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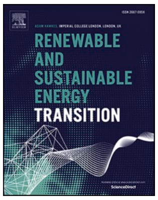

Full-length article

A multidimensional framework for analysis of Cuba's 100% renewable energy system and the interlinkages of sustainable development goals

Anaely Saunders Vazquez [a,*], Jyrki Luukkanen [a], Yrjo Majanne [b], Jarmo Vehmas [a], Jari Kaivo-Oja [a]

[a] *University of Turku. Finland Futures Research Centre (FFRC). Tampere Office. Hämeenkatu 15B 11, 33100, Tampere, Finland*
[b] *Tampere University. Faculty of Engineering and Natural Sciences, P.O. Box 589, 33014, Tampere, Finland*

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ABSTRACT

The global transition to renewable energy systems is imperative for climate sustainability. However, nations face significant challenges, including financial constraints, grid vulnerabilities, and dependence on fossil fuels. This study evaluates the feasibility of a 100% renewable electricity scenario for Cuba by 2050, employing a multidisciplinary framework integrating energy modelling (CUBALINDA), sustainability threshold quantification (Integrated SuWi Doughnut Approach), and cross-sectoral impact analysis (Dynamic Synergy Analysis).

Using CUBALINDA—an adaptation of the LINDA framework calibrated for Cuban conditions—a backcasting scenario was constructed based on solar PV, wind energy, and Power-to-X technologies, supplemented by energy storage and green hydrogen production to address renewable intermittency.

The Integrated SuWi Doughnut Approach reveals that while Cuba meets all social sustainability thresholds, it currently operates outside environmental limits regarding renewable energy share and ecological footprint. The Dynamic Synergy Analysis demonstrates that ammonia derived from green hydrogen could replace fertiliser imports, increase agricultural production, and reduce dependence on food imports.

Cuba's energy transition is technically feasible but requires coherent policies, intersectoral integration, and substantial infrastructure investments. Green hydrogen yields significant collateral benefits, fostering energy sovereignty and agricultural revitalisation. By 2050, solar photovoltaic and wind will dominate the energy mix (93 % renewable share), progressively replacing fossil fuels with sustainable biofuels and e-fuels.

Critical challenges include grid modernisation, seasonal supply-demand imbalances, and financing for hydrogen infrastructure, all of which require coordinated policy interventions and innovative financing mechanisms. This study provides a replicable framework for integrated energy-sustainability planning, emphasising the need for decomposition and resilience analyses to optimise transition pathways.

1. Introduction

The global energy transition has emerged as one of the most pressing challenges of the 21st century, driven by the urgent need to mitigate climate change, ensure energy security, and foster sustainable development [1]. Greenhouse gas emissions from the energy sector account for approximately three-quarters of global emissions, underscoring the need for rapid decarbonisation to meet the Paris Agreement's temperature targets [2].

In this context, renewable energy technologies have gained unprecedented momentum, with global capacity expected to triple by 2030 according to COP28 commitments [3]. However, this transition presents unique challenges for different geographical and socio-economic contexts, particularly for Small Island Developing States (SIDS) that face compounding vulnerabilities from climate change, limited energy resources, and economic dependencies [4].

Cuba, the largest island in the Caribbean with an area of 109,884 km^2 and a population of approximately 11.34 million inhabitants, represents a critical case study for renewable energy transitions in SIDS contexts [6]. The nation's geography comprises diverse climatic zones with substantial solar radiation, averaging 4–6 kWh/m^2/day (Fig. 1), and wind

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[*] Corresponding author at: University of Turku, Finland Futures Research Centre (FFRC), Tampere Office. Hämeenkatu 15B 11, 33100, Tampere, Finland.

E-mail addresses: asavaz@utu.fi (A.S. Vazquez), jyrki.luukkanen@utu.fi (J. Luukkanen), yrjo.majanne@tuni.fi (Y. Majanne), jarmo.vehmas@utu.fi (J. Vehmas), jari.kaivo-oja@utu.fi (J. Kaivo-Oja).

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Acronyms, abbreviations and units

AHP	Analytic Hierarchy Process
BCG	Boston Consulting Group
BESS	Battery Energy Storage Systems
CO_2	Carbon dioxide
COP28	Conference of the Parties to the United Nations Framework Convention on Climate Change No 28
FFRC	Finland Futures Research Centre
GDP	Gross Domestic Product
Gha	Global hectares
GHG	Greenhouse gases
GII	Gender Inequality Index
GWh	Gigawatt-hour
H_2	Hydrogen
HDI	Human Development Index
HLY	Healthy Live Years
ICE	Internal Combustion Engines
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LEAP	Long-range Energy Alternatives Planning
LINDA	Long-range Integrated Development Analysis
MCDM	Multi-Criteria Decision-Making
MERRA	Modern-Era Retrospective Analysis for Research and Applications
Mipymes	Mini, small, and medium-sized enterprises
MW	Megawatt
N_2	Nitrogen
NH_3	Ammonia
ONEI	Spanish acronym by the National Statistics and Information Office of Cuba
PV	Photovoltaic
SDGs	Sustainable Development Goals
SIDS	Small Island Developing States
SSI	Sustainable Society Index
SuWi	Sustainability Window
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TPES	Total Primary Energy Supply
UN	The United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific, and Cultural Organisation
USD	US dollar

speeds of 4–8 m/s in coastal areas (Fig. 2), providing significant renewable energy potential [7].

However, Cuba's current energy system remains heavily dependent on fossil fuels, with approximately 95 % of electricity generated from imported oil and domestically produced oil and natural gas, creating significant economic vulnerabilities and contributing to carbon emissions [6]. The country faces additional challenges, including ageing power generation infrastructure, frequent blackouts, transmission losses exceeding 15 %, and limited financial resources for infrastructure modernisation [6]. Population trends indicate a declining and ageing demographic structure, with projections suggesting the population will decrease from 11.34 million in 2020 to approximately 10.8 million by 2050, while the proportion of citizens over 60 years old will increase from 21 % to over 35 %, creating shifts in energy demand patterns and consumption profiles [9]. These demographic dynamics, combined with aspirations for economic development and environmental commitments, necessitate comprehensive energy planning that integrates sustainability considerations across environmental, economic, and social dimensions.

Energy system planning has evolved from single-objective optimisation towards multidimensional assessment frameworks that integrate technical, economic, environmental, and social considerations [10]. Multi-Criteria Decision-Making (MCDM) methods have become vital for optimising energy planning and policy formulation, with techniques such as the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and hybrid approaches enabling robust evaluation under uncertainty [11]. Long-range energy modelling tools, particularly the Long-range Energy Alternatives Planning (LEAP) system, have been widely applied for scenario analysis and backcasting to explore pathways toward 100 % renewable energy

Fig. 1. Cuba, photovoltaic power potential, 2026 [5].
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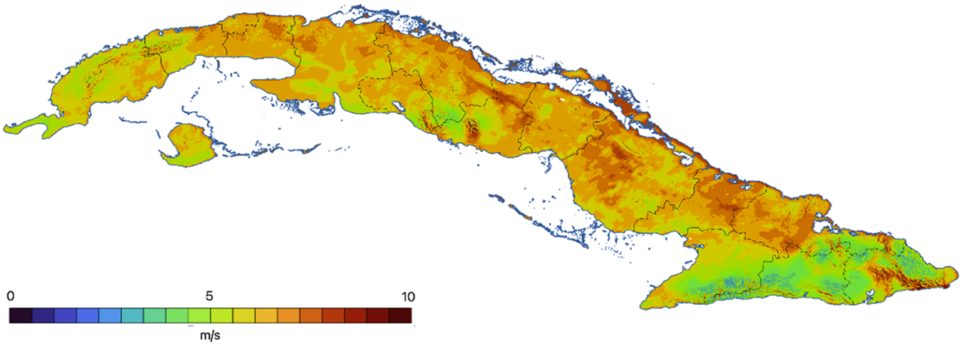

Fig. 2. Cuba Wind Map [8].
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systems [12]. Backcasting methodologies, which define normative future goals and work backwards to identify necessary interventions, have proven particularly effective for long-term sustainability planning in complex urban and energy systems [13]. However, despite these methodological advances, current approaches often suffer from fragmentation, with sustainability assessments, energy system modelling, and sectoral interaction analyses conducted in isolation rather than within integrated frameworks [14].

Furthermore, while numerous studies have examined renewable energy transitions for individual SIDS [15–16], there remains a critical gap in comprehensive methodological frameworks that simultaneously address social, economic, and environmental sustainability thresholds, technical energy system feasibility, and cross-sectoral synergies within integrated analytical structures. Existing energy planning studies typically focus on either supply-side optimisation or demand-side management, but rarely integrate both with explicit sustainability boundaries derived from planetary limits and social foundations [10]. Additionally, the quantification of sectoral interdependencies—particularly the co-benefits and trade-offs arising from emerging technologies such as green hydrogen—remains under-explored in the context of renewable energy transitions for developing nations [17].

The necessity for this research emerges from three critical gaps in the current literature. *First*, conventional energy planning methodologies lack integration with sustainability assessment frameworks that explicitly quantify environmental boundaries (planetary limits) and social foundations (SDG-aligned minimum standards). While the Doughnut Economics framework and Sustainability Window (SuWi) approaches have been applied in various contexts, their integration with detailed energy system models remains absent [10]. *Second*, existing energy transition studies rarely employ dynamic synergy analysis to quantify nonlinear interactions among sectoral variables that simultaneously contribute to multiple economic sectors (agriculture and industry [17]. *Third*, there is insufficient evidence on the technical and economic viability of 100 % renewable energy scenarios for Caribbean SIDS when analysed through integrated sustainability-energy-synergy frameworks that account for hourly supply-demand balance, storage requirements, and Power-to-X applications [16,18].

This study addresses these gaps by developing and applying a comprehensive, multidisciplinary framework that integrates sustainability assessment, energy system modelling, and dynamic synergy analysis in a coherent, sequential structure tailored to SIDS contexts. Cuba serves as an ideal case study due to its substantial renewable energy resources, documented energy challenges, demographic transitions, and policy aspirations toward energy sovereignty and sustainability [6].

This research makes three primary novel contributions to the energy planning and sustainability assessment literature:

1st: it introduces the Integrated SuWi Doughnut Approach, combining the Sustainability Window methodology with Doughnut Economics principles to establish quantitative sustainability thresholds (GDP_{max} and GDP_{min}) that serve as boundary conditions for energy scenario development. This integration provides explicit, measurable constraints that ensure energy transition pathways remain within planetary boundaries while meeting social foundations.

2nd: the CUBALINDA model, an adapted version of the Long-range Integrated Development Analysis (LINDA) model, is developed and specifically configured for Cuba's energy system, incorporating hourly-resolved supply-demand balancing, provincial-level allocation of solar PV and wind resources, pumped hydro storage, and green hydrogen production via Power-to-X pathways. This model enables backcasting analysis toward 100 % renewable electricity by 2050 with spatial and temporal resolution for Cuba.

3rd: The Dynamic Synergy Analysis Method, a novel quantitative framework, is presented to identify and measure synergies and trade-offs between development paths across different sectors of the economy, thereby quantifying co-benefits that extend beyond the energy sector alone.

The innovation of this work lies not only in these individual methodological contributions but, fundamentally, in their integration within a unified analytical framework to provide multidimensional policy advice across different sectors of the economy. This integrated approach transcends the limitations of isolated analyses and provides a replicable methodological blueprint for holistic energy-sustainability planning in resource-constrained island contexts.

The *primary objective* of this study is to illustrate the technical, economic, and sustainability viabilities of achieving a 100 % renewable electricity system in Cuba by 2050, using a scenario approach that employs an integrated multidisciplinary framework combining sustainability threshold analysis, long-range energy system modelling, and dynamic sectoral synergy quantification.

Specific objectives include:

1. To apply the Integrated SuWi Doughnut Approach to establish quantitative sustainability boundaries (environmental ceilings and social foundations) for Cuba's energy transition;
2. To illustrate the use of the CUBALINDA model for Cuba's electricity sector, incorporating hourly supply-demand profiles, renewable resource allocation, storage systems, and green hydrogen production;
3. To conduct backcasting scenario analysis, identifying a potential renewable energy portfolio (solar PV, wind, storage, Power-to-X) that achieves 100 % renewable electricity by 2050;
4. To illustrate the use of the Dynamic Synergy Analysis Method to quantify cross-sectoral synergies and trade-offs between economic sectors;
5. Synthesise integrated findings and provide evidence-based policy recommendations for Cuba's energy transition that balance technical feasibility, economic viability, and sustainability imperatives.

By addressing these objectives through rigorous, integrated analysis, this research aims to provide actionable insights for policymakers, energy planners, and international development agencies supporting renewable energy transitions in Cuba and similar resource-constrained contexts globally.

2. Methodology and tools

This study employs a novel multi-tool framework (Fig. 3) to analyse Cuba's sustainable energy transition. The CUBALINDA energy model for supply-demand simulation, the Synergy method for quantifying sectoral interdependencies, the Sustainability Window (SuWi), and the Integrated SuWi Doughnut Approach for assessing sustainability boundaries across environmental, economic, and social dimensions.

2.1. LINDA model for energy system analysis

The Long-range Integrated Development Analysis (LINDA) model is an intensity-based framework employing the Kaya identity for CO_2 emissions accounting. Adapted to the Cuban context as CUBALINDA, it constructs hourly-resolved energy supply and demand scenarios that ensure system equilibrium.

Fig. 4 shows the model's general architecture. CUBALINDA operates on an hourly balance basis. Changes in consumption are modelled hourly, using different load curves for weekdays and weekends across consumption sectors, and monthly averages for each month. Solar and wind power generation uses hourly radiation and wind speed data, while hydroelectric power generation uses monthly rainfall averages. The fossil-fueled power plant generation is modelled to cover the residual load.

Data inputs derive from three sources: the National Statistics and Information Office of Cuba (ONEI, by its Spanish acronym) [19] (historical power plant data), the International Energy Agency [20] (sectoral consumption), and the United Nations Statistics Office [21] (sectoral economic data). The model generates sectoral load curves accounting for temporal variations across weekdays, weekends, and seasons. Solar PV generation relies on MERRA-derived site-specific radiation data via renewables.ninja [22–23], while wind production incorporates MERRA wind speed data [24] for the planned wind farm locations.

The CubaLinda model, which focuses on the technological and economic aspects of development, is used to construct scenarios for future economic development across all sectors of the economy, project the intensity of electricity and fuel consumption, and generate electricity and fuel demand in these sectors. The model's outputs include fuel consumption, CO_2 emissions, the levelized cost of electricity (LCOE), and grid operating requirements (ramp rates and load duration curves) [25].

