic potential of hybrid renewable-energy systems (HRES) at Colombias two Caribbean airports *Gustavo Rojas Pinilla (ADZ)* located at San Andrés island and *El Embrujo (PVA)* located at Providencia island.

A two-stage workflow is developed. **Stage 1** reconstructs 2024 hourly demand by (i) distributing monthly utility-metered energy with a reference 24 hours load-share pattern, and (ii) adjusting that baseline using flight movements and ambient temperature from 2024; inputs are Open-Meteo re-analysis, Flightradar24 traffic logs, and Aerocivil electricity bills. **Stage 2** solves a mixed-integer linear programme that selects optimal capacities and hourly dispatch of photovoltaic (PV), wind, lithium-ion storage batteries (separate PV- and wind-coupled banks), and back-up diesel generation. Six energy systems are explored; four relevant configurations-full hybrid (PV + Wind + Diesel), Renewables-combined (PV + Wind), Renewables-only (PV) & (Wind), and Diesel Renewables (Diesel + PV) and (Diesel + Wind) are analysed in detail.

Results for 2024 show that a full hybrid can satisfy the airports loads at present-worth costs of US$ 458,000 for *Gustavo Rojas Pinilla* and US$ 11,700 for *El Embrujo*, reducing diesel use by 82 % and 79 %, respectively, relative to current practice. The battery banks operate at moderate time average states of charge (30 - 40 %) with roughly 280-416 equivalent cycles per year. The optimal system build-outs for **San Andrés** comprise approximately 1 ha of land for 2,461 PV modules (generating 1752 MWh annually), together with four mid-size wind turbines requiring about 2 ha (producing 1281 MWh), less than1 MWh of battery storage, and 580 MWh of diesel generation. In contrast, **Providencia** requires only 228 m^2 of land for 57 PV modules (producing 30 MWh), a single wind turbine occupying roughly 0.5 ha (generating around 31 MWh), about 16.5 kWh of battery storage, and 15 MWh of diesel use.

The methodology outlines a framework that utilizes publicly available data for demand analysis and a clear Mixed-Integer Linear Programming (MILP) optimization approach. This framework serves as a reproducible and adaptable model for small-island airports aiming to create resilient and low-carbon energy systems. It not only reduces reliance on diesel power but also promotes the development of locally generated energy solutions, thereby enhancing energy autonomy and sustainability in remote and island airport settings. The islands located in the Caribbean or in the Pacific often benefit from favourable weather conditions, including consistent solar irradiance and adequate wind speeds, which facilitate the effective implementation of renewable energy technologies, particularly solar and wind power systems.

1 Introduction

The aviation sectors electricity demand is projected to keep rising even as the industry pursues aggressive decarbonisation targets. According to the latest *Global Energy Review* the power sector now accounts for over one-third of energy-related CO$_2$ emissions world-wide, with small island grids among the most carbon-intensive sub-systems [Agency, 2024]. Although airports do not drive air traffic volumes themselves, airport electricity demand is strongly influenced by passenger throughput, as higher traffic increases terminal operations, cooling loads, ground services, and auxiliary systems. The 68th edition of *World Air Transport Statistics* reports that post-pandemic traffic has rebounded to 94% of 2019 levels, with compound annual growth again exceeding 3% [International Air Transport Association, 2024]. At isolated islands which lack inter-connection to large national grids, the result is a near-total dependence on diesel generation, exposing operators to volatile fuel costs and supply-chain risk.

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Recent studies demonstrate that hybrid renewable-energy systems (HRES) tailored to airport load profiles can slash both operating cost and emissions. [Xiang et al., 2021] showed that coupling photovoltaics, hydrogen storage and batteries can cover up to 85% of an international airports demand at positive net present value. More site-specific case work is emerging: [Selim et al., 2024] optimised an off-grid PV-wind-battery-hydrogen layout for Cairo International Airport, cutting diesel use by 82% without compromising reliability. A systematic review of 240 peer-reviewed papers nonetheless concludes that most published designs overlook land scarcity, short time-step demand variability and detailed cost break-downs, three issues that are acute at small island airports [Couto and Baltazar, 2025].

Against this background, the present study develops a two-stage framework that (i) reconstructs 1-hour electricity demand from sparse utility bills, traffic data and meteorology, and (ii) solves a mixed-integer linear programme to size and dispatch PV, wind, lithium-ion storage and back-up diesel generation. The method is applied to two Colombias Caribbean airports, *Gustavo Rojas Pinilla* and *El Embrujo*, where no hourly demand measurements are publicly available.

The remainder of the paper is organised as follows. Section 2 reviews recent HRES research for airport applications. Section 3 details the demand-synthesis algorithm and the MILP formulation. Section 4 describes the two study sites and input data sets. Results including validation, dispatch behaviour, economics and land take-are presented in Section 5; key findings and limitations are discussed in Section 6.

2 Literature Review

The transition to hybrid renewable energy systems (HRES) has gained momentum since 2020 in response to global decarbonization targets, increasing fossil fuel volatility, and the growing demand for resilient energy infrastructure. These systems integrate multiple sources-such as solar photovoltaics (PV), wind turbines, biomass, and diesel generators with energy storage to ensure continuous power supply, while minimizing environmental impact. Recent research underscores the importance of advanced optimization techniques, including particle swarm optimization (PSO), genetic algorithms (GA), and hybrid AI-based models, in reducing the levelized cost of energy (LCOE) and carbon emissions while enhancing reliability and economic efficiency [Ansari et al., 2023, Bamisile et al., 2024]. Further studies have highlighted the role of intelligent control systems and real-time decision-making frameworks in addressing renewable intermittency and adapting to variable load conditions [Ajiboye et al., 2023, Mendonça and Santos, 2025]. Comprehensive reviews also point to a broader shift toward multi-objective, techno-economic-environmental optimization models, which allow more tailored and site-specific HRES configurations in both urban and remote contexts [Giedraityte et al., 2025, Kumar and Channi, 2022].

The application of HRES in airport environments has emerged as a strategic solution for decarbonizing aviation infrastructure while meeting stringent energy reliability requirements. Airports pose unique challenges due to their high, variable electricity demands, limited available land, and the critical need for uninterrupted power. Several studies have evaluated airport HRES configurations integrating solar, wind, hydrogen fuel cells, and battery storage, optimized using tools like HOMER, fuzzy logic models, and multi-criteria decision-making frameworks [Jin and Li, 2023, Mizrak and Şahin, 2025]. These optimization efforts depend critically on access to high-resolution data, including hourly weather parameters (e.g., irradiance, wind speed, temperature), detailed demand profiles, and system-specific performance coefficients. [Alruwaili, 2022] emphasizes the need to model a wide range of airport energy loads-such as Heating, Ventilation, and Air Conditioning (HVAC), runway lighting, terminal operations, and transportation services-requiring integrated models that account for both real-time operations and forecasted trends. As airports begin to incorporate electric aircraft and ground vehicle charging infrastructure, new models increasingly integrate dynamic load-response strategies and AI forecasting techniques to support energy system resilience[Shayeghi et al., 2024].

When direct hourly electricity demand data is unavailable, researchers often adopt context-driven simulation techniques rather than relying solely on statistical or machine learning models. A widely used approach is to combine known monthly or annual energy consumption with normalized hourly distribution profiles derived from comparable facilities, such as other airports or large commercial buildings, and adjust these using scaling factors [Lamagna et al., 2020]. To improve realism, studies often incorporate operational proxies such as flight schedules and environmental drivers like ambient temperature. Because energy use in airports tends to correlate strongly with air traffic volume, flight frequency data is commonly used to approximate peaks and troughs in demand throughout the day [Alruwaili, 2022]. Likewise, temperature data is applied to account for HVAC-related loads using normalized or seasonally weighted modifier [Ruggles et al., 2020, Patidar et al., 2021]. These hybrid modeling approaches allow for credible simulation of hourly energy demand in airport HRES design, even in the absence of direct metering or fine-grained historical data.

3 Methodology

The modelling workflow has two clearly separated stages:

1. **Hourly demand synthesis**: Converts monthly utility bills, airport traffic and temperature into a 1-hour resolution load profile $d_{s,t}$ for each site s.
2. **HRES optimisation**: Chooses optimal PV, wind, battery and diesel sizes (plus hourly dispatch) that meet the synthesised load at minimum total cost.

Stage 1 produces only *data*; stage 2 is the only optimisation problem solved numerically.

3.1 Notation

Table 1: Sets and indices

$\mathcal{S}$	Sites: *San Andrés*, *Providencia*
$\mathcal{M} = \{1, \ldots, 12\}$	Calendar months of 2024
$\mathcal{H} = \{0, \ldots, 23\}$	Hour of day (local time)
$\mathcal{T} = \{0, \ldots, 8783\}$	All hourly indices in 2024 ($\lvert\mathcal{T}\rvert = 8\,784$)

Table 2: Decision variables

$p_{\mathrm{pv}_{\max}}$	Installed PV capacity [kW]
$p_{\mathrm{wt}_{\max}}$	Installed wind-turbine capacity [kW]
$b_{\mathrm{pv}_{\max}}$	Energy capacity of the PV-coupled battery [kW h]
$b_{\mathrm{wt}_{\max}}$	Energy capacity of the wind-coupled battery [kW h]
p_{pv_t}, p_{wt_t}	Renewable output per hour t [kW h]
p_{d_t}	Diesel generator output per hour t [kW h]
$b_{\mathrm{ch,pv}_t}$, $b_{\mathrm{dis,pv}_t}$	Charge / discharge power of PV-battery per hour t [kW h]
$b_{\mathrm{ch,wt}_t}$, $b_{\mathrm{dis,wt}_t}$	Charge / discharge power of wind-battery per hour t [kW h]
s_{pv_t}, s_{wt_t}	State of charge of the two batteries at end of hour t [kW h]
z_{pv_t}, z_{wt_t}	Binary: 1 ⇒ discharge, 0 ⇒ charge

Table 3: Parameters, resource data and physical constants.

$E_{s,m}$	Utility-metered energy for site s in month m [kW h]
r_h	Reference hour-of-day share ($\sum_h r_h = 1$)
$F_{s,t}$	Hourly flight movements (landings+take-offs)
$\Theta_{s,t}$	Ambient temperature [°C]
$I_{s,t}$	Solar irradiance [$\mathrm{W\,m^{-2}}$]
$v_{s,t}$	Wind speed [$\mathrm{m\,s^{-1}}$]
$\eta_{\mathrm{ch}}, \eta_{\mathrm{dis}}$	Battery charge / discharge efficiency (0.95)
α_{der}	PV derating factor (0.80)
γ_{temp}	PV temperature coefficient (-0.005 / °C)
$v_{\mathrm{ci}}, v_{\mathrm{r}}, v_{\mathrm{co}}$	Cut-in (2.8) / rated (9.5) / cut-out (25 m/s)
β_F, β_T	Tuned sensitivities to flights / temperature
$d_{s,t}$	Hourly electricity demand for site s [kW h] (output of Step 1)

3.2 Techno-economic parameters and cost annualisation

Techno-economic parameters were derived from vendor quotes obtained in 2024 for systems representative of small island airports. All capital costs are first converted to specific investment costs per unit of installed capacity and then annualised by dividing by the assumed technical lifetime of each technology. This corresponds to a straight-line annualisation with an implicit real discount rate of zero; the approach is conservative but keeps the formulation simple and transparent.

Vendor quotes and currency conversion. Three technology quotes were used as the primary cost anchors:

- **Photovoltaics (PV).** A rooftop system of 3.68 kW was quoted at 4 570 €, i.e. 1 242 €/kW.
- **Wind turbines.** A wind farm of 4 MW total capacity was quoted at 15 M€, corresponding to 3 750 €/kW.
- **Battery storage.** A 10 kWh lithium-ion system was quoted at 8 000 €, i.e. 800 €/kWh.

All prices were converted to U.S. dollars using an exchange rate of 1 € = 1.2 US$:

$$I^{\text{inv}}_{\text{pv}} \approx 1\,242 \times 1.2 = 1\,490 \text{ US\$/kW},$$
$$I^{\text{inv}}_{\text{wt}} \approx 3\,750 \times 1.2 = 4\,500 \text{ US\$/kW}.I^{\text{inv}}_{\text{b}} \qquad \approx 800 \times 1.2 = 960 \text{ US\$/kWh},$$

Diesel energy cost was inferred from the current electricity supplier, which operates diesel generators. The 2024 retail tariff of 1 438.29 COP/kWh was converted to U.S. dollars using the currency exchange of 1 US$ = 3 900 COP:

$$c_{\text{fuel}} = \frac{1\,438.29}{3\,900} \approx 0.37 \text{ US\$/kWh}.$$

An additional term c_{CO_2} internalises the environmental cost of diesel-related CO_2 emissions. Colombia applies a carbon tax of approximately 5 US$/$\text{tCO}_2$ for domestic aviation.[1]

To convert this into a cost per kilowatt-hour of diesel-generated electricity, an emission factor representative of small-island diesel gensets is required. According to the *IPCC 2019 Refinement to the 2006 Guidelines*, diesel stationary combustion has a CO_2 emission factor of 74,100 kgCO_2/TJ, which corresponds to 0.89–1.00 kgCO_2/kWh for generator efficiencies typical of 100–800 kW diesel sets.[2]

Based on this range, the model adopts the representative value

$$\varepsilon_{\text{d}} = 1.0 \text{ kgCO}_2\text{/kWh} = 0.001 \text{ tCO}_2\text{/kWh},$$

which, combined with the Colombian carbon tax, yields

$$c_{\text{CO}_2} = 5 \,\frac{\text{US\$}}{\text{tCO}_2} \times 0.001 \,\frac{\text{tCO}_2}{\text{kWh}} = 0.005 \text{ US\$/kWh}.$$

This value is used as the environmental penalty in the optimisation model.

Annualisation of investment costs. Instead of using a full discounted cash-flow model, this study employs a simple straight-line annualisation: the upfront investment is divided by the technical lifetime of each technology. With the assumed lifetimes

$$n_{\text{pv}} = 15 \text{ yr}, \qquad n_{\text{wt}} = 25 \text{ yr}, \qquad n_{\text{b}} = 15 \text{ yr},$$

the annualised specific CAPEX values become

$$\text{CAPEX}_{\text{pv}} = \frac{I^{\text{inv}}_{\text{pv}}}{n_{\text{pv}}} = \frac{1\,490}{15} \approx 99 \text{ US\$/kW yr},$$
$$\text{CAPEX}_{\text{wt}} = \frac{I^{\text{inv}}_{\text{wt}}}{n_{\text{wt}}} = \frac{4\,500}{25} = 180 \text{ US\$/kW yr}.$$
$$\text{CAPEX}_{\text{b}} = \frac{I^{\text{inv}}_{\text{b}}}{n_{\text{b}}} = \frac{960}{15} = 64 \text{ US\$/kWh yr},$$

For simplicity in the optimisation model, these are rounded to nearest convenient values and a modest margin is included to implicitly cover fixed operation and maintenance (O&M) costs. The base-case parameters used in the MILP therefore are:

$$\text{CAPEX}_{\text{pv}} = 99 \text{ US\$/kW yr}, \quad \text{CAPEX}_{\text{wt}} = 180 \text{ US\$/kW yr}, \quad \text{CAPEX}_{\text{b}} = 64 \text{ US\$/kWh yr}.$$

These annualised unit costs enter directly into the cost objective function in Section 3.4.

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[1] IATA (2025), *Taxes and Addressing CO_2 Emissions*, noting a Colombian carbon tax of approximately 5 US$/$\text{tCO}_2$.

[2] IPCC (2019), *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 2: Energy, Ch. 2 (Stationary Combustion).

Table 4: Technoeconomic constants for the base case.

Symbol	Meaning	Value	Unit
$\mathrm{CAPEX}_{\mathrm{pv}}$	Specific annualized CAPEX of the PV field	99	\$/kW
$\mathrm{CAPEX}_{\mathrm{wt}}$	Specific annualized CAPEX of the wind turbines	180	\$/kW
$\mathrm{CAPEX}_{\mathrm{b}}$	Specific annualized CAPEX of the batteries (both banks)	64	\$/kWh
c_{fuel}	Diesel fuel cost per kWh	0.37	\$/kWh
$c_{\mathrm{CO_2}}$	Cost assigned to diesel CO_2	0.005	\$/kWh
M	Big-M constant (used in C7)	10 000	kW
C_{cap}	Net cost associated to the installed capacity	-	\$
C_{op}	Net cost associated to the diesel usage	-	\$
C_{env}	Environmental cost penalty associated to the diesel usage	-	\$

Technology-sizing assumptions

To translate the optimisers continuous capacity decisions ($p_{\mathrm{pv}_{\mathrm{max}}}$, $p_{\mathrm{wt}_{\mathrm{max}}}$, $b*_{\mathrm{max}}$) into physically countable units, a set of unit-level conversion factors was adopted. These factors correspond to commercially available equipment and to practical installation requirements under Caribbean island conditions (e.g. spacing, maintenance access, shading constraints, turbine wake influence). Table 5 summarises the values used.

Photovoltaic modules and ground footprint. The PV module used as reference is the AIKO A-MAH54Mb bifacial module (445-460 W), whose dimensions (1.76 m × 1.13 m) yield an aperture area of approximately 2.0 m^2 per panel. However, total land requirement exceeds the raw module area because:

- panels are arranged in fixed-tilt rows, however several PV layouts are particularly suited for islands with severe land constraints, please see (section 7)
- inter-row spacing must prevent mutual shading during low-sun periods,
- clearances are required for walkable maintenance access, and
- peripheral buffer area is needed for mounting structures and cable routing.

Considering typical row-to-row spacing of 3–5 m for Caribbean latitudes and a ground coverage ratio between 0.40 and 0.55, the effective land-take is approximately 4 $\mathrm{m}^2/\mathrm{kW}_\mathrm{p}$, which is consistent with current utility-scale PV layouts. This value is adopted for converting PV capacity into footprint area.

Wind turbines and influence area. For wind power the selected reference technology is the 100 kW Innoventum medium-scale turbine.[3] Its rotor diameter is approximately 25 m. Although the airports require only a small number of wind turbines, each unit still imposes an influence area determined by wake losses and safety clearances.

A conservative spacing rule of 3–5 rotor diameters laterally and 6–10 diameters downstream is commonly applied for isolated wind turbines. Using a representative spacing radius of 40–45 m results in an effective land requirement of roughly 5 000 m^2 per 100 kW turbine. This area is not necessarily fully excluded from other uses but represents the operational wake-influence envelope adopted in Table 5.

Battery storage units. The battery reference is the SolarEdge 400 V home battery (approx. 10 kWh per module), whose physical form factor enables modular containerised installation.[4] To translate an optimised energy capacity into discrete units, a size of 10 kWh per battery pack is assumed. The footprint of individual battery cabinets is small relative to PV and wind, and therefore land area for batteries is not explicitly considered in the model.

3.3 Hourly demand synthesis (deterministic pre-processing)

Concept

Utility bills provide monthly energy totals but give no intramonthly resolution. It is distributed each months energy into hours using a baseline *hour-of-day* share, then perturb that baseline according to airport activity and temperature. Finally, it rescales the perturbed weights so that the sum for each month exactly matches the bill.

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[3] Innoventum 100 kW turbine: `https://innoventum.se/en/business/100kw/`.

[4] SolarEdge 400 V battery: `https://midsummerwholesale.co.uk/pdfs/se-solaredge-home-battery-400v-datasheet-eng.pdf`.

Table 5: Unit-level translation factors used to convert optimised capacities into numbers of PV modules, wind turbines and battery units.

Parameter	Value
PV module rating	460 W/module
PV footprint per $\mathrm{kW_p}$	4 m^2
Wind turbine rating	100 kW/turbine
Land per 100 kW turbine	5 000 m^2
Battery unit energy	10 kWh/unit

Airport demand profile Input

Step 1: Baseline replication The reference profile r_h (with $\sum_{h\in\mathcal{H}} r_h = 1$) retrieved from [Ortega Alba and Manana, 2017] is expanded to a year-long vector $w_t = w_{h(t)}$ by repeating it day-by-day. Figure 1 shows the *a priori* hour-of-day shape: it captures the characteristic twin-peak pattern of airport electricity use and therefore acts as the neutral baseline that subsequent temperature- and traffic-driven adjustments will amplify or attenuate.

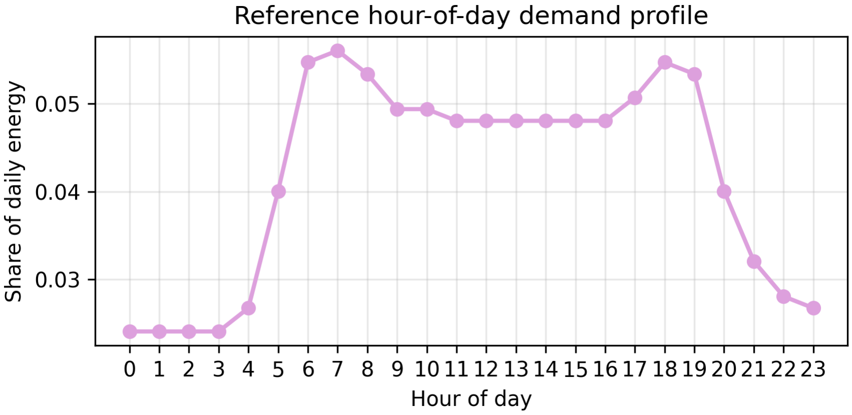

Figure 1: Reference hour-of-day profile (r_h) applied to distribute monthly utility-metered energy into 1-h resolution. Values sum to unity, so each point represents the share of a days energy assigned to that hour.

Step 2: Dynamic adjustment For each *site* s it accounts for (i) temperature and (ii) airport activity. Activity is first *smoothed* with a three-hour kernel $\boldsymbol{\kappa} = [0.5, 1.0, 0.5]$ to capture passengers arriving *before* and lingering *after* a flight:

$$\hat{F}_{s,t} = (\boldsymbol{\kappa} * F_{s,\cdot})_t.$$

Both drivers are then normalised to $[0, 1]$ so that no deviation maps to 0 and the site-specific extreme to 1:

$$F^*_{s,t} = \frac{\hat{F}_{s,t} - \min_t \hat{F}_{s,t}}{\max_t \hat{F}_{s,t} - \min_t \hat{F}_{s,t} + 10^{-6}}, \qquad \Theta^*_{s,t} = \frac{\Theta_{s,t} - \min_t \Theta_{s,t}}{\max_t \Theta_{s,t} - \min_t \Theta_{s,t} + 10^{-6}}$$

With empirically tuned sensitivities $\beta_F = 2.0$ (flights) and $\beta_T = 0.5$ (temperature), the unnormalised hourly weight becomes

$$\tilde{w}_{s,t} \;=\; w_t\big(1 + \beta_T \Theta^*_{s,t}\big)\big(1 + \beta_F F^*_{s,t}\big).$$

(The multiplicative form preserves the baseline diurnal shape while allowing either driver to amplify or attenuate it.)

Step 3: Monthly reconciliation Let $\mathcal{T}_m$ denote the hours in month m. Scaling ensures the reconstructed load exactly meets each utility bill:

$$d_{s,t} \;=\; E_{s,m}\,\frac{\tilde{w}_{s,t}}{\displaystyle\sum_{t'\in\mathcal{T}_m} \tilde{w}_{s,t'}}, \qquad t \in \mathcal{T}_m,\; s \in \mathcal{S}.$$

Thus $\sum_{t\in\mathcal{T}_m} d_{s,t} = E_{s,m}$.
The per-site time series $d_{s,t}$ is henceforth treated as *known data* by the optimisation model.

Step 4: Technology-specific capacity-factor computation To translate meteorological inputs into the *instantaneous availability* of renewable generation, each hour is assigned a capacity factor for wind and solar, respectively. These factors scale nameplate capacity into expected output and serve as exogenous inputs to the optimisation model.

Wind turbines Hourly wind capacity factor $\mathrm{CF}_{\mathrm{wt}}(t)$ follows a simplified turbine power-curve representation driven by wind speed v_t:

$$\mathrm{CF}_{\mathrm{wt}}(t) = \begin{cases} 0, & v_t < v_{\mathrm{ci}} \text{ or } v_t \geq v_{\mathrm{co}}, \\ 1, & v_t \geq v_{\mathrm{r}}, \\ \big[(v_t - v_{\mathrm{ci}})/(v_{\mathrm{r}} - v_{\mathrm{ci}})\big]^3, & \text{otherwise.} \end{cases}$$

This cubic relationship captures the partial-load behaviour between the cut-in (v_{ci}) and cut-out (v_{co}) thresholds, with rated output reached at v_{r}.

Photovoltaics The solar capacity factor $\mathrm{CF}_{\mathrm{pv}}(t)$ incorporates both the incoming irradiance and module-temperature derating:

$$\mathrm{CF}_{\mathrm{pv}}(t) = \alpha_{\mathrm{der}}\Big[1 + \gamma_{\mathrm{temp}}\big(\Theta_t - 25°\mathrm{C}\big)\Big]\frac{I_t}{1000}, \qquad 0 \leq \mathrm{CF}_{\mathrm{pv}}(t) \leq 1.$$

Here I_t is global horizontal irradiance ($\mathrm{W\,m^{-2}}$), γ_{temp} is the module temperature coefficient, and α_{der} aggregates wiring, inverter, and other system losses.

Role in the synthesis pipeline Whereas Steps 1–3 reconstruct the hourly *demand* series $d_{s,t}$ consistent with monthly utility bills and operational drivers (activity and temperature), Step 4 characterises the hour-by-hour *supply-side* variability of the renewable resources. Together, $d_{s,t}$, $\mathrm{CF}_{\mathrm{wt}}(t)$, and $\mathrm{CF}_{\mathrm{pv}}(t)$ form the deterministic time-series inputs required by the optimisation model for system design and dispatch.

3.4 Mathematical Model Formulation mixed-integer linear programme

Objective

Minimise the net present cost

$$\begin{aligned} \min\ C_{\mathrm{cap}} = \mathrm{CAPEX}_{\mathrm{pv}} p_{\mathrm{pv}_{\max}} + \mathrm{CAPEX}_{\mathrm{wt}} p_{\mathrm{wt}_{\max}} + \mathrm{CAPEX}_{\mathrm{b}}\big(b_{\mathrm{pv}_{\max}} + b_{\mathrm{wt}_{\max}}\big) \\ + C_{\mathrm{op}} + C_{\mathrm{env}} \end{aligned} \tag{1}$$

where the two flow-proportional terms are:

$$C_{\mathrm{op}} = c_{\mathrm{fuel}} \sum_{t\in\mathcal{T}} p_{\mathrm{d}_t}, \qquad C_{\mathrm{env}} = c_{\mathrm{CO_2}} \sum_{t\in\mathcal{T}} p_{\mathrm{d}_t}.$$

Physical & operational constraints

(C1) Solar availability. [Duffie et al., 2013] The instantaneous photovoltaic generation is limited by the installed capacity $p_{\mathrm{pv}_{\max}}$ and the time-varying solar capacity factor $\mathrm{CF}_{\mathrm{pv}}(t)$:

$$p_{\mathrm{pv},t} \ \leq \ p_{\mathrm{pv}_{\max}} \mathrm{CF}_{\mathrm{pv}}(t), \qquad \forall t.$$

This constraint ensures that the electrical output from PV modules never exceeds the physically available power at each hour, given the meteorological conditions.

(C2) Wind availability. [International Electrotechnical Commission, 2021] Wind-turbine generation is similarly constrained by the installed capacity $p_{\mathrm{wt}_{\max}}$ and a time-dependent capacity factor $\mathrm{CF}_{\mathrm{wt}}(t)$:

$$p_{\mathrm{wt}_t} \ \leq \ p_{\mathrm{wt}_{\max}} \mathrm{CF}_{\mathrm{wt}}(t), \qquad \forall t.$$

The capacity factor captures the behaviour of the turbine's power curve, including periods of low winds, operation near rated output, and shutdown at high wind speeds, thereby providing a realistic upper bound on feasible generation.

(C3) Battery state-of-charge dynamics. The evolution of stored energy in each battery follows the energy balance between charging and discharging:

$$\begin{aligned} s_{\mathrm{pv}_t} &= s_{\mathrm{pv}_{t-1}} + \eta_{\mathrm{ch}} b_{\mathrm{ch,pv}_t} - \eta_{\mathrm{dis}}^{-1} b_{\mathrm{dis,pv}_t}, \\ s_{\mathrm{wt}_t} &= s_{\mathrm{wt}_{t-1}} + \eta_{\mathrm{ch}} b_{\mathrm{ch,wt}_t} - \eta_{\mathrm{dis}}^{-1} b_{\mathrm{dis,wt}_t}, \qquad \forall t. \end{aligned}$$

These equations express conservation of energy within the storage systems, incorporating charge and discharge efficiencies η_{ch} and η_{dis}.

(C4) State-of-charge bounds. The energy content of each battery is limited by its physical capacity:

$$0 \leq s_{\mathrm{pv}_t} \leq b_{\mathrm{pv}_{\max}}, \quad 0 \leq s_{\mathrm{wt}_t} \leq b_{\mathrm{wt}_{\max}}, \qquad \forall t.$$

This prevents infeasible overcharging or negative states of charge.

(C5) Charging limited to on-site generation.

$$b_{\mathrm{ch,pv}_t} \leq p_{\mathrm{pv}_t}, \quad b_{\mathrm{ch,wt}_t} \leq p_{\mathrm{wt}_t}, \qquad \forall t.$$

This restriction prevents cross-charging, i.e. PV energy charging the wind battery and vice versa, ensuring that each storage unit operates independently and tracks the variability of its associated generator.

(C6) Hourly energy balance.

$$p_{\mathrm{pv}_t} + p_{\mathrm{wt}_t} + p_{\mathrm{d}_t} + b_{\mathrm{dis,pv}_t} + b_{\mathrm{dis,wt}_t} = d_t + b_{\mathrm{ch,pv}_t} + b_{\mathrm{ch,wt}_t}, \qquad \forall t.$$

At each hour, the total power produced and discharged must exactly match the electricity demand and any charging of the batteries. *Note: batteries charging/discharging efficiency is handled in C3 (set at 95%), AC/DC conversion efficiency is assumed to be negligible.*

(C7) Mutual exclusivity of charge / discharge.

$$\begin{aligned} b_{\mathrm{ch,pv}_t} &\leq M(1 - z_{\mathrm{pv}_t}), & b_{\mathrm{dis,pv}_t} &\leq M z_{\mathrm{pv}_t}, \\ b_{\mathrm{ch,wt}_t} &\leq M(1 - z_{\mathrm{wt}_t}), & b_{\mathrm{dis,wt}_t} &\leq M z_{\mathrm{wt}_t}, \qquad \forall t. \end{aligned}$$

Binary variables $z_{\mathrm{pv},t}$ and $z_{\mathrm{wt},t}$ enforce that each battery can either charge or discharge in a given hour, but not both. Although these logical constraints do not directly influence total cost, they reduce unrealistic switching behaviour and limit the number of charge-discharge cycles, resulting in more physically plausible battery usage patterns (see section 5.7.3).
Note: The constant M is a standard big–M parameter that activates or deactivates the bounds in (C7) according to the binary variable. When $z_{\mathrm{pv},t} = 0$, charging is permitted (up to M) and discharging is forced to zero; when $z_{\mathrm{pv},t} = 1$, charging is forced to zero and discharging is allowed. Choosing M sufficiently large ensures this logic is enforced without constraining the actual operating limits of the battery.

