Energy Conversion and Management: X 31 (2026) 102101

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Long-term decarbonization pathways for Cuba's electricity sector: a scenario-based analysis to 2050

Ernesto Carlos Casals Cunill [a,*], Carlos Alberto Masip Rodríguez [a], Leonardo Peña Pupo [b], Electo Eduardo Silva Lora [a], Osvaldo José Venturini [a], Adeoye Olasunkanmi Opelowa [a], René Lesme Jaén [a]

[a] Postgraduate Program in Energy Engineering, Excellence Group in Thermal Power and Distributed Generation-NEST, Federal University of Itajuba, Itajuba 37500-903, Brazil

[b] Finland Futures Research Centre (FFRC), Turku School of Economics, University of Turku, Turku 20014, Finland

ARTICLE INFO

Keywords:
Electricity sector
Decarbonization pathways
Renewable energy sources
Transport electrification
Island energy metabolism

ABSTRACT

The Republic of Cuba faces a critical energy trilemma characterized by severe reliance on imported fossil fuels and an obsolete electricity generation infrastructure. Addressing this challenge, this study evaluates long-term decarbonization pathways exclusively for Cuba's electricity sector from 2024 to 2050 using the Low Emissions Analysis Platform (LEAP). To improve methodological transparency, LEAP was configured using 2024 as the base year, with demand projections, generation capacity expansion, storage deployment, fuel-price assumptions, technology costs, and emissions factors represented across three scenarios. The assessment formally defines three structural frameworks: a policy-continuity baseline based on current governmental targets, a flexibility-oriented decarbonization pathway, and a 100 % renewable electricity scenario. Results indicate that while the policy-continuity scenario achieves a 35 % renewable generation share, its reliance on a conventional thermal baseload triggers a late-term emissions rebound, peaking at 12.82 million metric tons of CO_2-eq by mid-century. Conversely, the flexibility-oriented pathway appears to be the most cost-effective option. By capping thermal capacity at 1,500 MW and deploying large-scale energy storage, it reduces emissions by 67 % to 4.21 million metric tons of CO_2-eq and lowers annual production costs by approximately 200 million USD. Furthermore, sensitivity analyses demonstrate this flexible architecture is highly resilient to demand fluctuations. Although the 100 % renewable pathway suggests absolute electricity-sector carbon neutrality is technically achievable, its requirement for a 6,733 MW biomass scale-up introduces major capital and land-use conflicts. Ultimately, this research indicates that deep decarbonization could be an economically advantageous strategy,

Abbreviations: BAG, Bagasse; BESS, Battery Energy Storage Systems; BEVs, Battery Electric Vehicles; CAPEX, Capital Expenditure; CRUI, Imported Crude Oil; CRUN, National/Domestic Crude Oil; CSP, Concentrated Solar Power; DEMNONRES, Non-Residential Electricity Demand (Commercial, Industrial, and Public Services); DEMRES, Residential Electricity Demand; DEMTRAN, Transport Sector Electricity Demand; DG, Distributed Generation; DIST, Electricity Distribution; DSL, Diesel; EVs, Electric Vehicles; GDP, Gross Domestic Product; GHG, Greenhouse Gas; GOV, Governmental Scenario; GW, Gigawatt; GWP, Global Warming Potential; IDE, Ideal Scenario; IEA, International Energy Agency; kWh, Kilowatt-hour; LEAP, Low Emissions Analysis Platform; MINBIO, Biomass Resource Availability; MINCRU, Domestic Crude Oil Extraction; MINHYD, Hydropower Resource Availability; MINNGS, Domestic Natural Gas Extraction; MINSUN, Solar Energy Resource Availability; MINWIND, Wind Energy Resource Availability; MW, Megawatt; NGS, Natural Gas; O&M, Operations and Maintenance; OPEX, Operational Expenditure; OTEC, Ocean Thermal Energy Conversion; PHES, Pumped Hydroelectric Energy Storage; PNDES 2030, National Plan for Economic and Social Development until 2030; PWRBAT, Battery Energy Storage System; PWRBIO, Biomass Power Plant; PWRCSP, Concentrated Solar Power Plant; PWRCTE, Conventional Thermal Power Plant; PWRDSL, Diesel Power Generator; PWRHFO, Heavy Fuel Oil Generator; PWRHYD, Hydropower Plant; PWRLFO, Light Fuel Oil Generator; PWRMOV/FPP, Mobile Power Generation/Floating Power Plants; PWRNGS, Natural Gas Power Plant; PWROTEC, Ocean Thermal Energy Conversion Plant; PWRPHP, Pumped Hydro Energy Storage Power Plant; PWRSUN, Solar Photovoltaic Power Plant; PWRWIND, Wind Power Plant; RES, Renewable Energy Sources; RFN, Oil Refinery; SEN, National Electric System; SHP, Storage Hydropower; SoC, State of Charge; SSP, Storage Solar Photovoltaic Power; SWP, Storage Wind Power; tCO2-eq, Metric Tons of Carbon Dioxide Equivalent; TPP, Thermal Power Plant; TRANS, Electricity Transmission; TWh, Terawatt-hour; UPG, Upgraded Scenario; USD, United States Dollar; V2G, Vehicle-to-Grid; VRE, Variable Renewable Energy.

* Corresponding author.
E-mail addresses: d2025100206@unifei.edu.br (E.C. Casals Cunill), leonardo.penapupo@utu.fi (L.P. Pupo).

https://doi.org/10.1016/j.ecmx.2026.102101
Received 29 May 2026; Received in revised form 27 June 2026; Accepted 27 June 2026
Available online 29 June 2026

necessitating a paradigm shift from traditional baseloads toward system flexibility, provided significant external financial barriers can be navigated.

Introduction

Worldwide, more than 700 million people live on islands, which serve as ideal environments for reshaping energy metabolism toward 100 % renewable systems [1]. While the concept of island energy metabolism highlights the unique relationships between resources and geopolitical characteristics, Cuba's case is uniquely urgent [2]. Historically characterized by a high degree of vulnerability and dependency—from the Soviet era to the more recent reliance on Venezuelan oil—the nation remains exposed to global geopolitical fluctuations, leading to recurring energy shortages and blackouts [3].

Currently, Cuba's energy infrastructure is at a critical breaking point. Practically all thermal power units have exceeded their operational lifespan, with the majority of plants commissioned between 1960 and 1980, far surpassing the international 25–30 year standard [4]. This aging fleet, coupled with persistent fuel shortages and the impact of the long-standing U.S. embargo, has resulted in a regime of "permanent crisis" [5]. The embargo, in particular, acts as a structural barrier that restricts access to international financial markets, multilateral climate financing, and state-of-the-art energy technologies [5]. While solar PV deployment has surpassed 1,000 MW, the lack of grid-scale storage and demand flexibility limits its effectiveness in providing relief to the ongoing crisis [7].

The transition to a sustainable 100 % renewable energy system requires more than just technological replacement; it necessitates a multisectoral planning approach that integrates diverse storage capacities, such as PHES and batteries to balance variable production [8]. Unlike previous isolated studies that focus on specific aspects like biomass or solar potential, this research provides a comprehensive, system-wide approach to developing a long-term decarbonization strategy for Cuba [3].

Our primary objective is to evaluate and model three distinct decarbonization pathways through a long-term horizon extending to 2050. This study provides a detailed bottom-up simulation of electricity demand, specifically accounting for the disruptive impact of large-scale electric vehicle adoption and the techno-economic optimization of diverse storage configurations [7]. By analyzing a baseline **policy-continuity** plan, a **flexibility-oriented decarbonization**, and a **100 % renewable electricity** pathway, this research offers a data-driven roadmap that moves beyond aspirational goals to provide **methodological insights for evaluating sustainable electricity-sector pathways in Cuba, with potential relevance for similar island contexts** [7]. The overall methodological structure of this research, spanning from data collection to policy recommendations, is illustrated in the Analysis Framework (Fig. 1).

The genesis of this paper is presentations delivered at the Workshop on the Energy Metabolism of Islands and the subsequent discussions. The event was held in July 2023 with the support and organization of the Universidad de Oriente, under the coordination of Electo Silva Lora and Leonardo Peña Pupo, in Santiago de Cuba, Cuba.

Literature review

Studies on island energy transition

The literature on global energy transitions reflects a significant shift toward 100 % renewable energy source pathways, increasingly moving from isolated power sector models toward integrated "energy metabolism" frameworks [9]. This evolution is supported by advanced energy-economy tools like IntE3-ISL and open-source systems such as OSeMOSYS, which facilitate the assessment of long-term decarbonization impacts by modeling end-use electrification (e.g., EVs) alongside green hydrogen and synthetic fuel integration [10]. Such multi-sectoral approaches are critical, as current research often fails to account for the complexities of maritime transport, aviation, and cooling demands in insular systems [11].

Recent findings emphasize that technical feasibility alone does not guarantee a successful transition; rather, progress is frequently hindered by socio-technical and institutional barriers. In the Canary Islands, for instance, the failure to meet historical energy targets has been attributed to hierarchical planning instruments that exclude stakeholder perspectives, highlighting the necessity of participatory governance [12]. The social dimension is further underscored by the role of energy communities and the need to align technological transfers with local public attitudes, as seen in the Aegean archipelago [13]. Without such community-driven approaches, promising transition plans may face significant local opposition [14].

Furthermore, achieving 100 % RES systems requires resolving the disconnect between comprehensive strategic plans and practical implementation coherence. Lessons from frontrunner islands like Samsø in Denmark reveal that even robust municipal plans often struggle to balance competing interests across sectors like housing, tourism, and

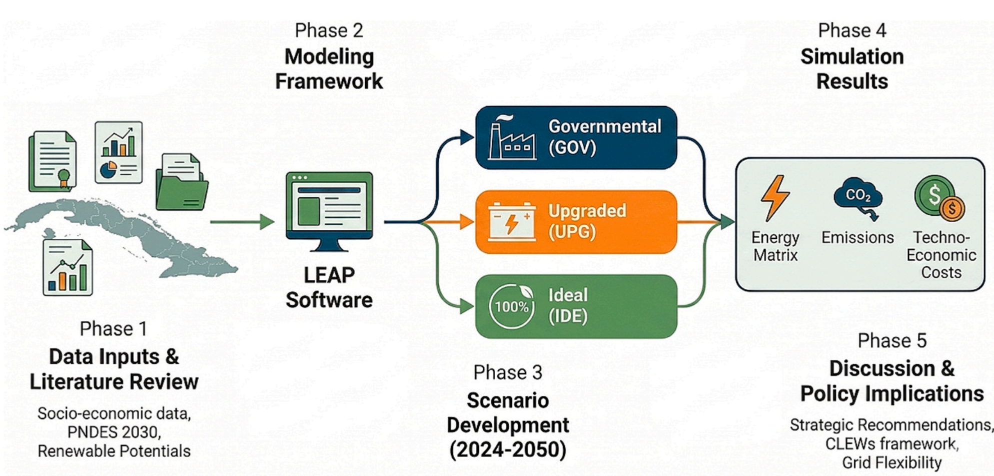

Fig. 1. Analysis framework.

agriculture [15]. Consequently, detailed techno-economic evaluations and the use of hybrid renewable mini-grids remain fundamental for identifying cost-effective solutions in geographically isolated and ecologically fragile contexts [16].

Despite the global surge in 100 % RES studies, a critical geographical imbalance persists. A systematic literature review on 100 % renewable island scenarios found that the majority focus on European territories, while other regions remain significantly underrepresented [11]. In the Caribbean, while recent studies have begun to explore decarbonization pathways for Barbados and the Dominican Republic, the region still lacks comprehensive, documented pathways for a 100 % RES transition [17]. Specifically, while recent assessments have explored the feasibility of 100 % renewable systems and their cross-sectoral impacts in Cuba [7], the granular stepwise transformation of existing conventional infrastructure into fully renewable systems remains a significant research gap that has not been extensively addressed in the broader literature of island energy scenarios [11].

Studies on Cuban energy transition

The energy transition in Cuba is situated within a broader regional shift where decarbonization is viewed as a catalyst for economic and social transformation across Latin America and the Caribbean [18]. While regional analyses emphasize the need to align new technologies with unique Caribbean socio-spatial structures [1], Cuba represents a distinct case due to its acute need to reduce fuel imports and address a critical inflection point in its aging electrical infrastructure [2].

Early research on the Cuban transition primarily focused on identifying baseline resource potential and establishing initial policy roadmaps. These foundational studies documented the country's significant solar, wind, and marine energy potential [19] and explored the specific viability of invasive species, such as *Dichrostachys cinerea* (marabou), as a sustainable biomass source for biofuel production [20]. On a localized scale, successful modeling of the “Isla de la Juventud” served as a proof-of-concept, demonstrating that 100 % renewable systems are technically feasible even within the constraints of the country's complex social development [21].

However, as the research has shifted toward long-term national scenarios for 2030 and 2050, significant gaps have emerged in the existing literature. While frameworks have been proposed to balance future supply and demand [22] and integrate multi-dimensional Sustainable Development Goal interlinkages [7], they often lack technical granularity. For instance, early 2030 roadmaps failed to account for large-scale storage technologies [22]. Although more recent assessments have begun to incorporate PHES and biomass-to-electricity pathways [23], they often omit to simulate the significant grid impacts of widespread electric vehicle adoption or the simultaneous integration of emerging technologies such as CSP and OTEC [3].

Furthermore, current models frequently treat energy as an isolated sector or focus heavily on high-level policy trade-offs—such as the competition between food security and energy crops within the Climate, Land, Energy, and Water nexus [24]. While these perspectives highlight the spatial and social justice dimensions of the transition [25], they leave a gap regarding the granular, bottom-up technical dynamics of the power grid. Specifically, there is a notable absence of studies that compare official governmental plans against more ambitious, technically optimized 2050 scenarios using detailed demand-side modeling [23]. Our study addresses these deficiencies by using the LEAP modeling tool to provide a high-resolution simulation of sector-specific demand and a techno-economic optimization of diverse storage configurations. Fig. 2 maps the evolution of previous literature leading up to this research, highlighting our contribution toward a comprehensive relevance for a resilient Cuban **electricity system.**

Cuban energy sector Characterization

The energy sector of the Republic of Cuba is characterized by a heavy reliance on fossil fuels, a high electrification rate, and a centralized yet increasingly DG infrastructure facing significant obsolescence challenges. The system remains predominantly dependent on thermal generation from domestic crude oil and imported fuels, despite the island's substantial potential for renewable energy.

