Title: Multidimensional Analysis of Interlinked Systems of 100% Renewable Energy in Cuba within the Framework of Sustainable Development

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ABSTRACT

Using multiple tools and models in a multidisciplinary and comprehensive analysis framework allows us to have a vision of synergistic development between different sectors of the economy.

This article aims to show the results of the construction of energy scenarios until the year 2050 for the case of Cuba, generating electricity using 100% renewable energy sources and storage and considering the Power to X approach (X is hydrogen). The analyses use the LINDA, Synergy, Sustainability Window (SuWi), and Doughnut Economy models, complementing the multidimensional analysis and sustainability framework.

Keywords: Futures Scenarios, Renewable Energy, LINDA model, Sustainability Window (SuWi), Doughnut Economy, Synergy analysis, Sustainable Development Goals (SDGs)

INTRODUCTION

Several countries are engaged in the energy transition, developing and building more sustainable energy systems using renewable energy sources. However, climate sustainability remains a challenge.

The Conference of the Parties to the United Nations Framework Convention on Climate Change, COP28, and the first Global Stocktake of the Paris Agreement may be the turning point in climate action during this critical decade to accelerate a transition that places economies on the path toward a new sustainable, high-growth, low-carbon economic model in a way that is both transformative and fair [1].

The International Renewable Energy Agency (IRENA) considers that, as part of the paradigm of accelerating the sustainable energy transition and reducing emissions before 2030, the deployment of renewable energy generation must be tripled, and energy efficiency doubled as essential levers to reduce greenhouse gas emissions by 22 Gigatons and maintain the objective of reducing the planet's temperature by 1.5°C [1].

Evaluating this context, using multiple tools and models in a multidisciplinary and comprehensive analysis framework, allows us to have a vision of synergetic development between different sectors of the economy.

In this article, energy scenarios are constructed until 2050 for the case of Cuba. The target is the generation of electricity using 100% renewable sources of energy and storage and considering the Power to X (X: batteries, pumped hydro, hydrogen, and other chemicals). The analyses are carried out using the LINDA model and other methods and tools that complement the multidimensional framework of the analysis.

The Synergy method can be used to analyze the linkages between sectoral developments, the production of hydrogen, and its use in other sectors, such as agriculture and industry. The Sustainability Window (SuWi) model and the Doughnut Economy model can be used to assess the sustainability of the constructed energy scenarios if suitable indicators exist.

METHODOLOGY AND TOOLS

LINDA MODEL

The Linda model is based on the so-called intensity approach using the Kaya identity to calculate CO_2 emissions [2]. The main balancing components of the model are illustrated in Figure 1.