2.2. Synergy method for identifying sectoral co-benefits and trade-offs

The Synergy Method quantifies interaction effects between paired variables in complex systems. Synergy occurs when the combined effect of variables x and y deviates from their individual arithmetic sum [26], expressed mathematically as Eq. (1):

$$\boldsymbol{z} = \boldsymbol{ax} + \boldsymbol{by} + \boldsymbol{cxy} + \boldsymbol{d} \tag{1}$$

Where:

- $\boldsymbol{z}$ = dependent variable
- $\boldsymbol{x}$ = first independent variable
- $\boldsymbol{y}$ = second independent variable
- $\boldsymbol{c}$ = synergy coefficient (interaction term)
- $\mathbf{cxy > 0}$ indicates positive synergy (multiplicative benefits)
- $\mathbf{cxy < 0}$ indicates negative synergy (trade-offs or conflicts)
- $\mathbf{cxy = 0}$ indicates delinking (no interaction between variables)
- and $\boldsymbol{a, b, c}$, and $\boldsymbol{d}$ are coefficients that determine how the output $\boldsymbol{z}$ depends on inputs $\boldsymbol{x}$ and $\boldsymbol{y}$

Applying this method to time-series data reveals constantly evolving interdependencies between socioeconomic and environmental indicators. Positive synergy indicates mutually reinforcing processes (where the outcome exceeds the sum of individual contributions), negative synergy reveals trade-offs, and zero synergy indicates a disconnection between variables. By mapping nonlinear interactions across sustainable development domains, the method identifies co-benefit opportunities and anticipates policy trade-offs, crucial for cross-sectoral planning of the energy transition [26].

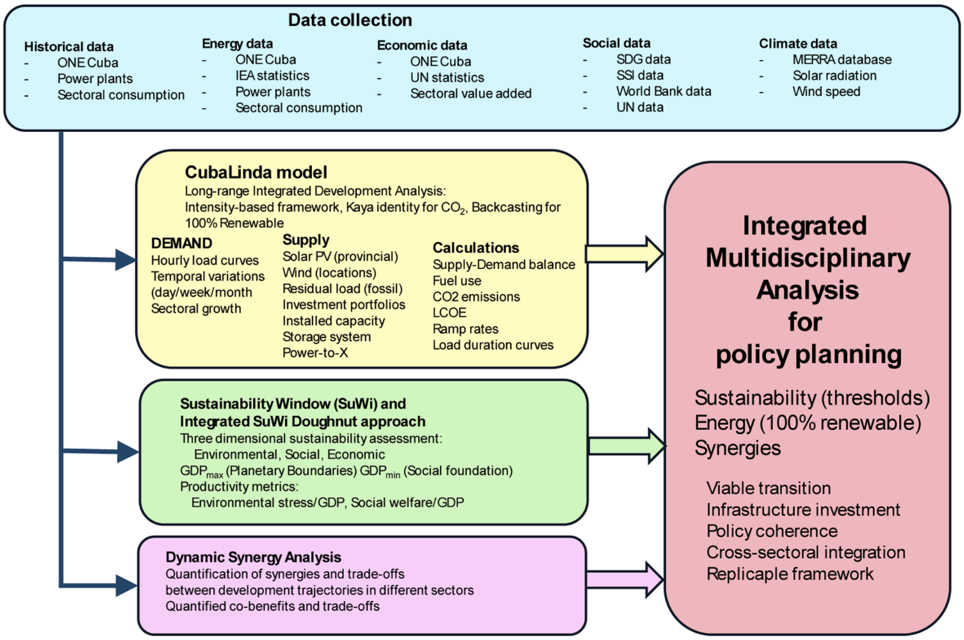


Fig. 3. Integrated Methodological Framework.

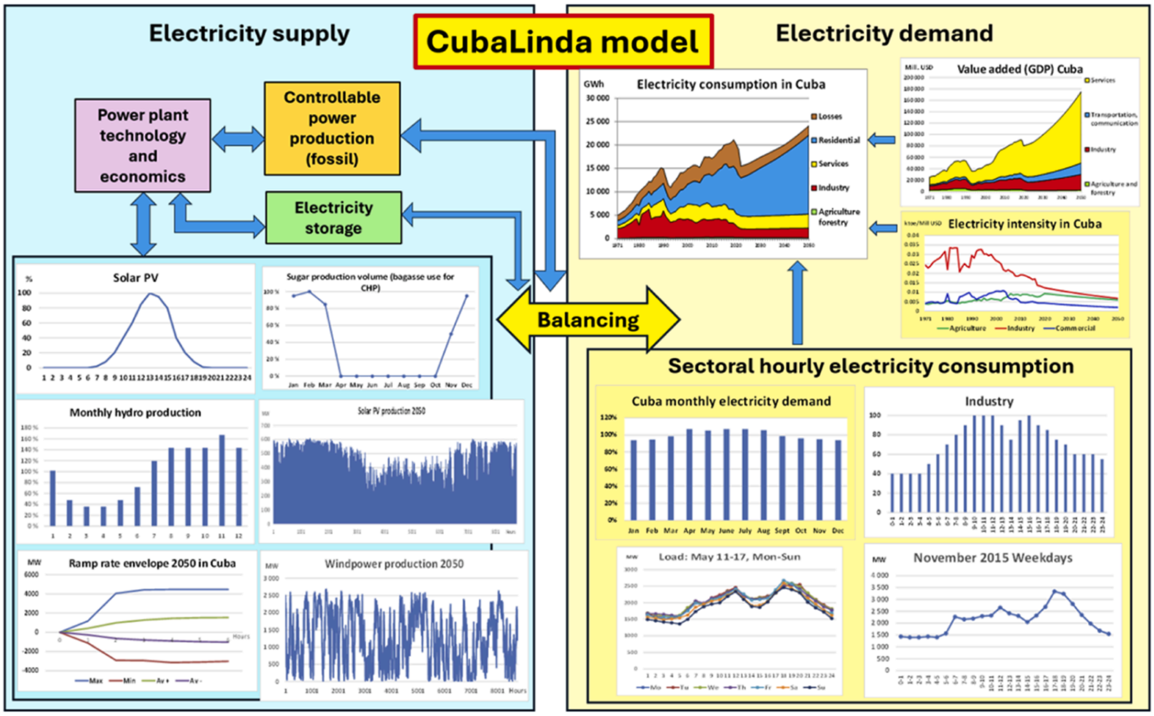


Fig. 4. CUBALINDA model.

2.3. *Sustainability window (SuWi) and doughnut approach*

The Sustainability Window method integrates environmental, economic, and social sustainability into a single quantitative framework, operationalising the Brundtland Commission’s concept of sustainable development [27]. It establishes boundary conditions through minimum (GDPmin) and maximum (GDPmax) economic output thresholds that maintain predetermined sustainability targets [28–31].

Operational Logic: Using time-series data indexed by time, the method calculates environmental stress and social welfare productivity relative to GDP. It defines GDPmax as the maximum economic output compatible with non-increasing environmental stress, and GDPmin as the minimum output required to maintain social welfare. The “Sustainability Window” lies between these thresholds, enabling analysis of current GDP positioning relative to sustainability goals [30].(Fig. 5).

SuWi's primary utility lies in the graphical and qualitative identification of the point of conflict between social and environmental objectives, the evaluation of the impact of alternative policies, and the outlining of a range of possibilities. It is an exploratory modelling tool based on scenarios that considers dual constraints. Its conceptual architecture is the search for a window of sustainability between a social floor and an ecological ceiling.

The Integrated SuWi Doughnut Approach establishes measurable, indicator-specific boundaries through three key innovations:

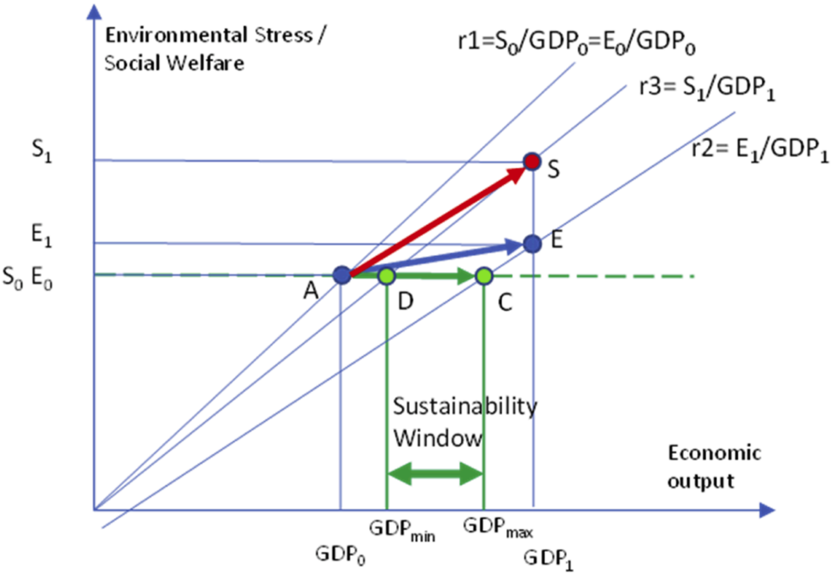


Fig. 5. Defining the *Sustainability Window* with maximum economic development, **GDP$_{\mathbf{max}}$**, to fulfil the relative environmental sustainability criteria, measured with different environmental indicators, and minimum economic development, **GDP$_{\mathbf{min}}$**, to fulfil the relative social sustainability criteria, measured with different socio-economic indicators.

a) Quantitative linkage: Introduces productivity metrics (environmental stress/GDP and social welfare/GDP) linking economic output to sustainability dimensions.
b) Dimensional Integrity: Evaluates socio-economic and environmental indicators separately from, yet relative to, economic output—accounting for inequality, governance, emissions, resource depletion, and ecosystem damage.
c) Operationalisation: Transforms Raworth's conceptual Doughnut Economy [32–33] into a measurable radial assessment where the outer ring represents GDPmax, the inner ring represents GDPmin, and actual GDP forms a third concentric circle.

The political implications of using this approach are reflected in the following: when GDP exceeds GDPmax, sustainability requires either reducing GDP or decreasing environmental stress intensity per unit of GDP through technological innovation, efficiency improvements, or structural economic shifts. Conversely, when GDP falls below GDPmin, sustainability requires either increasing GDP or enhancing the social welfare yield of GDP by reallocating resources toward well-being activities, such as education and health care. This framework accommodates both relative sustainability assessments (directional progress from base-year values) and absolute assessments anchored to downscaled planetary boundaries [34] and SDG-based social standards [32], enabling evidence-based identification of priority intervention areas [30].

3. Results and discussion

This section presents the integrated results from three complementary analytical frameworks applied to Cuba's energy transition pathway: (i) the CUBALINDA energy system model for technical-economic feasibility assessment (Section 3.2); (ii) the Integrated Sustainability Window (SuWi) Doughnut Approach for sustainability threshold evaluation (Section 3.3); and (iii) Dynamic Synergy Analysis for cross-sectoral impact quantification (Section 3.4). These results directly address the five specific objectives outlined in the Introduction, providing empirical evidence for the technical viability, economic implications, and sustainability performance of achieving 100 % renewable electricity in Cuba by 2050. The analysis reveals both opportunities and challenges inherent in this transition, with particular emphasis on the possible strategic role of green hydrogen as a cross-sectoral enabler.

3.1. *Current state of cubás energy system: challenges and context*

The Cuban energy system presents a complex case study in energy transition for Small Island Developing States (SIDS), characterised by significant structural challenges coupled with emerging transformation efforts [6]. Understanding current baseline conditions is essential for interpreting the magnitude of transformation required to achieve the 100 % renewable electricity target by 2050, while accounting for constraints.

3.1.1. *Situation of the Cuban energy system*

Fig. 6 depicts Cuba's energy system structure in 2022 through a comprehensive Sankey diagram, revealing material and energy flows across the entire value chain from primary energy sources to final consumption. Industrial electricity consumption accounted for 18 % of total electricity consumption, while the residential sector accounted for 61 %. The diagram illustrates a system overwhelmingly dependent on fossil fuel imports, with petroleum products accounting for approximately 95 % of total primary energy supply and a similarly dominant share in electricity generation [6]. This extreme import dependency creates severe economic vulnerabilities, particularly given Cuba's limited access to international energy markets and financial constraints.

Currently, the Cuban energy system faces an unprecedented crisis stemming from multiple converging factors. The electricity generation infrastructure is severely obsolete, with the average age of thermal power plants exceeding 40 years, and maintenance programs are delayed by financial constraints and the use of domestic fuel with a high sulfur content (>3.5 %), which accelerates equipment degradation [36]. Distributed electricity generation capacity, comprising diesel- and fuel-oil generators, nominally exceeds 2000 MW; however, due to a shortage of spare parts and fuel imports, only approximately 900 MW remain operationally available to respond to critical situations such as hurricanes [36]. These adverse conditions have led to a drastic increase in the frequency and duration of blackouts, with serious socioeconomic consequences.

Despite Cuba ranking second globally in the share of installed capacity allocated to distributed generation [37]—53 % of which comprises intermittent renewables, gensets, and cogeneration from the sugar industry—electricity generation has failed to stabilise and avert the ongoing crisis. In 2023, electricity demand grew by 11 %, with the highest daily consumption on record at 64.5 GWh [36]. This growth trajectory, combined with declining generation reliability, has exacerbated supply-demand imbalances.

The crisis reached critical levels in 2024, when the Cuban electrical system collapsed catastrophically. Following the passage of two hurricanes and an earthquake affecting the eastern provinces, three total system disconnections occurred, leaving most users without electricity for periods ranging from 4 to 15 days [36]. This event substantially

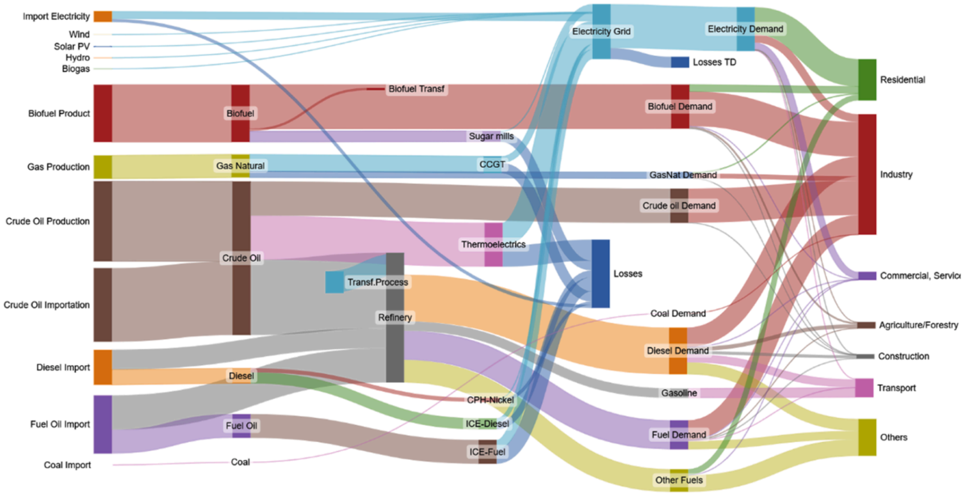


Fig. 6. Sankey diagram describing Cuba's energy structure. (Data from 2022). Made at SankeyMATIC.com [35].

impacted industrial production, public services, and the quality of life for the population, underscoring the fragility of the current system. System availability in 2024 declined to the lowest level recorded since 2019, with five large generation units (totalling approximately 33 % of national demand capacity) permanently lost, gensets operating at only 39 % availability, and mobile generation units decommissioned due to financing constraints [36].