(C8) Cyclic batteries state of charge.

$$s_{\mathrm{pv}_{|\mathcal{T}|-1}} = s_{\mathrm{pv}_{-1}}, \qquad s_{\mathrm{wt}_{|\mathcal{T}|-1}} = s_{\mathrm{wt}_{-1}}.$$

This wrap-around condition forces the final state of charge at the end of the simulation to equal the initial value, preventing the solver from artificially emptying a battery in the last hour to reduce operating cost. It ensures periodic consistency and a fair comparison between technologies over a complete year.

4 Description of the Case Study

This study analyses two Colombian island airports: **Gustavo Rojas Pinilla** on San Andrés (ADZ) and **El Embrujo** on Providencia (PVA). Three independent data sets feed the modelling workflow of Section 3: (i) hourly meteorology, (ii) hourly flight movements, and (iii) monthly utility-bill electricity totals.

4.1 Meteorological time series

Hourly global horizontal irradiance ($I_{s,t}$), at 2m height air temperature (Θ_t) and at 10m height wind speed ($v_{s,t}$) were required for calendar year 2024. Although the national climatic service (IDEAM) hosts station files on its Hydro-meteorological Open Data Portal,[5] those records do not provide uninterrupted hourly coverage for the two islands as of 7 July 2025.

Consequently, the *Open-Meteo* API[6] was queried on 7 July 2025 using each airports centroid:

Site	Latitude [°]	Longitude [°]
Gustavo Rojas Pinilla (SA)	12.5786	−81.6997
El Embrujo (PR)	13.3569	−81.3583

The variables `shortwave_solar_radiation`, `temperature_2m` and `wind_speed_10m` were requested. Open-Meteo blends ERA5 and ICON-EU re-analysis fields, delivering gap-filled 1 hour series that satisfy the temporal resolution stipulated in Section 3.

Figure 2 presents the resulting irradiance, temperature and wind-speed patterns for Gustavo Rojas Pinilla; Fig. 3 provides the same view for El Embrujo. Each figure compares the daily means in three representative demand months with the hourly profile of the respective peak-demand week.

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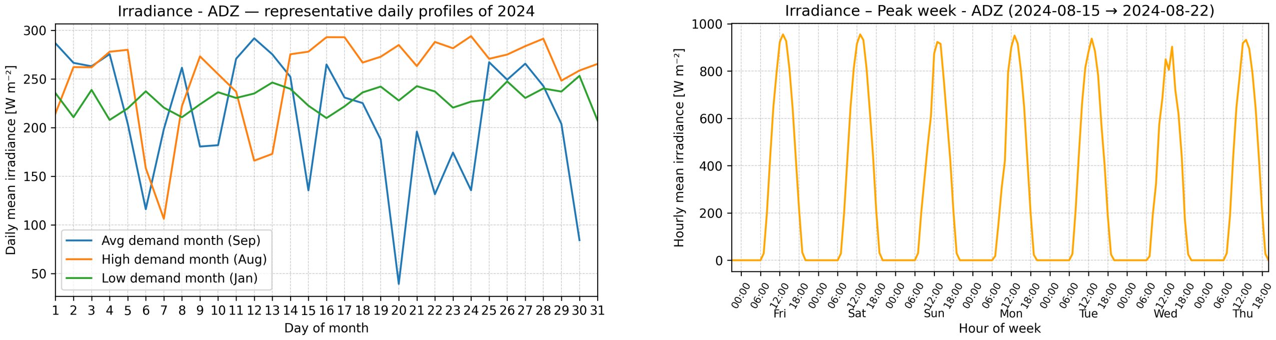
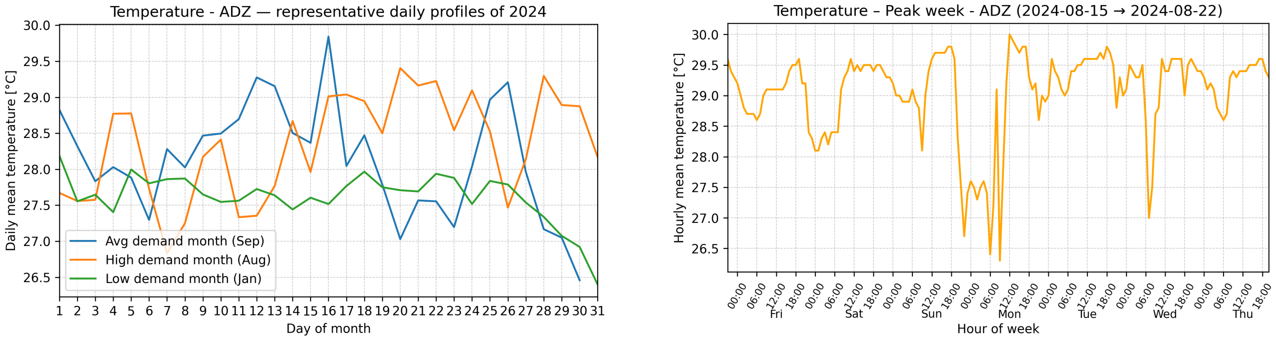
[5] `https://www.datos.gov.co/`

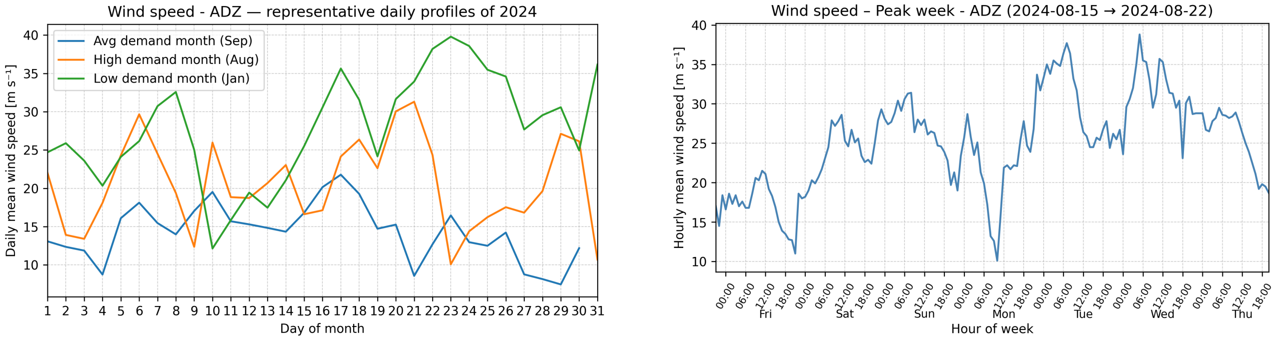
[6] `https://open-meteo.com/`



(a) Irradiance - daily means (b) Irradiance - peak week

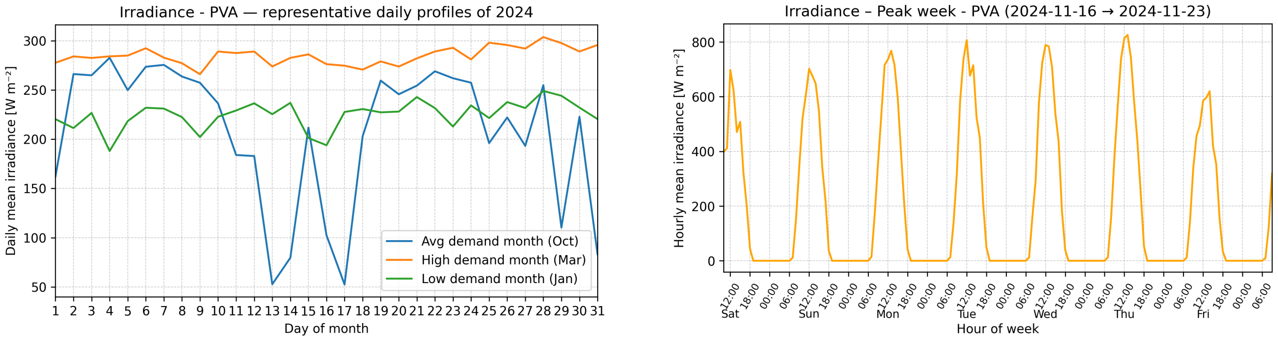


(c) Temperature - daily means (d) Temperature - peak week

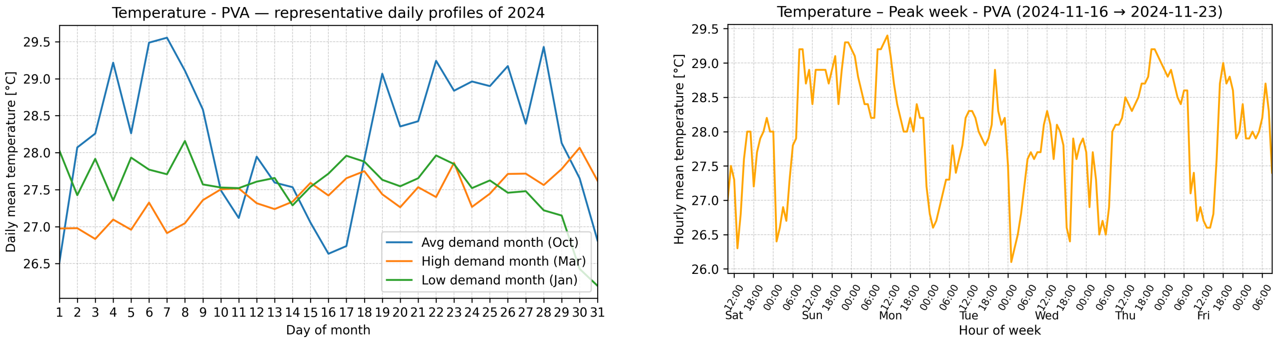


(e) Wind speed - daily means (f) Wind speed - peak week

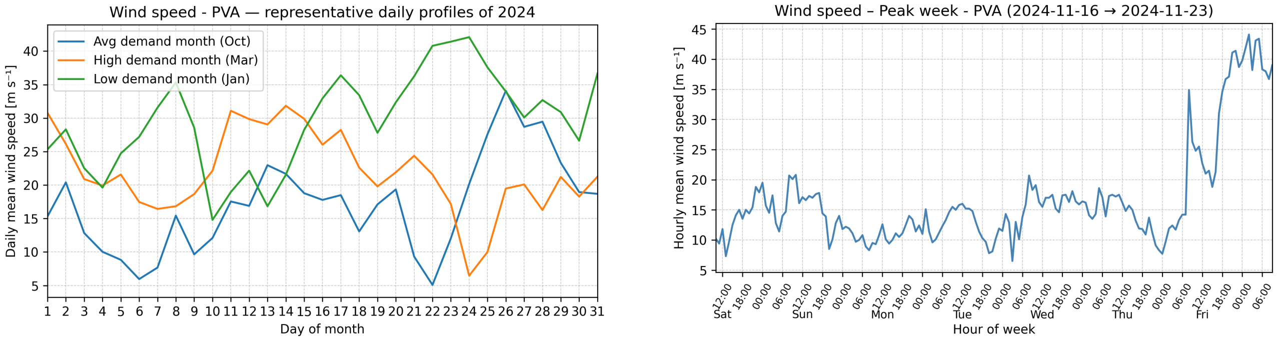
Figure 2: Gustavo Rojas Pinilla Airport ADZ: (left) daily averages for low-, average- and high-demand months; (right) hourly behaviour during the peak-demand week for solar irradiance, ambient temperature and wind speed.



(a) Irradiance - daily means (b) Irradiance - peak week



(c) Temperature - daily means (d) Temperature - peak week

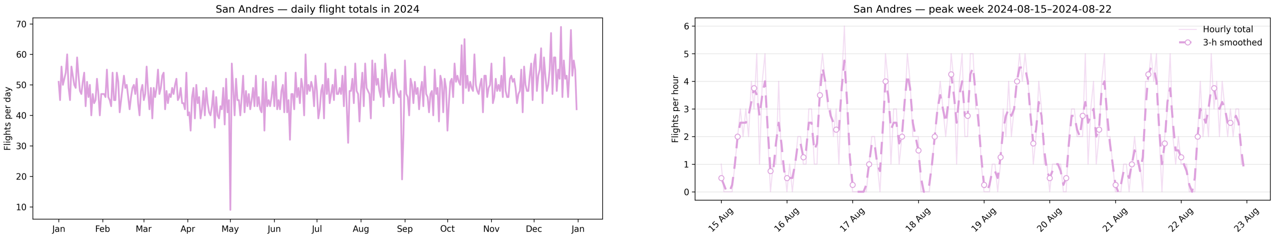


(e) Wind speed - daily means (f) Wind speed - peak week

Figure 3: El Embrujo Airport PVA: (left) daily averages for low-, average- and high-demand months; (right) hourly behaviour during the peak-demand week for solar irradiance, ambient temperature and wind speed.

4.2 Flight-movement logs

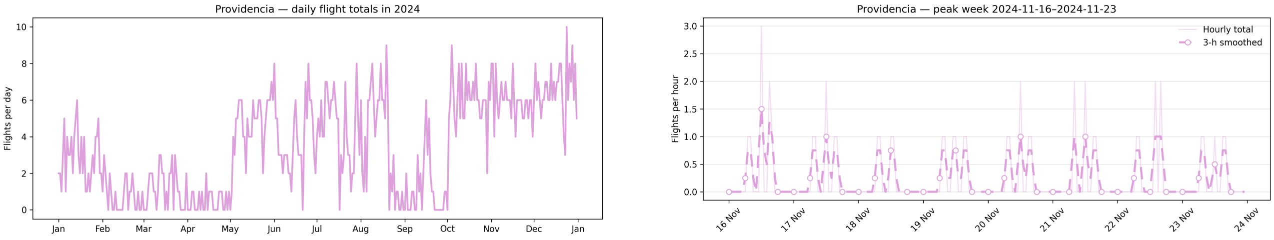
Monthly operation statistics were first downloaded from the Colombian Civil Aviation Authority (*Aerocivil*)[7] and disaggregated logs were requested by e-mail; the finest resolution available was one record per day, insufficient for the hourly synthesis defined in Section 3. Historical flight tracks were therefore retrieved from *Flightradar24*[8] via subscription API, listing every landing and take-off in 2024. A cross-check against Aerocivils daily totals revealed discrepancies below 4 % at both airports (attributed mainly to unscheduled charter flights). Such deviations were considered acceptable for load-profiling. Figure 4 plots the hourly movement counts together with the three-hour smoothing kernel $\boldsymbol{\kappa} = [0.5, 1.0, 0.5]$ used in Step 2 of the demand algorithm (subsection 3.3).


San Andres — daily flight totals in 2024

San Andres — peak week 2024-08-15–2024-08-22

(a) San Andrés - daily totals in 2024

(b) San Andrés - peak week (15-22 Aug 2024)


Providencia — daily flight totals in 2024

Providencia — peak week 2024-11-16–2024-11-23

(c) Providencia - daily totals in 2024

(d) Providencia - peak week (16-23 Nov 2024)

Figure 4: Hourly flight movements used as the activity driver in the demand-synthesis model. A dashed curve shows the 3-hour moving average $\hat{F}_{s,t}$.

4.3 Monthly electricity bills

Aerocivil supplied scanned monthly invoices for both airports. Each invoice contains the total energy delivered by the local utility, forming the $E_{s,m}$ inputs of Eq. (3.3). Table 6 lists the 2024 values. With these three data sets consolidated, the modelling workflow of Section 3 proceeds deterministically: the hourly demand $d_{s,t}$ is synthesised via Eqs. (1)-(4) and fed to the MILP optimisation in Section 3.

Table 6: Utility-metered electricity consumption in 2024. Percentages sum column-wise to 100 %.

	Gustavo Rojas Pinilla		El Embrujo	
Month	kWh	Share [%]	kWh	Share [%]
Jan	240 680	7.4	102	0.1
Feb	253 946	7.8	591	0.8
Mar	272 448	8.4	12 564	17.5
Apr	269 170	8.3	4 597	6.4
May	283 096	8.7	8 415	11.8
Jun	279 906	8.6	6 284	8.8
Jul	286 154	8.8	6 591	9.2
Aug	294 338	9.1	7 145	10.0
Sep	269 522	8.3	2 873	4.0
Oct	280 364	8.7	5 984	8.4
Nov	241 674	7.5	12 540	17.5
Dec	267 762	8.3	3 920	5.5
Total	3 239 060	100	71 606	100

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[7] `https://www.aerocivil.gov.co/`

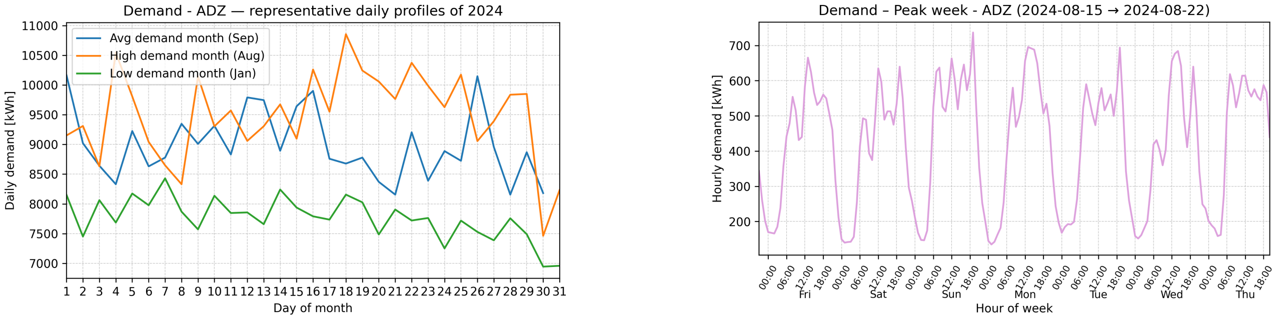
[8] `https://www.flightradar24.com/`

5 Results at Gustavo Rojas Pinilla and El Embrujo Airports

This section presents (i) validation of the synthesised hourly demand, (ii) dispatch behaviour under three reference configurations, (iii) a cost and battery-KPI comparison across all seven technology options, and (iv) the physical hardware required at each airport.

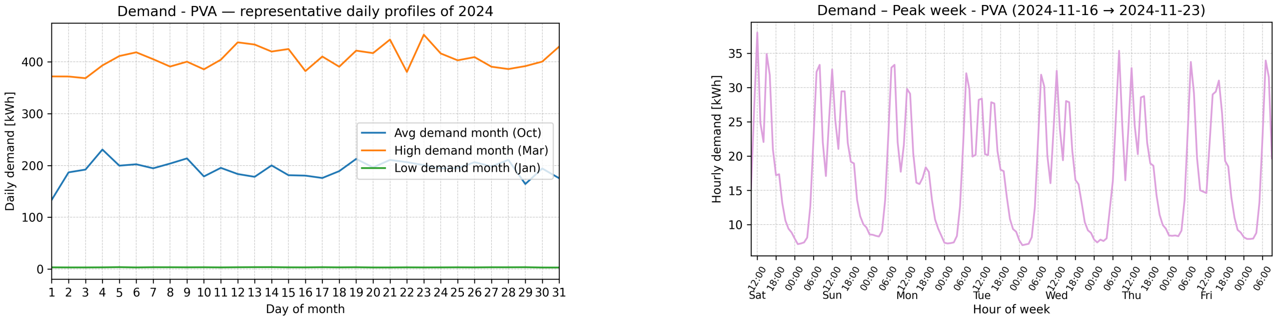
5.1 Demand-profile validation

Figure 5 compares the reconstructed loads with monthly utility bills. Panels (a) and (c) show *daily totals* for low-, average- and high-demand months-January, September and August at Gustavo Rojas Pinilla; January, October and March at El Embrujo-illustrating the seasonal spread imposed by the synthesis method (Section 3). Images (b) and (d) zoom into each airports *peak-demand week*, revealing the diurnal peaks that drive system sizing.



(a) **Gustavo Rojas Pinilla** - daily demand in Jan (low), Sep (avg) and Aug (high)

(b) **Gustavo Rojas Pinilla** - hourly demand during the peak week (15-22 Aug 2024)



(c) **El Embrujo** - daily demand in Jan (low), Oct (avg) and Mar (high)

(d) **El Embrujo** - hourly demand during the peak week (16-23 Nov 2024)

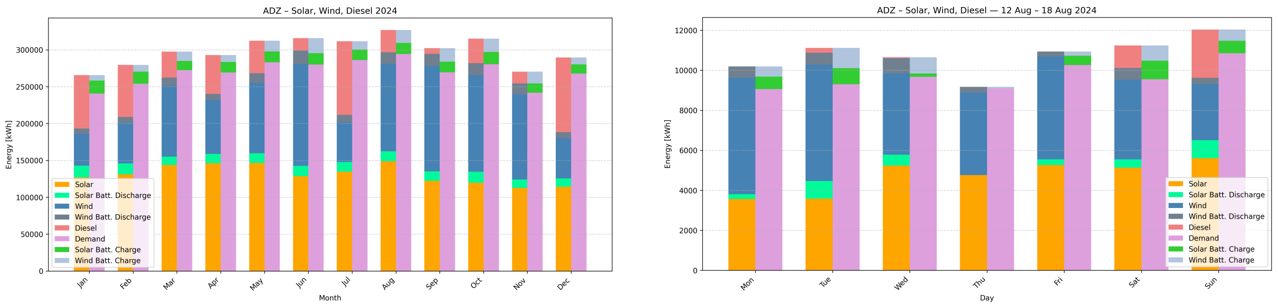
Figure 5: Electricity demand profiles for Providencia and San Andrés airports. Left column: **daily totals for three characteristic months** (note that the reference months differ between sites). Right column: **hourly demand during each sites peak-load week**.

5.2 Reference technology scenarios

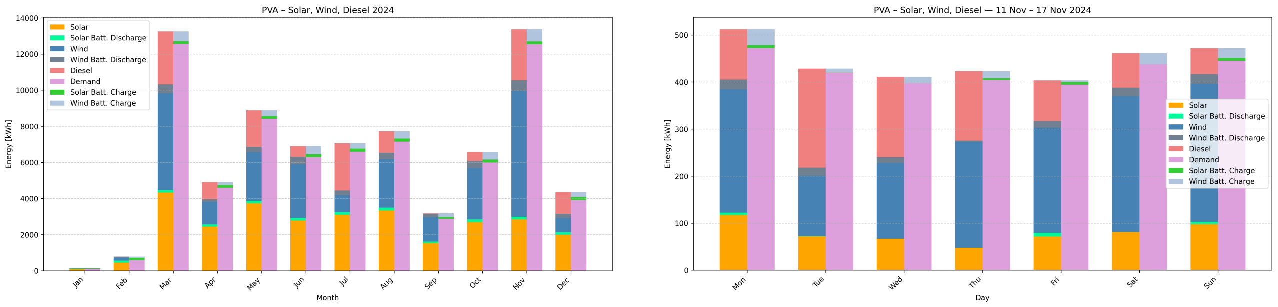
Four configurations are analysed in the main text:

1. **Full hybrid** (PV+W+D): solar, wind and diesel, each renewable source coupled to a battery bank.
2. **Renewables-combined** (PV+W): solar and wind with batteries; diesel disabled.
3. **Renewables-only** (PV) and (W): solar only and wind only with batteries; diesel disabled.
4. **Diesel Renewables** (D+PV) and (D+W): diesel generator combined with solar or Wind.

The remaining combinations (solar-only, wind-only, Diesel-Solar and Diesel-Wind) are reported in the section (iii) Supporting Work.



(a) Year 2024 HRES configuration - Gustavo Rojas Pinilla (b) Peak week (12-18 Aug) - Gustavo Rojas Pinilla



(c) Year 2024 HRES configuration - El Embrujo (d) Peak week (11-17 Nov) - El Embrujo

Figure 6: Full-hybrid configuration (solar, wind, diesel). Left-hand panels: monthly energy balance in 2024. Right-hand panels: daily balance during each airports peak-demand weeks 12-18 Aug. and 11-17 Nov. 2024. Within each time step, left bar is production and right bar usage

5.3 Full hybrid Energy configuration

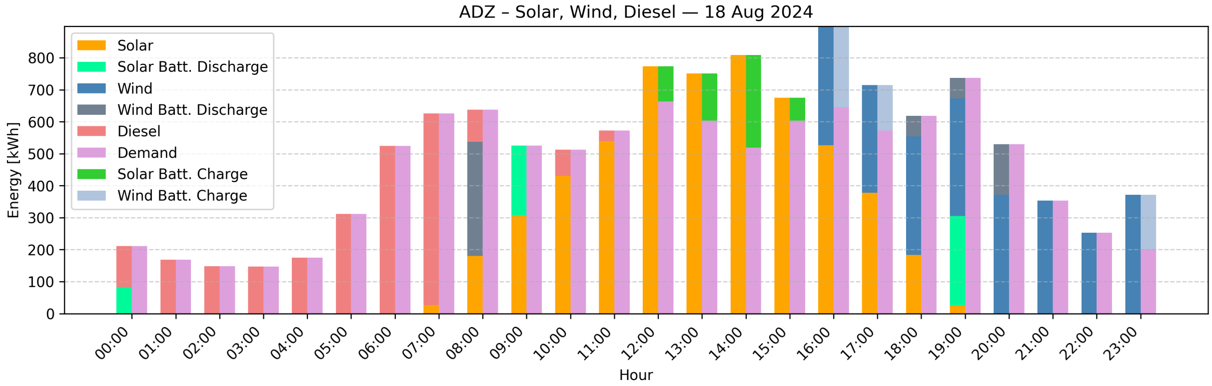
Figure 6 presents the results of the energy system simulation for the year 2024 at Gustavo Rojas Pinilla and El Embrujo airports, located in San Andrés and Providencia, respectively.

In Figure 6 (a) and (c) on the left-hand side, the performance of a hybrid energy system configuration, comprising solar, wind, and diesel generation, along with battery storage is illustrated. These plots show the contributions of each energy source and the dynamics of battery charging and discharging, ensuring that electricity demand at the respective airports is met throughout the year.

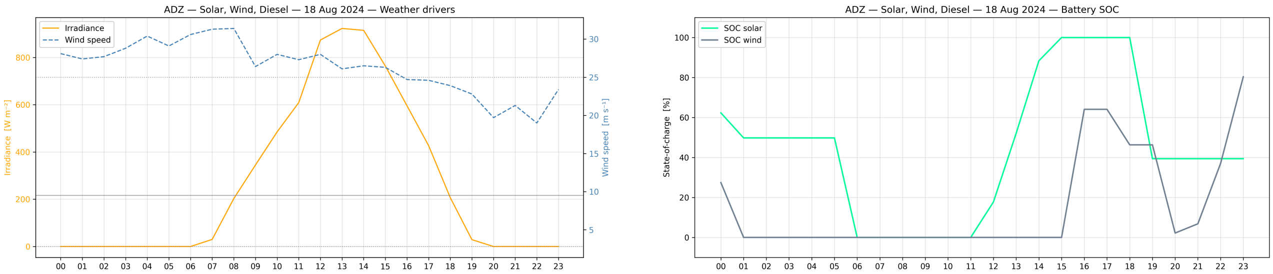
On the right-hand side, Figure 6 (b) provides a more detailed view of system behaviour during a representative peak-demand week (12 to 18 August 2024) at Gustavo Rojas Pinilla Airport. This temporal zoom allows for a closer inspection of operational patterns. For instance, diesel generation was required only on 3 days of the week; Tuesday, Saturday and Sunday, with renewable sources being sufficient on the remaining days. In contrast, Figure 6 (d) highlights the peak-demand week for El Embrujo Airport, occurring in November. All week, diesel generation was necessary. Nevertheless, reliance on solar and wind energy in both cases reflects favourable weather conditions that enabled high integration of clean, renewable energy sources.

The figure 7 illustrates how the hybrid system dynamically compensates for variability in renewable generation through battery storage and auxiliary diesel support, ensuring a continuous and reliable energy supply.

Figure 7 (a) presents a detailed analysis of the hybrid energy systems performance at Gustavo Rojas Pinilla Airport (San Andrés) for the electricity demand profile, specifically for the day 18 August 2024, the behaviour of the weather drivers (solar irradiance and wind speed) it is illustrated in Figure 7 (b), and Figure 7 (c) displays the corresponding state of charge (SOC) of the battery system over the same period. The data reveal that wind speeds exceeded 28 m/s from approximately 00:00 to 15:00, surpassing the operational safety threshold for the wind turbines. As a result, wind energy production ceased during this interval. To maintain power supply, the system relied on diesel generation and stored solar energy. From around 09:00 until 15:00, solar irradiance levels were sufficient to meet the demand predominantly through solar power. During the hours of peak irradiance, the system not only supplied the load but also recharged the battery, as evidenced by the increasing SOC curve in Figure 7 (c).


ADZ – Solar, Wind, Diesel — 18 Aug 2024

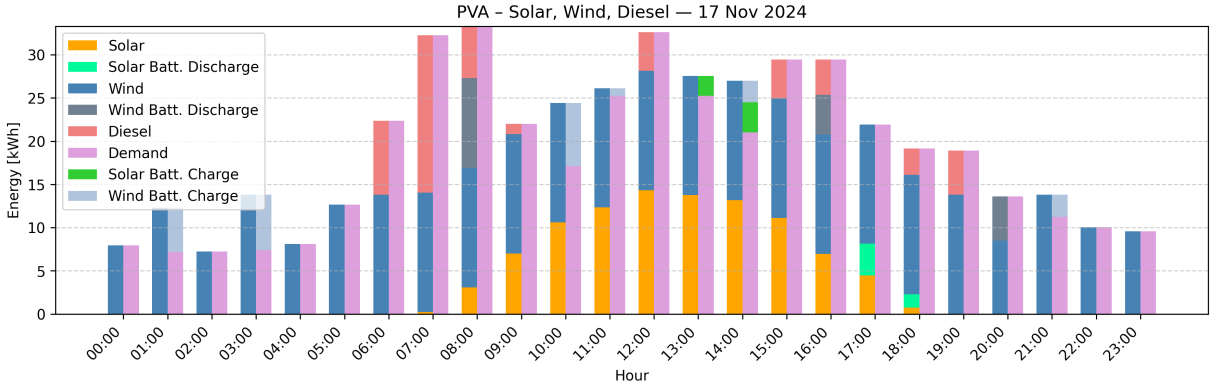
(a) Hourly balance - Gustavo Rojas Pinilla


ADZ — Solar, Wind, Diesel — 18 Aug 2024 — Weather drivers
ADZ — Solar, Wind, Diesel — 18 Aug 2024 — Battery SOC

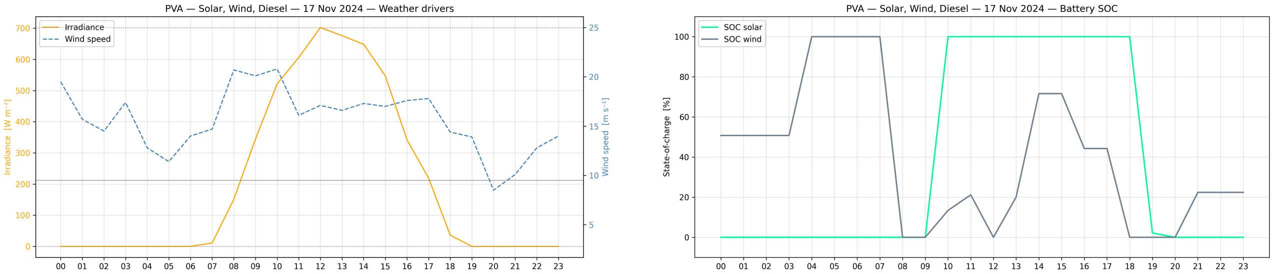
(b) Weather drivers

(c) Battery state of charge

Figure 7: Peak-demand day (18 Aug 2024) at Gustavo Rojas Pinilla Airport, full-hybrid case.