Primary energy resources and natural potential

Cuba's primary energy mix is dominated by fossil fuels. In 2024, the national production of natural gas reached 970.0 million cubic meters (MMm^3), a slight increase from the previous year [26]. While domestic crude oil production has historically provided a significant portion of the fuel for thermal generation, the country relies on imports to meet demand gaps. The U.S. Geological Survey has previously estimated that the North Cuba Basin holds mean undiscovered reserves of 4.6 billion barrels of crude oil and 9.8 trillion cubic feet of natural gas [27]. However, the extraction and use of domestic crude is complicated by its high sulfur content, which accelerates the corrosion of generation infrastructure [28].

Regarding renewable resources, Cuba possesses high potential, particularly for solar photovoltaic (PV) energy. The archipelago receives an average solar irradiation of approximately 5 kWh/m^2/day [29], with annual global irradiation values often exceeding 1,800 kWh/m^2 [30]. Wind energy potential is estimated at over 2,000 MW, concentrated largely on the north coast [31]. Hydropower potential is more limited due to the island's topography, estimated at around 650 MW, though much of this is in protected areas [32].

Electricity generation

As of 2024, Cuba's total installed power capacity stood at 5,344.8 MW, heavily dominated by fossil fuel technologies. The system consists mainly of DG engines (2,474.9 MW) and conventional thermal power plants (1,993.0 MW) [26]. As detailed in Fig. 3, these conventional TPP form the backbone of the island's baseload generation, operating predominantly on domestic heavy crude oil and imported fuel oil.

However, the operational availability of this infrastructure is severely compromised by advanced technological obsolescence. The country’s main thermoelectric plants were commissioned between 1967 and 1991, meaning that even the most modern unit has been in operation for over 33 years, significantly exceeding the international standard

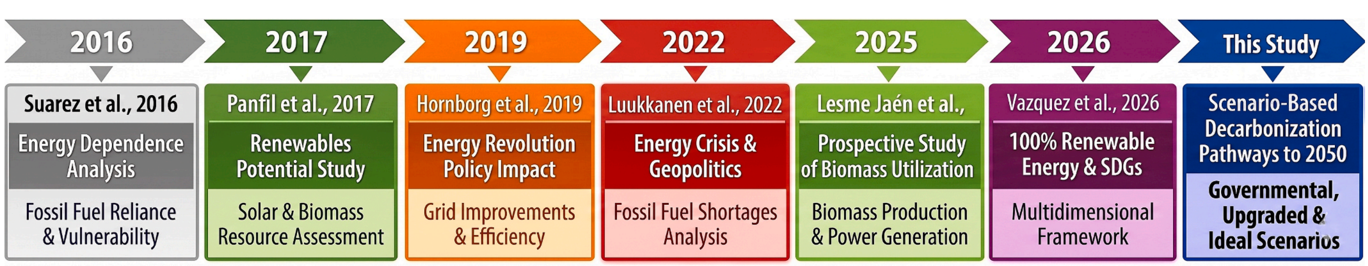

Fig. 2. Evolution of prospective energy transition studies on Cuba.

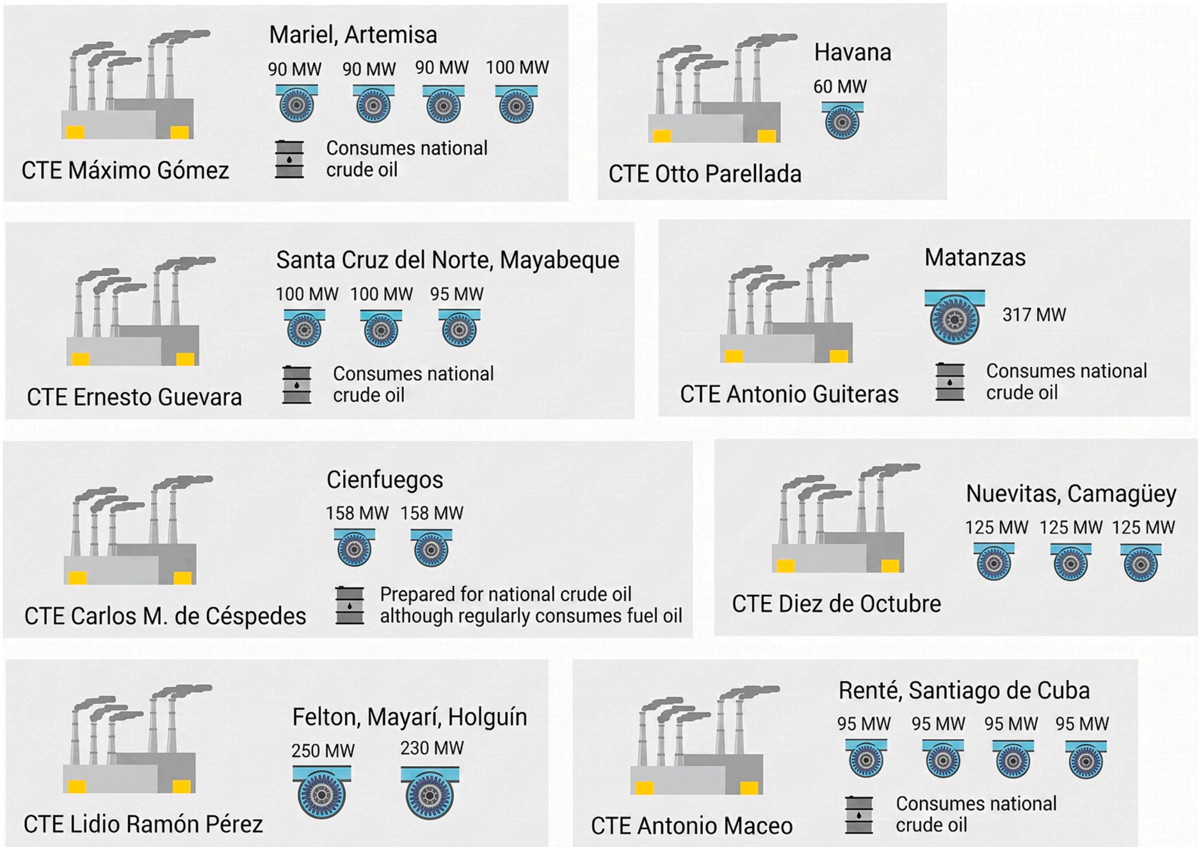

Fig. 3. Distribution of thermal power capacity in Cuba by 2022. .
Source: [33]

lifecycle of 25–30 years for such facilities [34]. For instance, major plants such as 'Mariel' and 'Renté' operate with equipment that has surpassed its intended lifespan by decades, leading to a regime of 'permanent crisis' characterized by frequent unscheduled outages, deferred maintenance, and a chronic lack of spare parts. This structural degradation, coupled with the low-quality high-sulfur domestic crude oil used as fuel, has resulted in a significant gap between installed and effective capacity, necessitating frequent load shedding and exacerbating the country’s energy vulnerability [35].

The total gross electricity generation in 2024 was 17,992.0 GWh. The generation mix was dominated by thermal power plants (8,836.2 GWh) and natural gas power plants, which contributed 2,684.1 GWh. DG technologies (diesel and fuel oil engines) provided 2,095.0 GWh. Renewable generation remains low; in 2024, solar PV generated 145.51 GWh, hydroelectric plants produced 91.4 GWh, and wind farms only 68.79 GWh [26].

A critical component of the 2024 energy balance was the “Mobile Generation” (floating power plants), classified under electricity imports, which supplied 3,647.1 GWh to the grid. System efficiency is challenged by aging infrastructure; transmission and distribution losses totaled 2,917.9 GWh, accounting for approximately 16 % of total generation [26].

As depicted in Fig. 4, the typical 24-hour generation dispatch profile relies heavily on domestic crude oil for baseload power. Furthermore, the evening peak demand is predominantly met by dispatching expensive and highly polluting distributed diesel and fuel oil engines, highlighting the severe economic and environmental inefficiencies of the current matrix.

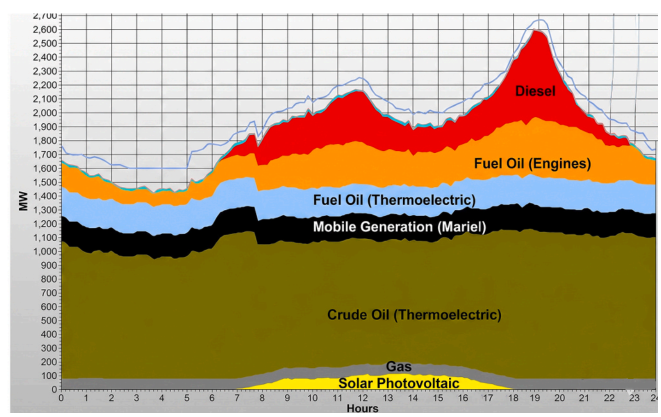

Fig. 4. Typical 24-hour electricity generation dispatch profile of the Cuban power sector in 2021. .
Source: [36]

Sectoral energy consumption

The total electricity consumption in 2024 was 17,992 GWh. This value represents a sustained contraction in national electricity demand, which has followed a downward trend in recent years as a direct consequence of the deepening energy crisis, persistent generation deficits, and widespread load shedding [26]. The reduction in consumption is primarily driven by the inability of the aging thermoelectric fleet to meet peak demand, coupled with significant fuel shortages that have forced a curtailment of activities in the state and industrial sectors [7]. Despite this overall decline, the residential sector remains the largest consumer, accounting for 8,721.7 GWh, or approximately 48 % of the total consumption. This high share is largely a legacy of the 'Energy Revolution' in the mid-2000 s, which promoted the massive electrification of cooking and household appliances, effectively shifting a significant portion of the primary energy burden to the electrical grid [37]. The state sector, comprising government services and industries, consumed 6,352.4 GWh in 2024 [26].

Other economic sectors show lower electricity consumption but high fossil fuel dependency, representing a significant 'latent demand' that could reshape the grid's load profile. The transport sector, for instance, relies almost exclusively on gasoline and diesel, consuming nearly 1 million tons of fuel annually. However, the roadmap toward electromobility suggests that the large-scale introduction of EVs and charging stations could increase the national peak demand by approximately 330 MW [28]. In the industrial sector, which currently accounts for approximately 10–13 % of electricity use [5], the sugar agro-industry utilizes biomass (bagasse) for cogeneration. Despite a theoretical potential to generate over 13,000 GWh annually from bagasse and residues [38], production has sharply declined; in 2024, biomass power plants—including new bioelectric facilities—generated only 365.38 GWh [26]. This performance gap is attributed to operational delays in the 25 planned biomass plants and critical water scarcity in several basins, which limits the condensation systems' capacity [39]. Consequently, integrating forest biomass such as *Dichrostachys cinerea* into a circular bioeconomy framework is essential to revitalize the sector's contribution by 2050 [38].

Methodology

Key modeling and demographic assumptions

The Low Emissions Analysis Platform (LEAP) [40] is a widely validated framework for integrated national energy planning and emission projections, having been successfully applied to model long-term decarbonization pathways in diverse global contexts [41]. Its capacity for detailed bottom-up simulation and multi-sectoral integration makes it a highly suitable tool to address the granular technical and demand-side gaps identified in previous Cuban studies.

The LEAP, Version 2026.6.0.5, was used with a time horizon from the Base Year (2024) to the Final Year (2050). The model focuses exclusively on the SEN electricity generation, transmission, distribution, and demand, and does not include other energy vectors like non-electric fuel consumption in industry or transportation. The key considerations for scenario design are summarized in Table 1.

The population growth rate was modeled using an official long-term demographic projection for Cuba covering the period 2024–2050 [44]. This approach allows the electricity-demand projection to reflect the expected demographic evolution of the country. This trajectory, displayed in Fig. 5, was prepared before the intensification of recent socioeconomic pressures affecting Cuba; therefore, it provides a conservative official baseline for long-term electricity-sector planning.

The GDP growth is justified using historical variation data for Cuba for the period 2000–2024 [42]. The selected value includes periods of rapid economic expansion, moderate growth, stagnation, and major contraction, including the post-2020 economic shock. Consequently, the 2.5 % rate provides a historical reference value that captures both growth and crisis periods in the Cuban economy.

Table 1
Key assumptions for all scenarios in the base year.

Key Assumptions	Value	Unit	Source
Income*	3260.1	Million Dollars	[42]
Population	9.75	Million People	
GDP*	9039.5	Million Dollars	
Income Growth Rate	2	%	Historical Estimation
GDP Growth Rate	2.5	%	Historical Estimation

Note: * Income and GDP values were calculated based on the government's conversion rate from Cuban pesos to U.S. dollars [43].

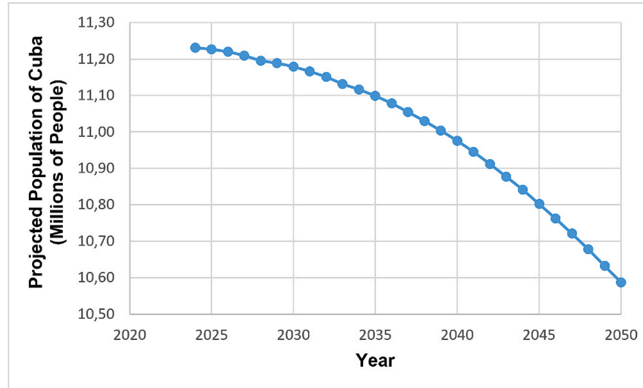

Fig. 5. Projected population of Cuba in millions of people (2024–2050) . Source: [44]

It is important to clarify that this projections is used as a planning reference rather than as a deterministic forecast.

Electricity generation system modeling

The structural architecture of the LEAP model is based on the Reference Energy System depicted in Fig. 6. This framework systematically maps the energy flows and interconnections from primary energy commodities (indigenous and imported) to power conversion technologies—including legacy thermal plants, prospective renewable assets, and storage systems—ultimately satisfying the final sectoral electricity demand.

The installed capacity and total generation for the base year 2024 were compiled using data from various sources and organized into Table 2.

The LEAP software assumes 100 % efficiency for renewable technologies to simplify comparisons with other technologies, since there are no significant energy losses in the direct conversion process. In the case of non-renewable technologies such as thermal and biomass plants, efficiencies are lower due to inherent losses in converting fuels to electricity. Efficiencies for non-renewable technologies have been obtained from the IEA. The LEAP has calculated the maximum availability using annual generation (GWh/year) and installed power [49].