3.1.2. Short-term response strategies and long-term vision

In response to these immediate challenges, Cuban authorities have implemented short-term measures to increase electricity generation capacity from natural gas and renewable sources, primarily solar photovoltaic (PV). The national plan envisions installing 2000 MW of solar PV capacity during 2025–2026 [38], representing a significant acceleration from historical deployment rates. Additionally, Battery Energy Storage Systems (BESS) with individual capacities of 50 MW each have been deployed at four electrical substations to store energy generated primarily by PV solar farms [39]. These BESS installations include not only battery arrays but also inverters, management systems, and control infrastructure designed to coordinate charging and discharging cycles, thereby ensuring operational efficiency and safety. The primary functions of these BESS are to compensate for frequency variations caused by intermittent solar generation and to contribute to achieving real-time balance between generation and consumption [39].

Energy conservation measures targeting the residential sector have also been implemented and require further intensification, given that this sector accounts for 61 % of total electricity consumption [39]. It is essential to clarify that in the residential sector, the measured consumption includes private businesses (restaurants and accommodations, called "casas particulares") and more than 8000 Mipymes (micro, small, and medium-sized enterprises), which should properly be allocated to the Services/Commerce sector in future statistical accounting [39]. This misclassification complicates demand-side management planning and policy formulation.

Despite severe financial constraints, the Cuban government has maintained its commitment to transforming the energy mix, enhancing energy efficiency, and reducing greenhouse gas (GHG) emissions [40]. To this end, renewable energy sources—including solar PV, biomass (primarily bagasse from sugarcane processing), and wind—are being progressively incorporated into electricity production. Cuban authorities have engaged in extensive discussions regarding various pathways to develop a 100 % renewable electricity system [41], supported by academic research and modelling efforts [42–45].

The *National Strategy for Energy Transition* in Cuba, formally approved in 2025, establishes three sequential stages [46]:

- Stage 1 (2025–2030): achieve a 24 % share of renewable energy sources in the electricity generation mix;
- Stage 2 (2030–2035): attain electrical independence through domestic fuel sources (primarily natural gas) combined with renewable sources;
- Stage 3 (2035 to 2050): materialise the vision of 100 % generation from renewable sources, ensuring sufficiency, sovereignty, security, and sustainability of energy supply to support national development.

Multiple modelling studies empirically support this strategic framework. Sagastume Gutiérrez et al. [42], Vázquez et al. [43], Luukkanen et al. [44], and Guevara-Luna et al. [45] have employed various analytical tools to model long-term scenarios and evaluate the feasibility of utilising Cuba's full renewable energy potential to achieve energy independence. Wang et al. [47] specifically demonstrated that hybrid wind-solar renewable energy systems, reinforced by efficient battery storage, can ensure a smooth transition while maintaining resilience against seasonal variability and extreme weather events such as tropical cyclones. Their analysis revealed that renewable energy systems outperform traditional diesel generation in terms of affordability over a 40-year operational lifecycle [47].

Building upon this contextual understanding of Cuba's current energy crisis and strategic vision, the following subsection presents the CUBALINDA model results, which quantitatively assess the technical feasibility and economic implications of achieving the 100 % renewable electricity target by 2050.

3.2. CUBALINDA backcasting scenario results: pathways to 100% renewables

This subsection presents the core results from the CUBALINDA energy system model, specifically configured for Cuba's electricity sector, to evaluate the technical and economic viability of achieving 100 % renewable electricity generation by 2050. The analysis employs a backcasting methodology [13,48], which defines the desired future state (100 % renewables by 2050) and works backwards to identify the necessary interventions, capacity expansions, and policy measures required to achieve this normative goal.

According to the IEA's definition in its 2025 scenarios, the evolution of the energy sector is influenced by multiple factors: macroeconomic trends, energy and other policies, technologies and markets, and consumer preferences. The IEA explains that, by using policies as a differentiating factor in scenario building, they serve as a partial guide to the trajectory's direction. They are sometimes imprecise, can have unforeseen consequences, and are subject to change. They may be met, exceeded, or not achieved; they may also be repealed or strengthened [49].

3.2.1. Economic development and electricity demand projections

Figs. 7 and 8 illustrate the projected economic development trajectory and corresponding electricity consumption across various economic sectors from 2020 to 2050.

The scenario assumes moderate GDP growth averaging 2.5 % annually, aligned with Cuba's medium-term development plans and accounting for demographic decline (the population is estimated to decrease from 11.34 million in 2020 to approximately 10.8 million in 2050) [9].

Projected electricity demand increases from approximately 17,500 GWh in 2020 to 24,000 GWh in 2050, representing a 37 % increase despite population decline. This growth is primarily driven by: (i) economic development and increased per capita consumption; (ii) expansion of the residential sector, including proliferation of private and family businesses and Mipymes; (iii) industrial revitalisation, particularly in biopharmaceuticals, chemicals, and construction materials; and (iv) electrification of transportation and agricultural processes. The residential sector exhibits the fastest growth trajectory when embedded commercial activities currently misclassified in statistical reporting are considered [36].

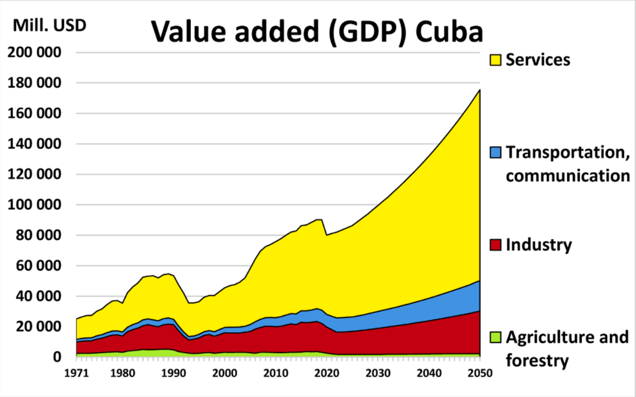


Fig. 7. Economic development in the scenario.

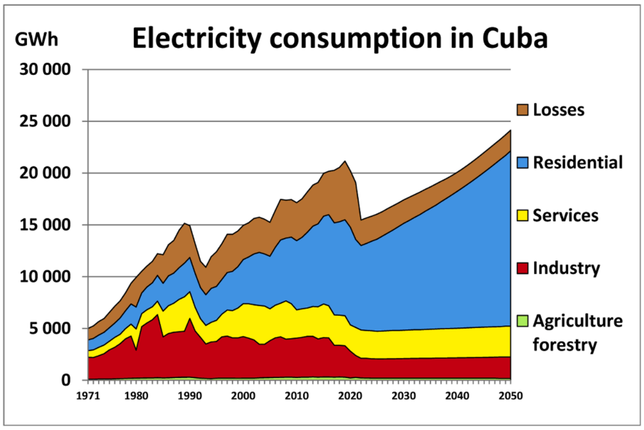


Fig. 8. Electricity consumption scenario in Cuba (in the different economic sectors).

In the scenario, industrial value added grows at 2.5 % per year from 2025 to 2050, and electricity intensity in the industrial sector declines by 2.0 % per year. These result in a very low growth of industrial electricity demand during that period. The scenario assumes that the electricity overproduction during periods of high wind velocities and solar radiation, and when the storage capacity is full, will be used for hydrogen production. This overproduction is not shown in Fig. 8 as industrial electricity consumption because hydrogen is treated as an alternative for cross-sectoral development. (See section 3.2.5 a).

3.2.2. *Renewable energy capacity expansion and generation mix*

Fig. 9 presents the evolution of electricity generation by source from 2020 to 2050 under the backcasting scenario.

Wind, solar, and biofuel energy production are increasing considerably in this scenario. In contrast, electricity production from fossil sources (crude oil, gas, diesel, and fuel oil) is reduced almost to zero due to investments in renewable capacity.

Table 1 provides a comprehensive overview of installed capacity, annual generation, and investment estimates for each technology.

Table 1
Scenario Results: Installed Capacity and Generation by Technology in 2050.

Technology	Installed Capacity 2020 (MW)	Installed Capacity 2050 (MW)	Annual Generation 2050 (GWh)
Solar PV	200	8500	13,000
Onshore Wind	12	5200	11,000
Biomass (Bagasse)	450	600	4000
Hydroelectric	65	70	243
Natural Gas Turbines	850	350	850
Thermoelectric	2400	80	250
Diesel/Fuel oil ICE (New tech)	1200	280	600
Battery Storage (BESS)	10	1300	4000
Pumped Hydro Storage	-	4000	

***Notes:*.**
- "New Technology" diesel/fuel oil ICE units refer to existing plants that have been retrofitted or fueled with biofuels or e-fuels instead of fossil fuels.
- The pumped hydro and battery storage capacity is 40,000 MWh (approximately 6.7 h average storage duration).
- Pumped hydro provides long-duration storage but contributes minimally to annual generation due to round-trip efficiency losses.
- Total production exceeds demand due to: (i) storage charging losses; (ii) transmission and distribution losses; (iii) curtailment during periods of excess generation; and (iv) electricity allocated to green hydrogen production via electrolysis.

Renewables dominate production in this backcasting scenario. Solar PV becomes the largest generation source, providing 46 % of total electricity (about 13,000 GWh) in 2050, followed by onshore wind power (about 11,000 GWh), accounting for approximately 39 % of generation. Biomass-based production (mainly sugar cane) is around 4000 GWh (13 % of electricity). Fossil generation declines to less than 7 % of total production, with remaining fossil capacity serving as backup for periods of low renewable generation or substituted by biofuels/e-fuels: fossil fuel production (gensets - new technology) is around 600 GWh, thermal power (old oil-fired condensing plants) is around 250 GWh, and gas turbines are around 850 GWh. Hydropower production is low due to low installed capacity (243 GWh). In this scenario, the pumped hydro and battery storage capacity is 40,000 MWh, and the storage supply is about 4000 GWh.

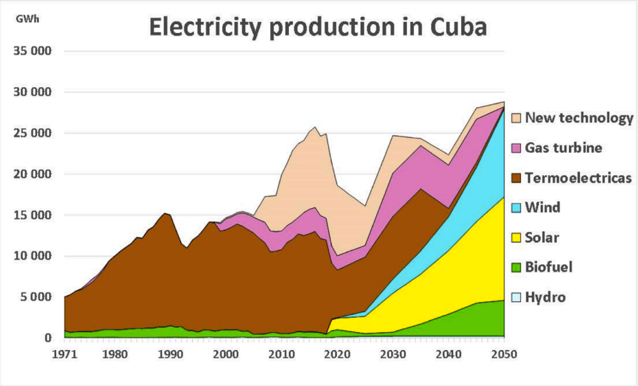


Fig. 9. Scenario for electricity production in Cuba by different sources.

Fig. 10 shows the annual electricity production of different energy sources in 2050 and the share of renewable/fossil energy in electricity production.

Renewables dominate production in this backcasting scenario, accounting for 93 % of total electricity generation in 2050. The remaining 7 % from fossil sources can potentially be eliminated through: (i) substitution with biofuels or e-fuels; (ii) additional renewable capacity expansion; or (iii) expanded storage infrastructure.

3.2.3. *Biofuel and e-fuel requirements for fossil fuel substitution*

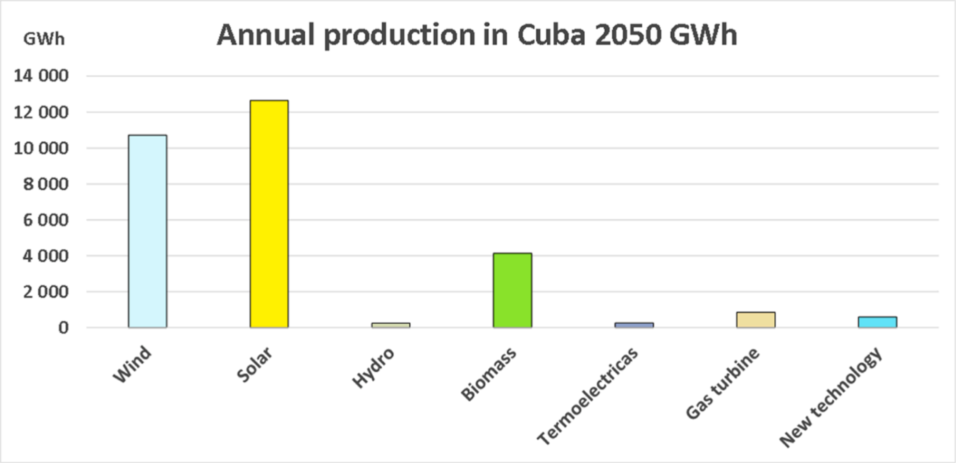
In this backcasting scenario, the use of biofuels and the production of e-fuels for combined-cycle gas turbines and for fuel oil- and diesel-powered plants/internal combustion engines (ICE)— the so-called "new technology" plants—are evaluated. To achieve truly 100 % renewable electricity generation, this fossil energy consumption must be replaced.

The e-fuels would be produced (derived from electrolysis: synthetic fuels produced from renewable electricity and captured CO_2) using surplus electricity from solar and wind power plants, allowing production to be maintained during periods of high demand.

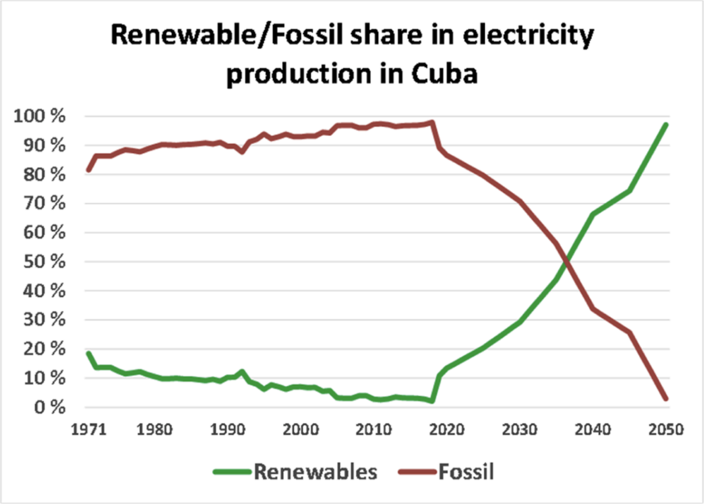
Table 2 quantifies the residual fossil-fuel substitution requirements and the associated economic implications.