PVA – Solar, Wind, Diesel — 17 Nov 2024

(a) Hourly balance - El Embrujo


PVA — Solar, Wind, Diesel — 17 Nov 2024 — Weather drivers
PVA — Solar, Wind, Diesel — 17 Nov 2024 — Battery SOC

(b) Weather drivers

(c) Battery state of charge

Figure 8: Peak-demand day (17 Nov 2024) at El Embrujo, full-hybrid case.

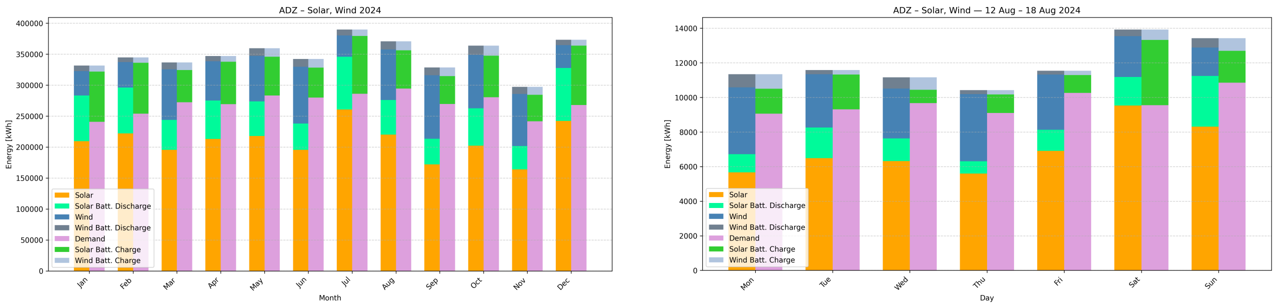
Figure 8 presents the performance of the hybrid energy system at El Embrujo Airport (Providencia) during a representative peak-demand day, specifically 17 November 2024. The figure (a) illustrates the energy supply configuration using solar, wind, and diesel sources in relation to the airport's electricity demand.

Figure 8 (b) shows the corresponding weather drivers solar irradiance and wind speed. At the same time, Figure 8 (c) details the state of charge (SOC) of the battery systems associated with solar and wind energy.

The figure 8 enables a detailed examination of the models operational performance in balancing supply and demand. There are periods when the system needs to use diesel generation. Despite this, during the early morning hours (00:00 to 05:00), the system relies only on wind energy.

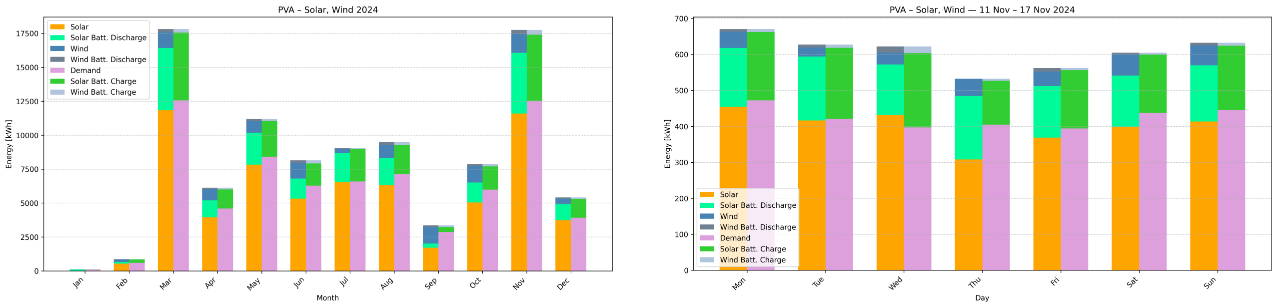
This operational pattern highlights the hybrid system's capacity for temporal energy shifting and prioritisation among resources, maximising the use of renewables where possible and leveraging diesel only when necessary. It highlights the importance of energy storage in enhancing the resilience and sustainability of energy supply at remote island airports.

5.4 Renewable Energy Configuration - Solar & Wind



(a) Year 2024 Solar & Wind - Gustavo Rojas Pinilla

(b) Peak week (12-18 Aug) - Gustavo Rojas Pinilla



(c) Year 2024 Solar & Wind - El Embrujo

(d) Peak week (11-17 Nov) - El Embrujo

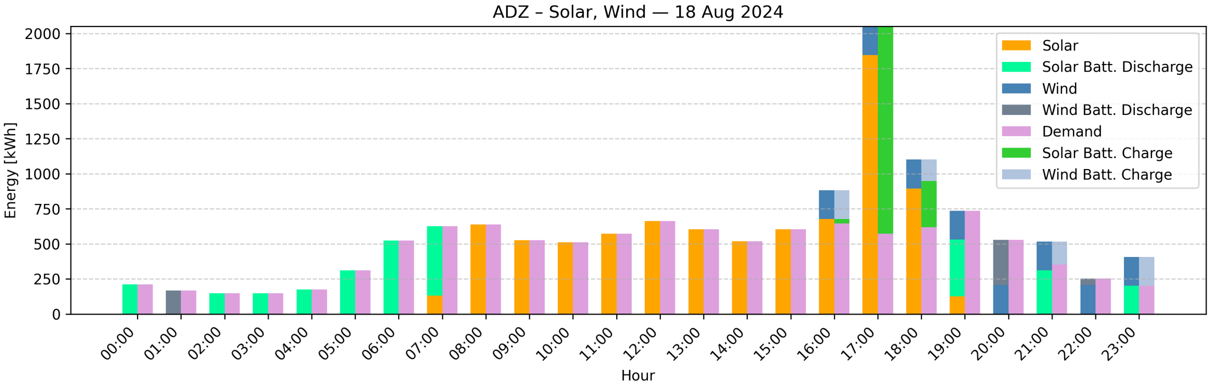
Figure 9: Renewables-combined configuration (solar + wind, no diesel).

Figure 9 illustrates the performance of a Renewables-combined hybrid energy system-comprising solar and wind energy sources supported by battery storage for the airports at San Andrés (Gustavo Rojas Pinilla) and Providencia (El Embrujo) during the year 2024. The configuration excludes any diesel generation, showcasing the potential of clean energy to meet demand under favorable conditions.

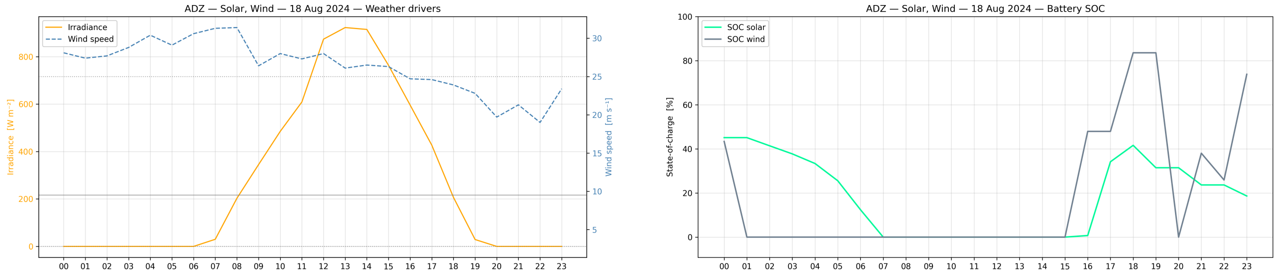
Figure 9 (a) presents the monthly energy combining Solar and Wind for Gustavo Rojas Pinilla Airport. Solar energy contributes most consistently across all months, with support from wind energy. The battery systems (both solar and wind) display regular charging and discharging activity, indicating active storage management to balance fluctuations in renewable generation. Figure 9 (b) focuses on the peak week (12-18 August) at Gustavo Rojas Pinilla Airport. The daily energy composition reveals the importance of battery discharge. Solar energy remains the main contributor, while wind and stored energy ensure the continuity of supply.

Figure 9 (c) presents the monthly energy using Solar and Wind for El Embrujo Airport. It can be observed that, from February to December, battery storage occurs primarily after the energy demand has been met, indicating surplus generation. Figure 9 (d) illustrates the peak demand week (11-17 November) at El Embrujo. The contribution of wind energy both directly and via battery discharge is minimal during this week. Solar energy is mainly utilized, and the balance between direct generation and battery solely is on renewable energy sources, provided that battery storage is adequately sized backup.

Overall, these figures highlight the technical feasibility of operating remote island airports using only renewable energy sources, provided that battery storage is adequately dimensioned to compensate for temporal mismatches between generation and demand.



(a) Hourly balance - Gustavo Rojas Pinilla



(b) Weather drivers

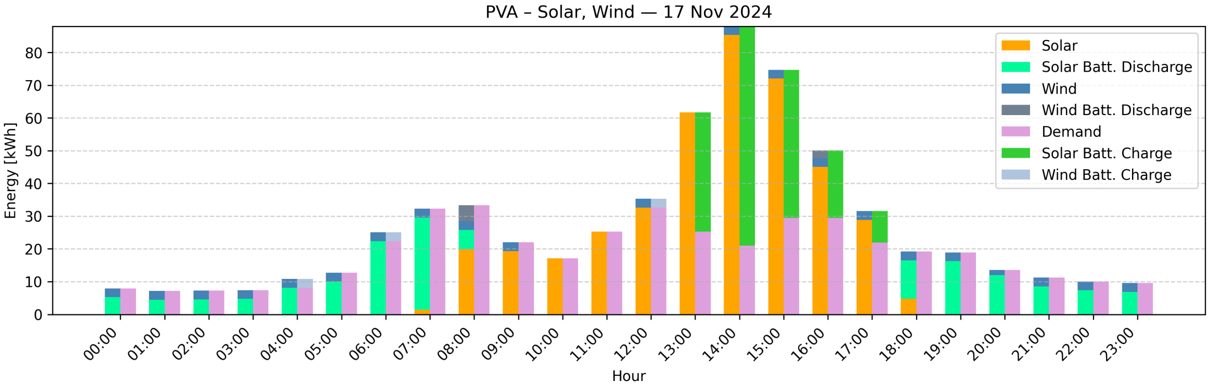
(c) Battery state of charge

Figure 10: Peak-demand day (15 Aug 2024) at Gustavo Rojas Pinilla, full-renewable case.

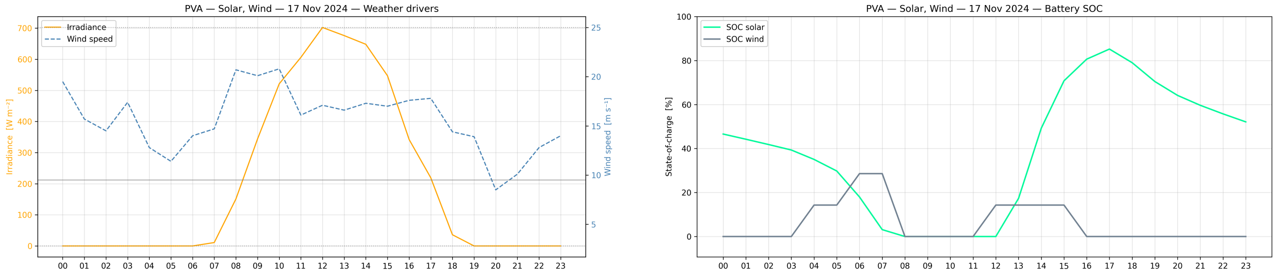
In figure 10 illustrates the operation of a full renewable hybrid energy system-based on solar and wind power with battery storage at Gustavo Rojas Pinilla Airport (San Andrés) during a peak demand day, specifically 18 August 2024. The figure is divided into three subplots: (a) hourly energy balance, (b) weather drivers, and (c) battery state of charge (SOC).

Figure 10 (a) shows the hourly energy balance. During early morning hours (00:00-06:00), the system relies almost entirely on battery discharges, mainly on solar. That day, demand was covered by solar energy generation from 08:00 to 15:00. Wind energy could not be used before 16:00, when the wind speed fell below 25 m/s, indicating the model considers the wind cut-out speed. Figure 10 (b) presents the weather drivers, including solar irradiance (left axis) and wind speed (right axis). Solar irradiance begins to rise around 06:00, reaches its peak between 12:00 and 14:00, and declines to zero after 19:00. The relatively high irradiance ensures strong solar generation during mid-day.

Figure 10 (c) illustrates the state of charge (SOC) of the solar and wind battery systems. At the beginning of the day, both batteries exhibit moderate SOC levels, which gradually decline during the early morning hours due to energy discharge in the absence of renewable generation. As solar irradiance increases after 08:00, the SOC of the solar battery begins to recover, until 16:00 when the demand has been covered and it is enough irradiance to store solar energy. In contrast, the wind battery exhibits less pronounced charging activity. This is attributed to wind speeds exceeding the operational threshold of the wind turbines, which temporarily stops wind energy production and limits charging capability. Nevertheless, the stored wind energy plays an important role in meeting demand during 01:00 and 20:00. Overall, Figure 10 demonstrates the feasibility of operating the airport entirely on renewable energy for a peak-demand day, leveraging battery storage to smooth out the intermittency of solar and wind generation. The strategic timing of charge and discharge cycles allows the system to remain diesel free while reliably meeting hourly electricity demand.



(a) Hourly balance - El Embrujo



(b) Weather drivers

(c) Battery state of charge

Figure 11: Peak-demand day (17 Nov 2024) at El Embrujo, full-renewable case.

Figure 11 provides a comprehensive view of the operation of the full renewable energy system at El Embrujo Airport on 17 November 2024, highlighting the interplay between solar and wind resources and battery storage in meeting hourly electricity demand under real case scenario.

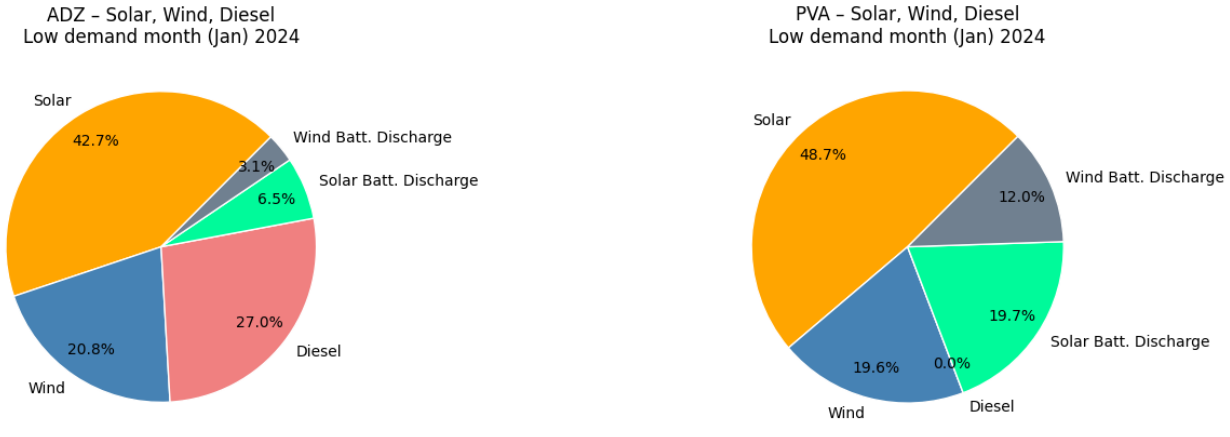
The energy demand exhibits a relatively stable profile throughout the day, while solar irradiance start to increases from 07:00 with peaks between 12:00 and 15:00. This period of high irradiance enables the solar battery to recharge effectively. During the early hours (00:00 to 06:00), when solar generation is unavailable, solar batteries and wind energy become the main source of supply. It is interesting that the SOC for solar is more than 40% at the end of the day and probably used the next day to compensate for the energy demand and generation, as shown on this day.

The system demonstrates effective temporal energy shifting-charging batteries during periods of surplus generation and discharging during deficits. This dynamic coordination between generation and storage ensures continuous power supply without the need for diesel backup. Overall, Figure 11 showcases the feasibility and reliability of operating the airport in Providencia entirely on renewable energy, emphasizing the critical role of storage in balancing intermittent resources with hourly load requirements.

5.5 Percentage Energy supply Demand HRES

it is interested to Analyse the Figures 12, 13,14, and 15 which illustrate the percentage contribution of different energy sources, like; solar, wind and diesel including battery usage for wind and solar during low, average, high demand months and during all year (2024). The left-hand side (LH) of each figure presents the energy mix for Gustavo Rojas Pinilla Airport in San Andrés, while the right-hand side (RH) shows the corresponding data for El Embrujo Airport in Providencia.

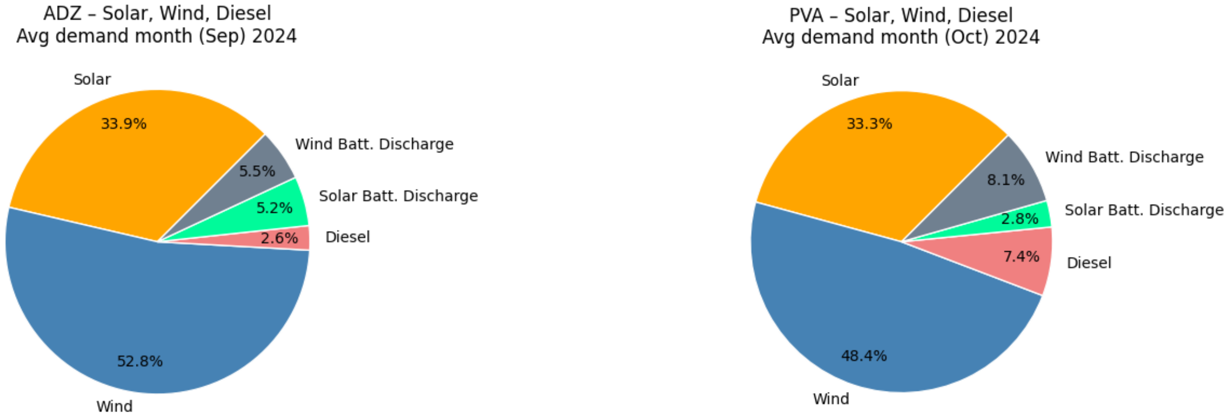
As shown in Figure 12 during the low-demand month of January 2024, El Embrujo Airport (Providencia) operated entirely on renewable energy sources, without reliance on diesel. The energy demand was fully met by a combination of solar and wind generation, with solar accounting for nearly 70% of the total supply. In contrast, at Gustavo Rojas Pinilla Airport (San Andrés), diesel contributed approximately 27% of the energy mix, indicating that around 73% of the demand was covered by solar, wind, and battery storage. Although the two airports differ in both demand levels and installed renewable capacity, these results highlight the potential of hybrid renewable energy systems (HRES) to deliver strong performance across diverse island contexts.



(a) Low demand (Jan) - **Gustavo Rojas Pinilla**

(b) Low demand (Jan) - **El Embrujo**

Figure 12: Energy-supply composition under the *Solar + Wind + Diesel* hybrid for low demand month.



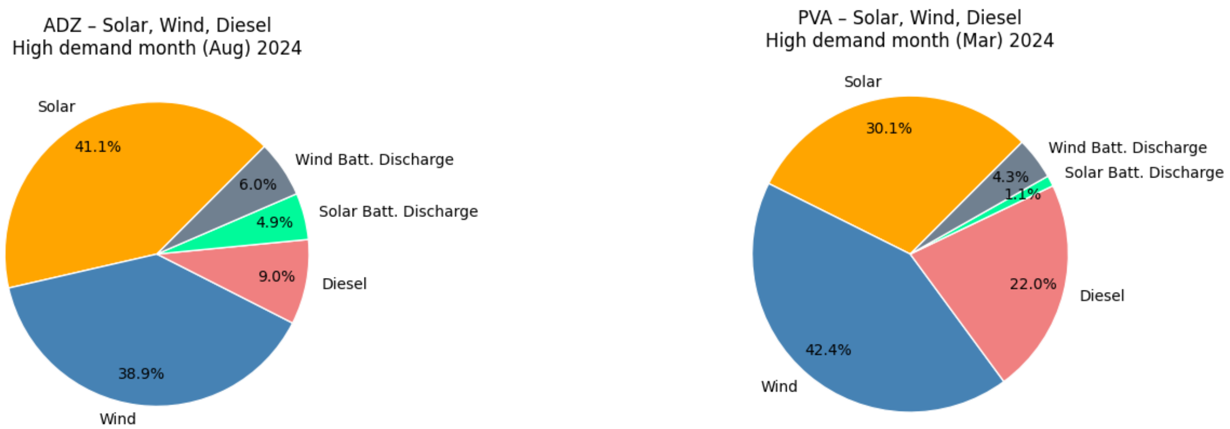
(a) Average demand (Sep) - **Gustavo Rojas Pinilla**

(b) Average demand (Oct) - **El Embrujo**

Figure 13: Energy-supply composition under the *Solar + Wind + Diesel* hybrid for average demand month.

As shown in Figure 13, more than 97% of the total energy demand was supplied by solar and wind sources during September at Gustavo Rojas Pinilla Airport (San Andrés) and 92% as well from renewable energy during October at El Embrujo Airport (Providencia). This indicates that the prevailing weather conditions during these months were more than sufficient to support the energy requirements of both airports through renewable generation alone. During the high-demand month of August 2024, Gustavo Rojas Pinilla Airport (San Andrés) met over 90% of its energy needs through wind and solar sources. In contrast, El Embrujo Airport (Providencia) reached its peak demand in March 2024, during which more than 22% of the energy supply had to be covered by diesel generation. These results, as illustrated in Figure 14, highlight the importance of complementing renewable energy systems with conventional sources like diesel to ensure reliability and robustness. This is particularly crucial in airport environments, where 24/7 operations demand uninterrupted energy to support critical infrastructure and services.

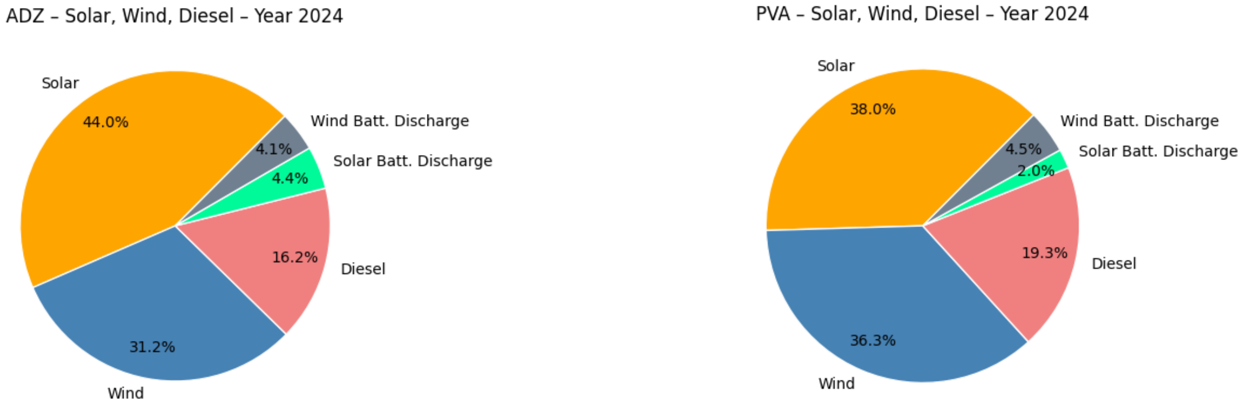
The annual energy distribution for 2024 indicates that Gustavo Rojas Pinilla Airport (San Andrés) obtained around 84% of its electricity from solar and wind sources, El Embrujo Airport (Providencia) reached 80% of its energy from renewable sources. As shown in Figure 15, wind and solar energy played a particularly dominant



(a) High month - **Gustavo Rojas Pinilla**

(b) High month - **El Embrujo**

Figure 14: Energy-supply composition under the *Solar + Wind + Diesel* hybrid for high demand month.



(a) Year 2024 - **Gustavo Rojas Pinilla**

(b) Year 2024- **El Embrujo**

Figure 15: Energy-supply composition under the *Solar + Wind + Diesel* hybrid for the whole year 2024.

role in both airports. This trend aligns with observed weather patterns, which reveal consistently strong wind speeds and high irradiance on the islands, positioning Gustavo Rojas Pinilla and El Embrujo Airports as a promising site for wind and solar energy deployment.

Both airports demonstrate favorable environmental conditions for implementing a hybrid renewable energy system combining solar, wind, and diesel backup. Although diesel remains part of the system to ensure reliability, the simulation results, based on real operational profiles and weather data, show a significant reduction in reliance on diesel generators. This represents a significant shift from the current fossil-fuel-dependent reality, highlighting the potential for a cleaner, more resilient energy future for these island airports.

5.6 Economic results and KPIs

Cost structure (Table 7). The *Gustavo Rojas Pinilla Airport* exhibits a strongly convex cost profile across the six energy systems. Moving from the diesel-only baseline to the *Solar, Wind, Diesel* hybrid reduces the present-worth system cost from (US$ 1.21 M) to (US$ 460 k), a 62 % saving even after financing PV (US$ 112 k), wind (US$ 67 k) and paired battery banks for both solar and wind around (US$ 62 k). The saving is driven primarily by an 82 % reduction in diesel OPEX (from US$ 1.20 M to US$ 214 k) and a large drop in the internal CO_2 penalty (US$ 16.2 k to US$ 2.9 k). Diesel-free operation (*Solar, Wind*) remains technically and financially more feasible than diesel use alone.

Pairing diesel with either solar or wind cuts total cost by roughly half relative to the diesel-only baseline, but these options remain more expensive than the full hybrid and deliver reductions in fossil-fuel use and CO_2. The economic pattern on San Andrés therefore points consistently to a tri-hybrid arrangement as the most cost-effective pathway to deep diesel displacement under a firm reliability constraint.

At the *El Embrujo Airport*, costs are two orders of magnitude smaller owing to the much lower electricity demand. The *Solar, Wind, Diesel* configuration again offers the lowest low-carbon cost: its present-worth cost of (US$ 11.7 k) sits well below the diesel-only case (US$ 26.9 k), yielding a 56 % cost reduction and cutting diesel OPEX and CO_2 penalty by around 79 %. A fully renewable energy configuration is technically feasible, and solar is more cost-effective than diesel-based use; however, the wind energy scenario is the most costly, 15.6 times more expensive than the hybrid configuration.

Table 7: Cost summary for every technology combination modelled. All values are present-worth U.S. dollars. – indicates that the particular asset is not installed in the scenario considered.

Scenario		**Total**	Solar CAPEX	Wind CAPEX	Solar Batt. CAPEX	Wind Batt. CAPEX	Diesel OPEX	CO_2 Penalty
Gustavo Rojas Pinilla Airport								
San Andrés	Solar, Wind, Diesel	458,349	112,049.10	66,925.16	37,710.88	24,022.72	214,739.72	2,901.89
	Solar	1,077,704	543,289.21	–	534,414.90	–	–	–
	Wind	7,155,003	–	1,864,109.10	–	5,290,894.28	–	–
	Solar, Wind	880,178	548,229.19	37,012.00	268,863.25	26,073.31	–	–
	Solar, Diesel	590,660	236,109.26	–	262,295.61	–	91,024.92	1,230.07
	Wind, Diesel	604,534	–	106,331.67	–	34,385.94	457,632.61	6,184.22
	Diesel	1,214,647	–	–	–	–	1,198,452.20	16,195.30
El Embrujo Airport								
Providencia	Solar, Wind, Diesel	11,686	2,567.94	2,485.28	351.85	703.51	5,502.67	74.36
	Solar	34,129	20,980.86	–	13,148.15	–	–	–
	Wind	170,088	–	15,617.03	–	154,471.44	–	–
	Solar, Wind	31,011	16,621.39	481.83	12,769.79	1,138.20	–	–
	Solar, Diesel	16,487	5,288.92	–	4,454.09	–	6,653.84	89.92
	Wind, Diesel	14,259	–	3,618.71	–	920.63	9,589.91	129.59
	Diesel	26,852	–	–	–	–	26,494.22	358.03

Battery utilisation and energy throughput (Table 8). Battery performance indicators show that all storage units operate well within typical manufacturer guidelines, both in terms of cycle count and average state of charge. On San Andrés, the PV-coupled battery in the *Solar, Wind, Diesel* case undergoes about 285 equivalent full cycles per year at an average SOC of 31 %. The wind-coupled unit cycles more frequently 417 cycles per year at a moderate average SOC of 37 %. The corresponding annual charge and discharge energies for both PV and wind coupled batteries indicate effective utilisation of the installed storage without deep cycling, suggesting long asset lifetimes. Even in the *Solar, Diesel* scenario, the PV battery cycles about 320 times per year, remaining well below one full cycle per day.

At El Embrujo the patterns are similar; nevertheless are scaled to the smaller load. for the scenario of Solar, wind and diesel the PV-coupled units accumulate 290 cycles per year at SOC 36 % , while wind-coupled batteries reach up to 331 cycles per year at SOC 32 %. Throughputs of several tens of MWh per year confirm that batteries are primarily providing firming and peak support rather than bulk energy shifting. Overall, the utilisation metrics show that modestly sized batteries can effectively stabilise variable generation without experiencing cycle intensities that would materially shorten their life.

Installed capacities and land take (Table 9). San Andrés requires a genuinely utility-scale intervention in the diesel-free case. The *Solar, Wind* solution installs around (5.5 MW of PV) (12,000 modules over 48,000 m^2), three mid-sized wind turbines with (206 kW), and roughly (4.6 MWh of batteries) across both renewable couplings. On the other hand, the *Solar, Wind, Diesel* hybrid relies on only (1.1 MW of PV), (372 kW of wind) and less than (1 MWh of batteries), the distributed storage needed is (59 PV-bank units and 38 wind-bank units), while still satisfying firm supply, allowing an energy system with a diesel backup will reduce both renewable capacities and land space.

Table 8: Battery key performance indicators. Cycle counts represent equivalent full charge–discharge events, and $\overline{\mathrm{SOC}}$ denotes the time-average state of charge. Reported values include the installed capacity of each battery bank and the annual charged and discharged energy. Dashes indicate that the respective battery is not present in the scenario.