The Maximum Availability parameter for thermal plants (39.96 %) reflects the current technical state and the high rate of forced outages of the Cuban aging infrastructure. In contrast, mobile generation units were modeled with a high availability (95 %) due to their role as a fast-response reserve.

The dispatch rule was configured using the Merit Order approach. Thermal plants, natural gas and biomass were assigned a priority of 1, acting as baseload or flexible generation to ensure system stability. VRE sources, such as solar and wind, were assigned a priority of 2, allowing the model to simulate their integration based on resource availability and load curve requirements. The diesel and fuel–oil generators were assigned order 3 to give priority to renewable energy sources.

To account for technological learning and infrastructure modernization, generation efficiencies were modeled as dynamic variables. Following IEA, thermal efficiencies for steam turbines were projected to increase from a baseline of 33 % to 45 % by 2030 [50]. This reflects the phased replacement of aging units with high-efficiency supercritical technologies. All technical specifications for the different technologies can be found in Table 3.

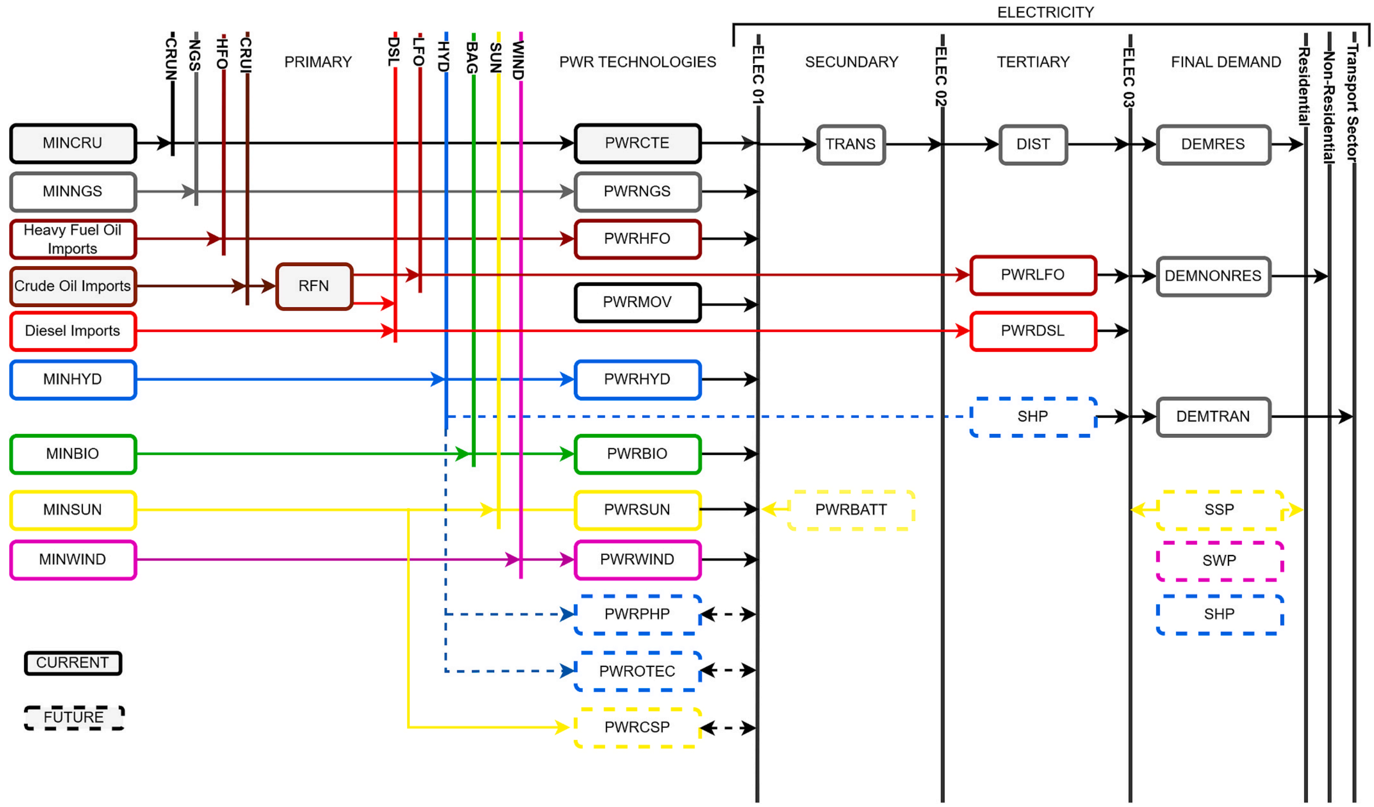

Fig. 6. Cuban reference energy system. (Note: definition of module technology codes and energy flows in the Abbreviations section).

Table 2
Energy capacity and generation in the base year.

Generation Technology	Installed Capacity (MW)	Historical Generation (GWh)	Source
PWRCTE	2608.0*	8836.2	[26]
PWRMOV	540.0	3647.1	[26,45]
PWRHFO	1385.2	1127.3	[46]
PWRLFO	1089.7	967.7	
PWRNGS	580.0	2684.1	[26]
PWRSUN	254.9	145.51	[47]
PWRWIND	11.8	68.79	[47,48]
PWRHYD	64.6	91.4	[26,48]
PWRBIO	439.65	365.38	[47,48]

Note: * Represents the nominal design capacity of the conventional base-load thermoelectric power plants operated by the Unión Eléctrica (UNE) [33].

Energy storage modeling

The BESS component was modeled with a storage duration of 6 h, aligning with current international industry standards for utility-scale applications. This duration is strategically selected to mitigate solar intermittency by shifting midday surpluses to the evening peak, as supported by technical guidelines from the National Renewable Energy Laboratory [51]. It was also modeled with a SoC of 20 %. This operational constraint is implemented to prevent deep discharge cycles that would otherwise accelerate degradation and shorten the asset's operational life. Maintaining this reserve also provides a critical buffer for emergency grid services and frequency regulation [52].

The PHES system was modeled with a storage duration of 10 full load hours and a SoC of 15 %. Unlike electrochemical storage, PHES provides long-duration energy discharge and mechanical inertia, both of which are critical for stabilizing an island grid with high penetration of VRE. The 10-hour duration ensures the system can bridge extended periods of low renewable availability, while the 15 % minimum charge serves as a technical buffer to maintain hydraulic head and prevent turbine cavitation, consistent with international benchmarks for large-scale hydroelectric storage [53].

Electricity demand modeling and efficiency

A 3 % average annual growth rate was assigned to the Residential and Non-Residential (Industrial/Commercial/Services) sectors to reach an estimated demand of approximately 20 TWh by 2030, in accordance with [3], and assuming the same growth rate until 2050. This rate balances general economic growth with efficiency gains.

Electricity losses were modeled to decrease significantly from the current system rate of 16 % to 8 % (5 % distribution and 3 % transmission) over the modeling horizon.

Official plans to electrify 45 % of transport by 2030 were taken into account [54]. The total energy required to charge the estimated number of EVs to meet the 45 % electrification target in Cuba per year was calculated according to [55], and the growth in transport demand was established. Considering only BEVs for the transition in Cuba, with an efficiency of 95 %, a distance traveled of 14,000 km/year, and a charge

Table 3
Technical parameters for electricity generation processes.

Generation Process	Process Efficiency (%)	Process Efficiency in 2030 (%)	Maximum Availability (%)	Merit Order
PWRCTE	33	45	38.68	1
PWRMOV	33	33	77.10	1
PWRHFO	33	48	9.29	3
PWRLFO	33	48	10.14	3
PWRNGS	35	60	52.83	1
PWRSUN	100	100	6.52	2
PWRWIND	100	100	66.55	2
PWRHYD	100	100	16.15	2
PWRBIO	22	35	9.49	1

Table 4
Projected fleet size, efficiency, and charging demand for BEVs [55].

Transport	Year	Efficiency (%)	Available Energy (MWh)	Charge per Vehicle (MWh)	Supplied Vehicles
Battery-Electric Vehicle	2023	95 %	28,500	3	10,710
	2050	95 %	28,500	2	12,050

Table 5
Multi-phase deployment schedule for national transport electrification [54].

Phase	Period	Electrified Vehicles	Imported Vehicles	Annual Increase in Energy (GWh)	Electrification (%)
1	2022–2026	12,700	17,218	79.61	24.46
2	2027–2030	4,787	22,000	71.28	21.26

of 3 MW/h per vehicle in 2030 and 2 MWh in 2050. Table 4 summarizes the metrics for the fleet size, efficiency and charging demand for EVs in Cuba by 2023 and 2050, and Table 5 represents the schedule for national transport electrification.

After obtaining the increase in electrical load for transportation, it is added to the current consumption and modeled as exponential growth until the planned electrification value is reached.

The 2023 hourly load curve was used to calculate the peak load percentage for every 1,000 h of the total, and these values subsequently entered into the software to model the system curve.

Techno-Economic framework

The techno-economic framework of this study is built upon a series of dynamic assumptions that reflect both localized market conditions and global technological trends. Regarding energy commodities, the model assumes a strategic differentiation between imported and indigenous resources, setting the price of imported petroleum at a baseline of 90 USD/barrel to account for international market volatility [48], while valuing domestic heavy crude at a marginal extraction cost of 14 USD/barrel [56]. This economic landscape is complemented by a sophisticated tariff structure for electricity consumers, which starts at 0.21 USD/kWh and is projected to decline to 0.19 USD/kWh by 2030, reflecting anticipated systemic efficiency gains from the transition [48].

To ensure financial accuracy, the CAPEX and OPEX profiles for each generation technology are derived from the NREL Annual Technology Baseline [57], incorporating learning curves that model significant cost reductions as these technologies mature throughout the simulation period, as presented in Table 6.

Technology cost and performance assumptions were derived primarily from international reference datasets and learning-curve projections. They should not be interpreted as Cuba-specific procurement costs. Actual implementation costs in Cuba may differ due to import restrictions, financing conditions, currency constraints, supply-chain limitations, and country-specific risk premiums.

Scenario Development

The formulation of long-term decarbonization pathways for Cuba's electricity sector relies on three distinct scenarios modeled in LEAP: the GOV, UPG, and IDE. These pathways evaluate a spectrum of policy ambitions from the 2024 baseline to 2050.

The GOV reconstructs Cuba's electricity trajectory to 2050 strictly as articulated by official policy — the National Plan for Economic and Social Development and Decree-Law No. 345 — operationalising the stated targets of 37 % renewable generation by 2030 and 100 % by 2050 [62,63] from a baseline with ~ 95 % fossil dependence. Its architecture centres on the staged deployment of solar PV (92 parks totalling 2,000 MW, with 1,000 MW synchronised by May 2025 and the remainder by 2031, plus 200 MW of BESS [62,64], complemented by 151 MW of wind capacity currently under construction against an aspirational 633–688 MW by 2030 [2], biomass generation contributing up to 14 % through 19 bioelectric plants with 612 MW, and a modernised 135 MW hydroelectric base including 74 new projects at 56 MW [65]. To bridge the transition, the GOV retains a fossil-reliability layer — 850 MW of recovered distributed generation, the sustained operation of critical thermal units, 800 MW of Russian-financed thermoelectric blocks in four 200 MW units, and a controlled phase-out of inefficient floating plants [66–68] before these units decline as renewable penetration stabilises. Sector coupling enters through an electromobility rollout targeting 45 % electrification of state transport, supported by 24 fast-charging stations, 500 public charging points, and the domestic assembly of 23,361 electric vehicles between 2020 and 2022 [69]. The cross-cutting framework is Decree 110, which mandates renewable energy in all new investments and targets the displacement of ~ 750,000 tonnes of imported fuel annually through the solar programme alone [64].

The UPG retains the policy-continuity scenario's regulatory baselines — PNDES 2030, Decree-Law 345 and the Decree 110 efficiency mandates — but pushes decarbonisation beyond stated policy ceilings along three reinforcing vectors. On the demand side, transport electrification rises to 75 % of the national fleet by 2050, equivalent to ~ 94,000 electric vehicles, deepening the daily load curve and requiring advanced demand-side management to absorb charging without compromising grid stability [28,69]. On the supply side, thermal capacity is structurally downsized to a 1,500 MW residual by 2050 — repurposed as high-efficiency backup, not as a primary generation layer — while wind capacity expands to 820 MW through foreign investment projects short of

Table 6
Capital and operational expenditure projections by technology.

Technology	CAPEX(MM USD/GW)			OPEX(MM USD/GW)		Variable Cost(MM USD/PJ)	Source
	2024	2035	2050	2024	2050		
PWRCTE	4015	3664	3186	85	70	2.22	[58]
PWRWIND	1,257.20	902.50	760.00	29	15		
PWRSUN	1,027.79	718.07	617.61	18	9,8		
PWRHFO	1,810.00	1,810.00	1,810.00	35.16	35.16	1.58	
PWRLFO	1,175.00	1,175.00	1,175.00	16.30	16.30	1.31	
PWRHYD	3,241.00	3,241.00	3,241.00	27	17		
PWRBIO	4,304.51	3,999.28	3,583.89	164	164	1.61	
PWRNGS	949.53	891.42	837.70	26	22	0.56	
PWRMOV	1,788.00	1,788.00	1,788.00	20.10	20.10	1.72	
PWRBAT	1,154.00	864.70	496.00	28	12		
PWRPHP	1,804.00	1,730.30	1,636.00	20	20	0.16	
PWROTEC	10,915.00	10,915.00	10,915.00	545.75	545.75		[59,60]
PWRCSP	6,975.00	3,911.00	3,150	67	40	1.03	[61]

the maximum theoretical potential [65]. The novel contribution is the explicit inclusion of dispatchable and baseload renewables absent from official planning: a 50 MW concentrated solar power plant with thermal energy storage for evening-peak dispatch [61] and a 60 MW ocean thermal energy conversion plant exploiting the Cuban coastal thermal gradient to supply firm, non-intermittent power [70]. System reliability under this high-RES configuration is anchored in a large-scale storage stack — 600 MW of pumped hydroelectric energy storage as the primary grid stabiliser [71] combined with 702 MW of battery energy storage systems designed to capture midday PV surplus and redistribute it to cover evening peaks and electrified-transport demand [65]. Together, these three vectors operationalise an indigenous-potential-maximising pathway that the GOV signals but does not yet fully integrate.