Substituting diesel and fuel oil with biofuels or e-fuels for the remaining 990 GWh of ICE generation imposes an additional annual cost of approximately USD 59 million, representing a 20 % premium over fossil fuel costs. However, this cost must be contextualised within broader economic considerations:

a) *Import substitution benefit:* Biofuels and e-fuels produced domestically eliminate the need for foreign exchange to import fuel for residual production(USD 290 million annually), enhancing energy sovereignty and reducing balance-of-payments pressures.



10a



10b

Fig. 10. Annual electricity production by different types of power plants in 2050 (10a), along with the Renewable/Fossil share in electricity production (10b) in the backcasting scenario.

b) *Carbon emission reduction:* Complete substitution eliminates approximately 750,000 tons of CO_2 annually from these plants, contributing to climate-mitigation commitments.
c) *Cross-sectoral synergies:* e-fuel production infrastructure can support other industrial applications, distributing costs across multiple value chains.
d) *Price trajectory:* Renewable fuel costs are projected to decline as technological maturation and economies of scale drive costs down, while fossil fuel prices face long-term volatility and potential carbon pricing [50].

This analysis demonstrates that achieving 100 % renewable electricity is technically feasible but requires strategic decisions regarding fuel substitution pathways and associated investments.

3.2.4. *Hourly supply-demand balancing and storage dynamics*

A crucial aspect of the CUBALINDA model is its hourly resolution, which enables detailed analysis of the supply-demand balance dynamics with high penetration of intermittent renewable energy sources. In this scenario, the total electricity demand in 2050 is 24,000 GWh, and the total production is 29,000 GWh. There is widespread use of intermittent renewable energy sources, making it necessary to assess what happens when their production varies rapidly.

Figs. 11, 12, and 13 present representative weeks from different seasons (January, June, and November) to illustrate the operational challenges and the storage system's performance.

3.2.5. *Analysis of the first week of January: high wind period*

Looking at electricity production and demand in the first week of January 2050, the renewable and storage capacities in the scenario are sufficient to meet all electricity demand, as seen in Fig. 9.

Fig. 11a depicts electricity supply, demand, and storage charging/discharging during January 1–2, 2050. During this period, high wind speeds (averaging 7–9 m/s) combined with moderate solar irradiation result in substantial renewable electricity generation.

The key elements that emerge from the analysis of this figure are:

- *Storage saturation:* Energy storage systems reach their maximum capacity (40,000 MWh) within the first 24 h (Fig. 11b), as renewable generation significantly exceeds demand during peak wind times at midday and in the evening.
- *Excess electricity generation:* Between hours 24 and 48, renewable production continues to exceed both demand and storage capacity, generating approximately 5000 MWh of excess electricity that the system cannot absorb.
- *Reduction* vs. *hydrogen production:* This excess electricity represents (i) restricted (wasted) energy if there is no alternative use, or (ii) a

Table 2
Biofuel and e-fuel requirements for fossil fuel substitution in the backcasting scenario for 2050.

Parameter	Value	Units	Observations
Electricity produced with diesel/fuel oil engines	990	GWh	Backup generation during low renewable periods
Efficiency of ICE engines	40	%	Typical for modern diesel/ fuel oil engines
Energy content of fuel/diesel required	2475	GWh	Calculated as 990 GWh/ 0.40
Fuel consumption	212.8	ktoe	
Fuel consumption (volume, diesel)	~255	Million liters	Assuming diesel density ~0.835 kg/L
International diesel price (2024)	1360[a]	USD/ton	Average global diesel price
Annual cost for diesel/fuel oil	290	Million USD	212.8 ktoe * 1360 USD/ton
Biodiesel/e-fuel price (estimated)	1640[b]	USD/ton	Current biodiesel market price
Price premium for renewable fuels	280	USD/ton	1640 – 1360 USD/ton
Additional annual cost for biofuel/e-fuel substitution	59	Million USD	212.8 ktoe * 280 USD/ton
Percentage cost increase	20.3	%	(59/290)/100

[a] One ton of diesel is about 1200 litres of oil. International price of diesel was 1.135 USD/litre. https://www.globalpetrolprices.com/.

[b] Price of biodiesel 1640 USD/ton https://www.imarcgroup.com/biodiesel-pricing-report.

valuable resource for, for example, the production of green hydrogen through electrolysis.

Fig. 11c extends the analysis from January 1 to 7, revealing the temporal variability of renewable production. Days 3 to 7 experience lower wind speeds (4–6 m/s), which reduces excess electricity generation but maintains a proper balance between supply and demand by discharging storage.

3.2.6. b) June week analysis: low wind, high solar period

In the first week of June 2050, due to low wind speeds, the installed renewable energy capacity will be insufficient to produce all the required electricity, as shown in Fig. 12. In this period, it is necessary to increase production using ICEs, thermoelectrics, and gas turbines (fossil, biofuel, or e-fuel) to meet demand. The stored energy can cover demand for only a few hours a week due to limited storage capacity.

Fig. 12 illustrates the resulting supply challenges:

- *Storage depletion:* Low wind production on June 1–3, despite high solar generation, results in rapid energy storage depletion (Fig. 12b), as nighttime and early morning demand cannot be met solely by solar PV.
- *Backup generation requirement*: To maintain supply-demand balance, dispatchable generation from natural gas turbines, diesel ICE units (operating on biofuels/e-fuels), and biomass plants must be activated, contributing approximately 15–20 % of the daily electricity supply during this period.
- *Recharge cycles*: Increased solar and wind production on June 4–5 enables partial storage recharge, but subsequent reductions in wind speed on June 6–7 again necessitate backup generation.

This analysis underscores the need to maintain dispatchable generation capacity (either fossil-fueled with biofuels/e-fuels or biomass-based) to ensure reliability during extended low-wind periods, even with substantial storage infrastructure.

3.2.7. c) November week analysis: high wind, moderate solar period

With increased wind speed in November, energy overproduction occurs again (see Fig. 13), and excess electricity is produced when the storage is full, with wind speeds frequently exceeding 8 m/s in coastal regions.

The conclusions of the analysis of the results shown in Fig. 13 are:

- There is a sustained generation surplus: Renewable production consistently exceeds demand and storage capacity for most of the week, resulting in a substantial electricity surplus (approximately 8000–10,000 MWh over 7 days).
- Opportunity for hydrogen production: This excess electricity is the primary resource for producing green hydrogen.

Hourly balance analysis reveals distinct seasonal patterns, underscoring the need for a diversified generation portfolio (solar, wind, biomass, storage, and limited backup) to ensure a reliable electricity supply year-round.

3.2.8. Power to X applications and green hydrogen

Power-to-X (P2X) is a fundamental concept in the energy transition that converts surplus renewable electricity into various chemicals, fuels, and energy carriers. At the heart of most Power-to-X concepts is the use of renewable electricity to produce hydrogen through water electrolysis [51]. This hydrogen can be used directly as an end-use energy carrier or converted into other products such as methane, syngas, liquid fuels, electricity, or chemicals [51].

Power-to-X can encompass three fundamental aspects: e-production, demand-side management, and temporary electricity storage [52] (See Fig. 14). This definition recognises that many of these technologies include aspects related to electricity storage and energy system flexibility.

Power-to-X is a critical sector-coupling technology that can play a fundamental role in decarbonising energy systems. The integration of P2X technologies into energy systems is of great importance for addressing the temporary imbalances created by intermittent renewable energy sources [53]. The concept allows for the interconnection of the electricity, heating/cooling, and transport sectors, with a particular emphasis on the importance of hydrogen in sector coupling [53].

Green hydrogen can play, too, a key role in decarbonising several industries whose emissions are challenging to abate, such as basic chemicals, aviation, steel production, shipping, and long-haul road transportation. Around 100 million tonnes of hydrogen (Mt H_2) were used in the energy sector in 2024, of which around 55 % was in industry, mostly to produce ammonia and methanol, and around 45 % was in refineries for hydrocracking and desulphurisation processes. Today, hydrogen is almost entirely produced from unabated fossil fuels, resulting in CO_2 emissions of 980 Mt CO_2. Low-emissions hydrogen meets <1 % of global hydrogen demand [49].

The Boston Consulting Group (BCG), in its 2023 report, considers that by 2050, the demand for low-carbon hydrogen will soar roughly to 350 −530 million tons per annum. To meet that demand, governments and companies must invest approximately $6 trillion to $12 trillion between 2025 and 2050 to produce and transport low-carbon hydrogen [54].

Carbon-free hydrogen is produced by splitting water into hydrogen and oxygen using renewable electricity-powered electrolysers. It is then further refined into methane (CH_4) and/or methanol (CH_3OH) through synthesis with carbon dioxide captured directly from air or flue gases of biomass-fired thermal power plants, and into ammonia (NH_3) through synthesis with nitrogen.

Hydrogen production fluctuates due to a variable renewable electricity supply. Still, hydrocarbon synthesising processes like Fischer–Tropsch [55], Sabatier [56], and Haber-Bosch [57] for ammonia production should be operated at steady states. Thus, buffer storage is needed to smooth the fluctuating hydrogen flow into a steady feed flow for refining processes.

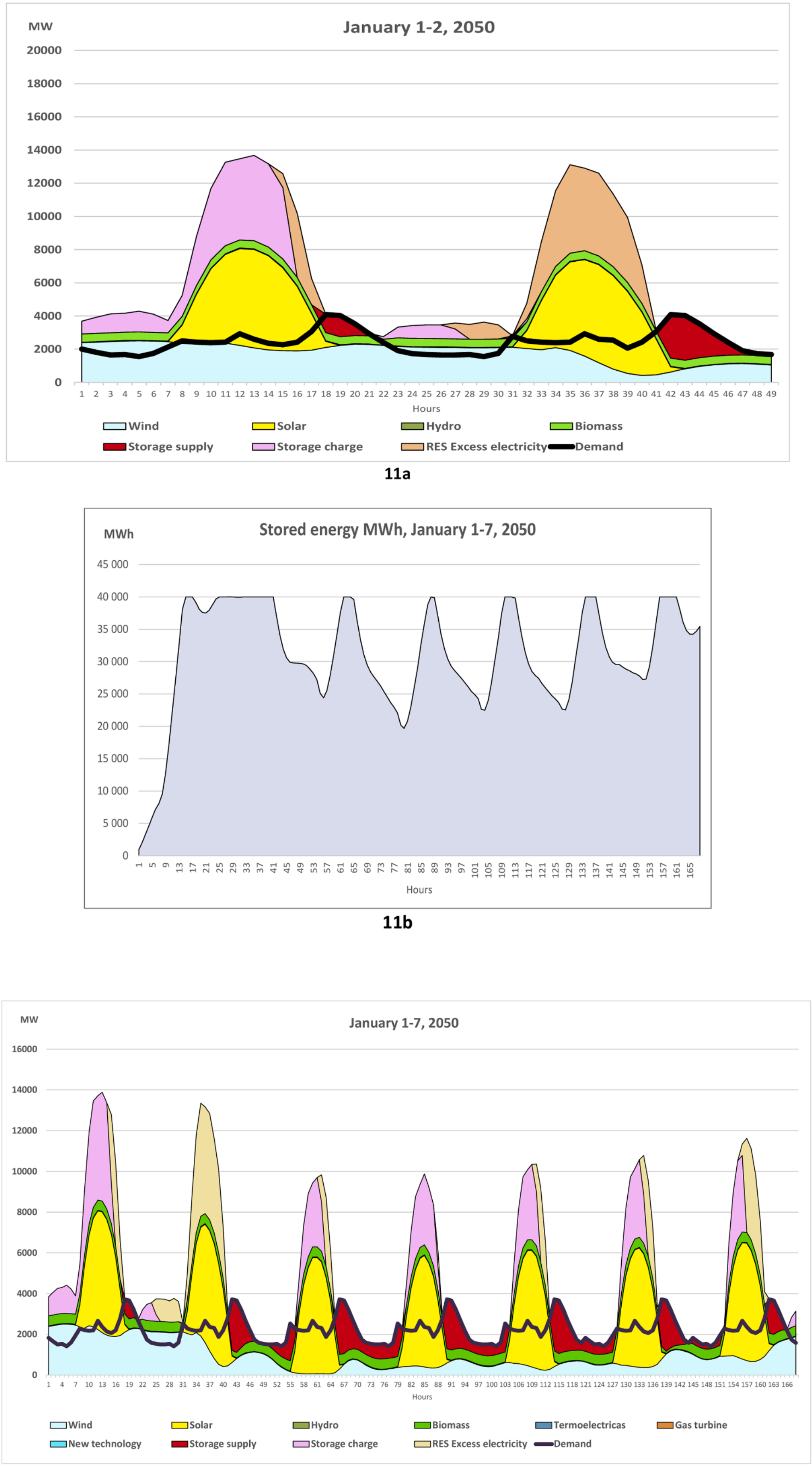


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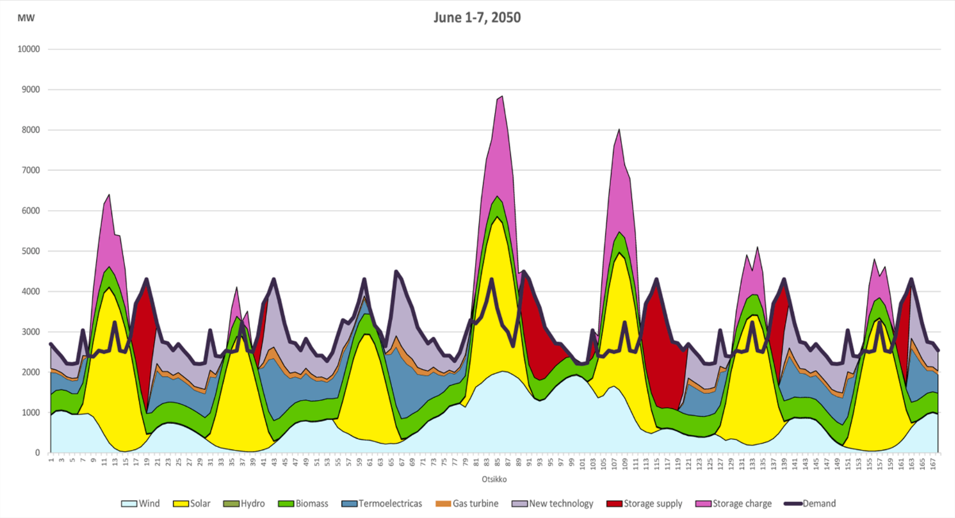
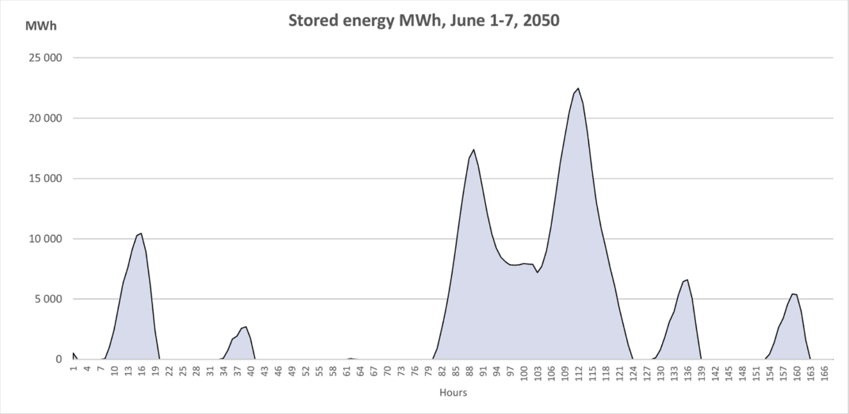
Fig. 11. Electricity supply, demand, and stored energy during January 1–2 (a) and January 1–7 (b and c).