Scenario		**PV-coupled battery**					**Wind-coupled battery**				
Site	Config	Cycles	$\overline{\mathrm{SOC}}$[%]	Cap. [kWh]	E_{ch} [kWh]	E_{dis} [kWh]	Cycles	$\overline{\mathrm{SOC}}$[%]	Cap. [kWh]	E_{ch} [kWh]	E_{dis} [kWh]
Gustavo Rojas Pinilla Airport											
San Andrés	Solar, Wind, Diesel	284.7	31	589.23	176,328.08	159,136.09	416.6	37	375.35	164,381.06	148,353.90
	Solar	164.7	48	8,350.23	1,445,966.21	1,304,984.51	–	–	–	–	–
	Wind	–	–	–	–	–	16.4	16	82,670.22	1,422,378.66	1,283,696.74
	Solar, Wind	181.2	16	4,200.99	800,448.66	722,404.91	337.7	20	407.40	144,648.22	130,545.02
	Solar, Diesel	322.3	46	4,098.37	1,388,434.75	1,253,062.36	–	–	–	–	–
	Wind, Diesel	–	–	–	–	–	328.9	47	537.28	185,752.50	167,641.63
El Embrujo Airport											
Providencia	Solar, Wind, Diesel	293.4	36	5.50	1,695.65	1,530.33	330.8	32	10.99	3,822.92	3,450.19
	Solar	141.0	50	205.44	30,453.22	27,484.03	–	–	–	–	–
	Wind	–	–	–	–	–	11.9	49	2,413.62	30,160.91	27,220.22
	Solar, Wind	113.2	15	199.53	23,749.87	21,434.26	97.9	9	17.78	1,830.40	1,651.93
	Solar, Diesel	258.6	40	69.60	18,917.43	17,072.98	–	–	–	–	–
	Wind, Diesel	–	–	–	–	–	315.1	47	14.38	4,765.50	4,300.86

El Embrujo, by contrast, remains a low-footprint site. Even the diesel-free *Solar, Wind* portfolio requires only (168 kW of PV) and a single small turbine, with a small area of land occupation. Solar, Diesel or Wind diesel energy configuration requires even less surface area.

Table 9: Installed generation and storage capacities, and associated physical footprints. PV areas correspond to module coverage, and wind areas represent turbine influence footprints. Battery values correspond to the installed usable capacity and the number of containerised units.

Scenario		**Photovoltaics**			**Wind**			**Batt. PV-bank**		**Batt. Wind-bank**	
Site	Config	kW	Modules	Area [m^2]	kW	Turb. [#]	Area [m^2]	kWh	Units	kWh	Units
Gustavo Rojas Pinilla Airport											
San Andrés	Solar, Wind, Diesel	1,131.81	2,461	9,844	371.81	4	20,000	589.23	59	375.35	38
	Solar	5,487.77	11,930	47,720	–	–	–	8,350.23	836	–	–
	Wind	–	–	–	10,356.16	104	520,000	–	–	82,670.22	8,268
	Solar, Wind	5,537.67	12,039	48,156	205.62	3	15,000	4,200.99	421	407.40	41
	Solar, Diesel	2,384.94	5,185	20,740	–	–	–	4,098.37	410	–	–
	Wind, Diesel	–	–	–	590.73	6	30,000	–	–	537.28	54
El Embrujo Airport											
Providencia	Solar, Wind, Diesel	25.94	57	228	13.81	1	5,000	5.50	1	10.99	2
	Solar	211.93	461	1,844	–	–	–	205.44	21	–	–
	Wind	–	–	–	86.76	1	5,000	–	–	2,413.62	242
	Solar, Wind	167.89	365	1,460	2.68	1	5,000	199.53	20	17.78	2
	Solar, Diesel	53.42	117	468	–	–	–	69.60	7	–	–
	Wind, Diesel	–	–	–	20.10	1	5,000	–	–	14.38	2

Resource utilisation (Table 10). The explicit accounting of resource use shows that the economics of each portfolio are closely linked to how effectively solar and wind potential are converted into useful electricity. In the case for Gustavo Rojas Pinilla Airport, the *Solar, Wind, Diesel* configuration uses about 97 % of the available solar resource and 70 % of the wind potential, leaving only 62 MWh of solar and 545 MWh of wind unutilised over the year. Purely renewable energy configuration, in contrast, leave large portions of their resource untapped: the *Solar* case converts only 55 % of the available solar energy, while the *Wind* case makes use of less than 10 % of the wind potential. The diesel-free *Solar, Wind* portfolio exhibits a more balanced pattern, converting around 37 % of the solar energy and over 95 % of the wind resource. When a single renewable is paired with diesel, resource utilisation shifts toward the dominant generator: in *Solar, Diesel* almost all solar energy is taken up by the system, and *Wind, Diesel* converts about 76 % of the wind potential.

At El Embrujo, the hybrid configuration again achieves higher utilisation than a single-renewable energy configuration. The *Solar, Wind, Diesel* system converts roughly 73 % of the solar resource and 49 % of the wind potential. The *Solar* system uses only about 30 % of its available solar energy, and the *Wind* configuration uses about 26 % of wind potential. In Solar-Diesel configuration, 85 % solar energy is taken up by the system, whereas Wind, Diesel use about 54 % of the wind potential

Across both airports, the share of potential energy that is actually converted, together with the associated infrastructure requirements, explains why hybrid solutions tend to perform best: they balance cost, resource efficiency and land use while maintaining a firm supply without oversized equipment or large volumes of unused generation.

Table 10: Solar, wind, and diesel resource utilisation in 2024. Reported values include total potential energy, the fraction used by the system, and unused potential. Dashes indicate that the respective resource is not available in the scenario.

Scenario		**Solar resource [kWh]**			**Wind resource [kWh]**			**Diesel [kWh]**
Site	Config	Potential	Used	Unused	Potential	Used	Unused	Used
Gustavo Rojas Pinilla Airport								
San Andrés	Solar, Wind, Diesel	1,813,350.96	1,751,814.28	61,536.68	1,825,494.25	1,280,796.37	544,697.88	580,280.5
	Solar	8,792,342.02	4,825,007.92	3,966,334.10	–	–	–	–
	Wind	–	–	–	50,846,655.21	4,800,120.57	46,046,534.64	–
	Solar, Wind	8,872,288.34	3,314,871.74	5,557,416.60	1,009,563.49	961,432.09	48,131.40	–
	Solar, Diesel	3,821,083.38	3,821,083.38	0	–	–	–	246,013.3
	Wind, Diesel	–	–	–	2,900,371.83	2,206,078.47	694,293.36	1,236,845.2
	Diesel	–	–	–	–	–	–	3,239,060.0
El Embrujo Airport								
Providencia	Solar, Wind, Diesel	42,212.73	30,979.98	11,232.76	64,507.83	31,810.57	32,697.26	14,872.1
	Solar	344,891.03	105,028.41	239,862.62	–	–	–	–
	Wind	–	–	–	405,355.36	104,707.59	300,647.77	–
	Solar, Wind	273,228.54	88,137.15	185,091.40	12,506.40	11,543.21	963.19	–
	Solar, Diesel	86,941.14	74,384.53	12,556.61	–	–	–	17,983.4
	Wind, Diesel	–	–	–	93,927.18	50,917.46	43,009.72	25,918.7
	Diesel	–	–	–	–	–	–	71,606.0

Taken together, the economic outcomes, storage performance indicators and resource-utilisation patterns consistently point to the same conclusion: A hybrid energy system configuration that retains a modest diesel unit alongside solar, wind and limited storage achieves the most effective balance between system cost, reliability and spatial footprint. These configurations make efficient use of the available renewable resources, avoid the need for oversized generation and storage, and operate batteries in conditions conducive to long service life. Fully renewable alternatives remain technically feasible, but they require substantially larger capacities and leave significant portions of the available resource unused when firm supply must be guaranteed. In the context of small island grids with constrained land and high fuel import costs, the hybrid solar-wind-diesel architecture therefore emerges as the most robust and cost-efficient pathway for delivering reliable, low-carbon power.

5.7 Clarification of multiple solutions and Battery Behaviour

This section explains why the optimal solution found by the model may include choices that at first glance seem unusual, for example, times when it is possible to generate more renewable energy but neither does so nor is it stored in the battery. It begins by clarifying what optimal means in the context of the model, introduces the idea of *optimality degeneracy* (that different programs of energy dispatched cost exactly the same), and explains the role of the charge-discharge exclusivity constraint, provides quantitative evidence using batteries KPIs also reveal side effects and conclude with ways to make the solver choose more intuitive solutions.

5.7.1 What the Objective Function Really Counts

The optimiser minimises one number: the yearly monetary cost. That number is the sum of

- investment in solar, wind and battery capacity (CAPEX),
- diesel fuel purchased over the year, and
- monetised diesel emissions, CO_2 because of the diesel consumption.

Anything not listed above carries no penalty. Table 11 illustrate this situation.

Table 11: Items that affect the cost (left) and items that do not (right).

Adds to the cost	**No cost attached**
• Solar, wind and battery CAPEX • Diesel fuel bought • Monetised diesel CO_2 emissions	• Renewable power that is not used • Whether battery charging happens earlier or later • wear and tear of the equipment

Given that the use of solar or wind energy is not penalised, any solution of an energy system that:

- meets the energy demand,
- complies with the defined technical limits (through the imposed constraints),

- does not result in higher diesel consumption,

yields exactly the same total cost. This multiplicity of feasible solutions in the cost function is known as *optimal degeneracy*: several energy dispatch solutions are equally cost-effective, and the solver may arbitrarily select any of them.

5.7.2 How is Optimal Degeneracy evidenced in the Results

Table 12 lists common patterns that may look unusual but arise naturally when the objective function is insensitive to internal battery states or the timing of renewable use.

Table 12: Typical "strange" schedules and the no-cost choice behind them.

What you might see	**Why it is allowed**
Battery state-of-charge remains nearly flat for long periods	Changing the SoC earlier or later has no cost impact.
Renewable energy not taken up even if the battery is not full	Charging has no economic value; leaving energy unused is equally cheap.
Diesel runs while renewables are available	The same total diesel must be burned eventually; only the timing changes.

These patterns reflect the models indifference to internal energy flows as long as external diesel use remains the same.

5.7.3 Why Charge/Discharge Exclusivity Matters

A key consequence of degeneracy is that, if the model is allowed to charge and discharge a battery in the same hour, even at very small magnitudes, it may do so without affecting total cost. Because these simultaneous flows are cost-neutral, the solver can generate rapid back-and-forth exchanges that satisfy technical constraints but do not represent meaningful physical behaviour.

The effect becomes evident in the battery KPIs. In unconstrained test runs (without the charge-discharge exclusivity constraint), several scenarios experienced implausibly high cycle counts. Table 13 shows representative examples: annual cycle counts reached PV 876 and wind 1,639 on San Andrés, and exceeded PV 1,319 and wind 1,463 on Providencia, the values are far above what the underlying profiles of renewable availability and demand would require.

To prevent this artificial micro-cycling, Constraint (C7) enforces that each battery can *either* charge *or* discharge in a given hour, but never both. This restriction does not influence cost or capacity selection, it only removes behaviour that degeneracy makes possible. With (C7) active, KPIs reflect physically meaningful use: cycle counts fall into the expected range (San Andres PV 284 and wind 416 cycles per year) and (Providencia PV 293 and wind 330 cycles per year) with moderate average SOC values consistent with the variability of the resources.

Table 13: Comparison of battery key performance indicators with and without the charge–discharge exclusivity constraint. Values are reported as "solar / wind" for each scenario, corresponding respectively to the PV-coupled and wind-coupled battery banks.

Site	Config	**Without (C7)**		**With (C7)**	
		Cycles	SOC [%]	Cycles	SOC [%]
Gustavo Rojas Pinilla Airport					
San Andrés	Solar, Wind, Diesel	876.5 / 1639.2	29 / 23	284.7 / 416.6	31 / 37
	Solar	406.9 / –	31 / –	164.7 / –	48 / –
	Wind	– / 19.8	– / 9	– / 16.4	– / 16
	Solar, Wind	465.4 / 657.6	31 / 25	181.2 / 337.7	16 / 20
	Solar, Diesel	624.8 / –	44 / –	322.3 / –	46 / –
	Wind, Diesel	– / 329.4	– / 17	– / 328.9	– / 47
El Embrujo Airport					
Providencia	Solar, Wind, Diesel	1319.1 / 1463.4	25 / 23	293.4 / 330.8	36 / 32
	Solar	141.8 / –	19 / –	141.0 / –	50 / –
	Wind	– / 12.5	– / 15	– / 11.9	– / 49
	Solar, Wind	128.9 / 54.5	17 / 7	113.2 / 97.9	15 / 9
	Solar, Diesel	593.9 / –	41 / –	258.6 / –	40 / –
	Wind, Diesel	– / 316.3	– / 20	– / 315.1	– / 47

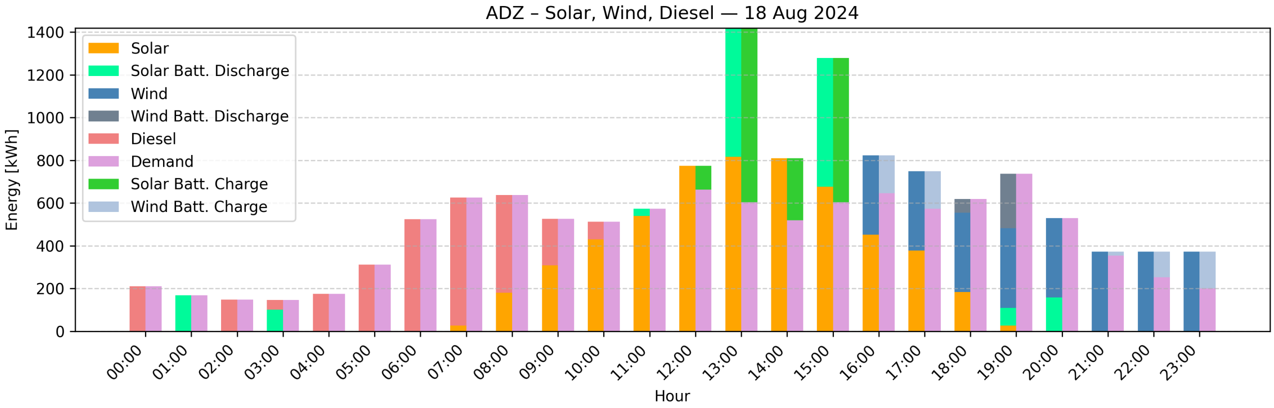


Figure 16: Example hourly dispatch for the *Solar, Wind, Diesel* configuration on San Andrés when simultaneous charging and discharging are allowed. The plot shows several hours (notably around 13:00 and 15:00) in which the model schedules both discharge and charge flows for the same battery. Because these internal flows carry no cost, the solver is free to generate such patterns even though they have no physical interpretation.

The behaviour illustrated in Fig. 16 is a direct manifestation of optimality degeneracy: once the model has satisfied demand and fixed total diesel use, it remains indifferent to the exact sequence of internal battery actions. When simultaneous discharging and charging are permitted, the solver therefore introduces small bidirectional flows that satisfy the state-of-charge update while leaving the objective value unchanged. These micro-oscillations inflate the apparent number of battery cycles and distort energy-throughput statistics, as reflected in the unrealistically high values reported in Table 13. Enforcing charge-discharge exclusivity removes this freedom, ensuring that battery KPIs reflect real physical behaviour instead of solver-generated distortions..

Constraint (C7) therefore serves an important interpretability function: it preserves the integrity of the KPI results by ensuring that battery usage statistics correspond to meaningful physical energy dispatch rather than behaviour artificially created by the solver.

5.7.4 Alternatives to encourage more intuitive energy-dispatch schedules

To prevent the situations described above, it is necessary to modify the implementation of the optimisation problem by adding elements that explicitly guide the model toward more intuitive solutions. Although degeneracy is inherent to the cost structure, several optional tie-breakers can steer the solver toward more intuitive schedules without meaningfully affecting cost or sizing, Table 14 summarises these methods, which are commonly implemented in the literature.

Table 14: Ways to reduce the freedom that leads to degeneracy.

Idea	**How it works**	**Pros**	**Cons**
Small fee or penalization on unused energy [Park et al., 2021]	Adds a small cost (e.g. 0.001 $/kWh).	It is Simple, and maintains a linear model.	It requires tuning of the penalty rate: if it is too high, it may affect the sizing of the capacities, and it also introduces a large number of variables, which slows down the optimisation process.
Two-stage solve [Karimi and Jadid, 2019]	First stage: minimise costs. Second stage: minimise wasted energy and unused energy.	Finds the most “efficient” energy dispatch, ensuring the utilisation of renewable energy and avoiding waste without increasing the total cost.	Solving the two problems separately increases computation time.
Assign Battery cycling cost [Zhao et al., 2025]	Add a small wear-and-tear cost per cycled kWh.	Leads to more reasonable battery-charging cycles.	It depends on battery-degradation data that are not known, and it may influence the sizing of the generation and storage capacities.
Constraints that force the system to utilise the renewable energy [Bird et al., 2014]	Prohibit the use of diesel whenever solar, wind, or battery energy is available.	Matches to standard operational rules	Introduces additional binary variables, slowing down the optimisation.
Adjustment of the energy dispatch schedule after the optimisation [Tseng et al., 1999]	Reorganises dispatch without changing diesel use and after finding a solution that minimises the cost	It does not affect the duration of the optimisation process.	The solution is no longer fully optimal, and it requires manual post-processing of the solution obtained from the solver.

Code Implementation notes. In the present study, two of the additional elements described above were tested: (i) a small fee applied to unutilised energy and (ii) forcing the use of renewable energy when available. Although both approaches maintained the same sizing of solar panels, wind turbines, and associated batteries, and the same annual diesel cost, they also considerably increased computation time. Therefore, they were tested only in selected configurations to validate their behaviour, but were not included in the final code.

5.7.5 How Optimal Degeneracy Affects the Calculation of Battery KPIs

Because the solver is free to choose among multiple dispatch schedules that yield the same total cost, the resulting battery state-of-charge (SOC) trajectories may differ across optimal solutions. These variations lead to different values for battery performance indicators (KPIs), even when diesel use, installed capacities, and overall system costs remain identical. Nevertheless, comparisons across modelling scenarios remain valid because all configurations are evaluated under the same optimisation structure and boundary conditions. Moreover, constraints such as (Constraint C7) restrict the solver from generating non-physical micro-cycling patterns. This ensures that SOC curves remain within realistic limits and that KPI differences reflect acceptable variations rather than the solver generating irregularities.

5.7.6 Conclusions of the Model

1. The model accounts only for what is explicitly implemented in the objective function. If not using renewable energy at a given moment does not result in a cost increase, then the model may choose not to

use it, as long as all constraints are satisfied. Internal flows that do not affect diesel use or capacity needs are cost-neutral.

2. As a consequence of the above, different energy dispatch schedules may appear, including some that are particularly unusual, and having the same associated cost (optimal degeneracy).
3. The charge-discharge exclusivity constraint prevents unrealistic battery switching and yields KPIs that reflect genuine physical use without altering the economic optimum.
4. Measures such as penalties on unused renewable energy, multi-stage optimisation, or the imposition of specific operational rules can help the model select more intuitive dispatch schedules without changing the final costs. However, these options entail a higher computational time.

5.8 Implementation barriers for the Hybrid System configuration

Implementing a hybrid energy system that combines both solar and wind power at the airports of Gustavo Rojas Pinilla and el Embrujo located at San Andrés and Providencia Island, presents some of challenges that need careful consideration. Key obstacles include environmental limitations that may restrict suitable sites for installation, regulatory issues that could impact project approval and compliance, and financial factors that affect the feasibility and long-term viability of the investment. The following subsections provide a comprehensive analysis of these implementation barriers, emphasising the critical issues that must be addressed to ensure the successful deployment of the proposed hybrid energy system.

5.8.1 Technical Challenges

The successful implementation of hybrid solar and wind energy systems at the airports of San Andrés and Providencia Islands depends on addressing several technical challenges. These challenges are especially significant due to the islands' geographic isolation, environmental conditions, and limited infrastructure. This section highlights the main technical constraints that must be taken into account for the design, installation, and operation of renewable energy systems at both airport facilities.

- **Grid Integration Issues**
  One of the main technical challenges is integrating renewable energy systems into the existing electrical grid. Both San Andrés and Providencia depend on small, isolated grid systems that may not have the stability and flexibility needed to accommodate the variable outputs from solar and wind sources. Issues such as grid instability, voltage fluctuations, and limited capacity for reverse power flow can complicate the connection of hybrid systems. These limitations are common in island power systems, where low inertia and minimal reserve capacity make them especially sensitive to variable generation [Aguirre and Ibikunle, 2014], [International Renewable Energy Agency (IRENA), 2019]. To enable reliable integration, it may be necessary to upgrade the grid infrastructure or implement microgrid technologies, which have proven effective in improving reliability in other insular regions [Espinar et al., 2020], [National Renewable Energy Laboratory (NREL), 2021].
- **Storage System Constraints**
  Given the intermittent nature of renewable energy, battery storage systems are crucial for ensuring energy availability. However, the tropical climate of the islands, which features high humidity and warm temperatures, can accelerate battery degradation and increase maintenance requirements. Elevated temperatures are known to reduce battery lifespan and efficiency, especially in lithium-ion and lead-acid technologies [Tan et al., 2013], [Bessa and Matos, 2020]. Additionally, the limited availability of advanced battery technologies and replacement parts on the islands presents logistical and financial challenges, as reported in studies of remote and islanded energy systems [International Renewable Energy Agency (IRENA), 2015], [Crossley et al., 2018]. Therefore, it is essential to select robust storage technologies that are designed for harsh environments; however, this choice may also raise the overall system cost due to the need for climate-adaptive materials and specialized installation [Huq et al., 2021].
- **Space Availability**
  Another significant constraint is the availability of suitable land or rooftop areas for installing solar panels and wind turbines. The airports in San Andrés and Providencia are relatively small, with limited open space. Rooftop installations may face restrictions due to structural limitations, such as load bearing capacity and shading issues [Jakhrani et al., 2012], [Basha et al., 2015]. Ground-mounted systems, meanwhile, must compete with other land-use priorities, including aviation safety zones and protected environmental areas, which are often prevalent in island settings [Lillo-Bravo et al., 2021]. To overcome these challenges,

detailed spatial planning and innovative system designs, such as elevated, bifacial panels, or building integrated photovoltaics may be necessary, especially at the highest and least obstructed points on the islands [Izquierdo et al., 2011], 2011; [Kaldellis and Zafirakis, 2012].

- **System Maintenance and Technical Capacity**
  The long-term sustainability of renewable energy systems relies significantly on regular maintenance and technical support. However, both islands experience a shortage of local expertise in renewable energy technologies. As a result, they often need to import technical personnel and specialized spare parts, which raises maintenance costs and leads to increased system downtime. Remote and isolated energy systems often face challenges, reporting increased repair times and higher operational costs due to geographic isolation. [McKenna et al., 2024], [OchoaCorrea et al., 2025]. To ensure reliability and longevity, developing local capacity through training programs and establishing supply chains for essential components is crucial; island-based renewable projects have successfully improved outcomes by investing in local workforce development [Rocky Mountain Institute, 2019], [Smith et al., 2024a].

5.8.2 Regulatory and Institutional Challenges

The successful implementation of hybrid renewable energy systems at the airports of San Andrés and Providencia depends not only on technical feasibility but also on the regulatory and institutional environment in which these projects are developed. These islands are governed by Colombian national law, have unique logistical and environmental contexts that present regulatory and administrative challenges. Such challenges could delay or hinder project execution. This section outlines the key regulatory and institutional obstacles that affect the deployment of solar and wind systems in these locations.

- **Grid Access Regulation**
  A significant barrier to connecting private or institutional renewable energy systems to the public grid is the absence of clear and streamlined policies. In Colombia, Law 1715 of 2014 encourages the integration of non-conventional renewable energy sources-such as solar and wind-into the national energy mix, enabling distributed generation and net metering. However, practical implementation of these provisions has been limited, particularly in remote and insular regions like San Andrés and Providencia, where grid interconnection remains underdeveloped [Rocha et al., 2022], [OECD, 2023]. Local utilities often lack the technical and administrative capacity to process interconnection requests efficiently, and regulatory oversight tends to be slow or inconsistent [OECD, 2023] [Smith et al., 2024b].

- **Permits and Bureaucratic Complexity**
  Obtaining the necessary permits for renewable energy installations, especially on public infrastructure such as airports, can be a complex and time-consuming process. Environmental licenses, aviation safety clearances, land use approvals, and coordination with various national and regional agencies can significantly delay project timelines. In Colombia, extensive bureaucratic hurdles have stalled many renewable projects, with companies reporting permit processing times of up to two years and a lack of clarity between agencies [Guides, 2023], [Circle, 2024]. The absence of a unified regulatory framework or clear procedural guidelines tailored to island contexts exacerbates uncertainty for both developers and public authorities [OECD, 2023].

- **Ownership Models and Institutional Responsibility**
  Ambiguities regarding ownership and operational responsibility pose a significant institutional barrier in Colombia's public infrastructure projects. There is currently no standardized framework to determine whether renewable energy systems should be owned and managed by the airport operator, the energy provider, or an external investor. This lack of clarity complicates financing, operation, and maintenance agreements. Moreover, benefits such as cost savings or environmental credits often lack equitable and transparent distribution among stakeholders, discouraging investment and long-term commitment. This challenge is particularly pronounced in Colombias non-interconnected zones, where unclear institutional roles and the absence of robust public-private frameworks hinder the deployment of distributed renewable systems [OECD, 2023], [Guides, 2024].

- **Alignment with Energy and Sustainability Policy**
  Colombia has made national commitments to renewable energy development through policies such as the Energy Transition Law (Ley 2099 de 2021) and its National Development Plan. However, the alignment of these national strategies with local implementation remains inconsistent, particularly in non-mainland territories like San Andrés and Providencia [Climate Transparency, 2023], [International Energy Agency (IEA), 2023]. While Aerocivil and other government entities have expressed sustainability goals for airport operations, these ambitions are often undermined by limited regulatory support, insufficient budget allocations, and weak integration within regional energy planning frameworks [OECD, 2023]. As a result,

renewable energy projects risk remaining isolated pilots rather than being incorporated into a comprehensive national energy transition strategy.

5.8.3 Financial and Economic Challenges

The long-term benefits of renewable energy systems are well understood, including lower operating costs and enhanced environmental sustainability. However, their implementation in remote areas like San Andrés and Providencia faces significant financial and economic challenges. These issues are especially evident in public infrastructure projects, such as airports, which demand high reliability, regulatory compliance, and consistent funding. The following subsections will highlight the key financial and economic obstacles to deploying hybrid wind and solar energy systems at the airports on these Colombian islands.

- **High Upfront Investment**
  Renewable energy systems usually require significant initial investments. The expenses associated with purchasing photovoltaic panels, wind turbines, inverters, battery storage systems, and related infrastructure (such as mounting structures and grid connection equipment) can be quite high. This is especially true for public-sector projects that operate under strict budget constraints. While these systems generally provide lower life-cycle costs than fossil fuel alternatives, the substantial upfront investment can delay or even stop project initiation. This issue is even more pronounced in island regions, where transportation and logistical expenses significantly raise the initial capital required [Agency, 2023], [Milone, 2022], [NedZero, 2024].
- **Inadequate Subsidies and Incentive Structures**
  Colombian legislation, particularly Law 1715 of 2014, provides tax incentives and other benefits for renewable energy projects. However, these incentives are primarily intended toward mainland applications and utility-scale installations. Consequently, the islands of San Andrés and Providencia have had limited access to these benefits, mainly due to administrative barriers and their exclusion from national energy planning. The lack of targeted subsidy programs or grants for remote or non-interconnected zones reduces the competitiveness of renewable energy systems relative to conventional diesel generation, which continues to benefit from government support for fuel transport and subsidies [OECD, 2023], [International Energy Agency (IEA), 2023].
- **Return on Investment (ROI) and Long Payback Periods**
  The economic feasibility of renewable energy systems is significantly impacted by lengthy payback periods, particularly considering the high costs associated with installation and maintenance on islands. For both investors and public entities, the uncertainty surrounding long-term operational savings-including potential changes in regulations, tariffs, or technology costs can diminish the appeal of these projects. The financial return on investment for public airports is often indirect, originating from reduced operating costs or environmental benefits. These intangible returns make it challenging to justify substantial capital expenditures without dedicated sustainability budgets or co-financing [Babinec et al., 2023], [BarandaAlonso et al., 2021], [McKenna et al., 2024].

5.9 Strategies for Overcoming Implementation Barriers

Successfully deploying hybrid renewable energy systems at the airports of San Andrés and Providencia requires a comprehensive approach that addresses technical, regulatory, financial, and operational barriers. These challenges are not unique to Colombia; island communities around the world have faced similar constraints and, in some cases, have developed effective strategies that can inform efforts in Colombias insular region. Drawing on international experiences from projects in the Caribbean, Pacific Islands, and remote European territories, this section proposes a series of actionable strategies based on global best practices, tailored to the Colombian context.

5.9.1 Technical Solutions

To overcome technical barriers such as system intermittency, storage limitations, and lack of technical expertise, targeted capacity building and system design strategies are essential. For instance, the Federated States of Micronesia and Fiji have implemented technician training programs alongside solar microgrid installations, ensuring local ownership and reducing maintenance costs over time [International Renewable Energy Agency (IRENA), 2019]. Similarly, modular design has been effectively deployed in Seychelles, where solar installations at airports and public facilities were designed to scale with growing demand and funding [United Nations Development Programme (UNDP), 2020]. In San Andrés and Providencia, a similar modular and scalable system would accommodate budget constraints and allow for adaptive expansion.

To address intermittency, hybrid optimization strategies can be adopted. For example, the Marshall Islands combined solar power with diesel backup and battery storage to ensure energy security at its airports, demonstrating a resilient model suitable for Providencia, where grid access is less stable [Asian Development Bank (ADB), 2015]. Moreover, microgrid deployment has proven effective in Hawaii, where airports and military bases use hybrid microgrids to maintain uninterrupted power during grid outages [U.S. Department of Energy, 2020].

5.9.2 Regulatory and Policy Strategies

Streamlining permitting and aligning renewable energy projects with national strategies has been critical in other regions. In Barbados, the government simplified its licensing and interconnection processes for solar installations on public buildings, resulting in faster deployment and increased investor interest [CARICOM Caribbean Community, 2021].

Additionally, the Azores Islands (Portugal) demonstrate how regional governments can play a key role in integrating airports into national and EU-level energy transition plans [European Commission, 2018]. Their renewable transition included island-specific planning tools and subsidies, showing how Colombia might better incorporate its island territories into national energy frameworks.

Institutional collaboration has also shown results in the Canary Islands, where coordination between local governments and Spains Ministry for Ecological Transition enabled the successful implementation of renewables at airports such as La Palma and El Hierro [López, 2020]. Similar coordination between Aerocivil, the Ministry of Energy, and local authorities could create a more supportive institutional environment in Colombia.