Building on the same policy baselines inherited from the GOV and UPG, the IDE operationalises the technical ceiling of Cuba's renewable potential to deliver a net-zero electricity sector by 2050. Four mutually reinforcing transformations structure the pathway: (i) the national transport fleet is fully electrified, deploying approximately 126,000 electric vehicles whose smart-charging protocols turn mobility into a decentralised demand-response asset, smoothing the load curve under high variable renewable energy penetration [69,72]; (ii) all carbon-intensive generation is decommissioned — the aging thermal fleet, gas-fired combined cycles and distributed diesel/fuel–oil gensets progressively disappear, leaving any residual assets either stranded or replaced by carbon neutral alternatives; (iii) renewable supply is pushed to its maximum estimated potential — biomass is scaled to exploit the full residues of the sugar and forestry industries as a renewable baseload [23], and onshore wind reaches its theoretical ceiling of 1,100 MW [73]; and (iv) an exceptionally large storage portfolio secures a 100 % RES grid, with 1,404 MW of battery energy storage supplying high-speed frequency regulation and short-duration shifting [65] and 1,200 MW of pumped hydroelectric energy storage — doubling the flexibility-oriented decarbonization scenario's capacity — acting as the long-duration buffer able to withstand multi-day low-renewable periods [71]. The pathway therefore represents the literature-grounded technical benchmark against which the more conservative previous scenarios are comparatively assessed.

To maintain methodological transparency and provide a clear comparison of the inputs used in the LEAP software, the foundational principles, structural paradigms, and specific numerical constraints underpinning each modeled pathway are systematically synthesized in Table 7.

Results

Governmental scenario (GOV)

The simulation results for the GOV delineate the projected evolution of Cuba's energy demand, power matrix, emissions, and economic indicators from 2025 to 2050.

To establish the baseline requirements for the power sector, Figs. 7 and 8 comparatively illustrate the projected final energy demand for the overall system and the transport sector, respectively, across all modeled pathways.

Total final energy demand grows continuously throughout the simulation period, driven by a sustained 3 % annual growth rate. The residential sector remains the primary consumer, with demand increasing from 9.31 TWh in 2025 to 19.49 TWh by 2050. Similarly, the non-residential sector, comprising industrial, commercial, and agricultural activities, scales from 7.28 TWh to 15.25 TWh. Electricity demand in the transport sector rises from 0.25 TWh in 2025 to 0.38 TWh by 2050, with growth stabilizing post-2035.

The generation matrix undergoes a significant expansion of solar photovoltaic capacity in the short term, increasing from 754.93 MW in 2025 to 2,405.33 MW in 2030, and reaching a plateau of 2,706 MW by 2035. This solar expansion translates into a substantial increase in electricity output, rising from 3.31 TWh in 2025 to a stable 11.85 TWh

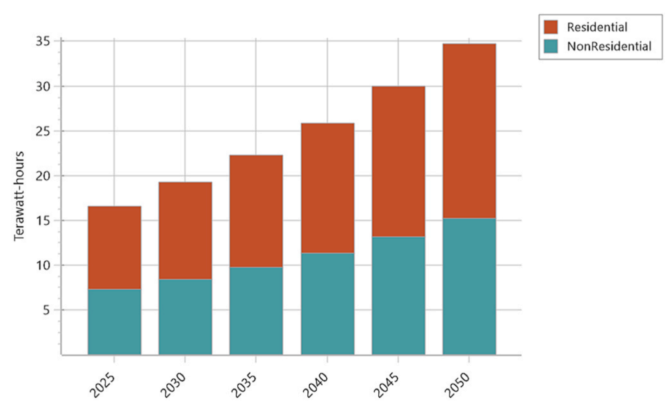

Fig. 7. Evolution of electricity demand for residential and non-residential sectors for all scenarios expressed in Terawatt-hours (TWh).

Table 7
Foundational policy objectives and technological targets by scenario.

Feature/Metric	Governmental Scenario	Upgraded Scenario	Ideal Scenario	Sources
Core Objective	Gradual transition & Energy Sovereignty	Aggressive Decarbonization & Grid Flexibility	Net-Zero Electricity & Full Fossil Phase-out	[62,63]
Policy Basis	PNDES 2030 & Decree-Law 345	Enhanced PNDES Framework	Full Decarbonization Vision	
Strategic Focus	State-led implementation	Emerging tech & demand management	Total energy sovereignty	
Renewable Share	35.55 % by 2050	45.35 % by 2050	100 % by 2050	[29]
Thermal Generation	Recovery of 850 MW of DG Installation of 800 MW of planned TPP by Russian loans Complete Phase-out of FPP	Capped at 1,500 MW	Fully Decommissioned	[66,67]
Transport Electrification	45 % of fleet	75 % (~94,000 EVs)	100 % (~126,000 EVs) Full V2G smart-charging integration	[28,69,72]
Energy Storage	BESS: 200 MW	PHES: 600 MW BESS: 702 MW	PHES: 1,200 MW BESS: 1,404 MW	[65,68,71]
Renewable Expansion	Solar: 2,000 MW (92 parks) Wind: 151 MW (currently under construction) Biomass: 612 MW (19 bioelectric plants) Hydro: 135 MW (technical limit)	Inherits the expansion of the GOV Wind: Expanded to 820 MW	Inherits the expansion of the GOV Wind: Maximized to technical potential of 1,100 MW Biomass: Scale-up to 6,733 MW to replace thermal baseload	[23,62,64,65,73]
Emerging Technologies		CSP: 50 MW plant OTEC: 60 MW plant for renewable baseload	Inherits the expansion of the UPG	[61,70]

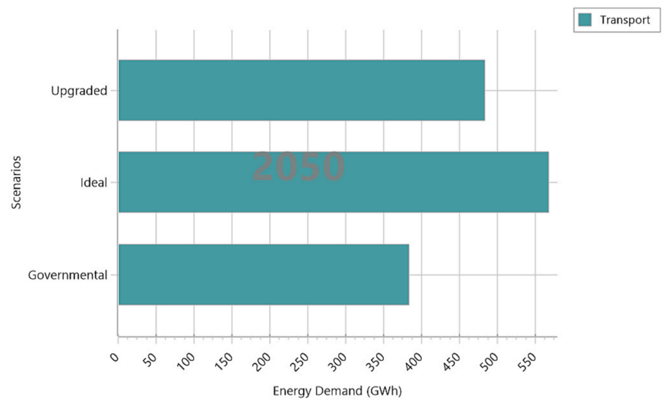

Fig. 8. Projected final electricity demand for the transport sector in 2050 across all scenarios expressed in Gigawatt-hours (GWh).

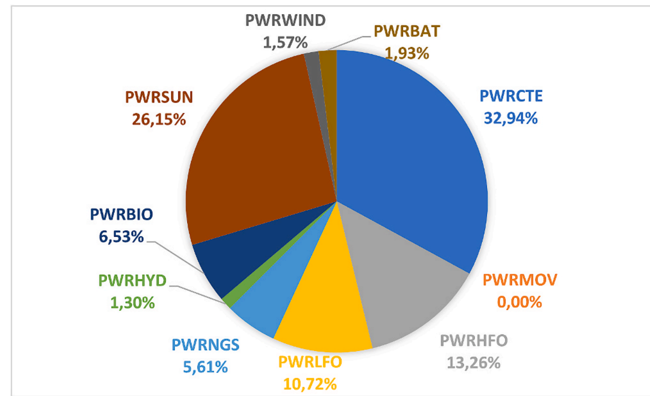

Fig. 10. Percentage share of total installed capacity by technology under the Governmental scenario in 2050.

from 2035 onward, represented in Fig. 9. Conversely, wind capacity remains constant at 162.80 MW from 2035 to 2050, contributing modest generation totaling 1.00 TWh by mid-century. While imported mobile generation is phased out entirely by 2030, dropping its output from 2.15 TWh in 2025 to zero, conventional thermal capacity expands from 2,608 MW to 3,408 MW by 2050. This reliance on thermal assets increases electrical output from 5.67 TWh in 2025 to 15.50 TWh by 2050. Energy storage remains at a fixed BESS capacity of 200 MW throughout the period. The final power capacity matrix is defined in Fig. 10.

The GHG emissions trajectory follows a non-linear path. Annual emissions initially decrease from 10.28 million metric tons of CO_2-eq in 2025 to a minimum of 6.30 million metric tons in 2030. Following this period, the trajectory reverses, with emissions climbing to 8.28 million metric tons by 2040 and to 12.82 million metric tons by 2050, as detailed in the final emissions assessment (Fig. 17).

Annual production costs escalate from $790.55 million USD in 2025 to $1,406.69 million USD in 2050. Variable O&M costs, largely influenced by fuel requirements for the thermal fleet, rise from $285.15 million USD to $367.76 million USD. By the end of the simulation period, annual sales revenue reaches $7,241.74 million USD, while annual CAPEX required for infrastructure maintenance and expansion total $576.90 million USD. More information is available in Fig. 11 and Table 8.

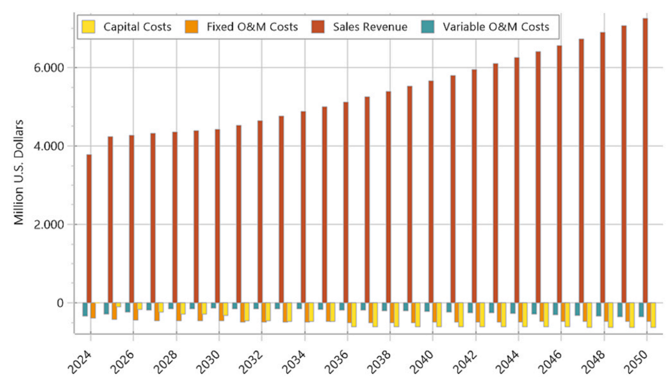

Fig. 11. Evolution of annual cash flows and system costs in million USD under the Governmental scenario from 2024 to 2050.

Upgraded scenario (UPG)

The simulation results for the UPG outline a structural transformation of the Cuban energy system between 2025 and 2050, characterized by the aggressive electrification of transport and the integration of large-scale storage capacity to replace fossil-fuel dependence. While the residential and non-residential sectors maintain their baseline trajectories, reaching 19.49 TWh and 15.25 TWh by 2050, respectively, the transport sector undergoes a targeted surge driven by the policy goal of electrifying 75 % of the national fleet, as previously depicted in the comparative demand analysis (Fig. 6 and Fig. 7). Consequently, transport electricity demand increases from 0.25 TWh in 2025 to 0.48 TWh by 2050, representing a 0.10 TWh increase over the policy-continuity baseline and establishing electric mobility as a structural component of the island's energy metabolism.

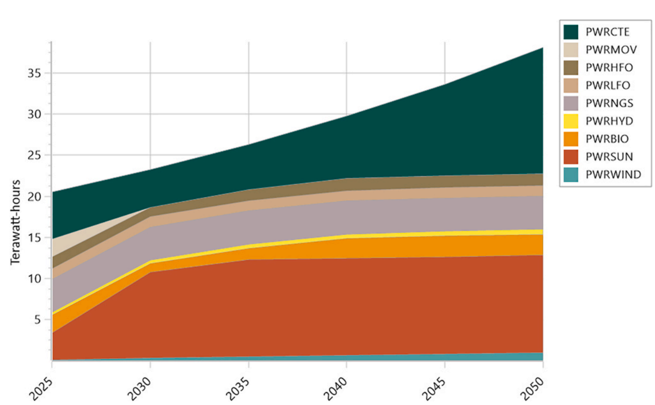

Fig. 9. Evolution of the electricity generation matrix (2024–2050) under the Governmental scenario expressed in Terawatt-hours (TWh).

This heightened demand is met through a paradigm shift in the power generation matrix, moving away from thermal dependence toward a flexible, renewable architecture. The scenario models a phased decommissioning of the aging thermal fleet, reducing installed capacity from 2,555.24 MW in 2025 to a residual 1,500 MW by 2050, thereby reducing fossil thermal generation down to just 2.20 TWh, as highlight Fig. 12. To offset this retirement, wind power attains 820 MW, resulting in a robust annual generation of 15.30 TWh by mid-century. This is supported by dispatchable renewable technologies, including a 50 MW CSP plant that generates 0.44 TWh and a 60 MW OTEC facility that provides a stable 0.53 TWh of baseload generation. Outlined in Fig. 13, grid stability is anchored by a combined storage capacity of 1,302 MW, consisting of 702 MW of BESS and 600 MW of PHES. This infrastructure allows for the effective shifting of 11.85 TWh of midday solar generation to peak consumption hours, successfully bridging the gap between variable resource availability and demand peaks.

Consequently, the environmental performance of the UPG reveals a sustained mitigation trajectory: annual emissions drop from 10.35 million tCO_2-eq in 2025 to a minimum of 4.62 million tCO_2-eq by 2035, and eventually reach 4.21 million tCO_2-eq in 2050. This represents a 67 % reduction compared to the 2050 baseline and prevents the significant

Table 8
Module cost balance for governmental scenario.

Module Cost Balance (Million USD)	2025	2030	2035	2040	2045	2050
Capital Costs	−82.69	−271.34	−433.15	−567.22	−572.12	−576.90
Fixed O&M Costs	−422.71	−451.38	−475.47	−492.16	−477.19	−462.03
Sales Revenue	4,235.85	4,413.51	4,994.67	5,654.54	6,396.73	7,241.74
Variable O&M Costs	−285.15	−146.23	−171.33	−227.34	−292.69	−367.76

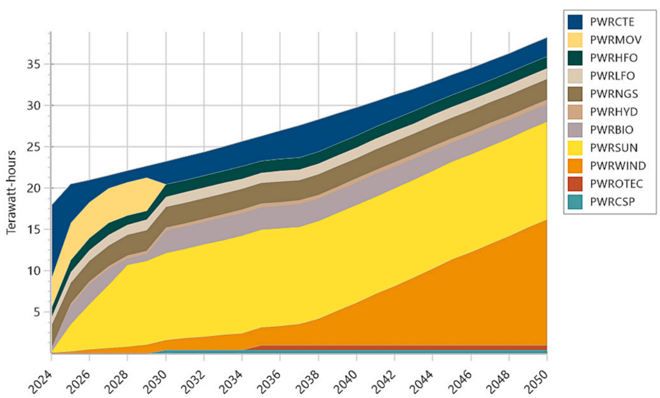

Fig. 12. Evolution of the electricity generation matrix (2024–2050) under the Upgraded scenario expressed in Terawatt-hours (TWh).