12a



12b

Fig. 12. Electricity supply and demand (a), and stored energy (b) during June 1–7.

3.2.9. Uses of hydrogen in a 100% renewable scenario for Cuba in 2050

Based on quantifying excess electricity through hourly analysis of supply and demand, the potential for green hydrogen production and its strategic applications within Cuba's energy and economic system are evaluated.

Using the results of the CUBALINDA backcasting scenario for 2050:

- Total annual electricity surplus: 5100 GWh (approximately 18 % of total renewable generation)
- Electrolyser efficiency: 45–50 % (based on higher heating value, consistent with advanced alkaline electrolysers projected for 2050) [58]
- Hydrogen production: 137,000 tonnes of H_2 annually

Hydrogen can significantly enhance the reactivation of processes in the Cuban industry, whose role in economic production has decreased significantly since 1996, thereby reducing industrial energy use [59]. Increasing productivity and efficiency in the chemical and construction materials industry is necessary. The future impact of hydrogen on the Cuban biopharmaceutical industry can be remarkable. This industry is one of the most important economic pillars of the Cuban economy, with production, for instance, of several vaccines against various bacterial and viral pathogens and the development of drugs for cancer treatment.

The hydrogen produced can be used in multiple ways (Table 3):

The agricultural and livestock sectors can also benefit from hydrogen production by producing fertilisers from ammonia, thereby reducing the high cost of imported fertilisers. Cuban agricultural production has decreased considerably, and food imports consume practically 100 % of export earnings [60] (see Fig. 15). The import and consumption of fertilisers have also reduced, resulting in low agricultural production.

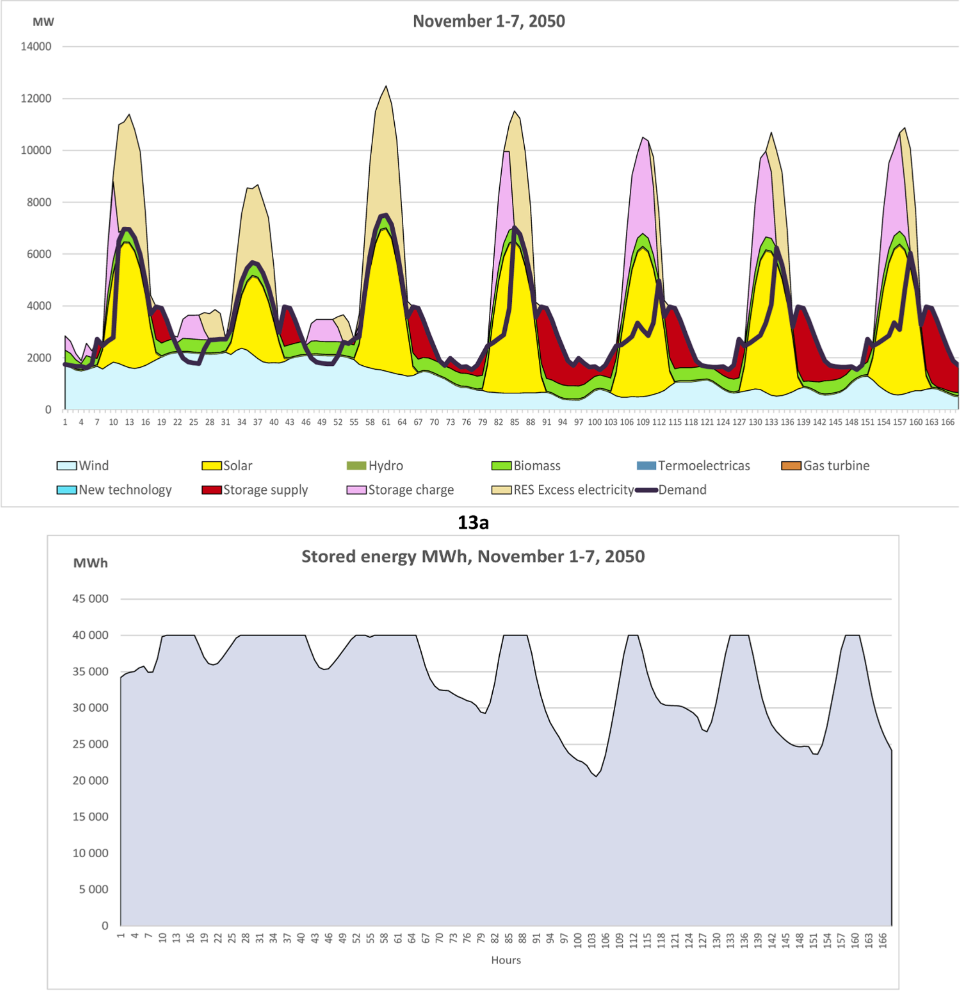
Economic feasibility considerations:

The levelized cost of hydrogen (LCOH) in this scenario is estimated at USD 2.5–3.5/kg of H_2, calculated as:

- LCOH = (Electrolyzer capital investment + Electricity cost + Operation and maintenance) / Annual H_2 production
- Electrolyser capital investment: USD 400–600/kW (projected for 2050) [57]
- Electricity cost: Marginal cost of excess renewable electricity (~USD 0.02–0.03/kWh) [61]
- Operation and maintenance: 2–3 % of annual capital investment

This LCOH is competitive with global green hydrogen cost projections for 2050 (USD 1.5–4.0/kg) [50] and substantially lower than current costs (USD 5–8/kg). Import parity prices for ammonia and synthetic fuels suggest economic viability, particularly given the benefits of energy sovereignty and reduced import costs.

The production, storage, transport, and processing of hydrogen require significant infrastructure investments. These investments, together with investments in solar and wind power generation and electricity transmission capacity, will certainly place a heavy burden on the Cuban economy. However, reduced fuel costs for oil used today can



13a

13b

Fig. 13. Electricity supply and demand (a), and stored energy (b) during November 1–7.

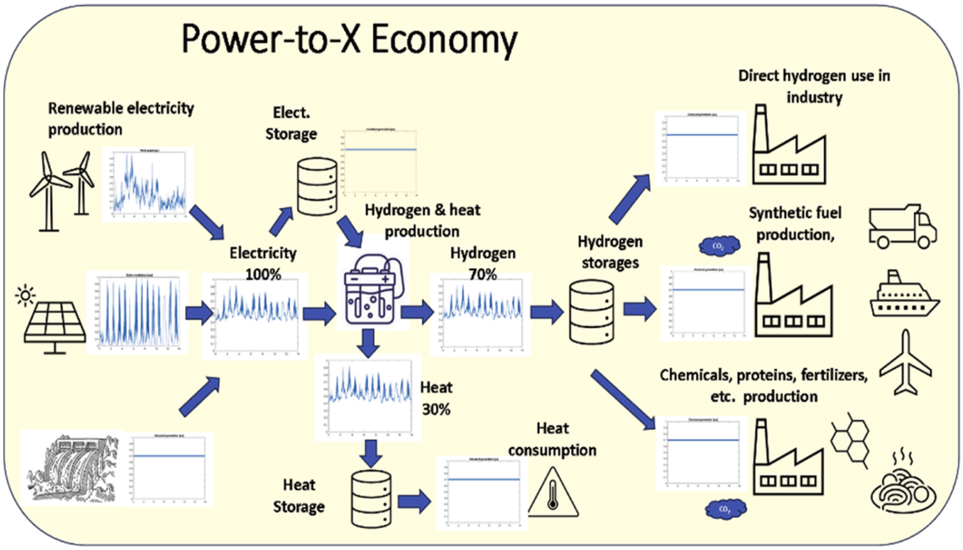


Fig. 14. The value chain of the P2X economy. Green hydrogen is produced by renewable-electricity-powered electrolysers and further processed into various carbon-neutral end products.

partly compensate for the required investments. Several research articles indicate that solar PV systems are the most optimal solutions for the energy transition for countries like Cuba [62].

Table 3
Summary of hydrogen's possible uses in Cuba.

Process Conversion	Quantification/ Potential Production	Applications	Economic Impact
Ammonia Synthesis (Haber-Bosch process) [57]	137,000 tons of H_2 → ~770,000 tons of NH_3 per year (conversion of $3H_2 + N_2 \rightarrow 2NH_3$)	Agricultural fertilisers, raw material for the chemical industry, and potential marine fuel	Cuba currently imports >500,000 tons of fertilisers per year at a cost exceeding $300 million [60]. Domestic ammonia production could substantially reduce dependence on imports and revitalise agricultural productivity.
Synthesis of e-fuels (Fischer-Tropsch or methanol) [55]: Utilisation of CO_2 captured from biomass combustion (sugar industry) or direct capture from the air	Potential production: ~200,000–250,000 tons per year of synthetic diesel or methanol	Substitute for imported fossil diesel in transportation and backup power generation.	
Direct applications of hydrogen		Industrial heat for the manufacture of chemicals and pharmaceuticals. Hydrogen fuel cell vehicles for public transportation. Metallurgical processes (Currently undergoing modernisation and with potential for future development).	
Balancing the grid through hydrogen storage		Long-term seasonal storage (hydrogen can be stored for months). *Re*-electrification using fuel cells or hydrogen turbines during extended periods of low renewable energy availability	

3.3. Integrated SuWi Doughnut Approach result

The Integrated Sustainability Window (SuWi) Doughnut Approach provides a comprehensive quantitative framework for evaluating Cuba's developmental trajectory across the three core dimensions of sustainability - environmental, economic, and social - with particular focus on the three pillars of the Green Economy: (i) Low carbon development, (ii) resource efficiency, and (iii) social inclusion [63]. This methodology integrates the Sustainability Window (SuWi) concept with Doughnut Economics principles to establish explicit, measurable thresholds that define the "safe and just operating space" for national development [64]. Simultaneous analysis across different dimensions enables comprehensive analysis, revealing interactions among sectoral developments and allowing problematic areas to be detected.

3.3.1. Data sources and methodological framework

The SuWi analysis employs multiple indicators to compare and provide a broader view of the green economy's development. The databases used in the analysis are:

1. Sustainable Development Goals (SDG) Database [65]: Cuba ranks 40th out of 166 countries in the Sustainable Development Report, indicating moderate overall SDG performance, with specific strengths in health and education but challenges in the economic and environmental dimensions.

2. Sustainable Society Index (SSI) [66–67]: The SSI dataset integrates indicators of Human, Environmental, and Economic well-being to provide a holistic assessment. Raw SSI data for Cuba (2000–2020) were utilised alongside SDG indicators for cross-validation.

3. Supplementary data sources:

- National Statistics and Information Office of Cuba (ONEI) [19,58]: GDP and macroeconomic indicators
- United Nations Development Programme (UNDP) [68]: Human Development Index (HDI)
- International Energy Agency (IEA) [69]: Energy consumption and CO_2 emissions.
- UNESCO Institute for Statistics [70]: Education indicators

Sustainability Window analyses have been conducted using several database indicators as a basis for constructing the Integrated SuWi Doughnut. It is possible to visualise sustainability in a doughnut form when the pairwise results, the quantified Sustainability Window, of all the social and environmental indicator pairs are arranged in a radial diagram [71].

The Integrated SuWi Doughnut can be seen as follows:

- *Inner limit (social base)*: Minimum GDP required to meet social sustainability thresholds across socio-economic indicators.
- *Outer limit (environmental ceiling)*: Maximum permissible GDP without exceeding environmental sustainability limits across environmental indicators.
- *Safe and equitable space (green doughnut area)*: GDP range that simultaneously satisfies all social bases and respects all environmental ceilings.
- *Actual development trajectory (red line)*: Evolution of real GDP between 2000 and 2020.

3.3.2. Sustainability threshold definition

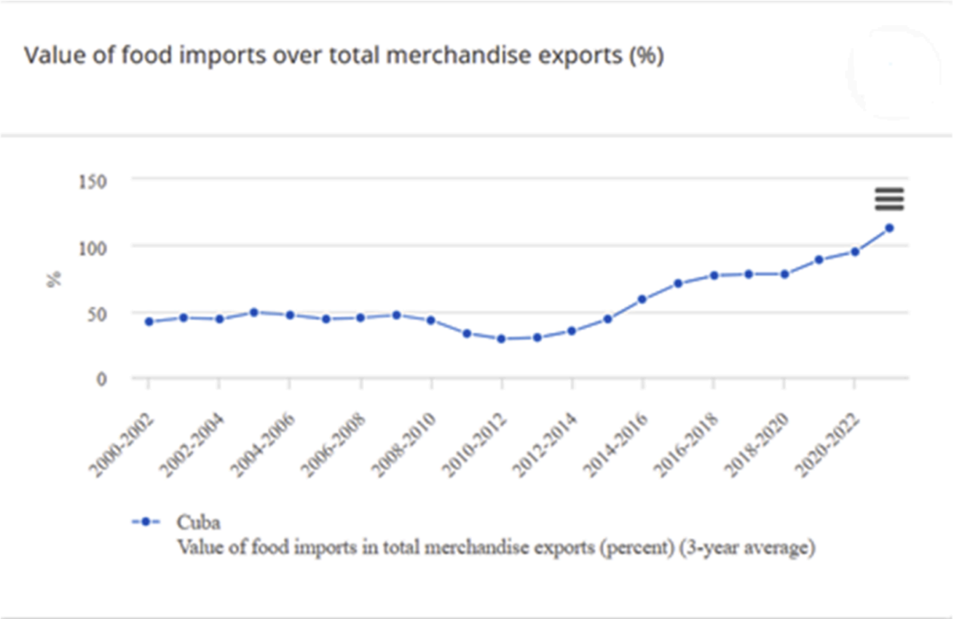
A) The ***absolute*** criterion for environmental sustainability is the condition in which environmental stress does not exceed a predefined sustainability level [72–74].

Downscaling the Planetary Boundaries enables the definition of absolute levels of environmental stress, provided they are suitable for national-level analysis.