5.9.3 Financial and Investment Mechanisms

Island airports worldwide have benefited from diverse financial strategies to reduce upfront costs and improve return on investment. Cape Verde employed public-private partnerships (PPPs) for solar installations at Sal and Boa Vista airports, offering energy-as-a-service contracts that shifted capital burdens to the private sector [United Nations Environment Programme (UNEP), 2019].

Green financing has been critical in island contexts. The Caribbean Development Bank (CDB) and Green Climate Fund (GCF) have funded renewable infrastructure in Grenada and Saint Vincent and the Grenadines, offering concessional loans and grants specifically for small island developing states (SIDS) [Green Climate Fund (GCF), 2020]. Accessing similar international funds could provide San Andrés and Providencia with much-needed capital.

Phased implementation, starting with pilot projects, has also been an effective strategy. The Pacific Islands Renewable Energy Investment Programme, supported by the Asian Development Bank (ADB), piloted solar microgrids in Tuvalu and Kiribati, then scaled based on performance evaluation and community feedback [Asian Development Bank (ADB), 2021]. Colombia could follow a similar pathway for its island airports.

5.9.4 Sustainability and Long-Term Monitoring

Comprehensive system lifecycle planning should include battery replacement cycles, photovoltaic panel degradation rates, and end-of-life recycling programs. This ensures both environmental compliance and budget planning for long-term sustainability.

Finally, long-term monitoring and community engagement are essential for ensuring the resilience and acceptance of renewable systems. In Palau, energy dashboards and community-based maintenance programs have led to improved system performance and ownership [International Renewable Energy Agency (IRENA), 2022]. Airports in Mauritius also include regular performance audits and lifecycle planning as part of their renewable energy strategy, highlighting the importance of data transparency and forward planning [World Bank, 2020].

By applying these global lessons-tailored to the logistical, institutional, and environmental realities of San Andrés and Providencia-Colombia can not only overcome implementation barriers but also set a model for renewable transition in island territories.

6 Conclusions

This study demonstrates that hybrid renewable-diesel energy systems constitute a technically viable and economically attractive route for deep-carbonisation of small, isolated airports. By coupling a data-driven *hourly demand synthesis* with a transparent mixed-integer linear optimisation, the work provides a reproducible blueprint that requires only openly available inputs (re-analysis weather, flight-movement logs and utility bills).

C1. Full hybrids minimise both cost and emissions. At **Gustavo Rojas Pinilla Airport** the optimal PV + Wind + Diesel portfolio lowers present-worth system cost by around 62 % and diesel use by 82 % relative to the diesel-only baseline. The same configuration at **El Embrujo Airport** cuts fuel consumption by 79 %/year while remaining marginally cheaper than the current solution using only Diesel generators.

C2. Diesel-free operation is feasible but not yet optimal for just wind scenario. Pure PV + Wind, and PV-only energy systems satisfy the 100 % reliability constraint for ADZ airport and it is cheaper than just a diesel base-only scenario, yet storage requirements increase annualised cost versus the full hybrid. In the wind-only scenario, prices for both islands will increase dramatically, making it, from a financial perspective, unattractive. The configuration with modest diesel back-up remains the least-cost hedge against peak-week energy deficits.

C3. Battery cycling is moderate, preserving longevity. Across all scenarios the PV-coupled bank cycles 113-322 times per year at 15-50 % mean state of charge; the wind-coupled bank sees up to 416 cycles but at shallow depth. These utilisation levels sit well below industry warranty limits, supporting a 15-year lifetime assumption without mid-life replacement.

C4. Land take is manageable. The hybrid energy system demands for ADZ Airport a total of 3 ha of land and for PVA Airport less than 1 ha for PV modules and wind turbines mitigating space concerns on the smaller island.

C5. Implementation depends on enabling policy. The primary barriers are institutional rather than technical. Harmonized grid interconnection standards for noninterconnected zones, well-defined ownership structures, and targeted concessional financing are essential to unlock private investment. Experience from other island states indicates that public-private support, purchase agreements and modular microgrid architectures can significantly accelerate deployment.

7 Recommendations for Future Work

Several avenues could further strengthen the analysis:

- **Cost realism.** Embed equipment depreciation, major- overhaul scheduling and possible fiscal incentives so that life-cycle costs reflect accounting practice rather than simplified cash-out models.
- **Site constraints.** Conduct high-resolution mapping of local topography and obstacle limitation surfaces (OLS), in accordance with ICAO Annex 14 and national airport regulations, to refine grading requirements and evaluate alternative spatial configurations for both photovoltaic (PV) arrays and wind turbines.
- **PV layout optimisation.** Beyond conventional south-facing fixed-tilt arrays, several photovoltaic (PV) configurations are particularly suited for islands where land scarcity, irregular terrain, and operational constraints near airports limit deployable area. Recent studies identify promising alternatives:

  (i) Eastwest (EW) fixed configurations. EW layouts improve land-use efficiency by enabling tighter row spacing and reducing shading losses, while producing a flatter generation profile beneficial for microgrid operation. Several studies find that EW configurations can achieve comparable or lower levelised cost of energy (LCOE) relative to south-facing systems [Khatib et al., 2022], [Alkan et al., 2023].

  (ii) Vertical bifacial PV (EW or NS). Vertical bifacial modules minimise land occupation, reduce soiling, and capture diffuse and reflected light more effectively conditions typical of coastal island environments. Recent analyses show that EW vertical bifacial layouts can generate dual morning evening production peaks and achieve high land-use efficiency [Kumar et al., 2025], [Patel et al., 2020].

  (iii) Single-axis tracking (SAT) systems. Where airports face severe land constraints, SAT systems offer higher generation per square metre. Tropical-climate assessments indicate that optimised bifacial-tracking layouts can increase annual yield by 1525% compared to fixed-tilt alternatives [Ponce-Jara et al., 2024], [Garcia et al., 2015].

  (iv) Highground-cover ratio (GCR) compact PV fields. High-GCR designs allow dense module packingparticularly when using bifacial moduleswhile maintaining acceptable shading losses. Studies show that such compact layouts can significantly increase power density in space-limited environments such as islands [Tonita et al., 2023].

(v) Floating PV (FPV). FPV systems deployed on reservoirs, lagoons, or protected marine areas circumvent land scarcity entirely. FPV enhances module efficiency due to evaporative cooling and offers synergies with water-resource management [Lopes et al., 2022], [Lakshitha et al., 2024].

Future work should evaluate these alternative layouts for island airports to determine optimal trade-offs between land-use efficiency, energy yield, shading, safety zones, and integration with airfield constraints.

- **Wind turbine siting and technologies.** Additional assessments are needed to refine the specification and placement of wind energy systems. These include:
  - analysing rotor-swept areas, tip heights, wake interactions, and turbulence intensity under airport-specific wind regimes;
  - evaluating compliance with aviation safety requirements, including radar interference, approach and take-off obstacle restrictions, and bird-strike risk within protected airfield surfaces;
  - exploring alternative turbine technologies such as low-tip-speed rotors, mid-height machines designed for constrained airspace, and small-cluster layouts optimised for turbulent island conditions;
  - assessing advanced control strategies (e.g., wake steering, curtailment optimisation, noise-reduction modes) to minimise interference with airport operations while improving annual energy production.
  - Expand the assessment of wind-energy systems to study the possibility of offshore installations, particularly if the geographic context allows (e.g., near islands or coastal zones). Offshore installations may offer higher and more consistent wind resources, fewer land use conflicts, and better spatial integration when ground onshore land is scarce or constrained (e.g., due to airport-safety zones), moreover evaluate ecological co-benefits such as reef creation or fish habitat enhancement, particularly where coral ecosystems or marine biodiversity are present [Werner et al., 2024].
- **Load characterisation.** Replace the current single-profile demand model with one that distinguishes major end uses (e.g. HVAC, airfield lighting, emerging e-mobility) and that can adapt automatically to future traffic growth or efficiency retrofits.
- **System robustness.** Explore long-term weather variability, gradual technology degradation and potential demand-response measures to confirm that the recommended capacities remain adequate under less favourable boundary conditions.

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II

Literature Study

previously graded under AE4020

Executive Summary

This research investigates the feasibility of implementing hybrid renewable energy systems, specifically solar and wind, at the airports of Gustavo Rojas Pinilla (San Andrés) and El Embrujo (Providencia), located in Colombia's Caribbean archipelago. These airports are vital nodes for transportation, economic development, and emergency access, particularly in the isolated and environmentally sensitive contexts of island territories.

The primary objective of this research is to collect, analyse, and integrate a comprehensive range of data sources necessary to assess the feasibility of transitioning airport operations from diesel-based power systems to hybrid clean energy configurations. The research centres on gathering detailed meteorological data, patterns of electricity consumption, specifications of airport infrastructure, and technical as well as policy constraints, all of which are essential for developing an informed and context-specific energy strategy.

Considering the archipelagos vulnerability to climate change, high energy costs, and reliance on imported fossil fuels, this research employs a multidisciplinary approach. It utilises simulation tools and frameworks for life-cycle cost assessment, carbon emission reduction estimates, and energy resilience analysis. Furthermore, the study will include a stakeholder engagement component to identify institutional, technical, and regulatory obstacles to implementation.

This research aims to systematically evaluate the technical, economic, environmental, and policy factors influencing the adoption of clean energy systems in isolated airport environments. The results of this assessment will inform the development of a decision-support framework that can guide sustainable energy transitions not only in San Andrés and Providencia, but also in similar contexts within other Small Island Developing States (SIDS).

By addressing a critical gap in the literature and practicespecifically, the integration of renewable energy into remote airport systemsthis research will contribute to ongoing discussions about sustainable aviation infrastructure, energy security, and climate action. It aligns with both national and international objectives.

Ultimately, this research aims to be established as a foundation for a comprehensive feasibility analysis that can act as a reference model for future implementations of hybrid energy systems in island aviation contexts. The findings will offer valuable insights for engineers, policymakers, airport authorities, and sustainability practitioners endeavouring to promote resilient, low-carbon energy systems in vulnerable regions.

1

Introduction

It is essential to reduce emissions and energy consumption at airports, particularly those located on islands, which are significantly impacted by emissions from other countries (Civil Aviation Authority of Solomon Islands, 2023) [6]. This important focus contributes to advancing energy solutions in these areas.

Islands often rely heavily on imports due to limited space and unfavourable conditions for local production. In the Caribbean, for instance, food imports account for at least 80% of the total food supply (Lamani, Drogué, Ducrot, et al., 2024) [21]. Similarly, many Pacific Island Countries and Territories (PICTs) are significantly dependent on imported foods, with most nations showing negative food balances (Davila, Burkhart, & OConnell, 2024) [9] . The airport remains the quickest way for them to bring in goods and communicate with other countries.

Small Island Developing States (SIDS) contribute minimally to global greenhouse gas emissions, accounting for less than 1% of the total. Despite this, they face disproportionate impacts from climate change, including rising sea levels, an increased frequency of extreme weather events such as hurricanes, and other climate-related hazards (Wikipedia contributors, 2025) [7]. The Solomon Islands, for instance, have reported negligible contributions to international CO emissions but are highly vulnerable to the catastrophic effects of climate change, experiencing recurring natural disasters (Civil Aviation Authority of Solomon Islands, 2023) [6].

Additionally, the Marshall Islands, a Pacific nation comprising over 1,100 low-lying islands, is at risk of disappearing beneath rising oceans. This situation has prompted the Marshall Islands to advocate for the inclusion of all industries, including international shipping and aviation, in global climate agreements to establish emissions reduction targets (Stefanini, 2015) [27].

Small Island Developing States (SIDS) bear a disproportionate burden from the impacts of climate change, despite making minimal contributions to global greenhouse gas emissions. Many of these islands possess significant renewable energy potential, particularly from solar and wind sources. However, limited financial resources and technical capacity often hinder their ability to effectively utilise these assets. An analysis of 36 small island economies revealed that the majority generate less than 10% of their electricity from renewable sources and continue to rely heavily on expensive fossil fuels (Bertoli, Laera, & van Dedem, 2024) [5]. While current levels of renewable energy adoption remain relatively low across many islands, the findings indicate considerable potential for expansion.

Implementing clean energy solutions at airports can significantly reduce greenhouse gas emissions and promote sustainable development, particularly on islands. A report by (International Civil Aviation Organization [ICAO], 2019) [17] highlights several benefits of renewable energy adoption at airports, including:

- Emission Reduction: Renewable energy sources produce fewer life-cycle emissions compared to fossil fuels, thereby directly decreasing an airport's carbon footprint.
- Operational Cost Savings: Renewable energy can reduce operating costs by lowering energy expenses.

- Energy Security: Renewable energy enhances energy security by reducing reliance on external supplies, which is especially advantageous for island communities.
- Regulatory Compliance: Adopting clean energy helps in meeting environmental regulations and sustainability objectives.

The strategic implementation of renewable energy solutions is particularly significant for island airports, where conventional energy sources are often limited and associated with high transportation costs. Investing in infrastructure such as solar or wind power can improve energy self-sufficiency, reduce operational expenses, and foster broader sustainable development on the island by attracting environmentally conscious tourism and businesses. Research on airport electrification emphasizes that effectively integrating local renewable energy sources requires the use of specialized optimisation tools and methodologies (Morch et al., 2024) [23]. Such integration not only contributes to reducing transport-related emissions but also aligns with broader policy objectives targeting the sustainability of critical infrastructure. Adopting clean energy technologies at airports thus supports both environmental goals and the long-term resilience and energy independence of island communities.

2

Aviation and Environmental Impact

The aviation sector is a rapidly growing source of greenhouse gas emissions, primarily due to increased air travel. Projections indicate that, without intervention, aviation emissions could rise by as much as 300% by 2050. These figures are supported by the International Council on Clean Transportation (ICCT) (Graver, Zhang, & Rutherford, 2019) [14], and the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change, 1999) [15]. The ICCT reported that in 2018, global commercial aviation emitted 918 million metric tons of CO, representing 2.4% of all CO emissions. Additionally, the IPCC has projected that, without significant mitigation efforts, aviation emissions could increase substantially by 2050.

It is vital for the aviation industry to lower emissions not only through the design of more efficient aircraft but also by enhancing the sustainability of airport operations. This research aims to evaluate the feasibility and potential of making airports cleaner by integrating renewable energy sources such as solar and wind power to mitigate their environmental impact.

2.1. Energy Challenges in the Caribbean and Pacific Islands

The Caribbean and Pacific Islands are significantly reliant on imported fossil fuels for energy generation. This dependence leads to elevated energy costs, greater vulnerability to price fluctuations, and considerable carbon emissions. Furthermore, the geographic isolation and small size of these islands pose additional challenges to energy security and sustainability. Nonetheless, these regions also possess abundant natural resources such as sunlight and wind, making them ideal candidates for the adoption of renewable energy.

Islands face unique energy challenges, including a high dependence on imported fossil fuels, elevated electricity costs, and vulnerability to climate change. On average, electricity generation on islands costs up to ten times more than on the mainland, with electricity prices in the Solomon Islands nearly seven times higher than in the U.S. In Pacific Island nations, fuel imports accounted for 13% of GDP in 2019, placing significant economic strain on these countries. Additionally, ageing infrastructure and frequent natural disasters increase the risk of power outages, exemplified by Dominicas prolonged blackout following Hurricane Maria in 2017 (International Energy Agency [IEA], 2024) [18].

Despite the substantial potential for renewable energy, many Small Island Developing States (SIDS) generate less than 10% of their electricity from renewable sources. However, the installed renewable energy capacity in SIDS more than doubled between 2010 and 2022, reaching 4.6 GW, with Caribbean islands alone holding 72 GW of solar capacity. Key solutions include:

- Distributed energy resources (DERs): Rooftop solar and small-scale energy systems to reduce dependence on centralized grids.
- Battery energy storage systems (BESS): Essential for integrating variable renewable sources and stabilizing island grids.
- Microgrids and Virtual Power Plants (VPPs): Decentralized systems for energy resilience, as seen in Puerto Ricos 1,000-panel microgrid and Gökçeada Islands VPP integration.

Improving energy efficiency reduces costs and emissions while strengthening grid resilience. For instance, Fijis appliance energy standards saved 9.3 GWh in one year, equivalent to its solar energy output in 2021. Expanding this program could cut the buildings sector's energy demand by 17% by 2030.

Digitalisation can optimise island electricity systems, enhancing energy planning and management. AI-driven forecasting and predictive maintenance are being trialled in Curaçao, whilst Barbados and Hawaii are implementing demand response mechanisms to reduce peak energy loads.

Many island nations, such as Fiji and the Maldives, have pledged to achieve net-zero emissions; however, implementation is slow due to financing constraints. Up to USD 6 trillion is required for SIDS to fulfil their Nationally Determined Contributions (NDCs). International cooperation, through climate finance, knowledge sharing, and blended finance, is essential for accelerating clean energy transitions. By integrating renewable energy, energy efficiency, and digital solutions, islands can lower energy costs, enhance resilience, and achieve energy security, ensuring a sustainable and low-carbon future (IEA, 2024) [18].

Initiatives worldwide have been launched to encourage these countries to implement clean energy solutions. For example, the World Bank has approved a $131.87 million regional project to enhance clean energy adoption and energy efficiency in Grenada, Guyana, and Saint Lucia. The initiative, in partnership with the Organization of Eastern Caribbean States (OECS) and the Caribbean Centre for Renewable Energy and Energy Efficiency (CCREEE), aims to reduce dependence on imported fossil fuels, which currently supply 90% of the region's energy.

The Caribbean Efficient and Green Energy Buildings Project will focus on:

- Retrofitting 500 public buildings with energy-efficient technologies, reducing electricity consumption by at least 20%.
- Integrating renewable energy sources, including solar power, to increase energy resilience and sustainability.

- Additionally, the project will support policy development for net billing, energy efficiency standards, and electric vehicle integration to promote long-term clean energy adoption.

Funding includes $100 million in concessional financing from the World Banks International Development Association (IDA), supplemented by grants and loans from the Global Environment Facility, the Clean Technology Fund, and the Canada Clean Energy and Forest Climate Facility. By fostering regional cooperation and capacity building, this initiative seeks to reduce carbon emissions, lower energy costs, and improve climate resilience across participating Caribbean nations (World Bank, 2025) [32].

3

Literature Review on Global Pathways to Sustainable Airport Energy Systems

The aviation industry is experiencing a paradigm shift as the urgency to address climate change drives airports and regulatory bodies to implement cleaner, more sustainable energy systems. Airport operations, traditionally dependent on fossil fuels, make a significant contribution to carbon emissions, not only from aircraft activity but also from ground support equipment, terminal operations, and auxiliary services. As global climate goals become more stringent, an increasing number of airports worldwide are moving towards renewable and hybrid energy models.

This chapter presents a comprehensive literature review of international case studies that illustrate the practical implementation and effectiveness of various clean energy technologies in airport environments. By examining real-world examples, including the use of solar, wind, hydro, hydrogen, and hybrid energy systems, this review offers valuable insights into technological feasibility, environmental benefits, and economic viability. These global experiences serve as reference models for evaluating renewable energy integration at Gustavo Rojas Pinilla and El Embrujo Airports in Colombia.

The review is organised into five thematic sections: solar energy, wind energy, hydro energy, hydrogen energy, and hybrid systems. Each section highlights key innovations, implementation challenges, and lessons learned, providing a multidimensional understanding of how airports can align operational demands with sustainability goals.

3.1. Solar Energy in Airport Operations

The transition towards sustainable aviation has become a global imperative due to the substantial carbon footprint associated with airport operations. With the growing emphasis on carbon neutrality, several international airports have adopted renewable energy solutions, particularly solar photovoltaics (PV), to decrease reliance on fossil fuels. This study assesses the feasibility of implementing clean energy at Gustavo Rojas Pinilla and El Embrujo Airports, drawing insights from global case studies. Numerous international airports have successfully integrated solar PV systems into their operations, providing viable models for the Caribbean, Pacific, and other airports around the world.

- **Vienna International Airport (Austria)** has been leading in solar energy adoption, aiming for CO neutrality by 2023. The airport operates seven rooftop PV systems and commissioned Austrias largest ground-mounted PV plant in 2022. This facility, covering 24 hectares with a peak capacity of 24 MW, produces 30 million kWh annually, meeting 30% of the airports electricity demand. The shift to solar energy, e-mobility, LED lighting, and district heating has resulted in annual savings of 21,000 tonnes of CO (Deimel-Zelenka, Santi, de Oliveira Luiz, & Mwangi, 2022) [10].

- **Brasília International Airport (Brazil)** has adopted a hybrid solar-powered aircraft ground operations system, replacing diesel-powered Ground Power Units (GPUs). The 3,360-panel solar PV system supplies 7% of the airports electricity consumption and contributes to an estimated reduction of 20,000 tonnes of CO per year. This initiative highlights the economic benefits of solar power, as it reduces operational costs and earns international sustainability recognitions, including the Brazilian GHG Protocol Gold Seal (Deimel-Zelenka et al., 2022) [10].

- **Moi International Airport (Kenya)** pioneered the Solar-At-Gate project by integrating 507 kW of solar PV to power aircraft pre-conditioned air (PCA) and electric GPU systems. Since its commissioning in 2019, the airport has achieved annual reductions of 704 tonnes of CO, with total savings reaching 1,932 tonnes by 2021. This initiative, funded through the 6.5 million ICAO-EU programme, illustrates the feasibility of adopting decentralized renewable energy at airports in developing nations regions (Deimel-Zelenka et al., 2022) [10].

3.2. Wind Energy in Airport Operations

The implementation of wind energy presents a viable solution for reducing operational costs, enhancing energy security, and contributing to global climate goals. However, technical, regulatory, and safety considerations must be evaluated to ensure feasibility. This research examines the potential integration of wind turbines at Gustavo Rojas Pinilla and El Embrujo airports, considering findings from international case studies and aviation safety research.

Integrating wind turbines near aerodromes presents several challenges, especially concerning aircraft operations, radar interference, and the effects of wake turbulence. According to (Van der Geest, 2016) [31], the construction of wind turbines in proximity to airports is increasingly problematic as both the aviation and renewable energy sectors compete for the same airspace, which highlights four primary considerations:

- **Collision Risk:** Wind turbines must adhere to ICAO Annex 14 regulations, ensuring they do not obstruct Obstacle Limitation Surfaces (OLS) or interfere with flight paths.

- **Impact on Aircraft Operations:** The presence of wind turbines may necessitate adjustments to flight procedures to guarantee safe operations, particularly for approach and departure routes.

- **Interference with Radar and Communication:** Wind turbines can disrupt air traffic control radar, navigation aids, and communication systems, requiring detailed safety assessments.

- **Wind Hindrance and Wake Turbulence:** Large wind turbines generate wake turbulence, which can pose hazards for aircraft, especially during take-off and landing phases.

The feasibility study of the wind turbines at Teuge Airport offers essential insights into risk assessment and strategies for mitigating risks associated with the installation of wind turbines near aviation facilities The study from (Van der Geest, 2016) examined the effects of five large wind turbines (150m in height and 90m in rotor diameter) situated 5km from the airport, specifically concentrating on:

- **Wake Effects on Aircraft:** The study revealed through empirical modelling that wind turbines cause significant disruptions to airflow, which could impact aircraft approaching the airport. The findings indicated that wake turbulence must be closely monitored and mitigated to prevent threats to aviation safety.

- **Collision Risk Assessment:** Wind turbines located near Teuge Airport contravened new Dutch regulations that limit obstacles near airports to a height of 100m within a radius of 5,100m. The study necessitated extensive safety assessments and stakeholder consultations to determine acceptable risk mitigation strategies.

- **Regulatory Adjustments and Risk Tolerance:** The assessment concluded that, although wind turbines presented certain risks to aviation operations, these risks could be effectively managed through procedural modifications and airspace design adaptations.

The lessons from the Teuge Airport study illustrate that risk mitigation strategies, such as adjustments to flight paths and safety assessments, can enable the harmonious coexistence of wind energy and aviation operations.

3.3. Hydro Energy in Airport Operations

Indira Gandhi International Airport (IGIA) in Delhi became the first airport in India to operate entirely on renewable energy sources in 2022, utilising both hydro and solar power. This strategic shift aligns with Delhi International Airport Limited's (DIAL) objective of achieving Net Zero Carbon Emissions by 2030, surpassing the global aviation targets set for 2050, (Airports Council International Asia-Pacific [ACI Asia-Pacific], 2022) [1].

Approximately 6% of IGIA's electricity demand is met through on-site solar power installations, which include a 7.84 MW plant located airside and additional rooftop systems totalling 5.3 MW on the roofs of the cargo terminal. The remaining 94% of the airport's energy requirements are fulfilled through a long-term power purchase agreement with a hydroelectric facility based in Himachal Pradesh, effective until 2036, (ACI Asia-Pacific, 2022) [1].

The transition to renewable energy is projected to reduce IGIA's indirect energy emissions by approximately 200,000 tonnes of CO annually. This substantial decrease underscores DIAL's commitment to environmental sustainability and positions IGIA as a leader in green airport operations, (ACI Asia-Pacific, 2022) [1].

In 2020, IGIA became the first airport in the Asia-Pacific region to achieve "Level 4+" under the Airports Council International's Airport Carbon Accreditation programme, reflecting its commitment to long-term absolute emission reduction targets in line with the UN's Intergovernmental Panel on Climate Change's 1.5-degree scenario. DIAL continues to implement various sustainability initiatives, including the introduction of TaxiBots to reduce aircraft fuel consumption during taxiing, the adoption of electric vehicles to phase out diesel and petrol vehicles, and comprehensive water management strategies (ACI Asia-Pacific, 2022) [1].

Delhi Airport's full transition to renewable energy sources exemplifies a considerable advancement in sustainable aviation practices. This initiative not only contributes to significant reductions in CO emissions but also sets a precedent for other airports to endeavour to achieve carbon neutrality.

3.4. Hydrogen Energy for Aviation

The aviation industry is transforming sustainable energy solutions to mitigate greenhouse gas emissions and reduce dependency on fossil fuels. Hydrogen energy is emerging as a viable alternative due to its zero-carbon emissions, high energy density, and ability to integrate with renewable energy sources. According to (Yusaf et al., 2024) [34], hydrogen fuel presents significant potential for decarbonizing aviation, yet challenges remain in infrastructure development, economic feasibility, and regulatory frameworks. Their study explores technological advancements, hydrogen fuel cell applications, and the role of hydrogen-powered aircraft in achieving sustainable aviation.

Hydrogen can be produced using various methods, each with different economic and environmental implications; the most prominent production methods include:

- **Electrolysis:** is a process that uses renewable energy sources such as solar or wind power to split water molecules into hydrogen and oxygen, resulting in zero-emission green hydrogen.
- **Steam Methane Reforming (SMR):** is the most prevalent method of hydrogen production, accounting for nearly 95% of global output. It typically produces gray hydrogen, unless combined with carbon capture technologiesthen it's classified as blue hydrogen to mitigate CO_2 emissions.

3.4.1. Hydrogen Storage Technologies

- Compressed hydrogen gas storage: Stored at high pressures (350700 bar) in specialised tanks.
- Compressed hydrogen gas storage: Stored at high pressures (350700 bar) in specialised tanks.

3.4.2. Hydrogen Fuel Cell Integration in Aviation

The study by (Yusaf et al., 2024) [34] highlights various applications of hydrogen fuel cell technology within airport ecosystems and aviation operations, including:

- **Hydrogen-Powered Ground Support Equipment (GSE):** Airports can significantly reduce CO emissions by replacing diesel-powered GSE with hydrogen fuel cell alternatives, including baggage carts, aircraft tugs, and shuttle buses.
- **Hydrogen Fuel Cells for Aircraft Auxiliary Power Units (APUs):** Hydrogen fuel cells can potentially replace traditional APUs, providing power for aircraft systems while reducing fuel consumption and emissions.
- **Hydrogen-Powered Aircraft:** The research investigates current advancements in hydrogen-fuel propulsion systems, including turboelectric and hydrogen combustion engines. Simulation models indicate that hydrogen-powered aircraft could attain energy efficiency levels up to 62% higher than those of traditional jet fuels.

3.4.3. Economic and Environmental Impact

- Hydrogen-powered aviation presents both environmental benefits and economic challenges.
- Carbon and NO Emission Reductions: Hydrogen-fuelled aircraft could eradicate CO emissions, considerably mitigating aviations effect on climate change.

3.4.4. Economic Viability

Current hydrogen production costs range from $4 and $6 per kg, rendering it pricier than conventional jet fuels. Nevertheless, the study observes that improvements in electrolysis efficiency and large-scale hydrogen production are anticipated to greatly reduce costs in the near future decade.

3.4.5. Challenges and Future Prospects

While the adoption of hydrogen in aviation presents promising opportunities, several barriers must be overcome:

- Infrastructure Development: Airports require the construction of hydrogen refuelling stations, hydrogen pipelines, and updated storage systems.
- Technological Gaps: Further research is necessary to enhance fuel cell efficiency, hydrogen combustion engines, and storage capacity.
- Safety regulations and Policy Support: Governments must establish strict hydrogen transport and safety regulations to ensure its safe integration into airport operations.

The study by (Yusaf et al., 2024) [34] concludes that hydrogen energy represents a transformative opportunity for aviation, providing a zero-emission, high-efficiency alternative to fossil fuels. However, its widespread adoption necessitates investment in infrastructure, advancements in storage technology, and the establishment of regulatory frameworks. If these challenges are successfully addressed, hydrogen-powered aviation could become a commercially viable solution within the next two decades.

3.5. Hybrid Systems and Energy Integration

When combined with solar power, wind energy offers a viable option for sustainable airport operations, as evidenced by a feasibility study conducted at Biratnagar Airport in Nepal.

3.5.1. Wind Energy Integration in Airports: Lessons from Nepal

The decarbonisation project at Biratnagar Airport evaluated the viability of wind and solar energy using PVSYST V6.8.7 and HOMER V2.81 software for simulation purposes (Yadav et al., 2024) [33]. The study assessed **Various configurations of wind turbines include:**

- EOLO 15 kW Vertical Axis Wind Turbines (VAWT)
- Tree-Shaped Wind Turbines (TSWT) of 58.5 kW and 585 kW

Energy output and performance:

- A 157 kWp solar PV plant was deemed sufficient to power the entire airport.
- Annual wind energy production reached 23,184 kWh, with the 15 kW wind turbine-grid scenario outperforming conventional grid-only scenarios.
- The Levelized Cost of Electricity (LCOE) was calculated at \$0.141/kWh, demonstrating competitiveness with traditional energy sources.

3.5.2. Economic Viability

- A sensitivity analysis of wind speed, interest rates, and turbine types indicated that wind turbines are economically viable when average wind speeds exceed 9 m/s and interest rates remain below 10%.
- The hybrid scenario of wind turbines and the grid resulted in improved cost savings and energy security, motivating airport authorities to invest in clean energy.

3.5.3. Environmental Impact

- The project mitigated 268.90 tonnes of CO emissions annually.
- The combined wind and solar system provided increased grid stability and resilience against power disruptions, which is a crucial factor for Caribbean airports that are frequently affected by hurricanes.