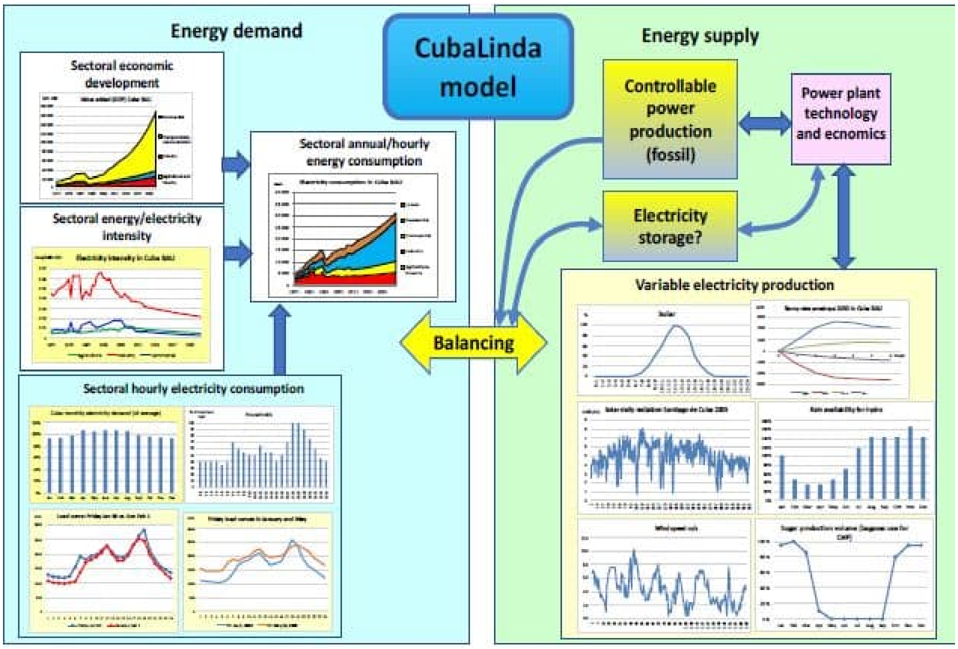


Fig. 1. Functioning of the CubaLinda model

Adapted to the Cuban context, the LINDA model is renamed CUBALINDA. This model is the so-called accounting framework model with which scenarios can be built for the energy supply and demand. The electricity demand and supply are modelled hourly. The model balances electricity supply and demand. The historical power plant data is from the National Statistical Office of Cuba [3], and the sectoral energy consumption figures are from the International Energy Agency IEA statistics [4]. The sectoral economic data of value added is from UN Statistics [5].

The energy demand for electricity and fuels is based on the constructed scenario for economic growth in different sectors and electricity and fuel intensities in different sectors of the economy. The hourly electricity demand is constructed based on user-given load curves for sectors and the future scenarios of the changes in load curves and the growth in sectoral consumption. The sectoral load curves are constructed separately for weekdays and weekends and the different months of the year.

Electricity supply scenarios are constructed based on user-given investments in different power plants. The solar PV power plants are situated in different provinces, and the incoming radiation is obtained from the MERRA database using renewables. ninja website [6]. The model uses hourly data from 2019 for different locations and combines the incoming radiation data with the installed PV capacity in different provinces defined in scenarios. The wind power production is based on wind speed information and its conversion to electricity output in the MERRA database 2019 [7] for different planned wind farm locations. Wind power capacity in the scenarios will be invested in these locations.

The CubaLinda model constructs scenarios for different sectors of the economy and calculates the fuel used in different sectors, related CO_2 emissions, and electricity production costs (Levelized Cost of Electricity, LCOE) based on user-given information of future investment costs, operation and maintenance costs, and fuel cost for different power plant types and fuels. The model also calculates the required ramping rates (need for maximum change in power production per hour) and load duration curves to assess types of power plant capacity investments.

LINDA model, like most energy models, is concentrated on technological and narrow economic aspects of development. It is possible to widen the perspective of analysis by using other tools and methods to capture the social aspects of development. In this article, we illustrate two novel methods that can be used parallel to energy-economic models to integrate sustainability and social development in the analyses. The methods illustrated here are Synergy method and Sustainability Window (SuWi) method and the Doughnut model derived from SuWi.

SYNERGY Methods [8]
We can define that synergy exists between two factors when their combined effect is greater or smaller than the sum of their separate effects. In mathematical form, this can be expressed with the following equation:

$$z = ax + by + cxy + d$$

Where *x*, *y* and *z* are variables, and *a, b, c*, and *d* are coefficients that determine how the output *z* depends on inputs *x* and *y*. In this case we assume a time-invariant system, where the parameters stay constant. If *y* is zero, the output is determined by *x* and the coefficients *a* and *d*. Coefficients *a*, *b*, and *d* determine the impact of the single inputs on the output. The synergy of the inputs *x* and *y* is determined by the component *cxy*, i.e., the co-effect of both inputs. Positive synergy shows that different development processes support each other, and the result is larger than the impact of the individual processes.

If we look at a change from A to B in Figure 2 (from the original state x_0y_0 to x_1y_1) we can determine the change in the area (Δz) to be:

$$\Delta z = a\Delta x + b\Delta y + c\Delta x\Delta y = y_0\Delta x + x_0\Delta y + \Delta x\Delta y$$

We can interpret the synergy of the inputs to be determined by the shaded area in Figure 2, which equals to $\Delta x\Delta y$

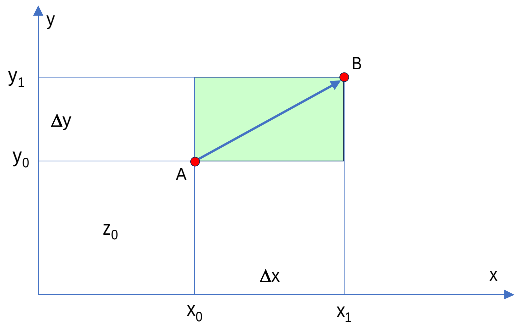


Fig. 2. Synergy between two variables *x* and *y* determined by their changes $\Delta x\Delta y$.

The synergy can also be negative, as shown in Figure 3, where the change in *y* is negative and $\Delta x\Delta y$ becomes negative. This is a trade-off situation: when one factor increases, the other factor decreases.