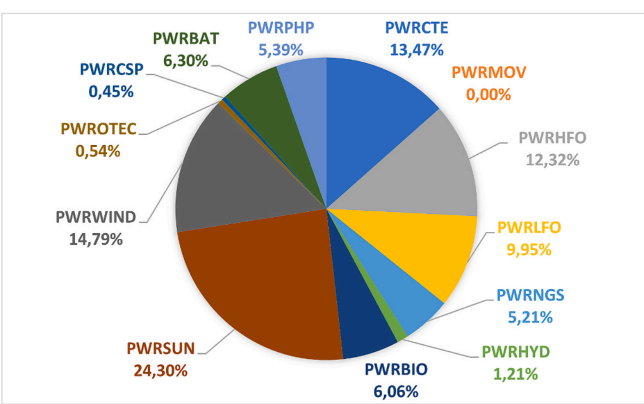

Fig. 13. Percentage share of total installed capacity by technology under the Upgraded scenario in 2050.

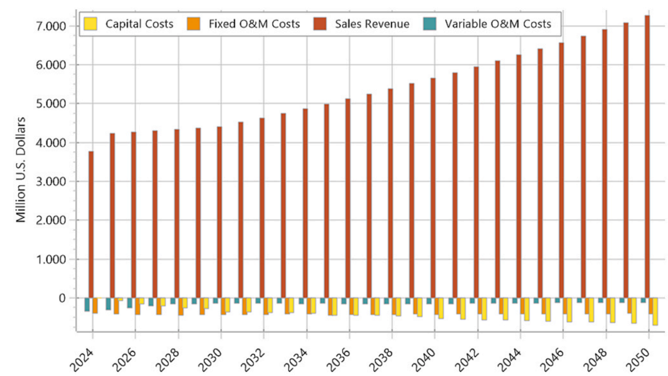

Fig. 14. Evolution of annual cash flows and system costs in million USD under the Upgraded scenario from 2024 to 2050.

late-term emissions rebound observed in the policy-continuity plan, summarized in Fig. 17.

From a techno-economic perspective, the scenario reflects a shift from operational expenditures to high upfront capital investments, with annual capital costs reaching $663.28 million USD by 2050. Despite these capital requirements, the UPG proves more cost-effective as variable O&M costs, a proxy for fossil fuel consumption, decline from $299.12 million USD to $119.36 million USD. Ultimately, total production costs in the UPG are approximately $200 million USD lower annually than the baseline scenario, demonstrating that profound decarbonization is not only technically feasible but also financially optimal for the Cuban energy matrix. Further data is shared in Fig. 14 and Table 9.

Ideal scenario (IDE)

The simulation results for the IDE delineate a radical transformation of the island's energy metabolism fundamentally altering the baseline demand shown in Fig. 7, defined by the complete electrification of the transport sector and the absolute stranding of all fossil-fuel assets. Previously outlined in Fig. 8, electricity demand within the transport sector scales aggressively to 0.57 TWh by 2050, supporting the integration of approximately 126,000 BEVs that operate as a decentralized demand-response mechanism through smart-charging protocols. This demand-side shift occurs in parallel with a total overhaul of the generation matrix, where conventional thermal capacity is systematically decommissioned from 2,483.81 MW in 2025 to zero operational capacity by 2045. High-carbon DG facilities, including those utilizing heavy fuel oil, light fuel oil, and natural gas, are also entirely phased out of the system.

To replace the eliminated thermal baseload, the scenario models a colossal expansion of indigenous renewable technologies to their maximum theoretical limits. Biomass capacity scales exponentially from 612 MW in 2025 to 6,733 MW by 2050, establishing a firm baseload that generates 18.16 TWh annually, as shown Fig. 15. Concurrently, wind power capacity reaches a ceiling of 1,100 MW, translating into a substantial electrical output of 6.75 TWh by mid-century. This is complemented by the massive generation of 11.85 TWh from solar photovoltaic arrays, alongside dispatchable contributions of 0.44 TWh from CSP and 0.53 TWh from OTEC facilities. Grid stability and inertia in this 100 % renewable system are anchored by a substantial deployment of storage infrastructure totaling 2.6 GW by mid-century, comprising 1,404 MW of BESS and 1,200 MW of PHES. The final form of the capacity matrix is presented in Fig. 16.

Environmental performance under the IDE follows a true Net-Zero trajectory, with annual greenhouse gas emissions declining precipitously from 9.65 million tCO_2-eq per year in 2025 to 2.50 million tCO_2-eq in 2030 and 1.45 million tCO_2-eq in 2035, ultimately reaching absolute zero before 2050. The ultimate environmental effectiveness of the modeled transitions is quantified in Fig. 17, which compares the total equivalent emissions across all scenarios.

From a techno-economic standpoint, the results reflect extreme capital intensity (Fig. 18 and Table 10), with annual CAPEX escalating to $2,833.97 million by 2050 and fixed O&M costs rising to $1,225.12 million. Total production costs peak at $4,361.48 million by the end of the simulation, the highest among all modeled pathways, while variable O&M costs reach $302.39 million due to the domestic supply chain logistics required for the biomass baseload. Finally, sales revenue reaches $7,279.77 million by 2050, reflecting the fully electrified demand

Table 9
Module cost balance for upgraded scenario.

Module Cost Balance (Million USD)	2025	2030	2035	2040	2045	2050
Capital Costs	−61.38	−317.59	−413.71	−497.74	−563.00	−663.28
Fixed O&M Costs	−414.27	−426.11	−433.90	−419.19	−401.42	−405.82
Sales Revenue	4,235.85	4,413.51	4,994.67	5,654.54	6,407.33	7,262.48
Variable O&M Costs	−299.12	−138.45	−142.11	−149.41	−126.71	−119.36

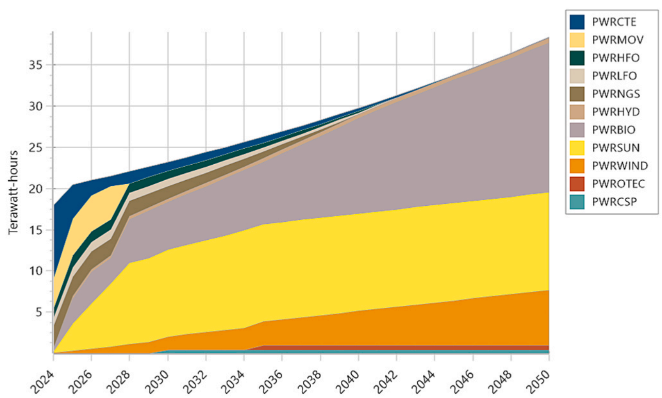

Fig. 15. Evolution of the electricity generation matrix (2024–2050) under the Ideal scenario expressed in Terawatt-hours (TWh).

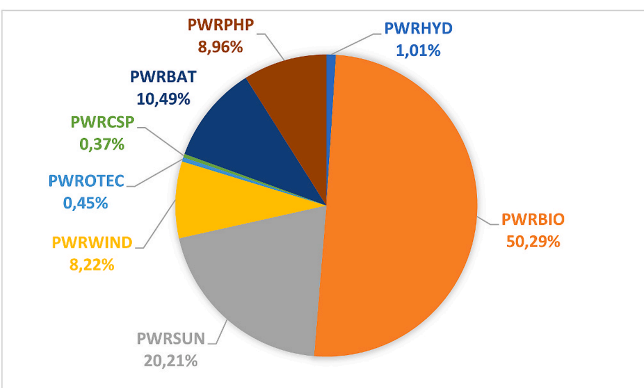

Fig. 16. Percentage share of total installed capacity by technology under the Ideal scenario in 2050.

profile.

Sensitivity analysis

To evaluate the model's robustness against uncertainties in long-term load forecasting, a sensitivity analysis was performed by varying only the projected electricity demand for the residential and non-residential sectors by ± 5 %. The analysis assessed the subsequent impacts on electricity generation, total production costs, and total CO_2-eq emissions by 2050, as presented in Fig. 19.

The analysis reveals that the LEAP optimization algorithm primarily accommodates a 5 % demand increase through the expansion of wind power capacity across all scenarios. For instance, a 5 % rise in residential demand increases wind generation by approximately 56 TWh in the UPG, 50.5 TWh in the GOV baseline, and 49 TWh in the IDE pathway. This preference is likely driven by wind energy's favorable balance of costs and availability; it provides a higher capacity factor than solar photovoltaics—including nighttime and overcast generation—while remaining less capital-intensive than utility-scale biomass.

Economically, the system exhibits higher sensitivity to fluctuations

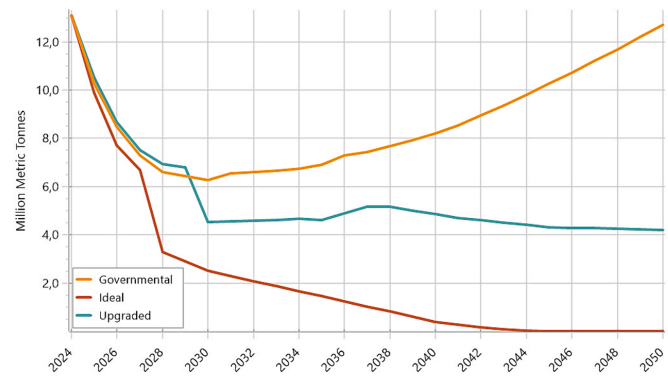

Fig. 17. Projected trajectory of total greenhouse gas emissions across all scenarios in million tCO_2-eq (2024–2050).

in the residential sector. The UPG demonstrates the largest variance in production costs when demand increases, but smaller relative savings when demand decreases. Specifically, a 5 % increase in residential demand yields the highest additional costs for the UPG (approximately 770 million USD, compared to 740 million USD in the GOV), while a 5 % decrease in non-residential demand results in the lowest relative savings for the UPG (roughly 180 million USD, compared to a 207 million USD reduction in the GOV). This asymmetric variance reflects the capital-intensive nature of dynamically expanding flexible renewable infrastructure, contrasting with the operational cost-driven baseline of the GOV.

The environmental outcomes present a notable non-linear response. In the UPG, a 5 % increase in demand correlates with a net decrease in total emissions, reducing them by approximately 1.3 million tCO_2-eq for the residential sector and 1.2 million tCO_2-eq for the non-residential sector. This occurs because the additional wind capacity, integrated to meet the higher load, simultaneously displaces the remaining residual fossil-fuel generation during off-peak hours. Conversely, a 5 % increase in residential demand under the GOV leads to higher emissions (an increase of roughly 0.6 million tCO_2-eq), as the rigid thermal infrastructure must consume more fossil fuels to cover the load. These results indicate that a flexibility-oriented matrix (UPG)—underpinned by a

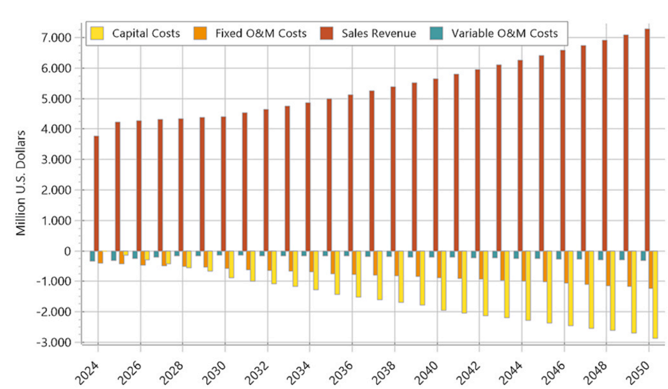

Fig. 18. Evolution of annual cash flows and system costs in million USD under the Ideal scenario from 2024 to 2050.

Table 10
Module cost balance for ideal scenario.

Module Cost Balance (Million USD)	2025	2030	2035	2040	2045	2050
Capital Costs	−141.35	−873.44	−1,404.73	−1,926.29	−2,345.55	−2,833.97
Fixed O&M Costs	−438.01	−594.14	−749.18	−884.53	−1,020.15	−1,225.12
Sales Revenue	4,235.85	4,413.51	4,994.67	5,654.54	6,416.16	7,279.77
Variable O&M Costs	−302.51	−144.96	−155.16	−202.92	−249.07	−302.39

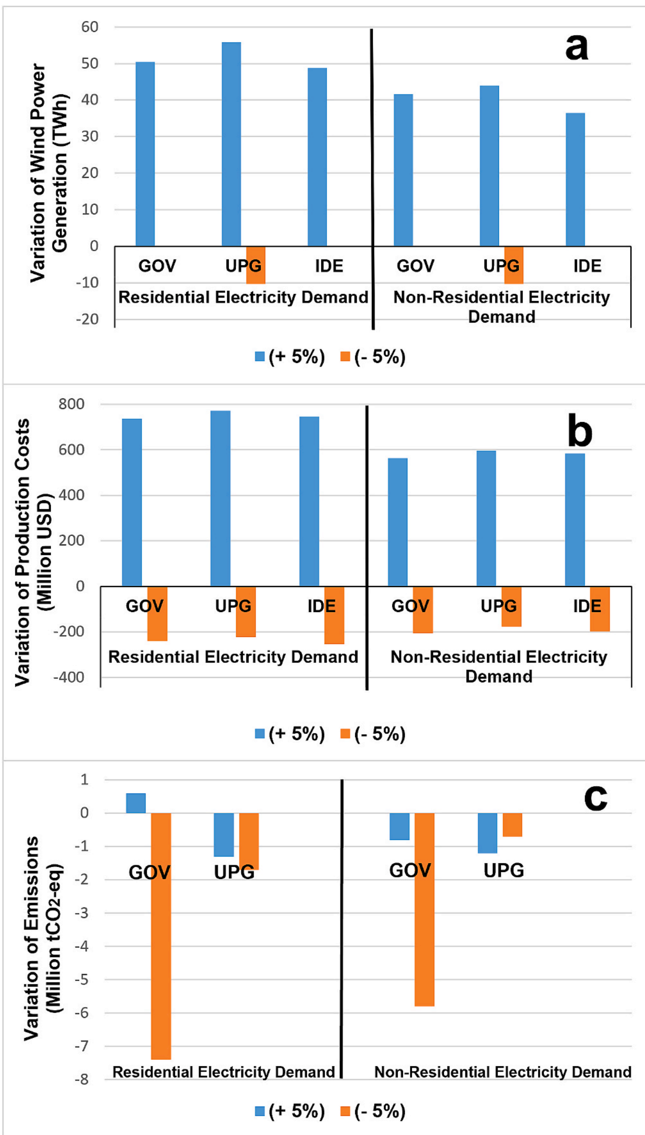

Fig. 19. Sensitivity analysis results evaluating the system's response to a ± 5 % variation in projected residential and non-residential electricity demand by 2050 across all scenarios. The panels illustrate the absolute variations in (a) wind power generation (TWh), (b) total production costs (million USD), and (c) total emissions (million tCO_2-eq).

diverse mix of battery energy storage, variable renewable energy, and firm renewable baseloads—is more resilient to demand fluctuations and can leverage capacity additions to further displace polluting sources, whereas a conventional thermal-based system remains environmentally vulnerable to load growth.