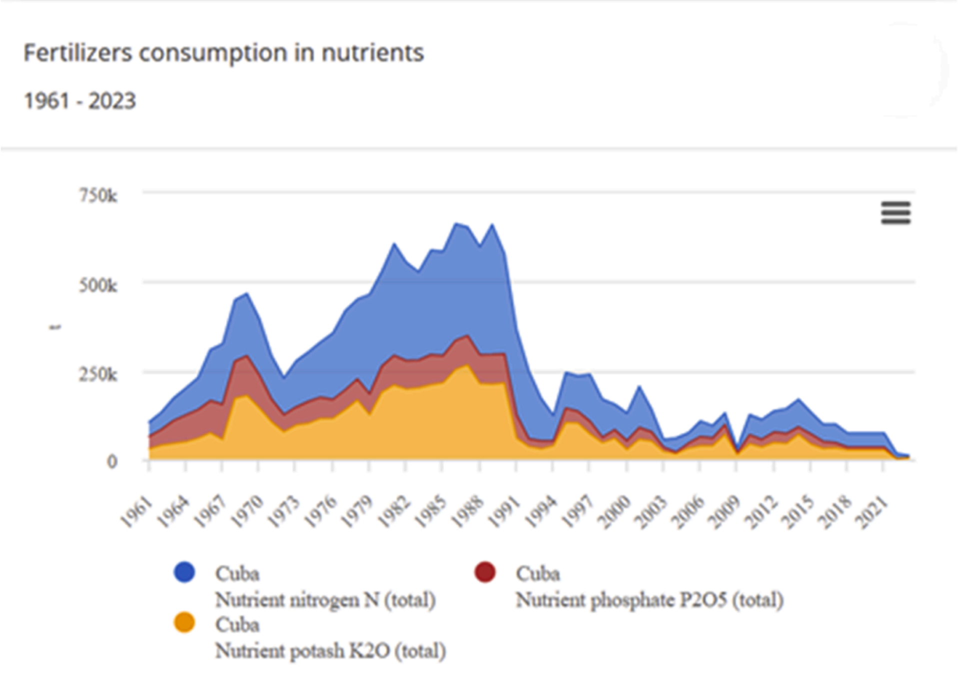
- CO_2 emissions: 1.8 tons of CO_2 per capita (equitable carbon budget allocation)
- Ecological footprint: 1.5 global hectares per capita (biocapacity constraint)
- Renewable energy: 30 % of total primary energy supply (minimum threshold for low-carbon transition) for 2020
- Biodiversity: SSI biodiversity index ≥ 5 (on 0–10 scale, indicating adequate protected area coverage and species protection) [67].

The social indicators and the targets are shown in Table 4.

B) This analysis also utilises the ***relative*** sustainability criterion, which states that the environmental stress should not increase. The relative sustainability criterion can be applied to some environmental indicators, such as CO2 emissions, because Cuba's per capita CO2



15a



15b

Fig. 15. Food Imports (a) and Consumption of Fertilisers (b) in Cuba [60].

emissions are notably low. The criterion for relative social sustainability in this analysis is that social welfare should increase.

The indicators used in the analysis are listed in Table 4:

3.3.3. *Relative sustainability analysis results*

In Fig. 16, which represents the Relative Sustainability across the 2000- 2020 period, the green line indicates the maximum economic development required to fulfil the environmental sustainability criteria, and the blue line indicates the minimum economic development required to fulfil the social sustainability criteria. The *red line* indicates the real GDP growth level during the analysed period. *The green area in the sustainability doughnut represents the potential for sustainable development.*

Principal Results:

1. Performance in social sustainability: All social indicators meet or exceed sustainability thresholds during the period 2000–2020. Specifically, this indicator shows relative sustainability:

- Adequate food security: Cuba's food security index has remained at the highest level from 2000 to 2020.
- Human Development Index (HDI): It increased from 0.694 (2000) to 0.759 (2020).

Table 4
Indicators used to construct the Integrated SuWi Doughnut model for Cuban development.

Dimension	Indicator	Acronym	Target	Scale/Unit	Rationale
Economic	*GDP*	*GDP*	Adjustment Variable	USD (PPP, constant 2017)	Economic dimension enabling social welfare and environmental management
Social	*Sufficient Food*	*Food*	≥ 9.5	*SSI scale (0–10)*	Food security, nutrition adequacy
	Human Development Index	*HDI*	≥ 0.7	*HDI scale (0–1)*	Composite of health, education, and income
	Healthy Life Years	*HLY*	≥ 9	*SSI scale (0–10)*	Population health outcomes
	Gender Equality	*Gender*	≤ 0.4	*GII scale (0–1)*	Women's empowerment, equality
	Years of Schooling	*Schooling*	≥ 14	*years*	Educational attainment, human capital
Enviromental	*Ecological Footprint*	*Footp*	≤ 1.5	*gha per capta*	Resource consumption within biocapacity
	Share of Renewable Energy	*RenewE*	≥ 30 %	*% of TPES*	Descarbonization progress
	CO_2 *emissions per capita*	*CO2*	≤ 1.8	*tons of* CO_2 *per capita*	Climate change mitigation
	Biodiversity Protection	*Biodiversity*	≥ 5	*SSI scale (0–10)*	Ecosystem integrity, protected areas

Notes:.
■ SSI scale: 0 = worst performance; 10 = best performance.
■ gha = Global hectares (standardised area unit for ecological footprint accounting).
■ TPES = Total Primary Energy Supply.
■ GII = Gender Inequality Index (0 = perfect equality, 1 = maximum inequality).

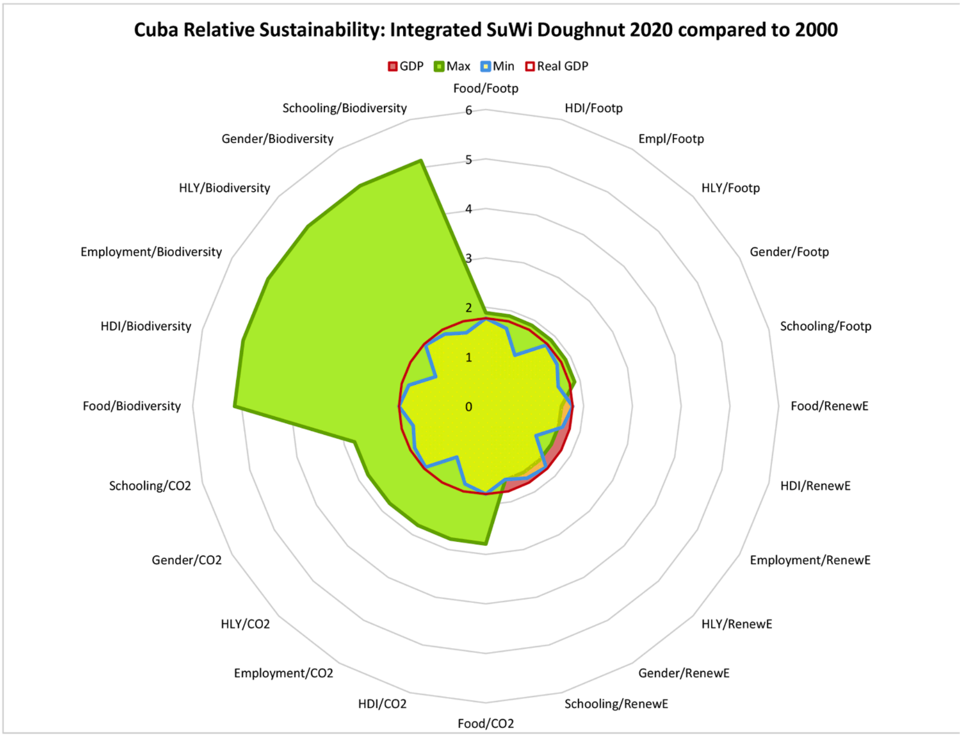


Fig. 16. Integrated SuWi Doughnut for relative sustainability.

- Healthy Life Years (HLY): Cuba's robust public health system increased the HLY scores from 2000 (9.40) to 2020 (9.60).
- Gender equality: The gender inequality index improved.
- Years of schooling: The average number of years of schooling increased from 12.45 (2000) to 14.43 (2020).

2. Environmental sustainability performance:

- Renewable energy deficit identified: The renewable energy axis (RenewE) exhibits a red zone, indicating that the share of renewable energy declined from 29 % (2000) to 11.1 % (2010) due to increased oil consumption and reduced biomass use, before recovering to 18.5 % (2020) with new solar installations [66]. This represents the primary environmental sustainability challenge under relative criteria.
- CO_2 emissions decreased from 2000 to 2020, from 2.4 to 1.6 tons per capita, showing relatively sustainable development.
- Ecological footprint decreased from 2.0 to 1.9 gha per capita
- Biodiversity: Protected area coverage improved from 1.8 to 5.2 in the SSI score.

The relative sustainability analysis reveals that Cuba's primary developmental challenge is accelerating the deployment of renewable energy to align economic activity with environmental sustainability criteria. While social welfare has been successfully maintained, the energy transition has lagged, creating a sustainability deficit. The 100 % renewable electricity scenario modelled in CUBALINDA directly addresses this deficit, projecting that the renewable electricity share will exceed 90 % by 2050, bringing the overall renewable energy share (electricity + transportation) to 60–70 %, well above the 30 % minimum threshold.

3.3.4. *Absolute sustainability analysis results*

Fig. 17 represents the Absolute Sustainability (absolute targets for environmental stress) analysis of Cuban development in 2020. The *green line* indicates the maximum economic development to fulfil the absolute environmental sustainability criteria, and the *blue line* indicates the minimum economic development to fulfil the social sustainability criteria. The *red line* indicates the real GDP growth level during the analysed period. The *green area, the sustainability doughnut, illustrates the possible area for sustainable development where both environmental and social sustainability are achieved.*

The scenario of absolute sustainability also satisfies all social sustainability criteria but fails to meet the environmental thresholds for both renewable energy and ecological footprint, as real GDP exceeds the maximum sustainable level in both dimensions.

Principal Results:

- Performance in social sustainability: All social indicators meet or exceed the defined sustainability thresholds in 2020.

- The sufficient food indicator is 10, exceeding the target of 9.5 for sustainability.
- HDI is 0.759, exceeding the target of 0.7
- Employment indicator is 8.7, exceeding the target of 7
- HYL is 9.6, exceeding the target of 9
- Gender equality Indicator is 0.495, exceeding the target of 0.4
- Expected years of schooling is 14.43, exceeding the target of 14

- Environmental sustainability performance:

- The renewable energy share was 18.5 %, while the national target for 2020 was 30 %.
- Ecological footprint in 2020 was 1.9 gha per capita, exceeding the global sustainability target of 1.5 gha per capita.
- CO_2 emissions per capita were 1.6 tons per capita, which is below the global sustainability target of 1.8 tons per capita
- The biodiversity index on the SSI scale was 5.2, exceeding the target of 5.

3. Some policies that can be implemented to improve the country's performance and keep it within the proposed limits include:

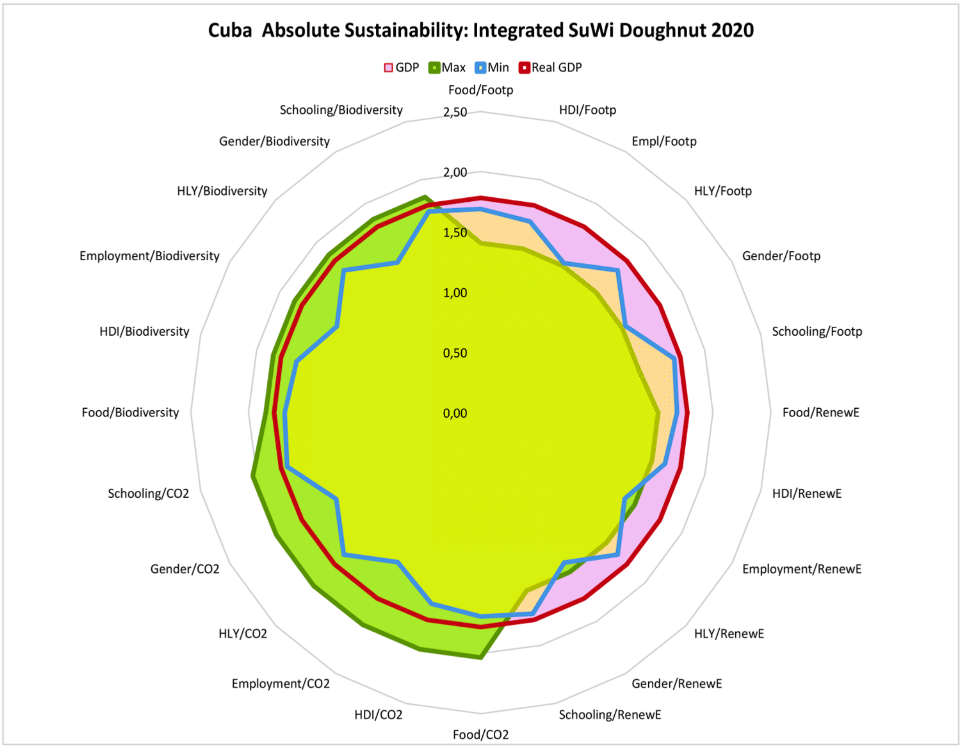
- The transition from fossil fuel use to renewable energy. The renewable energy gap can be closed through the CUBALINDA scenario, which projects that 93 % of electricity will come from renewable sources by 2050.
- Improvements in the ecological footprint require circular-economy strategies, reduced material imports, and increased local production.

These results provide a basis for targeted policy responses within specific economic sectors and facilitate direct interventions where sustainability deficits are most pronounced. The simultaneous analysis of multiple policy domains enables the formulation of more integrated and balanced strategies, in contrast to traditional single-sector assessments, which often overlook cross-sectoral interdependencies.

The Integrated Sustainability Window (SuWi) Doughnut Economy Approach offers a novel quantitative visualisation framework that effectively highlights critical sustainability gaps. This approach enhances the communication of complex development challenges and is particularly valuable in multi-stakeholder policy processes. By providing a clear and accessible visual representation, the approach supports informed decision-making and encourages meaningful feedback from diverse stakeholder groups.

3.4. *Dynamic synergy method results*

The dynamic synergy analysis presented in this study offers valuable insights into the complex interrelationships between development processes across multiple domains, particularly in contexts where energy planning must be integrated with broader socio-economic objectives.



. **17.** Integrated SuWi Doughnut for absolute sustainability.

Such analysis is especially pertinent when evaluating cyclical dependencies within economic systems, where sectoral interconnections are reinforced through both material value chains and non-material linkages [75].

The dynamic synergies in Fig. 18 are calculated from changes in the SDG indicators relative to the 2000 base year. Fig. 18. a demonstrates a pronounced positive synergy between the availability of medical professionals (measured per 10,000 population) and infant survival rates, reflecting Cuba's sustained investments in healthcare infrastructure and their measurable impact on population health. Fig. 18. b reveals a strong synergy between access to safely managed sanitation services and maternal survival rates, underscoring the interconnected nature of public health interventions and basic service provision.