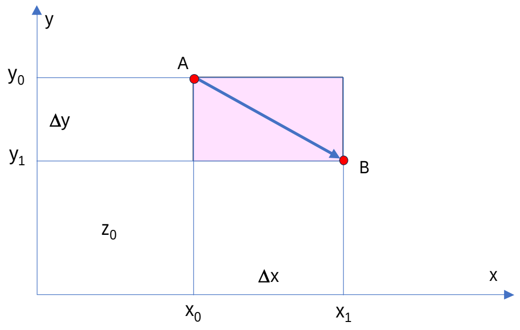


Fig. 3. Negative synergy or trade-off between *x* and *y* in the case where Δy is negative.

Figure 4 shows a case where synergy equals zero in a case where Δy is zero. This is a de-linking situation between the variables: the change in one variable does not impact the other variable.

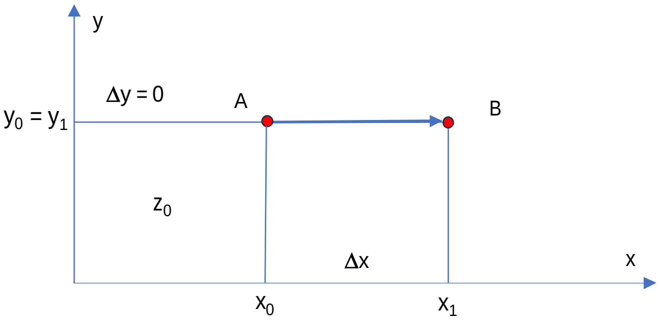


Fig. 4. Synergy between x and y equals zero, which is a de-linking situation.

This type of synergy (or trade-off) calculation does not imply a causal relationship between the variables. The calculation results only indicate possible (potential) causality.

Synergy analysis provides a useful tool for assessing the development in different fields and sectors to see whether they support or hinder each other's development. Synergy analysis between different social indicators and economic indicators can provide insightful information on how co-benefits can be achieved in development planning.

Sustainability Window (SuWi) and *Doughnut Economy*

The Sustainability Window is a novel tool to assess the sustainability of development in its three dimensions simultaneously (environmental, economic, and social) [9-12]. The method provides information on the maximum and minimum economic development required to maintain the direction of social and environmental development towards more sustainable objectives. In this sense, SuWi's analysis is based on the Brundtland Commission's approach [13]. It allows for analyzing the dynamics of the sustainability of societies using different indicators and periods and can be easily used for comparative analysis. Furthermore, sustainability trends can be linked to different sustainability policies to analyze their effectiveness. Sustainability Window can be used to analyze sustainability transitions in developing economies, for example, as explained by Geels et al. (2016) [14], Loorbach (2002), (2007) [15-16], and Kemp et al. (2005) [17].

In Figure 5, we analyze the sustainability in the dimensions of environmental stress and economic growth; the starting point of development is point A. This represents the indexed point for environmental stress (Env_0) and economic development (GDP_0). The line *r1* indicates the environmental stress productivity of GDP in this base year of analysis. Suppose the environmental stress in the final year of analysis is Env_1 and the corresponding economic development GDP_1. In that case, line *r2* represents the corresponding environmental stress productivity in point E. Suppose the sustainability criterion is that the environmental stress should not increase. In that case, we will have point F representing the maximum economic development, GDP_{max}, on the productivity line *r2* (final year productivity) to fulfill the sustainability criterion.

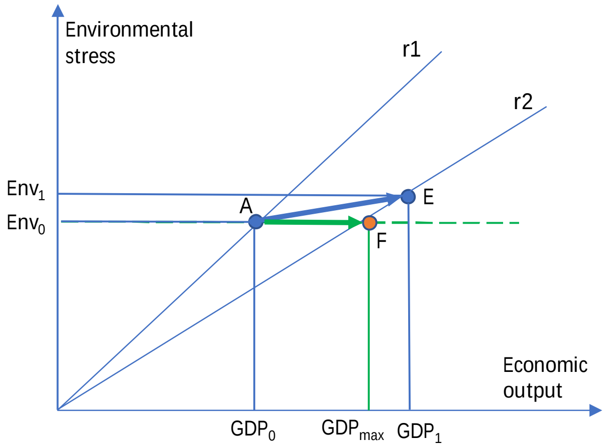


Fig. 5. Defining maximum economic development in the case where environmental stress is not increased.