It must be noted that while this ± 5 % demand variation provides valuable insights into load fluctuation resilience, it represents a limited uncertainty analysis. Other highly influential variables—such as global fuel prices, CAPEX trajectories, storage costs, thermal retirement schedules, and biomass availability—were not quantitatively tested. Consequently, the system's absolute robustness and economic performance remain subject to these external factors.

Discussion

Comparative scenario analysis

To provide a comprehensive overview of the long-term implications of the modeled pathways, Fig. 20 presents a summary dashboard of the key technical, environmental, and financial metrics projected for 2050. This holistic assessment juxtaposes the GOV, UPG, and IDE, highlighting the ultimate trade-offs between fossil-fuel reliance, capital expenditure, and decarbonization targets.

The comparative assessment of the scenarios reveals stark differences in how Cuba can navigate the trilemma of energy security, economic viability, and environmental sustainability up to 2050. While all three pathways integrate RES to varying degrees, their structural paradigms dictate vastly different long-term outcomes for the island's energy metabolism.

The GOV scenario, strictly aligned with current national plans, demonstrates the fundamental inadequacy of relying on conventional thermal baseload to support future demand. While the PNDES 2030 officially targets a 37 % share of renewable energy generation by 2030 and aspires to reach 100 % by 2050, the modeling reveals a stark contradiction. Even when integrating all existing government capacity expansion plans and accounting for justified demand growth, the GOV scenario only reaches a 35 % renewable generation share by 2050. The primary strength of this pathway lies in its realistic short-term execution, successfully achieving early emissions mitigation through the planned integration of 2,000 MW of solar photovoltaics. However, its critical weakness is the failure to decouple long-term economic growth from fossil fuel dependency. By continuously expanding conventional thermal capacity to meet baseload requirements, the GOV pathway triggers a severe late-term emissions rebound, peaking at 12.82 million tCO_2-eq per year by 2050. As demonstrated by sensitivity analyses, this conventional thermal-based system remains environmentally vulnerable to load growth. From a financial perspective, this scenario is highly inefficient in the long term; it incurs the highest variable operating costs, cementing an expensive carbon lock-in that leaves the Cuban economy highly susceptible to global oil market volatility.

In contrast, the UPG emerges as **a highly competitive** and balanced decarbonization pathway **under the projected cost trajectories.** Its core strength is the strategic pivot from a “thermal baseload” paradigm to a “system flexibility” approach, driven by the diversity of battery storage alongside variable and dispatchable renewable sources. By enforcing a phased retirement of aging thermal infrastructure, reducing it to a 1,500 MW backup, this scenario mitigates fossil fuel reliance. It compensates for the intermittency of VRE by deploying large-scale storage solutions, including 600 MW of PHES and 702 MW of BESS. Furthermore, it integrates emerging technologies, such as 60 MW of OTEC, to provide a stable, indigenous renewable baseload. Although this pathway has the drawback of requiring high upfront capital investments, which could rise to $663.28 million USD annually by 2050, it drastically reduces variable O&M costs. Consequently, the total annual production costs in the UPG scenario are approximately $200 million USD lower than those of the GOV baseline, thereby flattening the

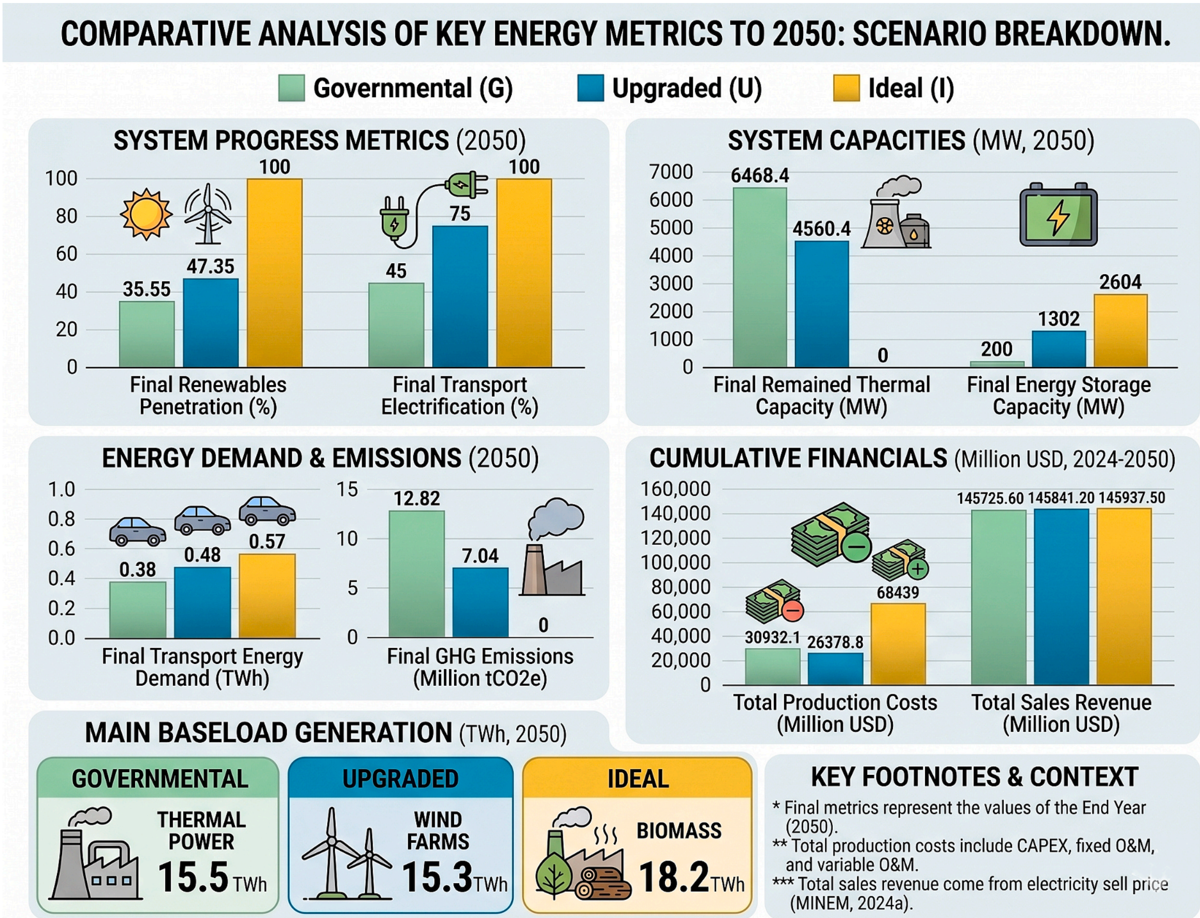

Fig. 20. Summary dashboard of key energy, cumulative financials, and annual emissions metrics by scenario in 2050.

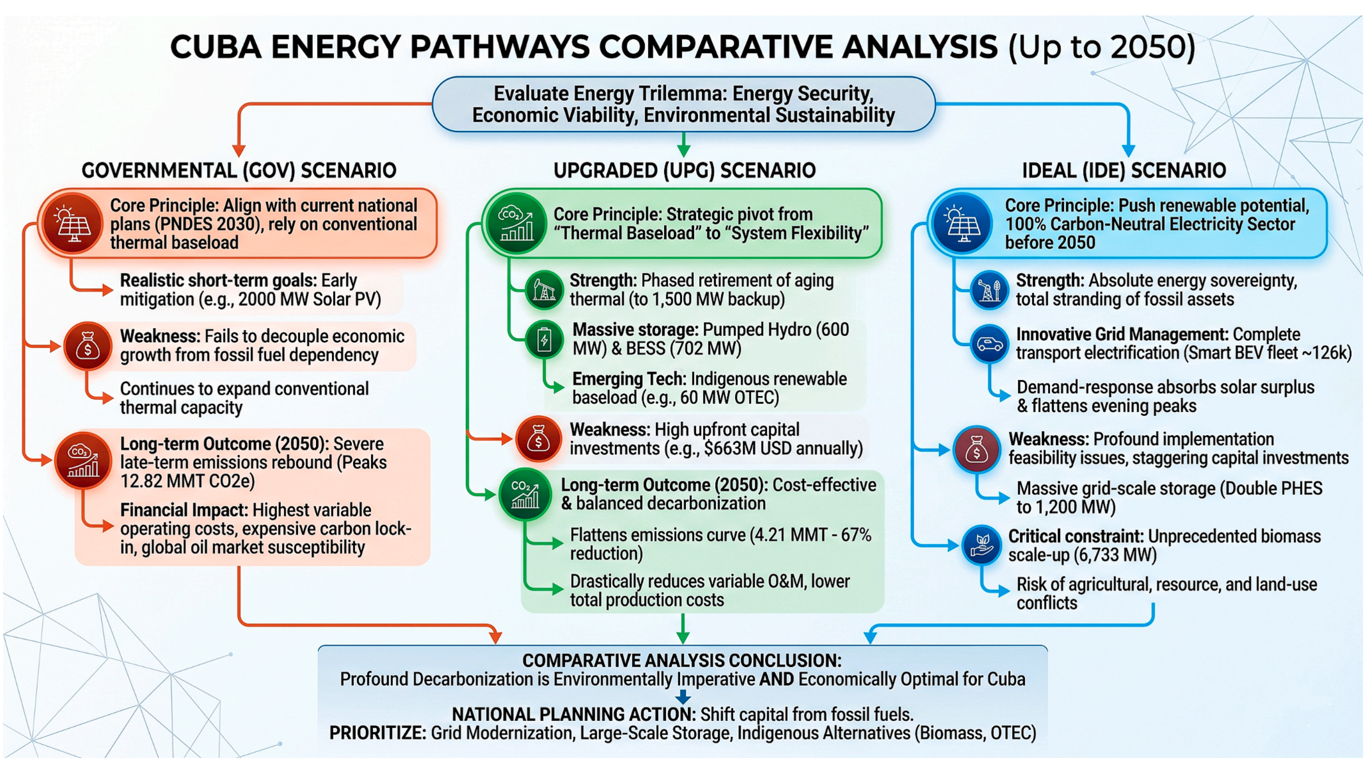

Fig. 21. Comparative analysis and trade-offs between scenarios through the lens of the energy trilemma.

emissions curve to 4.21 million tCO_2-eq by 2050 (a 67 % reduction) without compromising grid stability. Furthermore, sensitivity analyses indicate that this flexibility-oriented matrix is more resilient to demand fluctuations, actively leveraging capacity additions to further displace polluting sources even when load increases.

The IDE pushes the boundaries of the island's renewable potential, demonstrating that a 100 % carbon–neutral electricity sector is technically achievable before 2050. Its main strength is achieving absolute energy sovereignty through the total stranding of fossil fuel assets and the complete electrification of the transport sector. A highly innovative aspect of this scenario is its approach to grid management: rather than treating EVs merely as an added load, it leverages a projected fleet of 126,000 BEVs as a decentralized demand-response mechanism via smart-charging protocols, effectively absorbing solar surplus and flattening evening peaks. However, the IDE scenario presents profound weaknesses in terms of implementation feasibility. It demands staggering capital investments and large-scale storage deployment (doubling PHES capacity to 1,200 MW). Most critically, it relies on an exceptionally large scale-up of biomass capacity to 6,733 MW for baseload generation. This target could, in practice, pose major conflicts over agriculture, resources, and land use.

Ultimately, according to the comparative analysis summarized in Fig. 21, the results suggest that deep decarbonization is not only essential from an environmental standpoint, but is also more cost-effective under the modeling scenarios for Cuba. To avoid the costly stranded assets and emissions rebounds seen in the GOV scenario, national planning must shift capital away from conventional fossil-fuel infrastructure. Instead, investments must prioritize grid modernization, large-scale storage (PHES and BESS), and the technological maturity of indigenous baseload alternatives such as biomass and OTEC, as demonstrated by the UPG and IDE pathways.

Limitations

While this study provides a comprehensive long-term evaluation of decarbonization pathways for the Cuban power sector, several inherent limitations must be acknowledged regarding the modeling framework, data assumptions, and external socio-economic factors.

The use of the LEAP system provides a robust accounting framework for scenario-based policy analysis, but it also imposes specific methodological constraints. Primarily, LEAP lacks detailed market modeling and the endogenous economic optimization for hourly dispatch found in pure optimization tools like TIMES or Balmorel. Therefore, the results should be interpreted as long-term planning outcomes rather than as operational dispatch or grid-stability results. Furthermore, its limited spatial resolution means the model does not capture localized grid congestion, frequency stability issues, or specific transmission bottlenecks that often arise with high penetrations of VRE. Additionally, LEAP does not account for behavioral dynamics such as the "rebound effect," in which energy efficiency improvements and lower electricity costs might paradoxically stimulate higher energy consumption [74].

The reliability of long-term projections extending to 2050 is intrinsically subject to data uncertainties. Minor deviations in demographic trends, economic growth, and anticipated technological changes can lead to significant variations in outcomes over a multi-decade horizon. The techno-economic framework relies heavily on predictive learning curves for the CAPEX of solar, wind, and storage technologies. These assumptions presuppose a continuous global decline in technology costs and stable fuel prices, which may be disrupted by unforeseen global supply chain constraints, material shortages, or international market volatility [75].

Since technology costs and efficiency assumptions were extrapolated from global averages rather than regional Caribbean datasets, the lack of defined uncertainty bands for these capital expenditures limits the precision of the economic forecasts. Consequently, future research should cross-check these LEAP results with higher-resolution, hourly-dispatch optimization models to validate the system's operational confidence.

Finally, the model simulates scenarios under the assumption of unhindered policy implementation and frictionless capital flow, which does not reflect Cuba's complex reality. The simulation cannot fully quantify the significant financial bottlenecks stemming from the U.S. economic embargo, the lack of convertibility of the national currency, and limited access to international climate financing or multilateral credit [76]. These geopolitical factors represent critical barriers to securing the staggering investments required for the UPG and IDE pathways. Furthermore, the IDE reliance on a large expansion of biomass capacity oversimplifies significant environmental and spatial constraints. In practice, expanding biomass to such extremes entails severe land-use trade-offs, directly competing with agricultural land needed for food production [24], and posing risks to local biodiversity and soil metabolism [77]. Given these profound land-use and water constraints, evaluating a less extreme variant—such as an 80 % to 90 % renewable penetration pathway—would be highly beneficial in subsequent studies to identify a more pragmatic balance between decarbonization ambition and practical implementability.