3.6. Battery Storage Systems

Battery energy storage systems (BESS) are a critical component of hybrid renewable energy systems (HRES) for island-based airports, where grid connection is limited or non-existent. Effective energy storage improves system resilience, smooths intermittency from solar and wind, and enhances power reliability during peak demand or outages.

A recent comprehensive review by Psarros et al. (2024) analysed various island-based microgrids and concluded that integrating BESS into non-interconnected systems is essential to achieving more than 50% renewable energy integration. The study emphasised that BESS enables both short-term energy balancing and long-term reliability, making it indispensable for energy-autonomous islands [24].

Regarding storage technology selection, lithium-ion batteriesspecifically lithium iron phosphate (LFP)have emerged as the most effective solution for short-duration storage (less than 8 hours). According to the Grid

Energy Storage Report (2024), LFP systems now dominate the global short-duration storage segment, primarily due to their remarkable cost declineapproximately 90% since 2010alongside improvements in energy density, safety, and life cycle performance. This cost-effectiveness and reliability make them particularly well-suited for island-based hybrid energy systems where both operational safety and maintenance simplicity are critical [8].

A case study by Khamharnphol et al. (2023) demonstrated these benefits in practice: they implemented a solar/wind/diesel microgrid integrated with battery storage on Koh Samui, a tourist island in southern Thailand. Their optimization model minimized the levelized cost of energy (LCOE) to $0.184/kWh while achieving a renewable fraction of 76% and significantly reducing diesel consumption. This illustrates how BESS can be pivotal in transforming remote hybrid systems into economically and environmentally viable solutions [20].

4

Background and Rationale

This chapter outlines the geographical, environmental, and infrastructural context underlying the feasibility assessment of clean energy solutions for Gustavo Rojas Pinilla Airport in San Andrés and El Embrujo Airport in Providencia. By understanding the unique biodiversity, socio-economic development, and aviation infrastructure of Colombiaparticularly its Caribbean Island territoriesthis chapter establishes a foundational rationale for exploring sustainable energy alternatives tailored to these locations.

Colombia's exceptional biodiversity, coastal ecosystems, and commitment to environmental conservation through initiatives such as the Seaflower Biosphere Reserve provide a strong environmental imperative for sustainable practices. Furthermore, the countrys pioneering history in aviation and the growth of air travel over recent decades underscore the strategic role airports play in national and regional connectivity.

Considering the environmental sensitivity of San Andrés and Providencia, along with the increasing tourism-related pressures on their infrastructure, transitioning to renewable energy is not only essential for environmental reasons but also aligns strategically with Colombias sustainability goals. The following sections explore the islands' biodiversity, the evolution of aviation in Colombia, and a comprehensive overview of the airport facilities on both islands, providing context for the implementation of clean energy systems.

4.1. Geographical and Ecological Significance of Colombia and Its Islands

Colombia, situated in the northwestern region of South America, is renowned for its diverse geography and exceptional biodiversity. The country's landscape includes the Andes mountains, the Amazon rainforest, Caribbean and Pacific coastlines, and extensive plains, contributing to its status as one of the world's most biodiverse nations (Aldana-Domínguez et al., 2017) [2].

- **Species Richness:**Colombia is home to approximately 10% of the world's bird species, highlighting its rich avian diversity.
- **Marine Biodiversity:**Research conducted over the past decade has greatly enhanced our understanding of Colombia's marine biodiversity, featuring comprehensive species inventories and ecosystem characterisations.

Colombia holds the second-highest National Biodiversity Index globally, surpassed only by Indonesia, and is home to 10% of the planet's biodiversity. The Caribbean region of Colombia ranks as the second most diverse area for vegetation, following the Andean region (Echeverri et al., 2023) [12]. It also has islands in the Caribbean Sea, like San Andres and Providencia Islands. These 2 islands are protected by UNESCO for their nature and species.

4.1.1. Biodiversity and Conservation in the San Andrés Archipelago

The Archipelago of San Andrés, Providencia, and Santa Catalina, located in the Caribbean Sea, is recognised for its rich biodiversity and cultural heritage. In 2000, UNESCO designated this area as the Seaflower Biosphere Reserve, aiming to promote sustainable development and conservation of its unique ecosystems. It encompasses a vast marine area, including coral reefs, mangroves, and seagrass beds, which serve as habitats for numerous endemic and endangered species. This designation underscores the global significance of the archipelago's natural resources and the commitment to their preservation (Mancera Pineda, Osorio, Toro, & Velásquez-Calderón, 2025) [22].

Furthermore, analyses of marine science research in the archipelago reveal a diverse array of studies focusing on the area's unique marine ecosystems, underscoring the region's scientific interest and ecological significance. San Andrés, renowned for its vibrant "Sea of Seven Colours," is the largest island in the Sea Flower Biosphere Reserve and a centre of marine biodiversity. Its coral-based formation, composed of organic remnants of marine life, gives rise to its low-lying terrain adorned with coconut palms and pristine white-sand beaches. A popular destination for scuba divers, San Andrés attracts over a million visitors each year with its crystal-clear waters and flourishing coral reefs. However, this influx of tourism has imposed immense pressure on the islands delicate ecosystems, resulting in significant environmental challenges strain (UN News, 2022) [28].

As engineers, we must consider not only technological advancements but also their potential benefits for the environment and their role in promoting sustainability. Consequently, the adoption of clean energy solutions should take into account the environmental impacts associated with their implementation.

4.2. Historical and Contemporary Role of Aviation in Colombia

Colombia has a Historical Contribution to Aviation, such as Early Commercial Aviation; in 1919, Colombia became home to SCADTA (Sociedad Colombo Alemana de Transportes Aéreos), the world's second airline and the first in Latin America. SCADTA's establishment marked a significant milestone in global aviation history, setting precedents for international air travel and mail transport. SACADTA, nowadays known by the name of Avianca, is the world's second-oldest airline after KLM (El Tiempo, 2023) [13].

SCADTA's operations facilitated the establishment of air routes across challenging terrains, notably the Andes Mountains and the dense Amazon rainforest. This connectivity not only united remote regions within Colombia but also served as a model for overcoming geographical barriers in aviation worldwide.

The growth of air transport in Colombia over the past decade has been substantial, as it is shown in the Figure 4.1 (International Air Transport Association [IATA], 2019) [16]. The number of passengers travelling to and from Colombia increased from 19.9 million in 2008 to 33.5 million in 2018, reflecting an average annual growth rate of 6.2%. The International Air Transport Association (2019) highlights the critical role aviation plays in Colombias economy and connectivity.

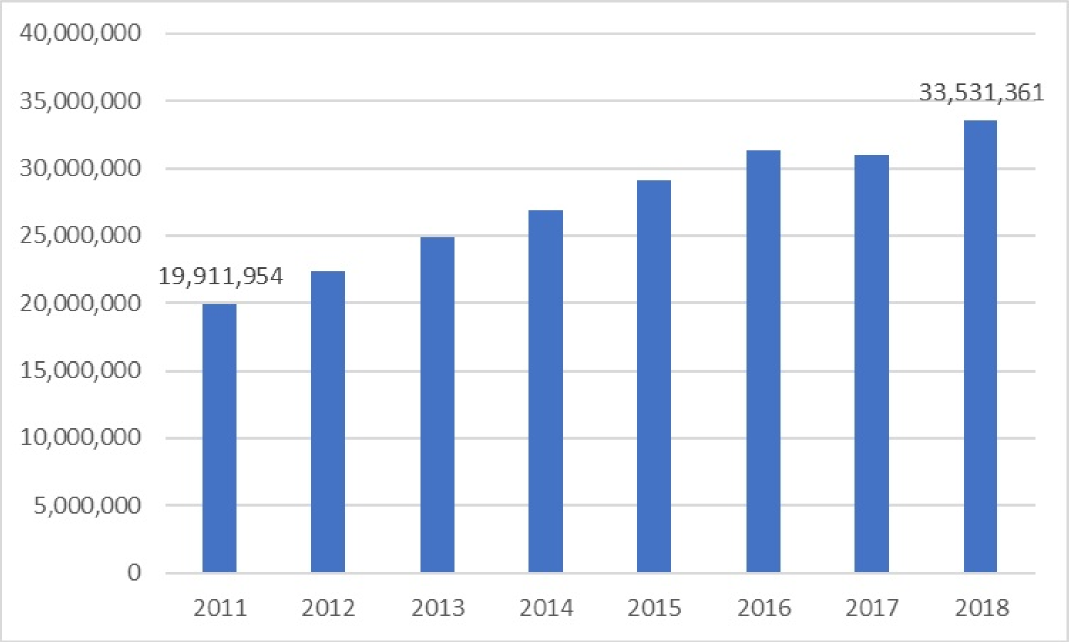


Figure 4.1: The Air Transport in Colombia layouts

The aviation industry has become a vital component of Colombia's economy, contributing to GDP growth and supporting various sectors, including tourism and commerce. The implementation of public policies has played a significant role in this sector development (Díaz Olariaga & Ávila Álvarez, 2015) [11].

4.3. Air Transport Connectivity in San Andres and Providence Islands

San Andres Airport is named Gustavo Rojas Pinilla in honour of the colonel who requested its construction. This airport has been operational since 1959, when it welcomed its first commercial flight.

4.3.1. Domestic Routes Airport Gustavo Rojas Pinilla

In the table below, you can see the National Routes of Gustavo Rojas Pinilla Airport, along with the airports, airlines, cities, types of aeroplanes, frequencies, and distances.

Table 4.1: National Routes Airport Gustavo Rojas Pinilla

City	Name of the airport	Airline	Airplane	Frequency	Distance (Approx)
Barranquilla	Aeropuerto Internacional Ernesto Cortissoz (BAQ)	Wingo	B738	7	776,4 Km
Bogotá	Aeropuerto Internacional El Dorado (BOG)	Avianca	A319 / A320	53	1206,7 Km
		LATAM	A319 / A320	27	
Cali	Aeropuerto Internacional Alfonso Bonilla Aragón (CLO)	Avianca	A319 / A320	4	1174,5 Km
		LATAM	A319 / A320	12	
Cartagena	Aeropuerto Internacional Rafael Núñez (CTG)	LATAM Wingo	A319 / A320 B738	7 4	714,2 Km
Medellín	Aeropuerto Internacional José María Córdova (MDE)	Avianca	A319 / A320	9	990,5 Km
		LATAM	A319 / A320	14	
		JetSMART Colombia	A320N	5	
Providencia	Aeropuerto El Embrujo (PVA)	Satena	AT45	24	93,4 Km

4.3.2. International Routes at Gustavo Rojas Pinilla Airport

Table 4.2: International Routes Airport Gustavo Rojas Pinilla

City	Name of the airport	Airline	Airplane	Frequency	Distance
Montreal, Canada	Aeropuerto Internacional Pierre Elliott Trudeau (YUL)	Sunwing Airlines (For a season Only)	B738	1	3732,9 Km
Ciudad de Panama, Panama	Aeropuerto Internacional de Tocumen (PTY)	Copa Airlines	B73G	4	466,6 Km

4.4. Airport Facilities at San Andres Gustavo Rojas Pinilla

The table below contains information about the airport Gustavo Rojas Pinilla facilities at San Andres, including general features, airside, navigation aids, the passenger terminal, load and support facilities (Unidad Administrativa Especial de Aeronáutica Civil [UAEAC], 2017a) [30].

Table 4.3: San Andres Gustavo Rojas Pinilla Airport Facilities

General Features	
Item	**Description**
Airport Commercial Service	Domestic/International
ICAO Reference Code	4C
ICAO/IATA Code	SKSP/ADZ
Elevation above sea level	6.2 m (20 ft)
Hours of Operation	24 Hours
Type of Operation	Civil and Military
Airport Authority Operator	Aerocivil Atlantico Regional
Established Procedures	IFR and VFR Operations Ceiling 420 (415) Visibility 2300 (C/D)
Air Traffic Control Tower	North side of the runway and across the passenger terminal. Visibility to thresholds reduced by trees and other obstacles.
Meteorological Services	Automatic Meteorological Station. EMA
Surface Limiting Obstacles (SLO)	Penetrations by roads, trees, houses, light poles, power lines, and the fence.

Airside			
Item	**Designation**	**Dimension**	**Strength**
Runway	06-24	2375 m x 45 m	PCN 98/F/A/W/T
Taxiway	A	22 m, 100 m threshold 24	PCN 54/F/A/W/T
Taxiway	B	22 m, 350 m threshold 24	PCN 54/F/A/W/T
Apron	Commercial	3 contact positions + Remote positions 26,017 m^2	Rigid Asphalt

Navigation and Aids	
Equipment and Aids	**Description**
VOR Doppler	Thomson 512 D, located on Cliff Hill, coverage of 200 nautical miles.
DME	Dual DME Wilcox brand model 5690
Radio beacon	Tecnasa 1000 A with 1 KW power, coverage 200 NM
Signals	Horizontal markings designating the runway, runway centerline, and touchdown zone.
Lights	Stop, threshold and runway edge lights lamps FAA type L 862, blue colour, which have a yellow-white filter. lamps FAA type L 850E, red colour located at the runway ends

Passenger Terminal	
Item	**Description**
Levels	3
Structure	Conventional masonry walls, finished in stucco and vinyl
Maximum height	15.5 m
Construction area	7,955 m^2
First Level	Access, Check-in counters, Passenger arrival and departure, Luggage, Airline offices, Authority offices, Pumps, Electrical room, General warehouse
Second Level	4 National boarding rooms, 1 international boarding room, Access control (Sterile area), Public waiting rooms, Food court, Commercial premises
Third Level	Administrative areas
Parking lots	90 spaces
Load	
Item	**Description**
Cargo Terminal	A cargo warehouse 660 m^2, operated by the company Deprisa
Support Facilities	
Item	**Description**
Control Tower	Conventional Structure 4 Levels, 9 m. high
Aeronautical Communications	ACC-SP (128.4 Mhz), APP-SP (119.3 Mhz), APP-SP (118.1 Mhz), EMG frequency (121.5 Mhz)
Other systems	Optical fiber, VCCS, Satellite system
ARFF (Aircraft Rescue and Firefighting)	Category 7 628 m^2, 1 Machine T - 1500, 2 Machines T - 6
Airport Health	Medical office, emergency, ambulance

4.5. Airport Facilities at Providencia El Embrujo

The table below provides details about the facilities at El Embrujo Airport in Providencia, including general features, airside, navigation aids, the passenger terminal, and support facilities. However, it does not include a cargo terminal, general aviation terminal, or military installations (Unidad Administrativa Especial de Aeronáutica Civil [UAEAC], 2017b) [29].

Table 4.4: Providencia El Embrujo Airport Facilities

<table>
<tr><th colspan="4">General Features</th></tr>
<tr><th colspan="2">Item</th><th colspan="2">Description</th></tr>
<tr><td colspan="2">Airport Commercial Service</td><td colspan="2">Domestic</td></tr>
<tr><td colspan="2">ICAO Reference Code</td><td colspan="2">2B</td></tr>
<tr><td colspan="2">ICAO/IATA Code</td><td colspan="2">SKSP/PVA</td></tr>
<tr><td colspan="2">Elevation above sea level</td><td colspan="2">8.93 m (29 ft)</td></tr>
<tr><td colspan="2">Hours of Operation</td><td colspan="2">1100-2300</td></tr>
<tr><td colspan="2">Type of Operation</td><td colspan="2">Civil</td></tr>
<tr><td colspan="2">Airport Authority Operator</td><td colspan="2">Aerocivil Atlantico Regional</td></tr>
<tr><td colspan="2">Established Procedures</td><td colspan="2">Only VFR Operations
Ceiling 1529 (1500) Visibility 8000 Category A</td></tr>
<tr><td colspan="2">Air Traffic Control Tower</td><td colspan="2">Located on the western side of the airport adjacent to the platform and the passenger terminal. Visibility at the thresholds is reduced by tall trees.</td></tr>
<tr><td colspan="2">Meteorological Services</td><td colspan="2">Automatic Meteorological Station. EMA</td></tr>
<tr><td colspan="2">Surface Limiting Obstacles (SLO)</td><td colspan="2">Antenna of 31 m height located at N 13 22 35.3 W 081 21 22.60, illuminated.</td></tr>
<tr><th colspan="4">Airside</th></tr>
<tr><th>Item</th><th>Designation</th><th>Dimension</th><th>Strength</th></tr>
<tr><td>Runway</td><td>17-35</td><td>1290 m x 14 m</td><td>PCN 18.6/F/C/X/T</td></tr>
<tr><td>Taxiway</td><td>A</td><td>15 m x 36 m</td><td>PCN 18.6/F/C/X/T</td></tr>
<tr><td>Apron</td><td>Commercial</td><td>2 Remote positions Key A and B</td><td>Rigid Asphalt</td></tr>
<tr><th colspan="4">Navigation and Aids</th></tr>
<tr><th colspan="2">Equipment and Aids</th><th colspan="2">Description</th></tr>
<tr><td colspan="2">VOR Doppler</td><td colspan="2">It does not have</td></tr>
<tr><td colspan="2">DME</td><td colspan="2">It does not have</td></tr>
<tr><td colspan="2">Radio beacon</td><td colspan="2">It does not have</td></tr>
<tr><td colspan="2">Signals</td><td colspan="2">Horizontal markings designating the runway, runway centreline, and touchdown zone.</td></tr>
<tr><td colspan="2">Lights</td><td colspan="2">The airport does not have edge or runway centreline lights.</td></tr>
</table>

Passenger Terminal	
Item	**Description**
Levels	1
Structure	Conventional masonry walls, finished in stucco and vinyl
Construction area	542 m^2
First Level	One waiting room, Aviation Security, baggage handling is manual.
Parking lots	There is no designated area

Support Facilities	
Item	**Description**
Control Tower	Conventional Structure 4 Levels.
Safety Equipment	Does not have X-ray equipment
ARFF (Aircraft Rescue and Firefighting)	Category 4 628 m^2 1 Machine 3.024 lt/min
Airport Health	It doesnt have

5

Meteorological Conditions

A comprehensive understanding of local meteorological conditions is essential for assessing the viability and efficiency of renewable energy systems at Gustavo Rojas Pinilla and El Embrujo Airports, situated in San Andrés and Providencia. Weather variables such as solar radiation, wind speed, sunshine duration, and atmospheric patterns directly influence the design, performance, and return on investment of clean energy technologies, particularly solar and wind power systems.

This section examines historical and contemporary weather data from meteorological stations in San Andrés and Providencia, two Caribbean islands in Colombia. By utilising long-term datasets, it provides insights into solar irradiation levels, sunshine availability, wind characteristics, and related atmospheric conditions. These environmental parameters lay the foundation for evaluating the technical feasibility of integrating renewable energy sources into airport operations at Gustavo Rojas Pinilla and El Embrujo Airports.

The chapter is organised into sections, detailing monthly sunshine averages, global irradiation, hourly radiation profiles, wind patterns, and temperaturehumidity interactionsall of which are critical for developing sustainable, island-specific energy strategies.

5.1. Monthly Average of Sunshine per Day

The table below displays the monthly averages of sunlight in San Andres and Providencia (hours of sunshine per day) over a period of 36 years. The data in the table were taken from January 1980 to December 2016 and were measured at meteorological stations located on these two islands (Benavides Ballesteros, Simbaqueva Fonseca, & Zapata Lesmes, 2017) [4].

Table 5.1: Monthly Average Sunshine Hours (hours of sunshine per day)

Location	**Monthly Average value (hours of sunshine per day)**												**Annual Avg.**	**Data Coverage (Years)**
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**		
San Andres Lat. 12.54 Long. 81.73 Elevation MASL (1)	8.2	8.6	9.2	9.4	7.6	6.1	6.6	7.2	6.3	6.0	5.9	6.9	7.3	Jan. 1980 to Dec. 2016 (36)
Providencia Lat. 13.36 Long. 81.36 Elevation MASL (7)	7.5	8.2	8.6	9.0	7.7	6.5	7.0	7.6	6.7	6.1	5.8	6.5	7.3	Jan. 1980 to Dec. 2016 (36)

5.2. Monthly Average of Days Without Sunshine

The table below shows the monthly average number of days without sunshine in San Andres and Providencia, (Benavides Ballesteros et al., 2017) [4].

Table 5.2: Monthly Average Days Without Sunshine (number of days without sunshine per month)

Location	**Monthly average days without sunshine**												**Annual Avg.**	**Data coverage (Years)**
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**		
San Andres Lat. 12.54 Long. 81.73 Elevation MASL (1)	0.33	0.15	0.03	0.21	1.55	2.79	2.42	1.39	1.91	3.33	3.55	1.70	1.61	Jan. 1980 to Ago. 2012 (33)
Providencia Lat. 13.36 Long. 81.36 Elevation MASL (7)	0.55	0.24	0.09	0.24	1.52	2.76	1.39	1.18	1.61	2.82	3.15	1.73	1.44	Jan. 1980 to Sep. 2012 (32)

5.3. Monthly average daily cumulative global irradiation received at the surface

The table below shows the monthly averages of daily cumulative global irradiation received at the surface in San Andres (Wh/mš per day). The measurement period spanned two years, from July 2014 to December 2016, (Benavides Ballesteros et al., 2017) [4].

Table 5.3: Monthly average daily cumulative global irradiation received at the surface (Wh/m^2 per day)

Location	**Monthly average daily cumulative global irradiation received at the surface (Average value Wh/m^2)**												**Annual Average**	**Data coverage (Years)**
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**		
San Andres	5242.0	5563.9	6481.5	6039.1	5649.6	4930.9	5860.0	5274.8	5103.3	4726.5	4295.7	4480.7	5313.1	July 2014 to Dec. 2016 (2)

5.4. Hourly averages of global irradiation at San Andrés in Wh/m^2.

The table below displays the Monthly Hourly Averages of Global Irradiation at the Sesquicentenario Airport (San Andrés) station in Wh/mš (Benavides Ballesteros et al., 2017) [4].

Table 5.4: Average Hourly Radiation (Wh/m^2) at Weather Station Apto. Sesquicentenario (San Andrés)

Weather Station Apto. Sesquicentenario (San Andrés) Average Hourly Radiation (Wh/m^2)												
Time	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
0-1	0.1	0.1	0.1	0.2	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.0
1-2	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1
2-3	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
3-4	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.1
4-5	0.2	0.2	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.0
5-6	0.1	0.3	0.1	0.2	0.3	0.4	0.2	0.2	0.1	0.3	0.4	0.1
6-7	1.6	2.8	10.1	27.5	34.8	32.7	26.3	37.8	39.2	42.3	28.1	4.6
7-8	57.7	83.3	103.3	158.3	156.0	143.7	140.0	173.7	167.3	206.3	161.7	74.7
8-9	268.6	314.6	333.1	314.6	351.7	315.1	346.1	353.3	331.9	401.5	340.8	266.9
9-10	485.2	530.0	563.9	369.1	527.8	467.3	511.5	449.3	545.0	568.1	495.3	444.3
10-11	643.1	705.0	779.4	621.8	661.5	583.9	647.2	612.3	661.7	631.7	583.9	570.7
11-12	723.4	826.0	892.5	832.5	765.5	666.5	756.1	694.0	733.9	712.8	640.6	630.1
12-13	765.4	866.4	910.2	893.5	792.2	671.3	773.8	708.2	694.2	620.6	590.3	691.3
13-14	770.3	855.3	909.7	879.0	742.3	648.3	741.8	686.3	660.7	579.1	558.5	632.6
14-15	644.5	734.9	798.3	762.6	649.4	547.9	642.0	655.4	555.8	475.5	440.5	532.1
15-16	478.8	553.3	602.2	600.9	483.0	431.1	488.9	484.8	392.3	298.8	284.9	378.6
16-17	300.7	330.2	398.3	291.3	320.7	270.1	324.9	279.9	231.7	156.6	146.8	202.1
17-18	97.0	138.5	162.5	167.8	143.2	128.5	150.7	124.5	83.2	31.7	23.2	51.7
18-19	4.4	12.1	17.3	18.3	20.8	23.5	30.3	14.7	5.7	0.5	0.2	0.5
19-20	0.2	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1
20-21	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
21-22	0.1	0.1	0.1	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1
22-23	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0
23-0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.0
Daily acc.	5240.8	5952.9	6480.8	6037.4	5649.3	4930.2	5579.6	5274.4	5102.7	4726.1	4295.1	4480.3

Legend	
🟩	Between 0 and 200 (Wh/m^2)
🟩	Between 200 and 400 (Wh/m^2)
🟨	Between 400 and 600 (Wh/m^2)
🟧	Between 600 and 800 (Wh/m^2)
🟥	More than 800 (Wh/m^2)

5.5. Wind at San Andres Island

5.5.1. Wind Direction

At higher altitudes, particularly between 300 hPa and the top of the troposphere, westerly winds dominate from December to May, while easterly winds prevail from June to October. November signifies a transition between these patterns.

At mid-levels (500 hPa), easterly winds are consistent throughout the year, with a slight southeast influence during May to June and September to October. Near the surface, trade winds remain steady all year long, (Ruiz Murcia, Serna Cuenca, & Zapata Lesmes, 2017) [25].

5.5.2. Wind Speed

Wind speeds significantly increase at 300 hPa from December to April. At the surface, speeds vary from 10 to 12 knots during January-February and June-August, but they drop to about 7 knots in September-October.

5.5.3. Air Temperature and Dew Point

From December to April, humidity levels decrease, showing a greater variation in temperature and dew point between 700 hPa and 300 hPa. In contrast, from June to October, both variables exhibit a more stable pattern. May and November act as transition months between these two behaviours.

5.6. Annual Surface Average Wind Speeds

The table below identifies locations with the highest annual surface wind speeds, recorded at a height of 10 m, in accordance with WMO international standards and regulations for the San Andres and Providencia Islands (Ruiz Murcia et al., 2017) [25].

Table 5.5: Annual average wind speeds (Kt)

Location	**Period**	**Annual average wind speeds (Kt)**												**Yearly**	**Position**
		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**		
San Andres	2002–2010	4.3	3.8	3.7	3.2	4.0	3.7	4.4	3.7	2.2	2.7	3.6	4.1	3.62	7
Providencia	2002–2009	4.2	3.4	3.4	3.0	3.1	3.9	4.0	3.2	2.4	2.5	3.2	3.7	3.35	10

6

Actual Energy Usage and Means

The San Andrés and Providencia archipelago relies predominantly on fossil fuel energy systems at its airports, with diesel-powered generators as the main source of electricity. This dependence arises from the islands' geographic isolation, the absence of grid interconnection with mainland Colombia, and the limited local renewable infrastructure. While this diesel-based model offers short-term reliability, it presents considerable economic, environmental, and logistical challengesespecially in terms of high transportation costs, fuel dependency, and greenhouse gas emissions.

To evaluate the feasibility and potential advantages of transitioning to clean energy alternatives at Gustavo Rojas Pinilla and El Embrujo Airports, it is crucial to understand their current electricity consumption patterns. This chapter presents energy usage data recorded at both airports over the past year (2024), highlighting monthly trends and total energy demands. These figures serve as a baseline for assessing future energy solutions and system sizing.

6.1. San Andres Airport Gustavo Rojas Pinilla Energy Consumption

Gustavo Rojas Pinilla Airport serves as the primary aviation hub of the archipelago and has a significant energy demand due to its 24-hour operations, terminal facilities, and airside activities. SOPESA (2025) reports that energy consumption at the airports in San Andrés and Providencia is supplied primarily through diesel-powered generation systems. The table below displays monthly electricity consumption data (in kilowatt-hours) from January 2024 to January 2025, (SOPESA, 2025) [26].

Table 6.1: San Andres Airport Gustavo Rojas Pinilla Energy Consumption

San Andres Airport Gustavo Rojas Pinilla Energy Consumption				
Reading Date	**Reading taken (kWh)**	**Billed reading (kWh)**	**Consumption Charged (kWh)**	**Consumption calculated by**
1/01/2025	0.0	17051.0	267.762	Reading Taken
1/12/2024	16929.3	16929.3	241.674	Reading Taken
1/11/2024	0.0	16919.4	280.364	Individual average
1/10/2024	16692.0	16692.0	269.552	Reading Taken
1/09/2024	16569.5	16569.5	294.384	Reading Taken
1/08/2024	16435.7	16435.7	286.154	Reading Taken
1/07/2024	16305.6	16305.6	279.906	Reading Taken
1/06/2024	39364.1	16178.4	283.096	Reading Taken
1/05/2024	16049.7	16049.7	269.170	Reading Taken
1/04/2024	15927.4	15927.4	272.448	Reading Taken
1/03/2024	15803.5	15803.5	253.946	Reading Taken
1/02/2024	15696.9	15688.1	240.660	Reading Taken
1/01/2024	15578.7	15578.7	254.364	Reading Taken

6.2. Providencia Airport El Embrujo Energy Consumption

El Embrujo Airport in Providencia has a considerably smaller footprint and lower passenger throughput than its counterpart in San Andrés, resulting in significantly reduced energy demands. Despite its limited size, the airport plays a crucial role in regional connectivity and must remain operational throughout the year.

The table below details monthly electricity consumption (in kWh) at El Embrujo Airport from January 2024 to January 2025. While certain anomalies in meter readings indicate occasional discrepancies, the overall trend demonstrates minimal energy consumptionhighlighting the feasibility of powering this airport with a small-scale renewable system with a hybrid configuration, (SOPESA, 2025) [26].

Table 6.2: Providencia Airport El Embrujo Energy Consumption

Providencia Airport El Embrujo Energy Consumption				
Reading Date	**Reading taken (kWh)**	**Billed reading (kWh)**	**Consumption Charged (kWh)**	**Consumption calculated by**
01/01/2025	0.0	198.0	3.920	Reading Taken
01/12/2024	627.0	2.0	12.540	Reading Taken
01/11/2024	526.0	82.5	5.984	Individual average
01/10/2024	413.0	73.4	2.873	Reading Taken
01/09/2024	289.7	69.1	7.145	Reading Taken
02/08/2024	0.0	58.3	6.591	Reading Taken
02/07/2024	0.0	48.3	6.284	Reading Taken
01/06/2024	38075.0	38.8	8.415	Reading Taken
02/05/2024	0.0	26.0	4.097	Reading Taken
01/04/2024	0.0	19.0	12.564	Reading Taken
02/03/2024	0.0	4812.0	591	Reading Taken
01/02/2024	4221.0	4221.0	102	Reading Taken
02/01/2024	0.0	4119.0	88	Reading Taken

7

Research Objectives and Questions

This chapter outlines the guiding objectives and research questions underpinning the feasibility study of clean energy implementation at San Andrés and Providencia airports. The research focuses on evaluating hybrid renewable energy systems, specifically the integration of solar and wind power to support aircraft operations and enhance energy efficiency at airport terminals in island environments.

Considering the environmental sensitivity, energy vulnerability, and geographical isolation of the archipelago, understanding the practical viability of clean energy infrastructure is relevant both regionally and globally. This research not only addresses engineering feasibility but also examines economic, environmental, and policy aspects. Such a multi-faceted approach ensures that the proposed clean energy transition can be implemented sustainably and effectively in Small Island Developing States (SIDS) like San Andrés and Providencia.