Figure 6 illustrates the procedure to determine the minimum economic development to fulfill the social sustainability criterion. In this figure, point A represents the starting point for analysis, having Soc_0 as the social welfare production and GDP_0 as the economic development, and line *r1* represents the social welfare productivity (for the productivity of different components, see e.g., Tamura et al. 2019 [18]). The final year of analysis is indicated with point S with social welfare Soc_1 and GDP_1, and the social welfare productivity is indicated with line *r3*. Now, the sustainability criterion is that the social welfare should not decrease, which means that point G on the line *r3* represents the minimum economic development, GDP_{min} to fulfill the sustainability criterion.

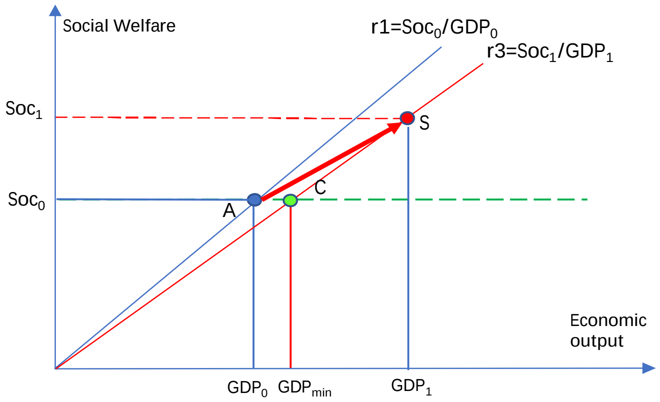


Fig. 6. Defining minimum economic development to fulfill the social sustainability criterion.

When the previous cases of environmental and social sustainability analyses are combined, we can define the minimum and maximum economic development to fulfill social and environmental sustainability criteria, the definition for the *Sustainability Window*. In Figure 7, the Sustainability Window is presented by combining the previous analyses. In this figure, the environmental stress productivity line *r2* determines the maximum economic development GDP_{max} and the social welfare productivity line *r3* the minimum economic development GDP_{min} to fulfill both sustainability criteria.

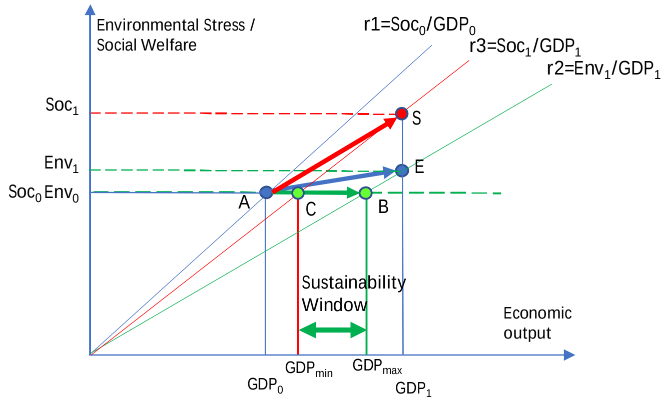


Fig. 7. Defining *Sustainability Window* with maximum economic development GDP_{max} to fulfill environmental sustainability criterion and minimum economic development GDP_{min} to fulfill social sustainability criterion.

Based on the selected indicators, the Sustainability Window analysis indicates the minimum economic growth rate to improve social conditions and the maximum economic growth rates that do not exceed environmental development limits. However, the analysis here does not refer to the absolute level of sustainability (usually, this cannot be determined) but rather determines whether the direction of change is towards a more sustainable state. The method can also be used to analyze the absolute level of sustainability if it can be determined.

The Sustainability Window analysis results can be visualized with a quantitative approach if used in the analysis of the Doughnut Economy (see Figure 8). According to Kate Raworth (2017) [19], “the environmental ceiling consists of nine planetary boundaries, as established by Rockström et al. (2009) [20], beyond which lie unacceptable environmental degradation and potential tipping points in Earth systems”.

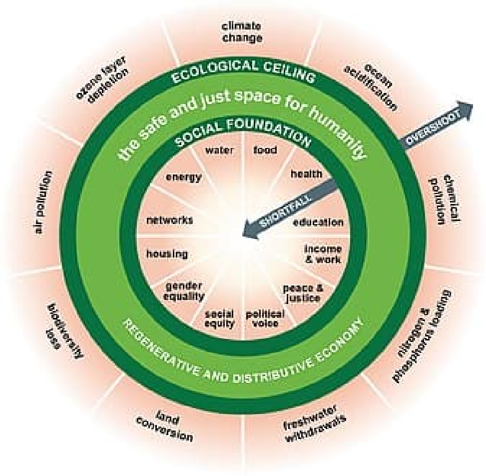


Fig. 8. Doughnut Economy [19]

The outer circle indicates the maximum economic development (GDP_{max}), and the inner circle indicates the minimum economic development (GDP_{min}). The twelve dimensions of the social foundation are derived from internationally agreed minimum social standards, as identified in the 2015 SDGs. Between the social and planetary boundaries lies an environmentally safe and socially just space where humanity can prosper: the doughnut. SuWi's analysis provides quantitative insights into these boundaries and economic development. The method provides a visual interpretation of the Doughnut and denotes where problem areas of unsustainable development exist.