In the specific case of Fig. 18c, it reveals particularly important perspectives for energy policy related to the synergy between GDP and CO_2 emissions. The synergy coefficients, which vary over time (2000–2005: strongly positive; 2000–2010 and 2000–2015: weak/negative; 2000–2020: strongly positive), indicate structural economic changes:

- 2000–2005: Economic growth strongly linked to fossil fuel consumption (energy-intensive growth model).
- 2000–2015: Decoupling period: economic contractions in some years, efficiency improvements, and structural shifts toward services.
- 2000–2020: Recoupling: economic recovery accompanied by increased energy consumption, demonstrating an incomplete structural transformation.
- 2000–2020: Recoupling: economic recovery accompanied by increased energy consumption, demonstrating an incomplete structural transformation. This pattern underscores the need for a proactive deployment of renewable energy (CUBALINDA scenario) to ensure that future economic growth is not again linked to fossil CO_2 emissions.

This dynamic synergy analysis indicates changes in the production system that are not linearly linked to economic output. The structural changes in the economy can be analysed using, for instance, decomposition analysis [75].

Fig. 19. a) shows the synergy between research and development (R&D) expenditures and GDP per capita. This result reinforces the critical role of research and development and scientific innovations in promoting economic development.

Economic growth does not always yield positive results across all spheres of life if planning processes cannot allocate resources to all required areas. Fig. 19. b) illustrates this type of case when, even though the economy is growing, the housing conditions in urban areas have not received enough investments, and the population in urban slums has increased, emphasising the need for targeted policy interventions to ensure equitable development outcomes.

These findings collectively demonstrate the utility of dynamic synergy analysis for uncovering the multifaceted linkages among sectors and indicators. By incorporating SDG metrics, the analysis integrates sustainability considerations directly into developmental assessments, providing a more holistic understanding of progress. Moreover, applying this approach to emerging sectors such as green hydrogen production could reveal additional co-benefits, identifying opportunities where energy transitions might simultaneously advance industrial revitalisation, agricultural productivity, and social welfare. The methodology thus serves as both a diagnostic tool for evaluating past development trajectories and a prospective framework for designing more integrated and sustainable policy interventions.

3.5. *Model and validation*

CUBALINDA Model Validation:

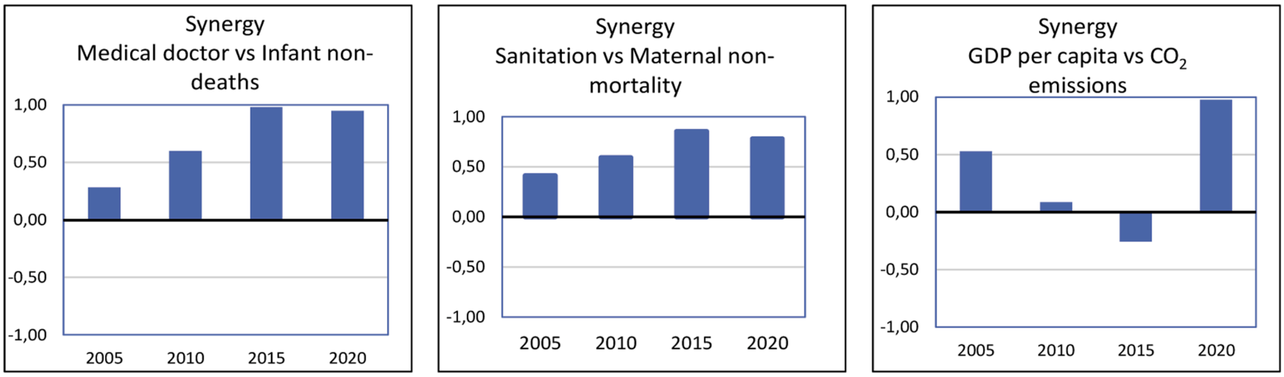
- Hourly demand profiles: Validated against 2018–2023 Cuban electricity system hourly load data.
- Renewable resource assessment: Solar and wind capacity factors calibrated using the MERRA database and validated against existing Cuban installations
- Investment costs: Based on IRENA 2023 cost projections with ±20 % sensitivity analysis

Key Limitations:

a) Transmission network constraints not fully modelled: Provincial-level aggregation may underestimate grid reinforcement costs
b) Climate change impacts on renewable resources: Future wind/solar patterns assumed stationary; climate projections not integrated
c) Socio-political feasibility: Model assumes sustained policy commitment and financing availability
d) Hydrogen infrastructure costs: A detailed technological and economic analysis of the hydrogen system is beyond the scope of this article

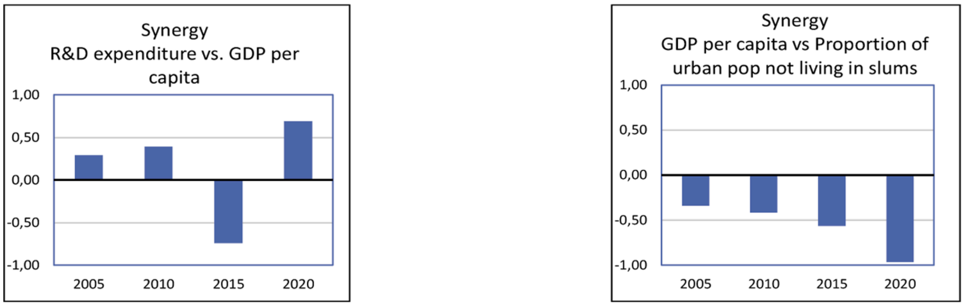
SuWi Doughnut Limitations:

- Relies on international databases (SSI, SDG) with 2–3 year data lags
- Indicator selection is subjective; alternative indicators may yield different boundaries
- Does not capture distributional equity within Cuba (spatial/demographic disparities) due to the lack of data with spatial disaggregation



18. a **18. b** **18. c**

Fig. 18. The Dynamic Synergy from the base year 2000 between Medical doctors per 10,000 population vs survival of infants (18. a). The Synergy between the proportion of the population using a safely managed sanitation service vs Maternal survival (18. b). Synergy between GDP per capita vs CO_2 emissions (18. c).



19. a **19. b**

Fig. 19. Dynamic Synergy (base year 2000) between the research and development expenditure as a proportion of GDP and GDP per capita (19. a). Synergy between GDP per capita and the proportion of the urban population not living in slums (19. b).

These limitations suggest directions for future research, including integrated transmission-generation planning, climate-resilient assessment of renewable resources, and spatially disaggregated sustainability analyses.

4. Conclusions

The application of the LINDA model to construct a 100 % renewable energy backcasting scenario for Cuba by 2050 demonstrates the feasibility of this objective contingent upon the implementation of effective policy measures, increased investment in electricity generation, transmission, and distribution infrastructure, and the adoption of enhanced energy efficiency and conservation strategies. A critical component of this transition involves investments and integration of energy storage systems and the production of green hydrogen. Green hydrogen can be utilised to generate e-fuels, serving as a viable substitute for fossil fuels in power generation. Moreover, the production of green hydrogen fosters cross-sectoral integration, particularly between agriculture and industry, thereby promoting cross-sectoral systemic synergies.

Under this envisioned renewable energy scenario, evaluating the influence of applied policies and measures on sustainable development and their alignment with the Sustainable Development Goals (SDGs) is essential. The Sustainability Window framework facilitates multidimensional analyses that capture the interactions between sectoral developments and identify critical problem areas. This approach provides a comprehensive basis for policy formulation, enabling targeted interventions in sectors requiring immediate attention. Simultaneous analysis across multiple policy domains promotes the development of more balanced, timely policies than isolated, sector-specific evaluations.

The Integrated SuWi Doughnut Approach offers an innovative quantitative visualisation tool that highlights development challenges and facilitates communication of complex issues. Visualisation plays a pivotal role in participatory policy planning, engaging actors, decision-makers, and stakeholders across diverse domains to ensure inclusive and collaborative strategy development.

Dynamic synergy analysis further enriches this framework by elucidating the complex interrelationships among societal activities. By incorporating SDG indicators, this method bridges the various dimensions of sustainability, yielding more profound insights into systemic interactions. Additionally, dynamic synergy analysis can be integrated with other planning methodologies to broaden the understanding of the potential outcomes of implementing measures to enhance societal well-being.

To achieve a more comprehensive and integrative perspective on sustainable development, it is essential to employ a suite of analytical tools and models, such as the Sustainability Window (SuWi), the Integrated SuWi Doughnut Approach, and Dynamic Synergy Analysis. These methodologies collectively offer robust support for planning and decision-making processes aimed at fostering sustainability. To further refine the analytical and planning framework, future research should explore integrating additional methods—such as decomposition analysis (to assess developmental drivers) and resilience analysis (to evaluate system adaptability and flexibility).

CRediT authorship contribution statement

Anaely Saunders Vazquez: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jyrki Luukkanen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yrjo Majanne:** Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Jarmo Vehmas:** Investigation, Conceptualization. **Jari Kaivo-Oja:** Investigation, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

References

[1] O.A. Marzouk, Expectations for the role of hydrogen and its derivatives in different sectors through analysis of the four energy scenarios: IEA-STEPS, IEA-NZE, IRENA-PES, and IRENA-1.5C, Energies 17 (3) (2024) 646, https://doi.org/10.3390/en17030646.

[2] P. Forster, C. Smith, T. Walsh, W.F. Lamb, R. Lamboll, B.D. Hall, M. Hauser, A. Ribes, D. Rosen, N.P. Gillett, M.D. Palmer, J. Rogelj, K.V. Schuckmann, B. Trewin, M. Allen, R.M. Andrew, R. Betts, A. Borger, T. Boyer, P. Zhai, Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence, Earth. Syst. Sci. Data 16 (2024) 2625–2658, https://doi.org/10.5194/essd-16-2625-2024.

[3] IRENA, Tracking COP28 outcomes: tripling renewable power capacity by 2030, Int. Renew. Energy Agency (2024). Abu Dhabi. ISBN: 978-92-9260-585-8, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Mar/IRENA_Tracking_COP28_outcomes_2024.pdf.

[4] W.L. Filho, A. Balogun, D. Surroop, A.L. Slvia, K. Narula, C. Li, J.D. Hunt, A. Gatto, A. Sharifi, H. Feng, S. Tsani, H. Azadi, Realising the potential of renewable energy as a tool for energy security in small island developing states, Sustainability 14 (9) (2022) 4965, https://doi.org/10.3390/su14094965.

[5] World Bank & Solargis. Global Solar Atlas. 2026. https://globalsolaratlas.info/download. [Accessed January 22, 2026] </Dataset>.