The study adopts a systems-based perspective and employs a combination of empirical data analysis, simulation modelling, and stakeholder consultation to evaluate the deployment of hybrid systems. The subsequent sections outline the general and specific objectives of the study and clarify the research questions that will direct further investigation.

7.1. Research Objectives

7.1.1. The main research objective is:

- To evaluate the technical, economic, and environmental feasibility of implementing a hybrid solar-wind energy system to support airport operations and enhance energy efficiency in airport terminals on the islands of San Andrés and Providencia.

7.1.2. Specific Objectives:

1. Assess the potential of solar and wind energy resources for electricity generation in San Andrés and Providencia.
2. Determine the current and projected energy consumption patterns at both airports.
3. Simulate and compare solar and wind energy system configurations using optimisation models.
4. Evaluate the economic viability and environmental benefits of implementing solar and wind energy in San Andrés and Providencia.
5. Identify regulatory, technical, and operational barriers to the deployment of hybrid systems and propose strategies for mitigation.

7.2. Research Questions

7.2.1. Primary Research Question:

- How feasible is it to implement a hybrid solar-wind energy system at San Andrés and Providencia airports to support aircraft operations and increase terminal energy efficiency?

7.2.2. Sub-questions

- What is the monthly and annual solar and wind energy potential available in the San Andrés and Providencia regions?
- What are the current energy consumption patterns and peak demand times at both airports?
- What system configuration (solar-wind ratio, storage capacity) is most optimal for each airport using energy modelling tools?
- How do the life-cycle costs and emission reductions of the hybrid system compare to the existing diesel-based system?
- What are the main technical, regulatory, and financial challenges to implementing renewable energy in Gustavo Rojas Pinilla and El Embrujo Airports?
- What strategies can be employed to overcome identified barriers and enable the long-term sustainability of clean energy infrastructure in San Andres and Providencia Airports?

8

Methodology

This chapter outlines the methodological framework employed to assess the feasibility of implementing hybrid clean energy systems specifically solar and wind technologies at the Gustavo Rojas Pinilla and El Embrujo Airports in San Andrés and Providencia. Given the unique energy challenges faced by insular airport infrastructures, a robust methodology integrating empirical data, simulation modeling, stakeholder input, and economic and environmental analysis is essential.

The study employs a mixed-methods approach, integrating quantitative techniques (such as technical and economic simulation, as well as environmental impact assessment) with qualitative methods (including stakeholder interviews and surveys) to provide a comprehensive and multidisciplinary analysis. Its aim is to assess system performance under realistic conditions, foresee operational and policy challenges, and propose actionable strategies for transitioning to clean airport energy systems in Small Island Developing States (SIDS).

8.1. Data Collection and Analysis:

This section outlines the types of data collected and the analytical techniques used. Data were obtained from national and local authorities, meteorological stations, airport operations, and energy utilities.

- Meteorological data (solar irradiation, wind speed/direction, sunshine duration) were gathered from IDEAM reports and airport weather stations to evaluate renewable resource potential.
- Electricity consumption records from 2024 to 2025 will be analysed to comprehend energy demand patterns and peak loads at the airport. If necessary, the analysis can be supplemented by the consumption profiles of other airports with similar characteristics.
- Economic data (diesel prices, energy tariffs, equipment costs) were obtained from utility bills and public procurement records.

These datasets serve as the empirical foundation for modelling the hybrid energy systems in the sections that follow.

8.2. Simulation and Modeling:

Energy modeling software will be used to simulate the performance of the hybrid solar-wind energy system under various scenarios. The simulations will consider different system configurations, energy storage options, and operational conditions.

To evaluate the technical and economic performance of clean energy solutions, this section implements energy system simulation tools. The following steps define the modelling methodology:

- A modelling software will be used to simulate the performance of the hybrid solar-wind energy system under various scenarios.
- Integration of meteorological data with current airport demand profiles to ascertain optimal system configurations (e.g., photovoltaic sizing, wind turbine selection, battery capacity).
- Comparative scenario analysis to evaluate diesel, solar, wind, and hybrid systems in terms of cost, reliability, and emissions.

This modelling approach guarantees precise predictions of system viability and financial sustainability.

8.3. Stakeholder Interviews and Surveys

Understanding local needs, operational constraints, and policy gaps is critical to successful implementation. This section describes the qualitative component of the methodology:

- Structured interviews with airport authorities (Aerocivil), local utility providers, and civil aviation regulators will gather technical constraints and regulatory limitations.
- Surveys conducted with local stakeholders, including tourism representatives and community leaders, will evaluate public perception, energy security concerns, and their willingness to adopt clean technologies.

The qualitative insights will guide policy recommendations and emphasise social considerations essential for project success.

9

Expected Outcomes

This section outlines the expected outcomes of the feasibility study evaluating hybrid clean energy systems, specifically solar and wind, to support airport operations in San Andrés and Providencia. Based on thorough data analysis, simulation, and stakeholder engagement, these results aim to guide energy policy, infrastructure design, and sustainability practices within the aviation sector, particularly for Small Island Developing States (SIDS).

The findings of this research will serve multiple purposes:

- Validate the technical viability of integrating renewable energy at island airports.
- Quantify potential reductions in operational costs and greenhouse gas emissions.
- Provide strategic recommendations for policy frameworks and infrastructure development.
- Contribute academically to the growing body of literature on sustainable aviation and energy transition in isolated territories.

9.1. Feasibility Assessment:

The research will offer a thorough evaluation of the technical and economic feasibility of deploying a hybrid solar-wind energy system at San Andres and Providencia airports, and it will include:

- Assessment of resource availability (solar irradiation, wind speed)
- Capacity for energy generation compared to current demand profiles at both airports
- Compatibility with current airport infrastructure
- Energy reliability and resilience in insular conditions

9.2. Design and Deployment Strategy:

A proposed system design will be created, considering local environmental, regulatory, and logistical constraints.

Deliverables may include:

- Optimal hybrid configurations (solar: wind and diesel ratios):
- Recommended sites for PV panels or wind turbines on airport premises
- Requirements and sizing for battery storage
- Deployment timeline with a phased implementation plan

This subsection will also ensure that the system architecture aligns with the available energy optimisation tools, as discussed in Chapter 10.

9.3. Environmental and Economic Benefits:

The research will quantify the potential of the positive impacts of renewable integration, focusing on:

- **CO Emission Reductions:** Comparing baseline diesel emissions with hybrid system projections.
- **Economic Savings:** Including levelized cost of electricity (LCOE), and payback period (PBP).
- **Operational Efficiency:** Reduced dependency on fuel imports and increased resilience during supply chain disruptions.

9.4. Policy and Regulatory Recommendations:

Recommendations for policy and regulatory frameworks to support the adoption of clean energy solutions in aviation will be provided.

Key considerations:

- Incentive structures for the adoption of renewable energy technologies.
- Safety and technical regulations, particularly concerning the installation of wind turbines near flight paths.
- Institutional frameworks required for financing and implementation.

Outcomes include:

- Policy briefs recommendations
- Risk and compliance frameworks
- Proposals for integration with national energy goals and ICAO climate targets.

10

Optimization Methods

Hybrid Renewable Energy Systems (HRES) offer a sustainable and cost-effective solution for integrating multiple renewable energy sources, such as solar, wind, and hydrogen. However, their efficiency and feasibility depend on proper system sizing and optimization. (Ammari, Belatrache, Touhami, & Makhloufia, 2022) [3], present a comparative analysis for optimizing and sizing hybrid renewable energy systems, various optimization algorithms and sizing methodologies have been developed to enhance the performance and economic viability of HRES.

10.1. Comparative Evaluation of Sizing Methods

Sizing methods for hybrid renewable energy systems fall into two broad categories:

10.1.1. Software-Based Sizing

- HOMER: A widely used tool that provides economic, technical, and environmental analysis, but its optimization capabilities are limited to simplified linear models.
- RETScreen: Offers meteorological data and financial evaluation, making it useful for preliminary assessments but lacking advanced probabilistic optimization.
- iHOGA: Uses multi-objective optimization but is constrained by a 10 kW load limit.
- TRNSYS: Offers high precision in system simulation, but lacks built-in optimization features.

10.1.2. Traditional Sizing Methods

- Analytical Method: Provides rapid sizing but is limited in flexibility.
- Iterative Approach: Uses recursive calculations but ignores some dynamic system parameters.
- Probabilistic Method: Accounts for uncertainties in renewable energy availability, but does not simulate dynamic system performance.
- Artificial Intelligence Methods: Used for complex and multi-objective optimization problems, but requires high computational resources.

The study concludes that AI-based methods provide the most accurate sizing results, while software-based methods such as HOMER and RETScreen offer practical solutions for real-world applications (Ammari et al., 2022) [3].

10.1.3. Optimization Algorithms for HRES

Optimization techniques are crucial for ensuring cost efficiency, reliability, and system resilience in hybrid energy systems, (Ammari et al., 2022) [3], classify optimization methods into three categories:

1. **Classical Optimization Methods**
    - Linear Programming (LP): Efficient for investment decisions but limited to linear relationships.
    - Mixed Integer Linear Programming (MILP): Commonly used in economic dispatch problems but has computational limitations for large-scale HRES.
    - Dynamic Programming (DP): Suitable for sequential decision-making but can be computationally intensive.
2. **Artificial Intelligence-Based Methods**
    - Genetic algorithm (GA): Mimics natural selection processes and it has been widely applied to hybrid solar-wind-diesel systems, demonstrating concurrent reductions in CO_2 emissions and levelized energy costs [19].
    - Particle Swarm Optimization (PSO): Inspired by swarm intelligence, PSO effectively minimizes life cycle costs (LCC) and optimizes battery storage sizing.
    - Fuzzy Logic Optimization: Used for multi-objective control strategies, offering real-time adaptability in variable renewable energy environments.
3. **Hybrid Optimization Methods**
    - GA-PSO Hybrid Algorithm: Combines evolutionary adaptability of GA with fast convergence of PSO, significantly improving system performance.
    - Simulated Annealing (SA) with Chaotic Search: Minimizes total life cycle costs, making it ideal for off-grid HRES applications.
    - Artificial Neural Networks (ANNs): Applied for predictive modeling in solar-wind hybrid systems, ensuring optimal system reliability and efficiency.

10.2. Comparative Analysis of Optimization Methods

The study compares various optimization techniques based on their efficiency, computational complexity, and application in hybrid energy systems, (Ammari et al., 2022) [3].

Table 10.1: Comparative Analysis of Optimization Methods

Optimization Method	**Objective**	**Advantages**	**Drawbacks**
Genetic Algorithm (GA)	Cost & Emission Reduction	Effective for multi-objective optimization	Computationally intensive
Particle Swarm Optimization (PSO)	Minimize LCC	Fast convergence, handles complex systems	Requires parameter tuning
Simulated Annealing (SA)	Minimize Total Life Cycle Cost	Avoids local optima, efficient for cost minimization	Slow convergence
Hybrid GA-PSO	Optimize Sizing & Reliability	Combines advantages of GA & PSO	High computational demand
Artificial Neural Networks (ANNs)	Predictive Load Management	Adaptive learning, useful for demand forecasting	Requires large training datasets

Considering the requirements for the Feasibility of hybrid systems utilising clean energy to support aircraft operations and Enhance Energy Efficiency within Airport Terminals for San Andrés and Providencia, classical optimisation methods appear to be the most suitable approach. These methods have been widely used in energy system design, investment decision-making, and operational optimisation, ensuring proven reliability, stability, and practical application in airport settings.

The selection of the specific optimisation method, such as Mixed-Integer Linear Programming (MILP), depends on the nature of the model, whether it is linear, involves discrete variables, or requires combinatorial decisions. Given the experience with classical optimisation approaches in real-world airport energy projects, their use in this research will facilitate effective cost modelling, power flow optimisation, and grid stability analysis while maintaining computational efficiency.

11

Significance of the Research

This research primarily focuses on evaluating the feasibility of implementing hybrid solar-wind energy systems at Gustavo Rojas Pinilla Airport in San Andrés and El Embrujo Airport in Providencia, Colombia. These two insular airports are essential for regional connectivity, economic development, and emergency response. However, both depend heavily on diesel-based energy systems, which are expensive, carbon-intensive, and susceptible to fuel supply disruptions due to their geographic isolation.

The significance of this study lies in its direct contribution to improving the sustainability, energy resilience, and operational efficiency of airport infrastructure in remote island environments. By utilising real-world meteorological data, energy consumption records, and simulation tools, this research provides site-specific solutions to decarbonise ground operations and minimise the environmental impact of aviation activities in San Andres and Providencia.

Although the primary focus is on San Andrés and Providencia, the findings and methodologies developed in this study can serve as a reference model for Small Island Developing States (SIDS) worldwide. These nations face similar challenges, such as energy dependence, exposure to climate risks, and limited access to diverse energy sources. Consequently, the results of this research may inform clean energy strategies for island airports globally, contributing to broader efforts in climate change mitigation, energy transition, and sustainable development.

11.1. Contribution to Clean Energy and Aviation Sectors

This study assesses the transition to clean energy at the intersection of aviation infrastructure and island energy systems. It contributes by:

- Providing a proof of concept for the adoption of hybrid energy in small regional airports.
- Providing a scalable framework for clean energy adoption in other SIDS and comparable island settings.
- Demonstrating how airport electrification can underpin wider national commitments to climate targets and energy independence.

11.2. Academic and Theoretical Relevance

From an academic perspective, this research:

- Enhances the interdisciplinary literature on renewable energy integration, airport systems, and island sustainability.
- Supports the theory of energy resilience, particularly in remote and vulnerable areas.
- Expands knowledge on hybrid optimisation methods by applying practical simulations and life-cycle assessments in real-world case studies.

11.3. Socioeconomic and Environmental Impact

The proposed research offers potential long-term benefits, which include:

- Reduced carbon emissions in aviation-related operations.
- Achieved operational cost savings due to a decreased reliance on diesel imports.
- Created jobs and built capacity through the installation and maintenance of renewable infrastructure.
- Enhanced energy security for local communities and critical infrastructure.

11.4. Policy and Global Development Alignment

This research aligns with several global and regional frameworks, including:

- United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 13 (Climate Action), and Goal 9 (Industry, Innovation, and Infrastructure).
- ICAOs global aviation climate targets, including the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).
- Colombias Nationally Determined Contributions (NDCs) under the Paris Agreement.

The outcomes will be beneficial for policymakers developing regulatory frameworks to support clean energy transitions in island aviation sectors.

12

Conclusion

The proposed research aims to explore the feasibility of implementing hybrid renewable energy systemsspecifically solar and windat Gustavo Rojas Pinilla Airport (San Andrés) and El Embrujo Airport (Providencia). The study addresses the urgent need for sustainable energy transitions in Small Island Developing States (SIDS), where energy insecurity, environmental vulnerability, and high operational costs persist. By utilising abundant solar resources and wind energy, the hybrid system could provide an innovative solution to reduce the carbon footprint and enhance the resilience of aviation infrastructure in these regions. This research will contribute to sustainable aviation practices and offer a pathway for island regions to achieve their clean energy goals. It can be applied to other Caribbean and Pacific Islands or countries worldwide.

By concentrating on these two insular airports in Colombia, this research adopts a multidisciplinary approach, merging technical simulations, environmental assessments, and stakeholder perspectives to ascertain the feasibility of clean energy alternatives. The results contribute to the expanding academic and policy-oriented dialogue on sustainable aviation, particularly in remote and ecologically sensitive areas.

This research purpose is to confirm that transitioning to hybrid, clean energy systems at San Andrés and Providencia airports is not only feasible but highly beneficial. As Colombia strives toward its environmental commitments, these airports could serve as national and international models for sustainable air transportation in SIDS. Implementing such systems would not only reduce emissions but also strengthen the energy resilience and self-sufficiency of island airportsushering in a new era of cleaner, smarter, and more sustainable aviation.

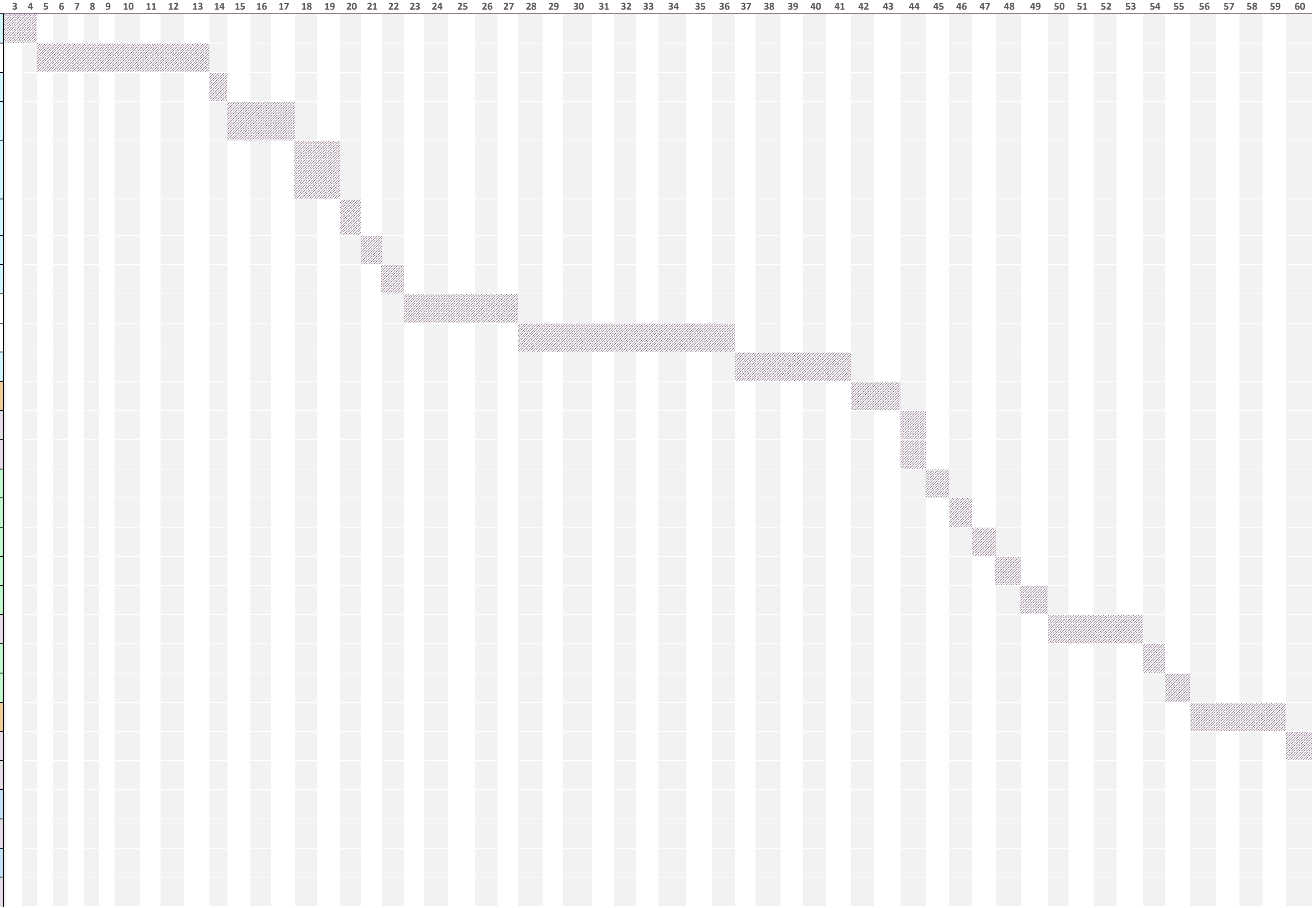
Appendix A: Master Thesis Project Planning

The Master Thesis Project Planning is presented on the next page

Thesis Project Planning

▨ Plan Duration

Start Date	ACTIVITY	PLAN START (WEEK)	PLAN DURATION (WEEKS)
29/05/2024	Define problem topic	1	4
01/07/2024	Summer Break	5	9
10/09/2024	Develop prelim. research question	14	1
17/09/2024	Literature study - identify gaps in the literature	15	3
09/10/2024	LS - Investigate in depth existing approaches for self-sustainable Airports	18	2
23/10/2025	Develop research question, objective, scope	20	1
30/10/2024	Develop methodology	21	1
06/11/2024	Update planning	22	1
13/11/2024	Sick	23	5
20/12/2024	Break Winter	28	9
17/02/2025	Write Literature Study - draft, feedback	37	5
24/03/2025	Literature study - hand-in	42	2
10/04/2025	Kick-off Meeting	44	1
10/04/2025	Submit the Kick-off Form	44	1
25/03/2025	Case Study Analysis	45	1
01/04/2025	Technological Assessment	46	1
15/04/2025	Economic Analysis	47	1
05/05/2025	Stakeholder Analysis	48	1
12/05/2025	Generating results	49	1
19/06/2025	Mid-term meeting	50	4
20/06/2025	Sensitivity Analysis	54	1
26/06/2025	Writing conclusion	55	1
22/07/2025	Submit draft Thesis	56	4
28/07/2025	Green light Review	60	1
29/07/2025	Maternity Leave	61	16
17/11/2025	Writing and incorporating feedback	77	1
19/11/2025	Request examination Form AE-3	78	1
03/12/2025	Thesis hand-in	79	2
19/12/2025	Defence	81	3



III

Supporting work

1

Appendix 1: Additional results

This chapter presents a detailed sensitivity analysis of four energy system configurations: *Solar-only* (S), *Wind-only* (W), *Solar + Diesel* (S+D), and *Wind + Diesel* (W+D). Each configuration is evaluated for both airports under study, providing a comprehensive understanding of system performance under varying conditions.

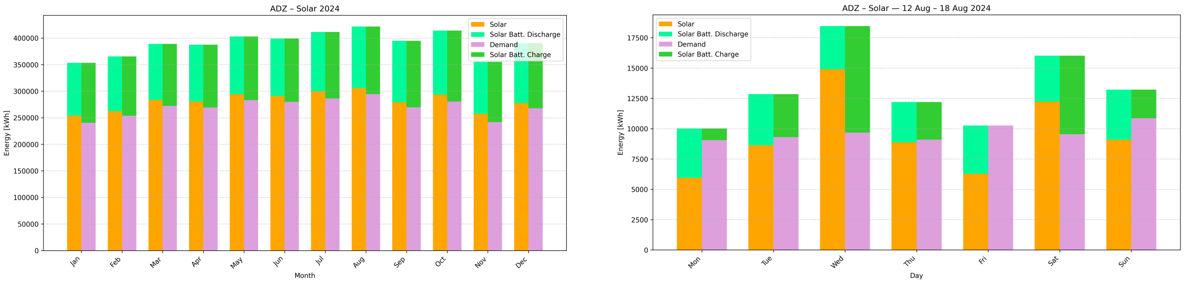
For each configuration and airport, the analysis is structured around three key perspectives:

1. The monthly energy balance for the year 2024,
2. The daily energy balance over the identified peak-demand week, and
3. A detailed assessment of the single most demanding day, including hourly energy dispatch, weather drivers, and battery state of charge (SOC).

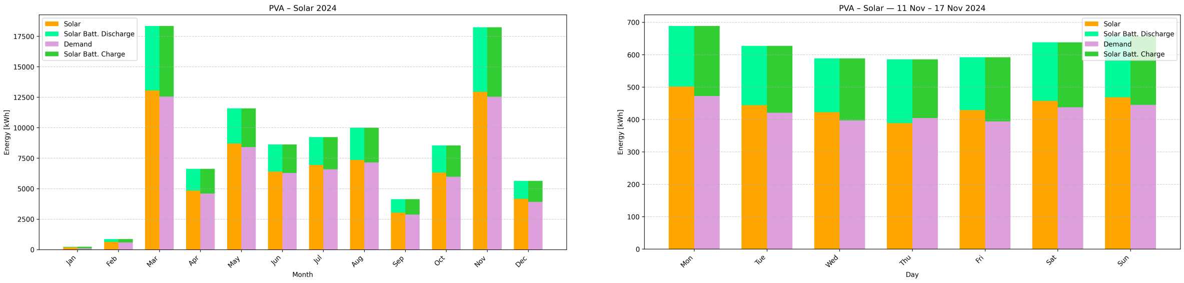
In addition to these performance views, the chapter explores specific model behaviors and sensitivities. This includes an examination of how the system responds to the introduction of new constraints and variables, as well as the implications of these modifications on the results. The discussion is grounded in the underlying mathematical formulation and methodological approach employed in the model, offering insights into both the technical robustness and practical implications of the hybrid energy system design.

1.1. Additional energy configurations

1.1.1. Solar-only configuration (S)

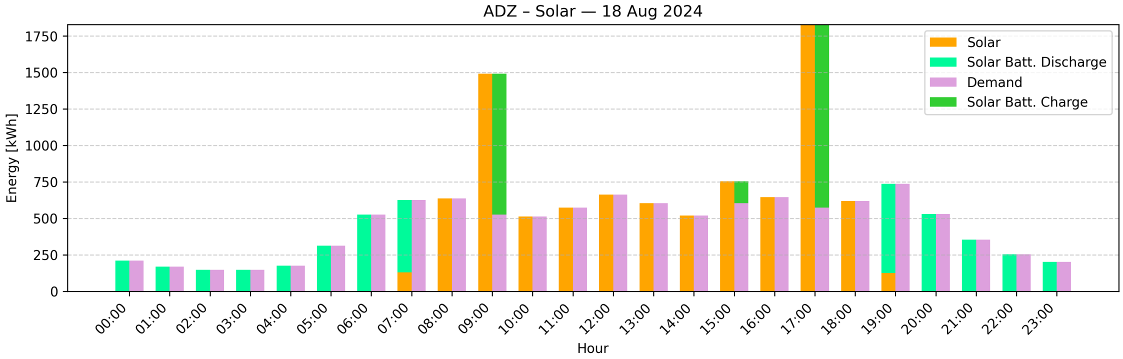


(a) Monthly 2024 - Gustavo Rojas Pinilla (b) Peak week (12-18 Aug) - Gustavo Rojas Pinilla

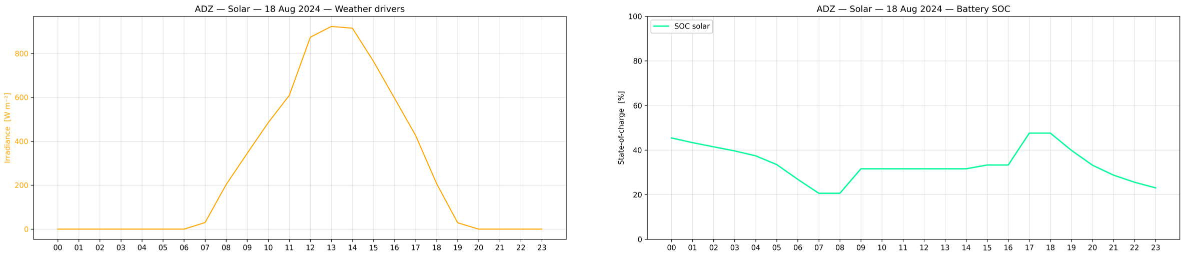


(c) Monthly 2024 - El Embrujo (d) Peak week (11-17 Nov) - El Embrujo

Figure 1.1: Solar-only dispatch results.

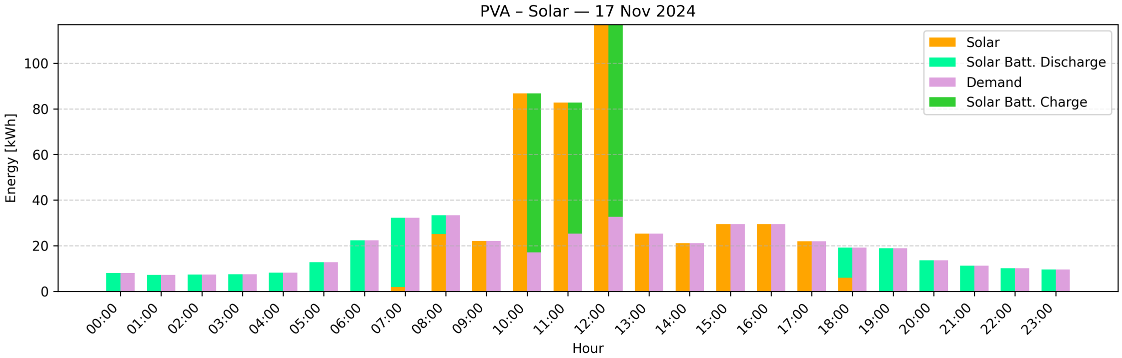


(a) Hourly balance - Gustavo Rojas Pinilla

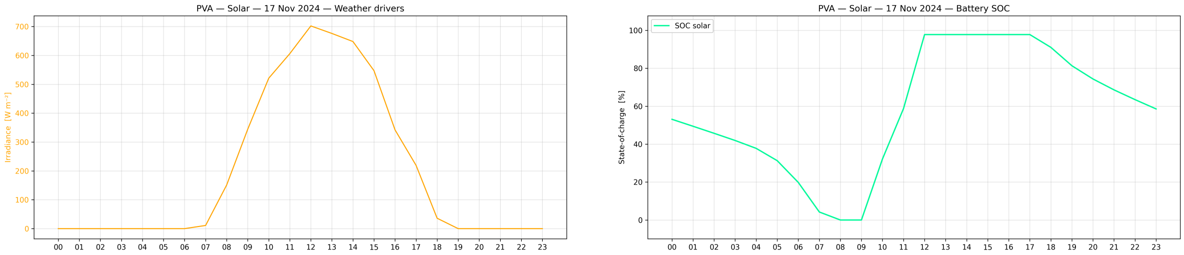


(b) Weather drivers (c) Battery SOC

Figure 1.2: Peak-demand day (15 Aug 2024) at Gustavo Rojas Pinilla Solar-only scenario.



(a) Hourly balance - El Embrujo

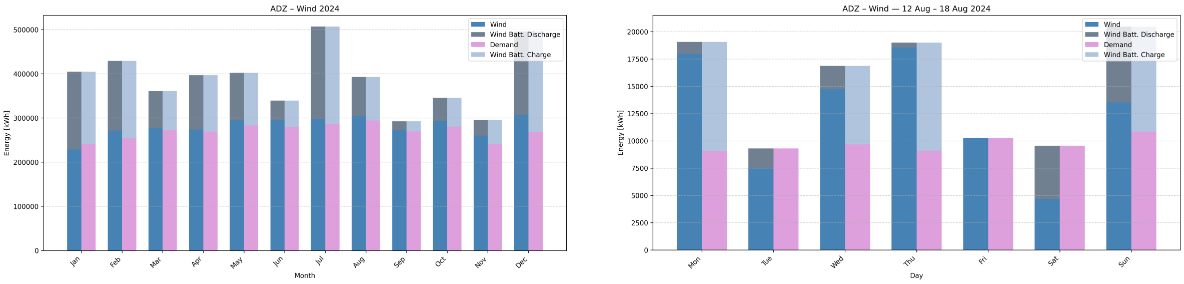


(b) Weather drivers

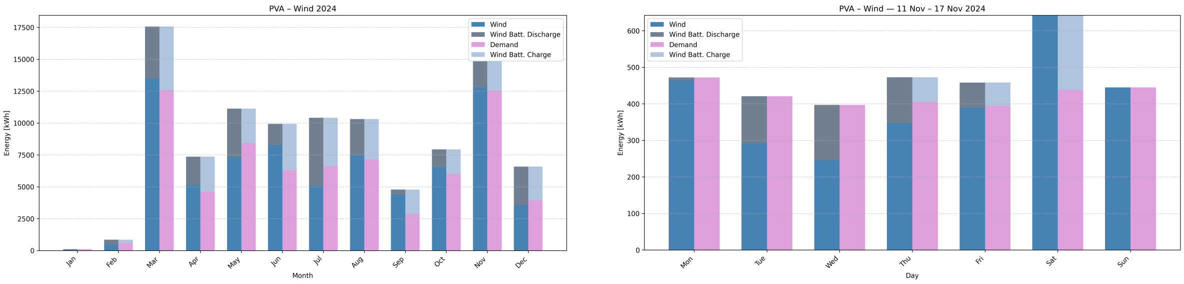
(c) Battery SOC

Figure 1.3: Peak-demand day (17 Nov 2024) at El Embrujo Solar-only scenario.