SCENARIOS. CUBA CASE

Situation of the Cuban energy system

In Cuba, 95% of electricity generation is based on fossil fuels. Currently, the Cuban energy system faces a severe crisis, caused mainly by the obsolescence of its generating plants and the delay in maintenance deadlines, which are more frequent due to the use of national fuel with high sulfur content. There are more than 2000 MW of distributed generation, in units made up of diesel engines and fuel oil engines, but due to lack of spare parts and the lack of imported fuel, there is only 900 MW to respond to complex and specific situations, such as the passage of a hurricane. All these adverse conditions cause an increase in blackouts.

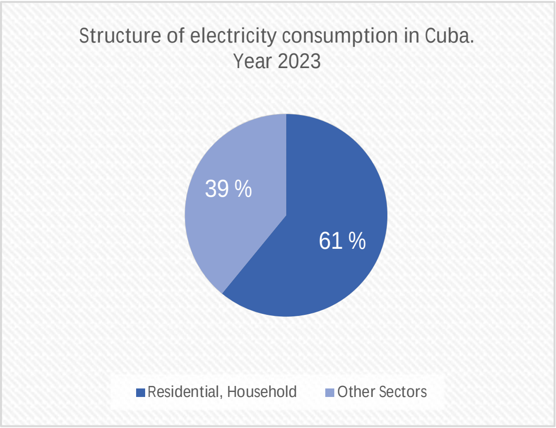


Fig. 9. Structure of electricity consumption in Cuba [21].

During the analysis, in the National Assembly, of the energy situation in 2023, the Minister of Energy and Mines, Vicente de La O, explained that the electrical service has improved by 70% compared to 2022, demand has grown by 11%, with a historical maximum consumption in one day of 64.5 GWh [21]. Several electricity generation units are in the process of repair and recovery, new wells have been drilled for crude oil extraction, and electricity generation has increased with accompanying gas.

Energy saving measures have been implemented, and they have to be increased for the Residential sector since 61% of electricity consumption in the country corresponds to this sector (See Figure 9). It is essential to clarify that in the residential sector, the measured consumption includes private businesses (restaurants and accommodations, called "private homes") and more than 8,000 Mipymes (micro, small, and medium-sized enterprises), which should actually be considered within the Services/Commerce sector.

However, despite the country's financial difficulties, the Cuban government affirms that to achieve a change in the energy mix, increase energy efficiency, and reduce GHG emissions, it is necessary to incorporate renewable energy sources, such as solar photovoltaics, biomass, and wind power, in the production of electricity [22]. In 2014, the Council of Ministers approved the "Policy for the Prospective Development of Renewable Sources and the Efficient Use of Energy" to make the most of the renewable resources available nationally. Cuban authorities have also discussed different possibilities and paths to develop a 100% renewable electricity system [23].

Scenario construction for renewable integration – towards 100% renewables

A scenario up to 2050 has been built on economic development and electricity demand, and the backcasting scenario method has been used [24] to analyze the possibilities of reaching the 100% renewable scenario. In constructing the backcasting scenario, the objective to be achieved in 2050 is the starting point, and the model's input data are modified depending on the different possibilities that exist to achieve the objective. Economic development is projected based on historical data on economic and energy-intensive sectors' Value added.

The projected economic development implies a growth in electricity consumption, with the residential sector being the fastest growing when considering the growth of private and family businesses and mini, small, and medium-sized businesses (see Figure 10).