[6] D. Icaza, D. Vallejo-Ramírez, C.G. Granda, E. Marn, Challenges, roadmaps, and smart energy transition towards 100% renewable energy markets in American Islands: a review, Energies 17 (5) (2024) 1059, https://doi.org/10.3390/en17051059.
[7] J.C. Antuña-Sánchez, R. Estevan, R. Román, J.C. Antuña-Marrero, V.E. Cachorro, A. Rodríguez-Vega, A.I.M. de Frutos, Solar radiation climatology in Camagüey, Cuba (1981-2016), Remote Sens. 13 (2) (2021) 169, https://doi.org/10.3390/rs13020169.
[8] World Bank & Technical University of Denmark. Global wind Atlas (GWA 4.0). 2026. https://globalwindatlas.info/en/[Accessed January 22, 2026] </Dataset>.
[9] L. Vashold, J.C. Cuaresma, A unified modelling framework for projecting sectoral greenhouse gas emissions, Commun. Earth. Environ. 5 (2024) 139, https://doi.org/10.1038/s43247-024-01288-9.
[10] B.K. Nimako, S. Carpitella, A. Menapace, Novel multi-criteria decision analysis based on performance indicators for urban energy system planning, Energies 17 (20) (2024) 5207, https://doi.org/10.3390/en17205207.
[11] S.K. Sahoo, B.B. Choudhury, P.R. Dhal, M.S. Hanspal, A comprehensive review of multi-criteria decision-making (MCDM) toward sustainable renewable energy development, Spectrum Oper. Res. 2 (1) (2025), https://doi.org/10.31181/sor21202527.
[12] N. Abdelmeguid, D.M. Ibrahiem, Decarbonizing Egypt's energy sector: pathways for an accelerated energy transition, Rev. Econ. Polit. Sci. 10 (4) (2025) 303–322, https://doi.org/10.1108/REPS-03-2024-0001.
[13] S. Bibri, Backcasting in futures studies: a synthesised scholarly and planning approach to strategic smart sustainable city development, Eur. J. Fut. Res. 6 (2018) 13, https://doi.org/10.1186/s40309-018-0142-z.
[14] J. Ferdous, F. Bensebaa, A.S. Milani, K. Hewage, P. Bhowmik, N. Pelletier, Development of a generic decision tree for the integration of Multi-criteria decision-making (MCDM) and multi-objective optimization (MOO) methods under uncertainty to facilitate sustainability assessment: a methodical review, Sustainability 16 (7) (2024) 2684, https://doi.org/10.3390/su16072684.
[15] H. Meschede, P. Bertheau, S. Khalili, C. Breyer, A review of 100% renewable energy scenarios on islands, WIREs Energy Environ. 11 (6) (2022) e450, https://doi.org/10.1002/wene.450.
[16] C. Breyer, A.S. Oyewo, A. Kunkar, R. Satymov, Role of solar photovoltaics for a sustainable energy system in Puerto Rico in the context of the entire Caribbean featuring the value of offshore floating systems, IEEe J. Photovolt. 13 (6) (2023) 842–848, https://doi.org/10.1109/JPHOTOV.2023.3319022.
[17] S. Han, P. Dong, Y. Guo, M.U. Aslam, R. Xu, Harnessing technological innovation and renewable energy and their impact on environmental pollution in G-20 countries, Sci. Rep. 15 (2025) 2236, https://doi.org/10.1038/s41598-025-85182-0. PMid:39824979 PMCid:PMC11748615.
[18] P. Hoody, A. Chiasson, R.J. Brecha, The transition to a renewable energy electric grid in the Caribbean island nation of Antigua and Barbuda, Energies 16 (17) (2023) 6206, https://doi.org/10.3390/en16176206.
[19] O.N.E.I. Anuario estadístico de Cuba, Capítulo 10: minería Y Energía, Anuario Estadístico de Cuba, Ed (2024), 2024, https://www.onei.gob.cu/sites/default/files/publicaciones/2025-07/10-mineria-y-energia_aec2024.pdf [Accessed January 13, 2026] </Dataset>.
[20] IEA, World Energy Statistics. International Energy Agency, 2025, Paris https://www.iea.org/data-and-statistics/data-product/world-energy-statistics, Licence: Terms of Use for Non-CC Material. [Accessed Sept. 18, 2025] </Dataset>.
[21] UNDESA, United Nations. SDG indicators - metadata repository, 2025. https://unstats.un.org/sdgs/dataportal/countryprofiles/cub [Accessed March 22, 2025]. </Dataset>.
[22] Renewables. Ninja, Hourly energy production simulator for wind and solar photovoltaic farms. [Software, Dataset], 2023. https://www.renewables.ninja/[Accessed June 07, 2023].
[23] I. Staffell, S. Pfenninger, N. Johnson, A global model of hourly space heating and cooling demand at multiple spatial scales, Nat. Energy 8 (2023) 1328–1344, https://doi.org/10.1038/s41560-023-01341-5.
[24] NASA, MERRA-2: modern-era retrospective analysis for research and applications. [Software, Dataset], 2023. https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2 [Accessed December 14, 2023].
[25] J. Luukkanen, O. Akgün, J. Kaivo-oja, M. Korkeakoski, T. Pasanen, J. Panula-Ontto J, et al., Long-run energy scenarios for Cambodia and Laos: building an integrated techno-economic and environmental modelling framework for scenario analyses, Energy 91 (2015) 866–881, https://doi.org/10.1016/j.energy.2015.08.091.
[26] J. Luukkanen, J. Vehmas, J. Panula-Ontto, A. Francesca, J. Kaivo-oja, T. Pasanen, et al., Synergies or trade-offs? A new method to quantify synergy between different dimensions of sustainability, Environ. Policy Gov. 22 (2012) 337–349, https://doi.org/10.1002/eet.1598.
[27] Brundtland, G.H. Our common Future World Commission on Environment and Development. 1987. https://doi.org/10.1017/S0376892900016805.
[28] J. Luukkanen, Sustainability window analysis (SuWi). Sustainability of Chinese development in relation to poverty - environment nexus. 2013. The paper was presented at the CHEC seminar in Tampere, Finland, https://www.researchgate.net/publication/342751026_Sustainability_Window_Analysis_SuWi_Sustainability_of_Chinese_development_poverty_environment_nexus.
[29] J. Luukkanen, J. Kaivo-oja, J. Vehmas, J. Panula-Ontto, L. Häyhä, Dynamic sustainability. Sustainability window analysis of Chinese poverty-environment nexus development, Sustainability 7 (11) (2015) 14488–14500, https://doi.org/10.3390/su71114488.
[30] J. Luukkanen, J. Vehmas, J. Kaivo-oja, T. O'Mahony, Towards a general theory of sustainable development: using a sustainability window approach to explore all possible scenario paths of economic growth and degrowth, Sustainability 16 (2024) 5326, https://doi.org/10.3390/su16135326.
[31] A. Saunders, J. Luukkanen, Sustainable development in Cuba assessed with sustainability window and doughnut economy approaches, Int. J. Sustain. Dev. World Ecol. 29 (2) (2022) 176–186, https://doi.org/10.1080/13504509.2021.1941391.
[32] K. Raworth, Doughnut economics: seven ways to think like a 21st-century economist. https://www.hive.co.uk/Product/Kate-Raworth/Doughnut-Economics–Seven-Ways-to-Think-Like-a-21st-Century-Economist/21739630, 2017 [Accessed April 15, 2023].
[33] K. Pokkinen, Utilisation of Doughnut Model in Sustainable development: City Portrait of the Tampere Region. Master's Thesis, LUT School of Energy Systems, Lahti University of Technology (LUT), Lappeenranta, Finland, 2021.
[34] J. Rockström, W. Steffen, K. Noone, Å. Persson, F.S. Chapin, E.F. Lambin, et al., A safe operating space for humanity, Nature 461 (7263) (2009) 472–475, https://doi.org/10.1038/461472a. PMid:19779433.
[35] S. Bogart, SankeyMATIC: build a Sankey diagram. [Software] https://sankeymatic.com/build/2025 [Accessed January 12, 2026].
[36] R. Alonso Falcón, O. Figueredo Reinaldo, L.F. Acosta, C.F. Sosa, Cuba: incrementan precios de la electricidad, combustible y gas licuado, CUBADEBATE (2024). http://www.cubadebate.cu/noticias/2024/01/08/cuba-incrementan-precios-de-la-electricidad-combustible-y-gas-licuado-video/ [Accessed January 08, 2024].
[37] M. Brandts, P. Bertheau, D. Rojas Plana, K. Lammers, M.A. Rubio Rodriguez, An energy system model-based approach to investigate cost-optimal technology mixes for the Cuban power system to meet national targets, Energy 306 (2024) 132492, https://doi.org/10.1016/j.energy.2024.132492.
[38] O. Figueredo Reinaldo, A.A. Montero, Y. Héctor Rodríguez, G. Mok Rodríguez, E. G. Díaz, Ministro de Energía y Minas ofrece detalles del programa de recuperación del SEN, CUBADEBATE (2024). http://www.cubadebate.cu/noticias/2024/12/19/ministro-de-energia-y-minas-ofrece-detalles-del-programa-de-recuperacion-del-sen/ [Accessed January 09, 2025].
[39] W.Díaz Ballaga, Instalan sistemas de baterías para controlar variaciones de frecuencia provocadas por los parques solares, Periódico Granma (2025). https://www.granma.cu/cuba/2025-08-05/instalan-sistemas-de-baterias-para-controlar-variaciones-de-frecuencia-provocadas-por-los-parques-solares-05-08-2025-23-08-28 [Accessed August 6, 2025].
[40] EOP. Gutiérrez y TLG. Pérez, Tercera Comunicación Nacional a la Convención Marco de las Naciones Unidas sobre Cambio Climático, 2020, Cuba, AMA. http://www.cambioclimatico.gov.co/3ra-comunicacion-cambio-climatico [Accessed March 15, 2022].
[41] R. Tamayo, Sesión del Consejo Nacional de Innovación: vamos a trabajar con todas las energías, CUBADEBATE (2021). http://www.cubadebate.cu/noticias/2021/10/16/sesion-del-consejo-nacional-de-innovacion-vamos-a-trabajar-con-todas-las-energias/ [Accessed October 16, 2024].
[42] A. Sagastume Gutiérrez, J.J. Cabello Eras, D. Huisingh, C. Vandecasteele, L. Hens, The current potential of the 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. 172 (2018), https://doi.org/10.1016/j.jclepro.2017.11.209, 11.209.
[43] L. Vazquez, Y. Majanne, M. Castro, J. Luukkanen, O. Hohmeyer, M. Vilaragut, et al., Energy system planning towards renewable power system. Energy matrix change in Cuba by 2030. IFAC-PapersOnLine. (2018), 51(28), 11.756. https://doi.org/10.1016/j.ifacol.2018.11.756.
[44] J. Luukkanen, A. Saunders Vazquez, Y. Majanne, M. Korkeakoski, Modelling Cuban energy system with CUBALINDA model. Prospects for 100% renewable scenario, in: J. Luukkanen, A. Saunders Vazquez, J. Laitinen, B. Auffernann (Eds.), Cuban Energy Futures - Political, Economic, Social, and Environmental Factors, FFRC eBook 3, Turku, 2022, pp. 226–254. http://urn.fi/URN:ISBN:978-952-249-569-3.
[45] M.A. Guevara-Luna, J. Madrazo, E. Meneses, H. Mora, A. Clappier, Strategies toward an effective and sustainable energy transition for Cuba. Renew. & sustain, Energy. Rev. 197 (2024) 114387, https://doi.org/10.1016/j.rser.2024.114387.
[46] MINEM, Estrategia Nacional para la Transición Energética en Cuba. (Documento De Trabajo), La Habana, Cuba, 2025.
[47] J. Wang, C. Song, Z. Huang, A. Campbell, M. Konarova, Remote island renewable transition potential: affordable, reliable and sustainable generation optimisation for Mornington Island, Renew. Sustain. Energy Transit. 5 (2024) 100084, https://doi.org/10.1016/j.rset.2024.100084.
[48] J. Robinson, S. Burch, S. Talwar, M. O'Shea, M. Walsh, Envisioning sustainability: recent progress in the use of participatory backcasting approaches for sustainability research, Technol. Forecast. Soc. Change (2011) 756–768, https://doi.org/10.1016/j.techfore.2010.12.006.
[49] IEA, World Energy Outlook (WEO), Int. Energy Agency (2025). http://www.iea.org.
[50] F. Frieden, J. Leker, Future costs of hydrogen: a quantitative review, Sustain. Energy Fuels 8 (2024) 1806–1822, https://doi.org/10.1039/D4SE00137K.
[51] C. Wulf, P. Zapp, A. Schreiber, Review of power-to-X demonstration projects, Europe. Front. Energy Res. 8 (2020) 191, https://doi.org/10.3389/fenrg.2020.00191.
[52] J. Burre, D. Bongartz, L.C. Bre, K. Roh, A. Mitsos, Power to X: between electricity storage, eProduction, and demand side management, Chemie Ingenieur Technik 92 (1–2) (2019) 74–84, https://doi.org/10.1002/cite.201900102.
[53] Q. Wang, Z. Hou, Y. Guo, L. Huang, Y. Fang, W. Sun, Y. Ge, Enhancing energy transition through sector coupling: a review of technologies and models, Energies 16 (13) (2023) 5226, https://doi.org/10.3390/en16135226.

[54] BCG, Building the green hydrogen economy, Infrastruct. Strat. 2023 (2023). https://www.bcg.com/publications/2023/strategies-to-build-green-hydrogen-economy [Accessed April 18, 2025].
[55] A. Darmawan, M. Aziz, Process and products of biomass conversion technology, Innov. Energy Convert. Biomass Waste. (2021) 25–60, https://doi.org/10.1016/B978-0-323-85477-1.00004-X.
[56] C. Vogt, M. Monai, G.J. Kramer, et al., The renaissance of the Sabatier reaction and its applications on Earth and in space, Nat. Catal. 2 (2019) 188–197, https://doi.org/10.1038/s41929-019-0244-4.
[57] I.I. Cheema, U. Krewer, Operating envelope of Haber-Bosch process design for power-to-ammonia, RSC. Adv. 8 (61) (2018) 34926–34936, https://doi.org/10.1039/C8RA06821F. PMid:35547069 PMCid:PMC9087324.
[58] S.Z. Al Ghafri, S. Munro, U. Cardella, T. Funke, W. Notardonato, J.P.M. Trusler, J. Leachman, R. Span, S. Kamiya, G. Pearce, A. Swanger, E.D. Rodriguez, P. Bajada, F. Jiao, K. Peng, A. Siahvashi, M.L. Johns, E.F. May, Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities, Energy Environ. Sci. 15 (2022) 2690, https://doi.org/10.1039/D2EE00099G.
[59] A.S. Vazquez, J. Kaivo-oja, J. Luukkanen, Energy economy in Cuba and future challenges, in: J. Luukkanen, A. Saunders Vazquez, J. Laitinen, B. Auffernann (Eds.), Cuban Energy Futures - Political, Economic, Social, and Environmental Factors, FFRC eBook 3, Turku, 2022, pp. 133–170. http://urn.fi/URN:ISBN:978-952-249-569-3.
[60] FAO, FAO statistics. 2025. https://www.fao.org/faostat/en/#country/49 [Accessed January 22, 2025] </Dataset>.
[61] IRENA. Electrolyser costs. 2026 https://www.irena.org/Energy-Transition/Technology/Hydrogen/Electrolyser-costs [Accessed January 22, 2026].
[62] A.S. Oyewo, A. Kunkar, D. Bogdanov, C. Breyer, Defossilising Caribbean's energy system: highlighting on e-fuel imports, grid. Integration, and accelerated transition, IET Renew. Power Gener. 18 (Suppl. 1) (2024) 4650–4678, https://doi.org/10.1049/rpg2.13173.
[63] M. Finkbeiner, E.M. Schau, A. Lehmann, M. Traverso, Towards life cycle sustainability assessment, Sustainability 2010 2 (10) (2010) 3309–3322, https://doi.org/10.3390/su2103309.
[64] B. Corona, L. Shen, D. Reike, J.R. Carren, E. Worrell, Towards sustainable development through the circular economy: a review and critical assessment on current circularity metrics, Resour., Conserv. Recycl. 151 (2019) 104498, https://doi.org/10.1016/j.resconrec.2019.104498.
[65] J.D. Sachs, G. Lafortune, G. Fuller, The SDGs and the UN Summit of the Future. Sustainable Development Report 2024, 2024, Paris: SDSN, Dublin: Dublin University Press. doi:10.25546/108572. https://dashboards.sdgindex.org/downloads [Accessed January 27, 2024]. </Dataset>.
[66] G. Van De Kerk, A. Manul, Sustainable Society Index 2014, Sustain. Society Found. (2014).
[67] SSI. Sustainable Society Index. 2022. https://ssi.wi.th-koeln.de/[Accessed November 20, 2024]. </Dataset>.
[68] UNDP. Human Development Reports. 2023. http://hdr.undp.org/en/data [Accessed November 15, 2024]. </Dataset>.
[69] IEA, CO2 Emissions statistics, Int. Energy Agency (2023). https://www.iea.org/reports/co2-emissions-in-2022# [Accessed June 18, 2024]. </Dataset>.
[70] UNESCO. Database. 2022. http://data.uis.unesco.org/[Accessed April 10, 2025]. https://doi.org/10.18356/22202293-2022-3-3 </Dataset>.
[71] J. Luukkanen, J. Vehmas, J. Kaivo-oja, Quantification of doughnut economy with the sustainability window method: analysis of development in Thailand, Sustainability. 13 (2021) 847, https://doi.org/10.3390/su13020847.
[72] J. Vehmas, J. Luukkanen, J. Kaivo-oja, Linking analyses and environmental kuznets curves for material flows in the European Union 1980-2000, J. Clean. Prod. 15 (17) (2007) 1662–1673, https://doi.org/10.1016/j.jclepro.2006.08.010.
[73] J. Kaivo-oja, J. Vehmas, J. Luukkanen, A. Note, De-growth debate and new scientific analysis of economic growth, J. Environ. Prot., Spec. Issue Environ. Manag. 05 (15) (2014), https://doi.org/10.4236/jep.2014.515140.
[74] J. Kaivo-oja, J. Panula-Ontto, J. Luukkanen, J. Vehmas, Relationships of the dimensions of sustainability as measured by the Sustainable Society Index framework, Int. J. Sustain. Dev. World Ecol. 21 (1) (2014) 39–44, https://doi.org/10.1080/13504509.2013.860056.
[75] L. Vazquez, J. Luukkanen, H. Kaisti, M. Käkönen, Y. Majanne, Decomposition analysis of Cuban energy production and use: analysis of energy transformation for sustainability, Renew. Sustain. Energy. Rev. (2015) 49, https://doi.org/10.1016/j.rser.2015.04.156.