1.1.2. Wind-only configuration (W)

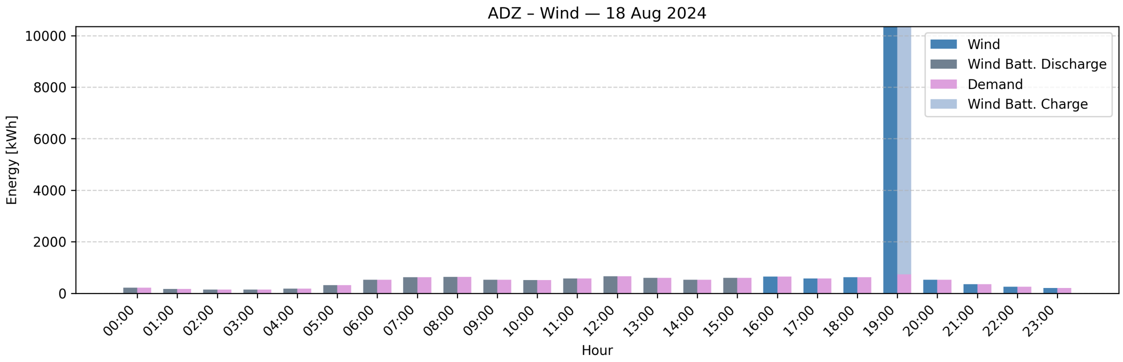


(a) Monthly 2024 - Gustavo Rojas Pinilla
(b) Peak week (12-18 Aug) - Gustavo Rojas Pinilla

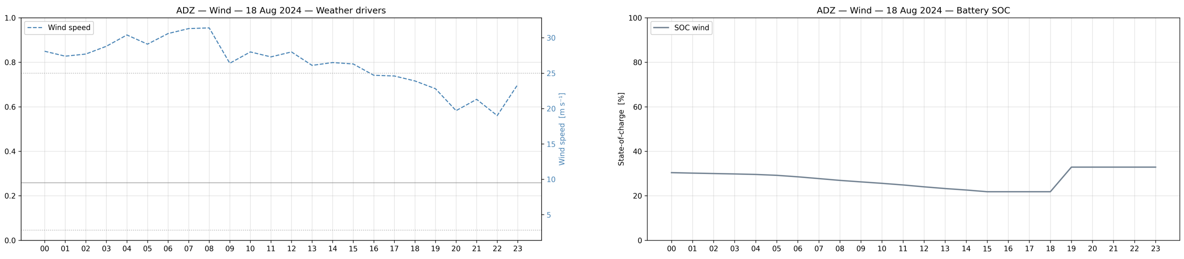


(c) Monthly 2024 - El Embrujo
(d) Peak week (11-17 Nov) - El Embrujo

Figure 1.4: Wind-only dispatch results (diesel disabled).

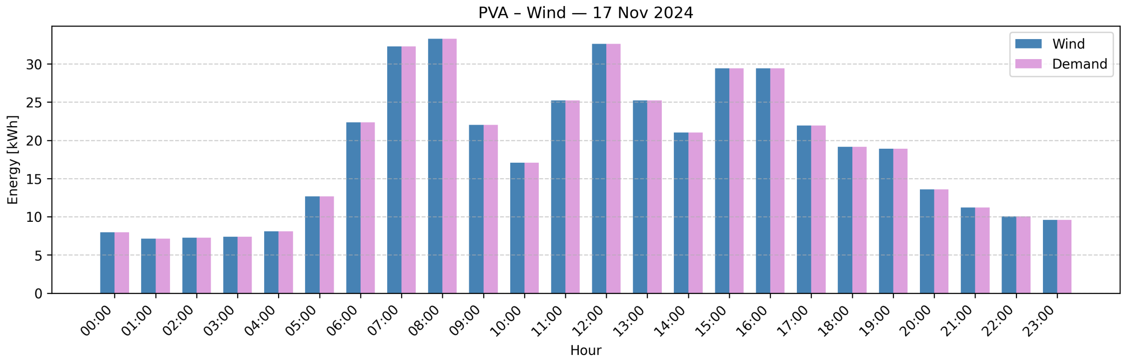


(a) Hourly balance - Gustavo Rojas Pinilla

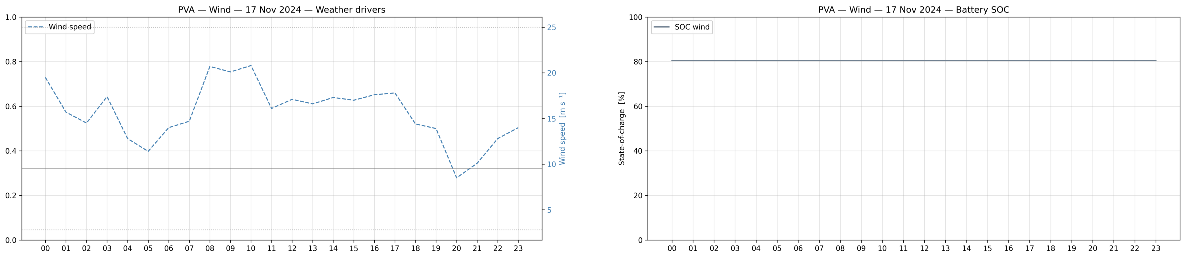


(b) Weather drivers
(c) Battery SOC

Figure 1.5: Peak-demand day (15 Aug 2024) at Gustavo Rojas Pinilla Wind-only scenario.



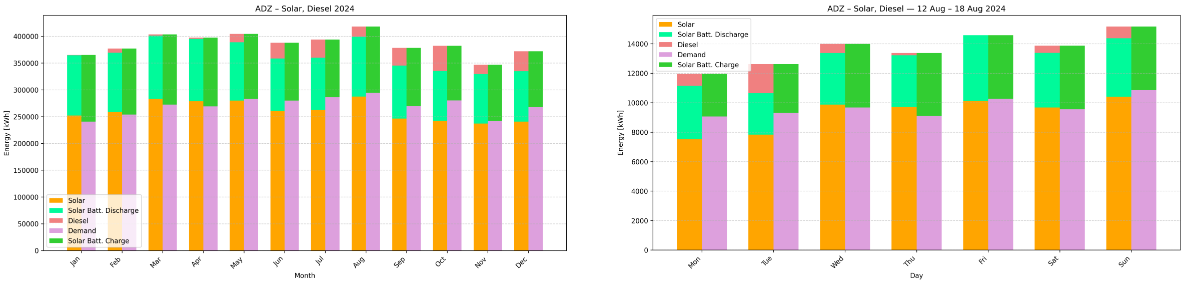
(a) Hourly balance - El Embrujo



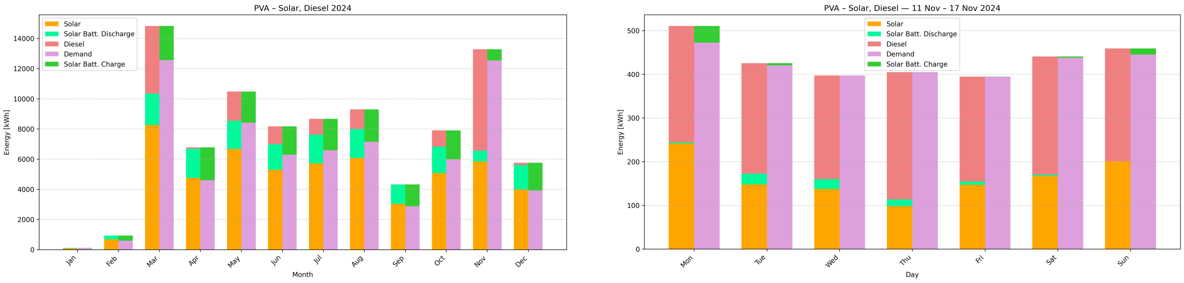
(b) Weather drivers (c) Battery SOC

Figure 1.6: Peak-demand day (17 Nov 2024) at El Embrujo Wind-only scenario.

1.1.3. Solar + Diesel configuration (S+D)

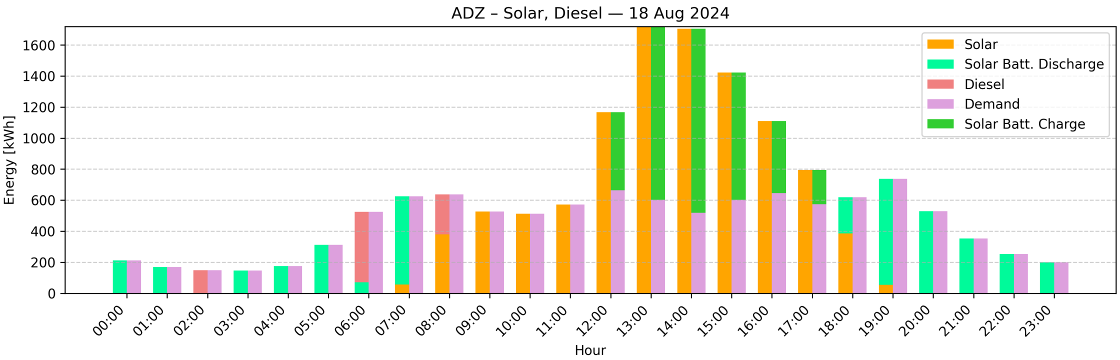


(a) Monthly 2024 - Gustavo Rojas Pinilla (b) Peak week (12-18 Aug) - Gustavo Rojas Pinilla

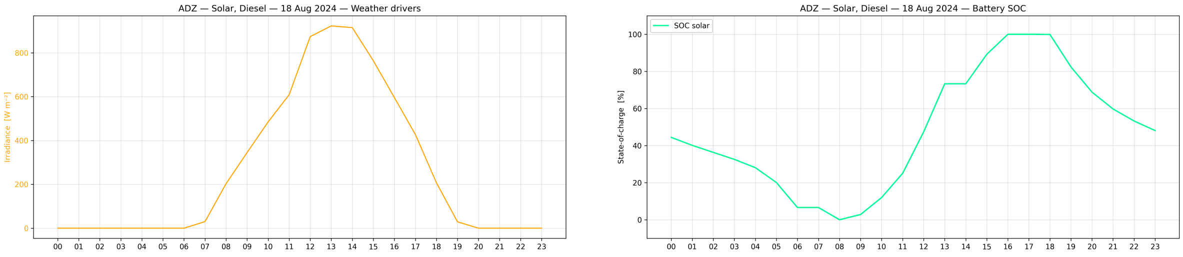


(c) Monthly 2024 - El Embrujo (d) Peak week (11-17 Nov) - El Embrujo

Figure 1.7: Solar + Diesel dispatch results.

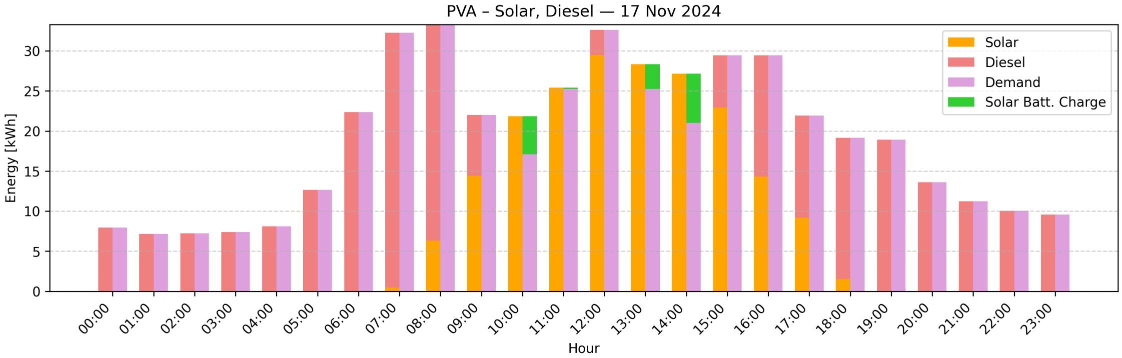


(a) Hourly balance - Gustavo Rojas Pinilla

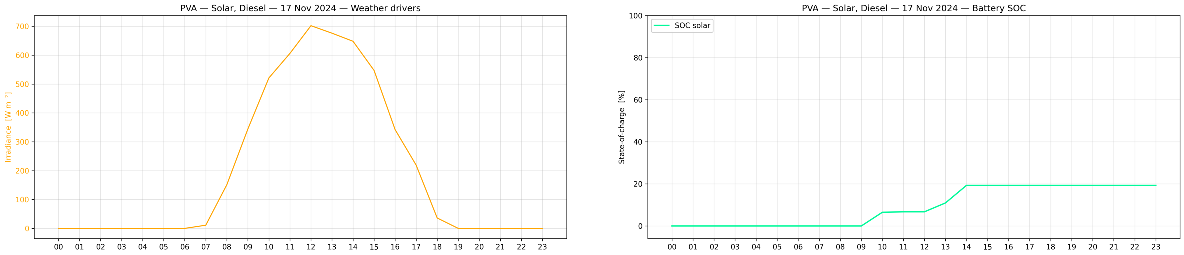


(b) Weather drivers (c) Battery SOC

Figure 1.8: Peak-demand day (15 Aug 2024) at Gustavo Rojas Pinilla Solar + Diesel scenario.



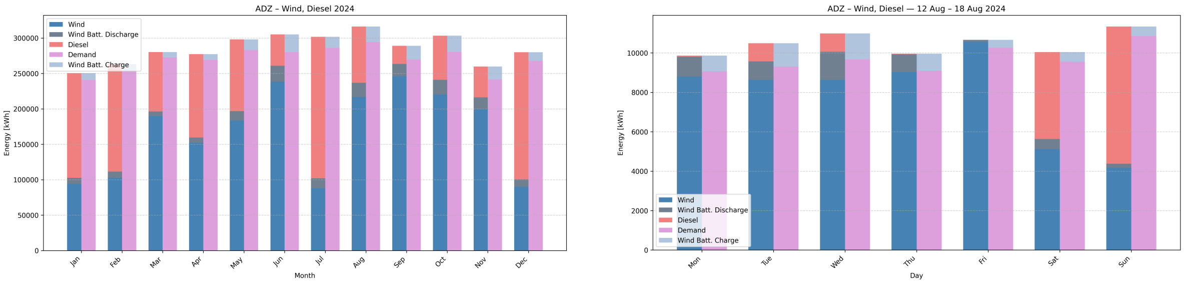
(a) Hourly balance - El Embrujo



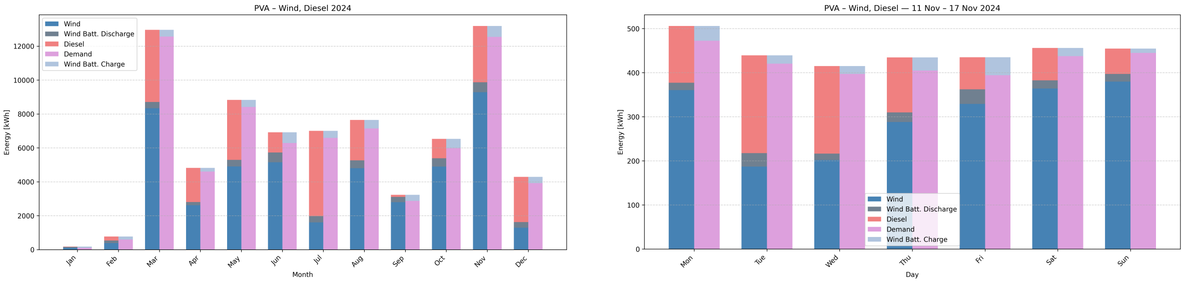
(b) Weather drivers (c) Battery SOC

Figure 1.9: Peak-demand day (17 Nov 2024) at El Embrujo Solar + Diesel scenario.

1.1.4. Wind + Diesel configuration (W+D)

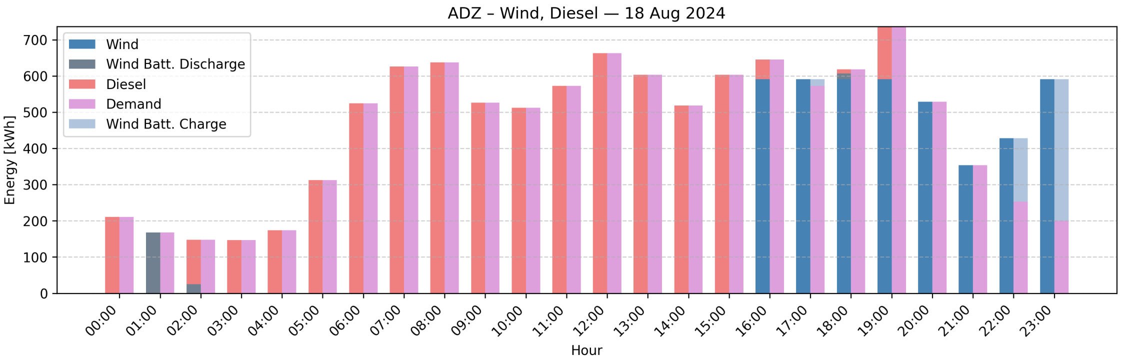


(a) Monthly 2024 - Gustavo Rojas Pinilla (b) Peak week (12-18 Aug) - Gustavo Rojas Pinilla

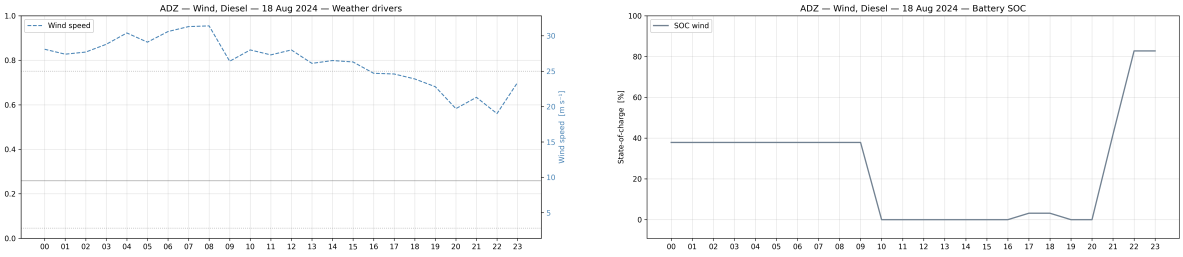


(c) Monthly 2024 - El Embrujo (d) Peak week (11-17 Nov) - El Embrujo

Figure 1.10: Wind + Diesel dispatch results.

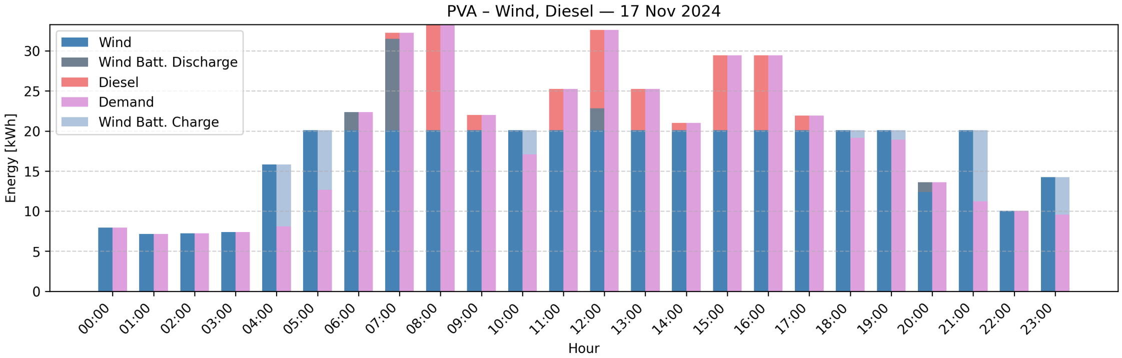


(a) Hourly balance - Gustavo Rojas Pinilla

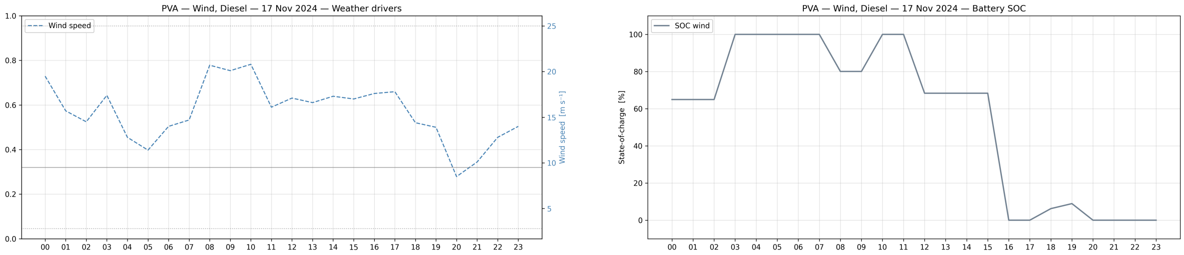


(b) Weather drivers (c) Battery SOC

Figure 1.11: Peak-demand day (15 Aug 2024) at Gustavo Rojas Pinilla Wind + Diesel scenario.



(a) Hourly balance - El Embrujo



(b) Weather drivers

(c) Battery SOC

Figure 1.12: Peak-demand day (17 Nov 2024) at El Embrujo Wind + Diesel scenario.

2

Appendix 2: Code documentation

2.1. Overview

This document describes the structure and functionality of the code used to model and optimise hybrid renewable energy systems (HRES), for small island airports located in (San Andrés and Providencia islands). The implementation is based on the `Pyomo` optimisation library and uses annual hourly-resolution data for weather and demand.

The code base is organised around a main Jupyter notebook, `run_all.ipynb`, and a `src/` package containing the model formulation, configuration data, analysis functions and plotting utilities.

The code is located in: `https://gitlab.tudelft.nl/ato_msc_theses/feasibility-study-of-hybrid-solar-wind-energy-systems-for-sustainable-airport-operations-for-islands/-/tree/51c97905d95a04a0d1b498ae317e878fdf119f3a/`

2.2. Repository Structure

At a high level, the project is organised as:

- **run_all.ipynb**: main entry point that runs the full pipeline.
- **src/**: Python package with the model and utilities:
    - `config.py`: configuration and techno-economic data.
    - `model.py`: Pyomo optimisation model.
    - `analysis.py`: post-processing, KPIs and scenario logic.
    - `plot_functions.py`: all plotting and figure generation.
    - `utils.py`: various helper functions.
- **data/**: input data (weather, demand, flights, etc.).
- **runs/**: outputs of each pipeline run, containing:
    - `figures/`: PNG figures for each site and scenario.
    - `artifacts/`: per-scenario time series and artefacts.
    - `summaries/`: roll-up Comma-Separated Values (CSV) tables across all scenarios.

Each run is stored in a subfolder `runs/<run_name>/`, so different cases (e.g. with/without battery simultaneity constraints) can be compared.

2.3. Main Notebook: `run_all.ipynb`

The notebook acts as the driver for the full analysis.

2.3.1. Imports and Setup

The first cell imports:

- Site configuration and techno-economic parameters from `src.config`.
- Plotting functions from `src.plot_functions`.
- Analysis utilities from `src.analysis`.
- Path helpers from `src.utils`.
- The optimisation model builder and solver from `src.model`.

2.3.2. Function `run_scenario`

The function `run_scenario` executes the full pipeline for a single combination of:

- Site (e.g. San Andrés, Providencia),
- Weather and demand data,
- A technology combination (solar, wind, diesel),
- A set of constraint flags.

The steps are:

1. Construct human-readable and file system labels for the scenario from the technology combination.
2. Choose the initial battery state of charge (SOC) based on the combination, for (pure-renewable cases use a fixed SOC, others use the common initial SOC).
3. Call `optimize_or_read` to either:
    - build and solve the Pyomo model using the given weather, demand, flags and parameters (mode `"optimize"`), or
    - verify that a previous solution exists (mode `"read"`).
4. Build the energy time-series dataframe `df_energy`, which contains columns such as demand, solar and wind generation, diesel generation and battery charge/discharge flows.
5. Compute cost components (CAPEX, diesel OPEX, CO_2 penalty) and the total objective value.
6. Compute battery key performance indicators (cycles per year, average SOC) when batteries are present.
7. Compute physical sizing (number of PV panels, wind turbines, battery racks and associated areas).
8. Compute battery and renewable utilisation statistics, including renewable potential, actual generation, and unused potential.
9. Build potential time series for solar and wind based on the installed capacities.
10. Generate all scenario-specific figures (energy bar plots, SOC and weather plots, potential vs utilised plots, pie charts).
11. Save per-scenario CSV files (energy, costs, KPIs, sizing) in the corresponding subfolder

    under `runs/<run_name>/artifacts/`.

2.3.3. Function `run_pipeline`

The function `run_pipeline(mode="optimize", run_name="base", flags=...)` coordinates a full experiment across all sites and technology combinations:

1. Create the run directories under `runs/<run_name>/` (figures, artifacts, summaries).
2. Loop over all sites defined in `SITES`:
   - Read the site-specific weather and demand CSV files.
   - Characterise demand periods (average, high and low months, and peak week/day).
   - Generate site-level weather and demand plots.
3. For each technology combination in `TECH_COMBOS`:
   - Call `run_scenario` and collect the resulting cost, KPI, sizing and battery summaries.
4. Assemble and save global roll-up tables:
   - Cost summary for all scenarios.
   - KPI summary (including battery cycles and SOC).
   - System size summary.
   - Battery and renewable utilisation summary.

The notebook then calls `run_pipeline()` for a baseline run and a second time with modified constraint flags to disable the battery simultaneity constraint (Constraint 7), enabling a direct comparison.

2.4. Configuration: `src/config.py`

The module `config.py` centralises all configuration and techno-economic parameters:

- Colour mappings and aggregation rules used by the plotting functions.
- The master hourly index for the study year (2024) and common filesystem paths.
- Site metadata such as coordinates, monthly energy consumption, plain names, and airport codes.
- Common model parameters used for all scenarios, including:
  - Solar derate factor and temperature coefficient,
  - Wind turbine cut-in, rated and cut-out wind speeds,
  - Battery charge/discharge efficiency,
  - Diesel generator maximum power,
  - Cost coefficients and CO_2 emission factor.
- Sizing constants to translate capacities (kW, kWh) into numbers of panels, turbines and battery racks, and their corresponding areas.
- Binary flags that enable or disable groups of constraints (e.g. cyclic SOC, mutual exclusivity of charge/discharge) and the list of technology combinations explored.

2.5. Optimisation Model: `src/model.py`

The optimisation model is implemented using Pyomo in `model.py`. The main function `build_model` receives weather and demand time series, configuration flags and techno-economic parameters, and constructs a mixed-integer linear programme.

2.5.1. Decision Variables

For each hour of the year, the model decides:

- Solar, wind and diesel generation (kW),
- Battery charge and discharge flows (kW) for separate solar and wind batteries,
- Battery states of charge (kWh).

In addition, the installed capacities of solar PV, wind and batteries are decision variables (kW or kWh).

Binary variables are used to prevent simultaneous charging and discharging when the corresponding constraint is active.

2.5.2. Constraints

The main constraints include:

- Resource availability constraints for solar and wind, based on irradiance, temperature and wind-speed-derived capacity factors.
- Battery state-of-charge dynamics with charge/discharge efficiency and upper bounds.
- Logic constraints that tie charging to available solar or wind generation.
- A diesel capacity constraint limiting maximum diesel output.
- Hourly energy balance: the sum of renewable generation, diesel generation and battery discharges must match demand plus battery charges.
- Mutually exclusive charge/discharge constraints for batteries (if enabled).
- Cyclic SOC constraints to enforce that the final SOC equals the initial SOC.

2.5.3. Objective Function

The objective is to minimise the sum of:

- Capital expenditure (CAPEX) for installed capacities,
- Diesel fuel operating costs (OPEX),
- A cost term proportional to diesel-related CO_2 emissions.

Technology-availability switches allow the same model to represent different combinations of solar, wind and diesel by fixing variables and deactivating constraints.

2.6. Analysis and KPIs: `src/analysis.py`

The module `analysis.py` provides functions to:

- Characterise representative periods (average, high and low months; peak week and peak day).
- Convert Pyomo variables into pandas time series and build the combined energy dataframe joining demand, generation and battery flows.
- Compute cost components: total cost, CAPEX by technology, diesel OPEX and CO_2 penalties.
- Derive battery key performance indicators such as cycles per year and average SOC.
- Translate capacities into numbers of physical components and land requirements.
- Reconstruct solar and wind potential from the weather data and compute unused renewable energy.

These functions are used by `run_scenario` and `run_pipeline` to populate the per-scenario CSV files and the global summary tables.

2.7. Plotting: `src/plot_functions.py`

The module `plot_functions.py` contains all figure-generation code. It includes:

- Monthly, weekly and daily bar plots of energy balances, with an option to display supply and demand sides in a balanced stacked format.
- Peak-week line plots of generation and demand.
- Plots of daily battery SOC together with irradiance and wind speed.
- Monthly and period-specific plots comparing renewable potential vs utilised energy.
- Pie charts showing the contribution of each source and battery discharge to total energy supplied.

Site-level plots visualise weather and demand characteristics, while scenario-level plots show how each technology configuration operates over representative periods.

2.8. Utilities: `src/utils.py`

The `utils.py` module provides small utilities that are reused across the code base:

- Safe extraction of numerical values from Pyomo components.
- Conversion of Pyomo variables into pandas Series indexed with the master hourly index.
- Helper functions to force time series to date-time indices, and to resample from hourly to daily resolution.
- Functions to build consistent file system paths for sites and scenarios.
- Small formatting helpers, such as creating human-readable week labels and compact scenario tags.

2.9. How to Run the Pipeline

To reproduce the optimisation runs:

1. Place the required weather and demand CSV files in the expected locations (using the plain site names specified in `config.py`).
2. Open `run_all.ipynb` in a Jupyter environment where all Python dependencies (including `Pyomo` and the chosen solver) are installed.
3. Execute the cells defining `run_scenario` and `run_pipeline`.
4. Call `run_pipeline()` for the baseline case, and, if desired, additional calls with modified constraint flags or run names to generate alternative scenarios.

The resulting figures and summary tables will be stored under `runs/<run_name>/`.

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