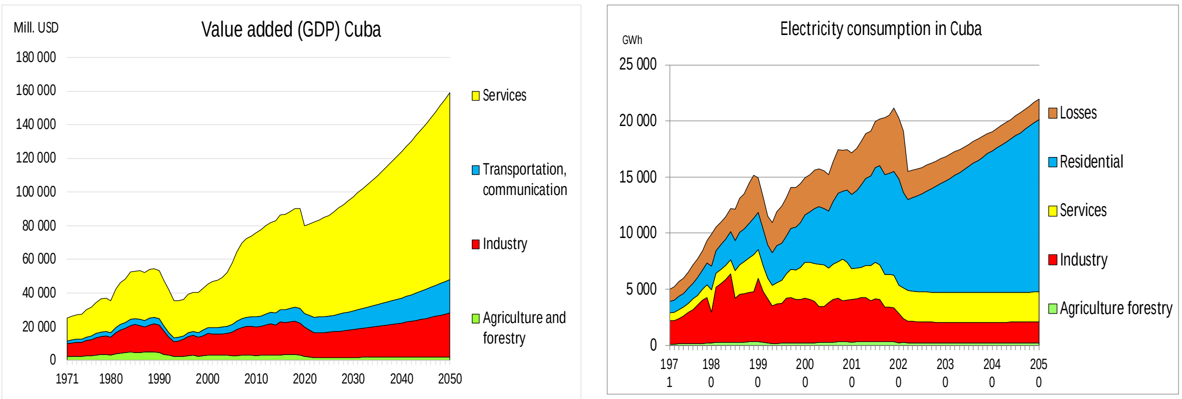


Fig. 10. A scenario for economic development and electricity consumption in Cuba in different sectors of the economy

In this scenario, a considerable increase in investments in solar and wind energy and storage is also needed. The electricity generation by each of the sources is shown in Figure 11.

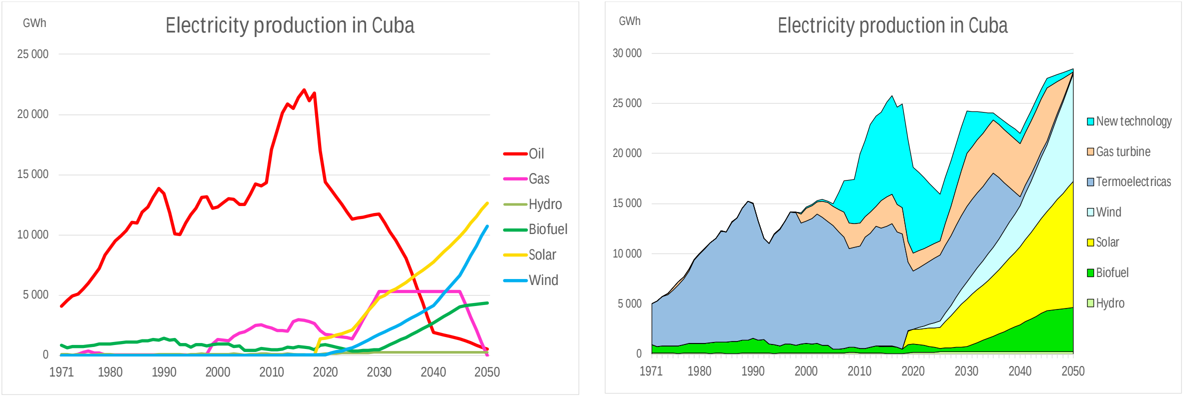
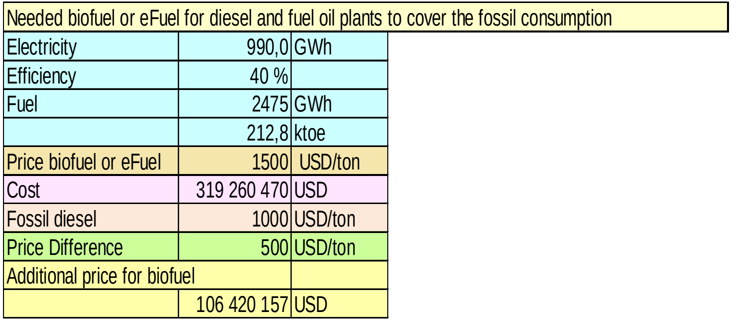


Fig. 11. Scenario for electricity production in Cuba by different sources.

The production of electricity with wind energy, solar energy, and the use of biofuels increases considerably. In contrast, electricity production with fossil sources (crude oil, gas, diesel, and fuel oil) is reduced almost to a minimum due to investments in renewable capacity.

In this scenario, it is evaluated that generation using combined cycle gas turbines and the use of fuel oil and diesel plants/internal combustion engines (ICE), so called “new technology” plants, will be maintained, but with the change of their fuel from fossil to biofuels (eFuels). The amount of biofuel and eFuel necessary for these ICEs, efficiency, generation, prices, and costs, important elements for decision-makers, have also been estimated (Table 1).