See Table 11 for the qualitative taxonomy of key uncertainties treated as limitations in this study.

Table 11
Key uncertainty parameters and expected directional influence on results.

Parameter	Expected Influence	This Study	Future Work Suggestions
Population & GDP Growth	Demand and capacity requirements	Official projections	Sensitivity Analysis
Fuel prices	Relative cost of GOV vs UPG	Fixed Trajectory	Future price bands
CAPEX/storage cost	UPG & IDE feasibility	Learning-curve assumption	Future uncertainty ranges
Biomass availability	IDE feasibility	Technical ceiling	CLEWs nexus analysis
Thermal retirement	Baseload Generation	Scenario-defined	Endogenous retirement

Implications and strategic recommendations

It must be emphasised that the three scenarios presented in this study serve distinct analytical purposes and should not be read as equally immediately implementable policy alternatives. The policy-continuity scenario reproduces the explicit commitments already embedded in Cuba's official planning instruments. The Upgraded and Ideal Scenarios, by contrast, should be interpreted strictly as technical–economic pathways under assumed implementation capacity: they operationalize literature-estimated ceilings of renewable potential, accelerated transport electrification and large-scale storage, assuming that financing constraints, currency convertibility, the persistence of external sanctions and the institutional capacity to absorb multi-billion-dollar investment programmes can be overcome in the modelled horizon. Therefore, they function as stress tests of the power-sector response envelope, not as prescriptive policy pathways.

To realize the most favorable outcomes of this research, Cuban policymakers and energy planners must implement a strategic roadmap focused on regulatory reform, system flexibility, and cross-sectoral integration.

(1) Reform of financial and regulatory frameworks for renewable investment

To mobilize the massive capital required for the UPG and IDE pathways, Cuba must address a dual challenge: navigating major external constraints while deepening internal regulatory reforms. A critical barrier to this transition is the long-standing U.S. embargo, which has intensified in recent years, creating an 'oil blockade' and significantly restricting the country's access to international financial markets, multilateral climate financing, and state-of-the-art energy technologies [78]. These external pressures exacerbate the perceived investment risk and complicate the acquisition of essential components for renewable infrastructure [21]. Consequently, alongside efforts to mitigate the impact of these sanctions, authorities should optimize the Single Window for Foreign Investment to reduce bureaucratic friction and develop transparent, long-term Independent Power Producer contracts [7]. Establishing an independent regulatory body or public utility commission remains essential to guarantee fair pricing mechanisms and provide a stable legal framework that can attract Foreign Direct Investment despite the complex geopolitical landscape.

(2) Prioritization of grid modernization and Large-Scale storage

As the penetration of VRE increases, capital must be actively redirected away from maintaining obsolete thermal power plants toward grid modernization. Policies must aggressively incentivize the deployment of BESS and PHES to manage intermittency [22]. Furthermore, legislation should mandate that all new generation projects include a proportional storage component to ensure frequency stability and load shifting.

(3) Integration of electromobility as a decentralized grid asset

To achieve the transport decarbonization modeled in the scenarios, the deployment of EVs must be tightly coupled with power sector planning. Policymakers must establish a regulatory framework for electromobility that mandates smart-charging protocols and V2G capabilities [28].

(4) Implementation of a CLEWs framework for biomass expansion

To avoid the severe resource conflicts identified in the IDE scenario, the expansion of biomass capacity must be strictly regulated. Agricultural and energy policies must be integrated using a Climate, Land, Energy, and Water systems (CLEWs) nexus approach [24]. The state must enforce strict sustainability criteria, ensuring that the use of sugarcane bagasse and invasive species (e.g., marabou) for bioelectricity does not compete with arable land required for domestic food security or degrade soil metabolism and local biodiversity [79].

(5) Decentralization and Prosumer Empowerment

Finally, the transition to a highly distributed renewable matrix requires devolving decision-making power to local territories. The government should legally and financially empower Municipal Energy Management Systems (MEMS) and foster the creation of Renewable Energy Communities (RECs) [80]. Additionally, electricity tariffs must be progressively restructured to eliminate perverse subsidies while protecting vulnerable populations. Cost-reflective pricing, combined with incentives for net metering, will be essential to encourage end-use energy efficiency and to stimulate the emergence of local “prosumers”[81].

Conclusions

This study evaluates long-term decarbonization pathways for Cuba’s electricity sector up to 2050, indicating that navigating the country's energy trilemma requires a structural shift in the island's energy metabolism rather than mere technological substitution. The assessment suggests that deep decarbonization of the power grid transcends environmental compliance; it appears to be an economically preferable strategy to enhance energy sovereignty and insulate the national economy from the volatility of global fossil fuel markets.

A critical insight derived from the comparative and sensitivity analyses is the inherent vulnerability of maintaining a conventional thermal baseload. Pathways reliant on rigid fossil-fuel infrastructure exhibit a limited capacity to accommodate demand growth without proportionately increasing greenhouse gas emissions and variable operational costs. Conversely, pivoting toward a flexibility-oriented matrix—driven by the diversity of battery storage alongside variable and dispatchable renewable sources—demonstrates significant systemic resilience. As evidenced by the model's response to demand fluctuations, a flexible grid architecture can effectively leverage load growth to accelerate the integration of high-capacity variable renewables, such as wind power, thereby further displacing residual off-peak thermal generation. This dynamic indicates that shifting from baseload reliance to system flexibility transforms potential demand shocks into catalysts for deeper decarbonization.

Furthermore, the analysis critically examines the boundaries of achieving absolute electricity-sector carbon neutrality. While technically achievable, pushing the system to a 100 % renewable frontier relies heavily on a substantial scale-up of firm biomass capacity. This requirement exposes inherent vulnerabilities within the Climate, Land, Energy, and Water (CLEWs) nexus, potentially placing energy targets in direct competition with national food security and sustainable land use.

The importance of this paper for the scientific community is threefold. First, it addresses a critical geographical and methodological gap in island electricity-sector decarbonization literature, providing the first high-resolution, bottom-up simulation for Cuba that integrates sector-specific demand, transport electrification, and diverse storage configurations within a single LEAP framework. Second, it calls into question the long-term viability of incremental 'baseload + renewables' strategies for aging island grids, suggesting that without aggressive thermal phase-out and flexibility investments, emissions rebounds are likely under the modeled capacity mix. Third, it introduces a novel metric for SIDS: **the potential economic advantages of** flexibility-driven pathways over fossil-dependent ones, challenging conventional planning paradigms that prioritize short-term asset recovery over long-term systemic efficiency.

Despite these insights, several methodological and contextual limitations must be acknowledged. First, technology costs and efficiency parameters were primarily extrapolated from global averages; future research should incorporate defined uncertainty bands to strengthen the precision of the economic forecasts. Second, while the LEAP software provides a robust accounting framework for long-term planning, it lacks the endogenous economic optimization of hourly dispatch. Subsequent studies should cross-check these findings using high-resolution optimization models to validate the system's operational confidence. Moreover, given the profound land-use constraints of a total fossil-fuel phase-out, evaluating a less extreme variant would be highly beneficial in future works. Finally, the simulations assume unhindered capital flow, which does not reflect the significant financial bottlenecks imposed by the U.S. economic embargo, currency constraints, and limited access to multilateral climate finance. Overcoming these real-world barriers requires future investigations to focus on innovative financial mechanisms capable of unlocking the capital necessary for this critical transition.

CRediT authorship contribution statement

Ernesto Carlos Casals Cunill: Writing – original draft, Validation, Software, Methodology. **Carlos Alberto Masip Rodríguez:** Writing – original draft, Validation, Software, Methodology. **Leonardo Peña Pupo:** Writing – original draft, Methodology, Investigation, Formal analysis, Supervision. **Electo Eduardo Silva Lora:** Writing – review & editing, Supervision, Methodology, Investigation. **Osvaldo José Venturini:** Writing – review & editing, Supervision. **Adeoye Olasunkanmi Opelowa:** Writing – review & editing. **René Lesme Jaén:** Writing – review & editing.

Funding

This work was supported by the Research Support Foundation of the State of Minas Gerais (FAPEMIG); the National Council for Scientific and Technological Development (CNPq); the Coordination for the Improvement of Higher-Level Personnel (CAPES); and the BRICS project: CNPq/FINEP/MCTIC/BRICS STI nº 28/2023 – Process 440006/2024–4. In addition, this paper has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No [101205310], M4IEMA project.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the Universidad de Oriente (Santiago de Cuba) for hosting the Workshop on the Energy Metabolism of Islands in July 2023, which inspired this research.

Declaration for the use of Generative AI

During the preparation of this paper, the authors used Gemini Pro Version for the following purposes:

- Assistance in drafting and improving the language of certain paragraphs.
- Translation of text in some figures from the original Spanish into English.
- Generation of conceptual sketches of figures (flowcharts and system architecture).

After using this tool, the authors thoroughly reviewed and edited all generated content, verified the accuracy of the translations, completely redesigned the final figures and assume full responsibility for the published content.

Data availability

Data will be made available on request.

References

[1] Harrison C, Popke J. Geographies of renewable energy transition in the Caribbean: Reshaping the island energy metabolism. Energy Res Soc Sci 2017;36:165–74. https://doi.org/10.1016/j.erss.2017.11.008.
[2] Panfil M, Whittle D, Silverman-Roati K. What's next for Cuba's electricity sector? Electr J 2017;30(8):38–44. https://doi.org/10.1016/j.tej.2017.09.006.
[3] Podkovalnikov SV, Chudinova LY. Cuba: energy crisis and strategic energy's partnership with Russia. латинская АМерика/Latinskaia. Amerika 2025;11:64. https://doi.org/10.7868/s3034557x25110054.
[4] Guevara-Luna MA, Madrazo J, Meneses E, Mora H, Clappier A. Strategies toward an effective and sustainable energy transition for Cuba. Renew Sustain Energy Rev 2024;197:114387. https://doi.org/10.1016/j.rser.2024.114387.
[5] Revista Z. Cuba at the Inection Point: Geopolitical Coercion, Structural Crisis, and the Negotiated Transition of 2026. *Zenodo (CERN European Organization for Nuclear Research)* . Published online March 13, 2026. doi:10.5281/zenodo.19007106.
[6] Clappier A, Madrazo J, Guevara-Luna MA, Belalcazar LC. Cuban's energy strategy into 2030: General design features toward a sustainable transition (version 2). *HAL (Le Centre pour la Communication Scientifique Directe)* . Published online November 1, 2019. Accessed January 2025. https://hal.science/hal-02874566.
[7] Vazquez AS, Luukkanen J, Majanne Y, Vehmas J, Kaivo-oja J. A multidimensional framework for analysis of Cuba's 100% renewable energy system and the interlinkages of sustainable development goals. Renewable Sustainable Energy Transition 2026;9:100144. https://doi.org/10.1016/j.rset.2026.100144.
[8] Tavana A, Leelaprachakul T, Kim S, Tokuda D. Transition to a 100% renewable grid for a remote island: a case study of Tsushima Island. Japan Renew Energy Focus 2024;52:100657. https://doi.org/10.1016/j.ref.2024.100657.
[9] Berjawi AEH, Walker S, Patsios C, Hosseini SHR. An evaluation framework for future integrated energy systems: a whole energy systems approach. Renew Sustain Energy Rev 2021;145:111163. https://doi.org/10.1016/j.rser.2021.111163.
[10] Plazas-Niño F, Tan N, Howells M, Foster V, Quirós-Tortós J. Uncovering the applications, developments, and future research directions of the open-source energy modelling system (OSeMOSYS): a systematic literature review. Energy Sustainable Development 2024;85:101629. https://doi.org/10.1016/j.esd.2024.101629.
[11] Meschede H, Bertheau P, Khalili S, Breyer C. A review of 100% renewable energy scenarios on islands. *Wiley Interdisciplinary Reviews Energy and Environment* . 2022; 11(6). doi:10.1002/wene.450.
[12] Escamilla-Fraile S, Cruz-González RL, García-Afonso Ó, Calero-García FJ, González-Díaz B, Ramos-Real FJ. Scenario-based analysis of energy transition for an outermost EU Territory: the case of Tenerife island. Energy Convers Manage: X 2025;26:100917. https://doi.org/10.1016/j.ecmx.2025.100917.
[13] Katsaprakakis DA, Proka A, Zafirakis D, et al. Greek Islands' energy transition: from lighthouse projects to the emergence of energy communities. Energies 2022; 15(16):5996. https://doi.org/10.3390/en15165996.
[14] Stephanides P, Chalvatzis K, Li X, et al. The social perspective on island energy transitions: evidence from the Aegean archipelago. Appl Energy 2019;255:113725. https://doi.org/10.1016/j.apenergy.2019.113725.
[15] Jantzen J, Kristensen M, Christensen TH. Sociotechnical transition to smart energy: the case of Samso 1997–2030. Energy 2018;162:20–34. https://doi.org/10.1016/j.energy.2018.07.174.
[16] Eras-Almeida AA, Egido-Aguilera MA. Hybrid renewable mini-grids on non-interconnected small islands: review of case studies. Renew Sustain Energy Rev 2019;116:109417. https://doi.org/10.1016/j.rser.2019.109417.
[17] Harewood A, Dettner F, Hilpert S. Open source modelling of scenarios for a 100% renewable energy system in Barbados incorporating shore-to-ship power and electric vehicles. Energy Sustain Dev 2022;68:120–30. https://doi.org/10.1016/j.esd.2022.03.004.
[18] OECD, Commission E, America CDB of L, Caribbean EC for LA and the. *Latin American Economic Outlook 2022* . Organization for Economic Cooperation and Development; 2022. doi:10.1787/3d5554fc-en.
[19] Trapanese M, Viola A. Small Island developing states: Overview about wind, solar and marine energy in Cuba. Published online October 1, 2019:1-6. doi:10.23919/oceans40490.2019.8962624.
[20] Alba-Reyes Y, Pérez MPO, Barrera EL, Martínez Y, Cheng K. Thermochemical conversion processes of Dichrostachys cinerea as a biofuel: a review of the Cuban case. Renew Sustain Energy Rev 2022;160:112322. https://doi.org/10.1016/j.rser.2022.112322.
[21] Korkeakoski M. Towards 100% renewables by 2030: transition alternatives for a sustainable electricity sector in isla de la juventud. Cuba Energies 2021;14(10): 2862. https://doi.org/10.3390/en14102862.
[22] Vazquez L, Majanne Y, Castro M, et al. Energy system planning towards renewable power system: energy matrix change in cuba by 2030. IFAC-PapersOnLine 2018;51 (28):522–7. https://doi.org/10.1016/j.ifacol.2018.11.756.
[23] Jaén RL, Pupo LP, Lora EES, Eras JJC, Gutiérrez AS. Assessing biomass production and electricity generation potential in current and future decarbonization scenarios in Cuba until 2050. Energ Conver Manage 2025;332:119698. https://doi.org/10.1016/j.enconman.2025.119698.
[24] Malin P, Sascha P. Pathways for the Cuban energy transition and its CLEWs interactions. *KTH Publication Database DiVA (KTH Royal Institute of Technology)* . Published online January 1, 2022. Accessed February 2026. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-318630.
[25] Hornborg A, Cederlöf G, Roos A. Has Cuba exposed the myth of "free" solar power? Energy, space, and justice. Environ Plann E: Nat Space 2019;2(4):989–1008. https://doi.org/10.1177/2514848619863607.
[26] ONEI. *Anuario Estadístico de Cuba 2024. Minería y Energía. Edición 2025* . ONEI; 2025. https://www.onei.gob.cu/sites/default/files/publicaciones/2025-07/10-mineria-y-energia_aec2024.pdf.
[27] Soligo R, Jaffe AM. *Energy Balances and the Potential for Biofuels in Cuba* . J. Benjamin-Alvarado; 2010. http://www.redciencia.cu/geobiblio/paper/2010_CubaS%20Energy%20Future_cap4.pdf.
[28] Fernández MC, Llanes MV, Hernández JC. Electromobility and Energy transition in Cuba. Sustainability 2024;16(22):9688. https://doi.org/10.3390/su16229688.
[29] Brandts M, Bertheau P, Plana DR, Lammers K, Rodríguez MAR. An energy system model-based approach to investigate cost-optimal technology mixes for the Cuban power system to meet national targets. Energy 2024;306:132492. https://doi.org/10.1016/j.energy.2024.132492.
[30] Domínguez J, Bellini C, Martín AM, Zarzalejo LF. Optimizing solar potential analysis in Cuba: a methodology for high-resolution regional mapping. Sustainability 2024;16(18):7899. https://doi.org/10.3390/su16187899.
[31] Roque-Rodríguez A, Alonso-Díaz Y, Soltura-Morales R. Estimation of Cuban wind resource: WASP model vs WEST model. Revista Cubana De Meteorología 2020;26 (4). https://www.redalyc.org/journal/7019/701977551007/701977551007.pdf.
[32] Belt JAB, Usaid T, Globerson M, et al. DRAFT The Electric Power Sector in Cuba: Potential Ways to Increase Efficiency and Sustainability. Published online March 23, 2011. Accessed February 2026. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.184.8865.
[33] Reinaldo OF, Tamayo EC. Cuba en Datos: Apuntes necesarios sobre las termoeléctricas que debes conocer. September 14, 2022. http://www.cubadebate.cu/especiales/2022/09/14/cuba-en-datos-apuntes-necesarios-sobre-las-termoelectricas-que-debes-conocer/.