Table 1. Biofuel and e-Fuel needed to cover the fossil consumption



Needed biofuel or eFuel for diesel and fuel oil plants to cover the fossil consumption		
Electricity	990,0	GWh
Efficiency	40 %	
Fuel	2475	GWh
	212,8	ktoe
Price biofuel or eFuel	1500	USD/ton
Cost	319 260 470	USD
Fossil diesel	1000	USD/ton
Price Difference	500	USD/ton
Additional price for biofuel		
	106 420 157	USD

The annual electricity production of different energy sources in 2050 in this scenario, together with renewable/fossil share in electricity production, is shown in Figure 12. In this scenario, renewables already dominate production. Solar PV has the highest share of production (about 13 000 GWh), followed by wind power (about 11 000 GWh). Biomass-based production (mainly sugar cane) is about 4 000 GWh, fossil-based ICE production (New technology) is about 600 GWh; thermoelectrics (older oil-fired condensing power plants) is about 250 GWh, and gas turbines are about 850 GWh. The hydro production is low due to the 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 3 700 GWh.

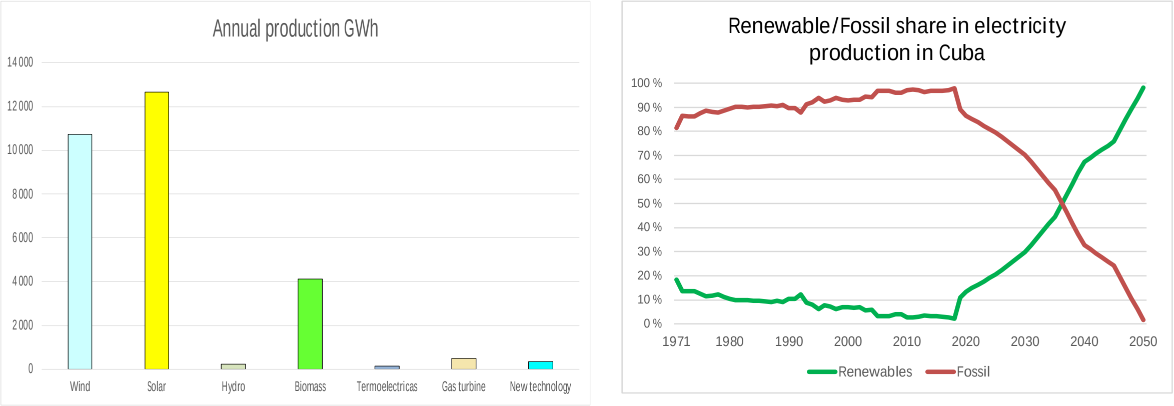


Fig. 12. Annual electricity production by different types of power plants in 2050 and Renewable/Fossil share in electricity production