[34] Iakovleva E, Guerra D, Shklyarskiy AY. Alternative measures to Reduce Carbon Dioxide Emissions in the Republic of Cuba. J Ecol Eng 2020;21(4):55–60. https://doi.org/10.12911/22998993/119800.

[35] Wondratschek F. Between Investment Risk and Economic Benefit: Potential Analysis for the Reactivation of the Hershey Railway in Cuba. *Transactions on Transport Sciences* . Published online June 4, 2024. doi:10.5507/tots.2024.007.

[36] Reinaldo OF. Preguntas ineludibles para entender el porqué de los apagones en Cuba. August 14, 2021. http://www.cubadebate.cu/especiales/2021/08/14/preguntas-ineludibles-para-entender-el-porque-de-los-apagones-en-cuba/.

[37] Anaely SV. Cuban Energy Futures: The Transition towards a Renewable Energy System – Political, Economic, Social and Environmental Factors. Published online October 28, 2022. Accessed March 2026. https://www.utupub.fi/handle/10024/168301.

[38] Álvarez YC, Borges RJ, Alfonso-Francia G, et al. Transition to a circular bioeconomy in the sugar agro-industry: predictive modeling to estimate the energy potential of By-Products. Technologies 2025;13(6):238. https://doi.org/10.3390/technologies13060238.

[39] Camaraza-Medina Y, Escalona AAS, Retirado-Mediaceja Y, Morales OFG. Use of air cooled condenser in biomass power plants: a case study in Cuba. Int J Heat Technol 2020;38(2):425–31. https://doi.org/10.18280/ijht.380218.

[40] Heaps CG. *LEAP: The Low Emissions Analysis Platform* . 2022. https://leap.sei.org.

[41] Simsek Y, Sahin H, Lorca Á, Santika WG, Urmee T, Escobar R. Comparison of energy scenario alternatives for Chile: towards low-carbon energy transition by 2030. Energy 2020;206:118021. https://doi.org/10.1016/j.energy.2020.118021.

[42] ONEI. *Anuario Estadístico de Cuba 2024. Cuentas Nacionales. Edición 2025* . ONEI; 2025. https://www.onei.gob.cu/sites/default/files/publicaciones/.

[43] Ministerio de Economía y Planificación. Comienza este 23 de agosto venta de divisas en el mercado cambiario cubano. Published online 2022. https://www.mep.gob.cu/sites/default/files/Documentos/Comienza%20este%2023%20de%20agosto%20venta%20de%20divisas%20en%20el%20mercado%20cambiario%20cubano%281%29.pdf.

[44] ONEI, Centro de Estudios de Población y Desarrollo, CEPDE. *Proyecciones de La Población Cubana 2015 - 2050* . ONEI; 2015. https://www.onei.gob.cu/proyecciones-de-la-poblacion-cubana-20152050.

[45] Reinaldo OF, Montero AA, Rodríguez YH, Rodríguez GM, Díaz EG. Ministro de Energía y Minas ofrece detalles del programa de recuperación del SEN. Cubadebate: Published online; 2024.

[46] ONEI O. *ELECTRICIDAD EN CUBA. INDICADORES SELECCIONADOS 2024* . 2025. https://www.onei.gob.cu/sites/default/files/publicaciones/2025-05/electricidad-en-cuba.-2024-edic-2025.pdf.

[47] OLADE. Estadísticas Energéticas de América Latina y El Caribe . 2025.

[48] MINEM. Estrategia Nacional Para la Transición Energética de Cuba. Published online 2024.

[49] Galán-Cano L, Cámara-Aceituno J, Terrados-Cepeda J, Hermoso-Orzáez MJ, Barragán-Escandón EA, Nieto ÁIM. Exploring energy scenarios and driving forces of CO2 emissions of regions: the case of a southern region of Spain through LEAP analysis. Energy Rep 2025;13:4563–85. https://doi.org/10.1016/j.egyr.2025.03.065.

[50] International Energy Agency IEA. *Latin America Energy Outlook 2023* . Organization for Economic Cooperation and Development; 2023. doi:10.1787/fd3a6daa-en.

[51] Bowen T, Chernyakhovskiy I, Denholm P. *Grid-Scale Battery Storage: Frequently Asked Questions* . 2019. doi:10.2172/1561843.

[52] Team UO of EE and RE (EERE) Strategic Analysis, Cole W, Ramasamy V, Turan M. *Cost Projections for Utility-Scale Battery Storage: 2025 Update* . 2025. doi:10.2172/2583471.

[53] IRENA. Innovation Landscape Brief: Innovative Operation of Pumped Hydropower Storage . IRENA; 2020.

[54] Pedrotti A. Cuba introducirá más de 56.000 vehículos eléctricos para su flota estatal antes del 2030. *Mobility Portal* . Published online 2021. https://www.mobilityportal.eu/es/notes/cuba-introducira-mas-de-56-000-vehiculos-electricos-para-su-flota-estatal-antes-del-2030.

[55] Agora Verkehrswende. 2024. https://www.agora-verkehrswende.org/.

[56] Curbelo JJ. El petróleo cubano: circunstancias. 2014. https://s3.amazonaws.com/rgi-documents/a7112220b3cd18bd3fc97143259b6dfbf1209f87.pdf.

[57] Mirletz B, Vimmerstedt L, Stehly T, et al. 2024 Annual Technology Baseline (ATB) Cost and Performance Data for Electricity Generation Technologies. *OSTI OAI (US Department of Energy Office of Scientific and Technical Information)* . Published online January 1, 2024. doi:10.25984/2377191.

[58] NREL. 2024 Electricity ATB Technologies and Data Overview. Published online 2024. https://atb.nrel.gov/electricity/2024/index.

[59] Langer J, Quist J, Blok K. Recent progress in the economics of ocean thermal energy conversion: critical review and research agenda. Renew Sustain Energy Rev 2020;130:109960. https://doi.org/10.1016/j.rser.2020.109960.

[60] Tobal-Cupul JG, Garduño-Ruiz EP, Gorr-Pozzi E, et al. An assessment of the financial feasibility of an OTEC ecopark: a case study at cozumel Island. Sustainability 2022;14(8):4654. https://doi.org/10.3390/su14084654.

[61] Peña Pupo L, Hidalgo González R, Gutiérrez Urdaneta L, Domínguez Abreu H. Integration Proposal of a Solar Thermal Power Plant to the Cuban National Electric System. Published online 2018.

[62] Ministerio de Economía y Planificación M de E y P. La transición energética muestra el camino. November 20, 2024. https://www.mep.gob.cu/es/noticia/la-transicion-energetica-muestra-el-camino.

[63] Ministerio de Justicia M de J. *Decreto-Ley No. 345 Del Desarrollo de Las Fuentes Renovables y El Uso Eficiente de La Energía* . 2019. https://www.gacetaoficial.gob.cu/sites/default/files/goc-2019-o95.pdf.

[64] Márquez SV. Desafío Energético de Cuba: Hacia una Transición Sostenible. *Tribuna de La Habana* . Published online January 27, 2025. https://www.tribuna.cu/ciencia/2025-01-27/desafio-energetico-de-cuba-hacia-una-transicion-sostenible.

[65] MINEM. Energías Renovables y Eficiencia Energética. *Infopower: Actualidad y tecnología de producción y uso eficiente de la energía* . 2024;(74). https://www.minem.gob.cu/es/actividades/energias-renovables-y-eficiencia-energetica.

[66] Cubadebate. Rusia concede a Cuba crédito para la construcción de termoeléctricas. 2015. http://www.cubadebate.cu/noticias/2015/10/20/rusia-concede-a-cuba-credito-para-la-construccion-de-termoelectricas/.

[67] MINREX M. Soluciones complejas en el camino de la recuperación eléctrica. 2025. https://cubaminrex.cu/es/soluciones-complejas-en-el-camino-de-la-recuperacion-electrica.

[68] Prensa Latina. Cuba septuplicará generación de energía por radiación solar. August 3, 2024. https://www.prensa-latina.cu/2024/08/03/cuba-septuplicara-generacion-de-energia-por-radiacion-solar/.

[69] Pedrotti AC. *Vehículos Eléctricos: Una Opción Sostenible Para Cuba* . Cuba. Cu.; 2021.

[70] Alejandro R, Melissa A, Reyes D, et al. Thermal Efficiency Dataset Around Cuban Seas (TEDACS). *ScienceDB* . Published online August 8, 2023. doi:10.57760/sciencedb.10037.

[71] Peña PL, Fariñas WEY, Brito SAL. The role of hydropower in the cuban electricity System and future plans toward 2030. In: Cuban Energy Systems Development-Technological Challenges and Possibilities. Finland: University of Turku; 2022. p. 255.

[72] Extremera DSM, Castro IMM, Padrón AP. Vehículos Eléctricos del Caribe, asegurando el ciclo de producción para una movilidad sostenible (+ Video). *Cubadebate* . Published online 2024. http://www.cubadebate.cu/especiales/2024/07/22/vehiculos-electricos-del-caribe-asegurando-el-ciclo-de-produccion-para-una-movilidad-sostenible-video/.

[73] Perez AS. Study Finds 21 Regions with High Potential for the Development of Wind Farms in Cuba. *POWERMAG* . Published online 2024. https://www.powermag.com/study-fnds-21-regions-with-high-potential-for-the-development-of-wind-farms-in-cuba/.

[74] Bahta ST, Gebreslassie MG, Mebrahtu AH. Projecting Ethiopia's energy future to 2060: scenario analysis of demand, electrification, and GHG emissions using the LEAP model. Sustainable Energy Res 2025;12(1). https://doi.org/10.1186/s40807-025-00211-w.

[75] Tan N, Harrison J, Howells M. Comparing long-term power sector pathways in viet nam: a simple cost-optimization approach with OSeMOSYS. Energies 2024;17(23):6158. https://doi.org/10.3390/en17236158.

[76] Análisis FAC. de La Economía Cubana En El Marco de Su Contexto Político-Social. Universidad de Sevilla; 2024.

[77] IRENA. *Sustainable Bioenergy Potential in Caribbean Small Island Developing States* . International Renewable Energy Agency; 2024.

[78] Revista Z. Cuba at the Inection Point: Geopolitical Coercion, Structural Crisis, and the Negotiated Transition of 2026. *Zenodo (CERN European Organization for Nuclear Research)* . Published online March 13, 2026. doi:10.5281/zenodo.19007105.

[79] Gutiérrez AS, Eras JJC, Huisingh D, Vandecasteele C, Hens L. The current potential of low-carbon economy and biomass-based electricity in Cuba. the case of sugarcane, energy cane and marabu (Dichrostachys cinerea) as biomass sources. J Clean Prod 2017;172:2108–22. https://doi.org/10.1016/j.jclepro.2017.11.209.

[80] Herrera I, Banacloche S, Lechón Y, Domínguez J. Assessing the socioeconomic and environmental impact of hybrid renewable energy systems for sustainable power in remote Cuba. Sustainability 2025;17(17):7592. https://doi.org/10.3390/su17177592.

[81] Korkeakoski M. State of play for 100% renewable energy futures for Cuba: recent changes and challenges. Sustainability 2022;14(21):13825. https://doi.org/10.3390/su142113825.