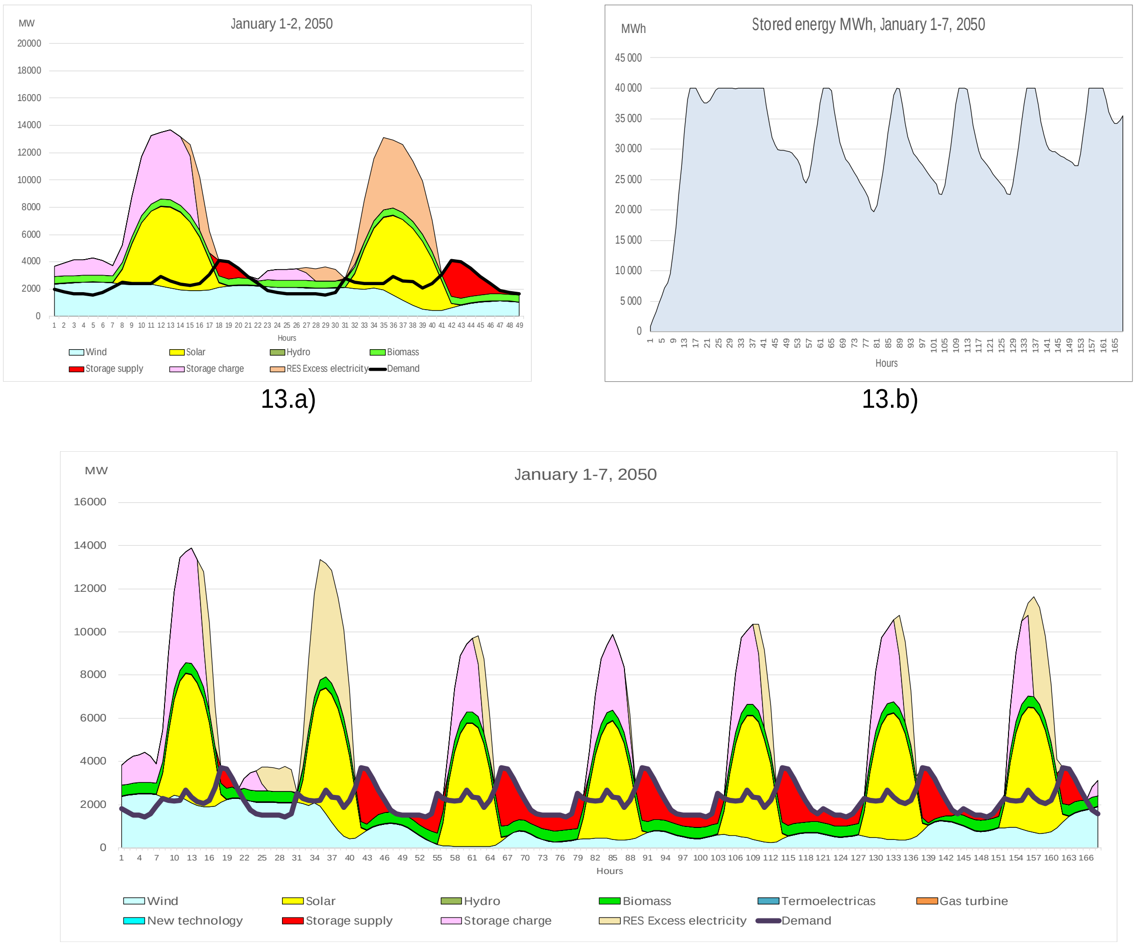
In this scenario, the total demand is 24 000 GWh, and the total production is 29 000 GWh.

However, by using intermittent renewable energy sources to a large extent, it is necessary to evaluate and consider what happens when production with these sources changes rapidly.

Looking at electricity production and demand in the first week of January 2050, the renewable energy capacity, together with the increase in storage capacity, is sufficient to produce all the electricity needed, as can be seen in Figure 13.

Figure 13. a) details what happens on the first two days of January. In the first 24 hours, the storage reaches its maximum capacity (Figure 13. b). Although a small percentage of the stored energy will be used to cover the energy demand, between 24-48 hours, there is an overproduction of renewable energy that will be wasted if not being able to assimilate this overproduction in the storage.

This excess electricity (shown inn Fig. 13.a, c), which cannot be stored, can be used to produce hydrogen in electrolyzers.



13.a)

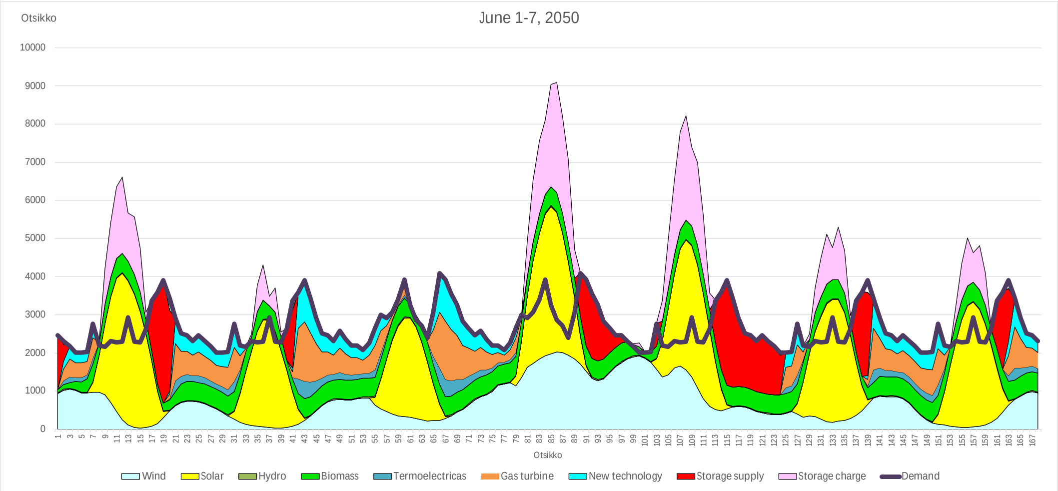
13.b)

13. c)

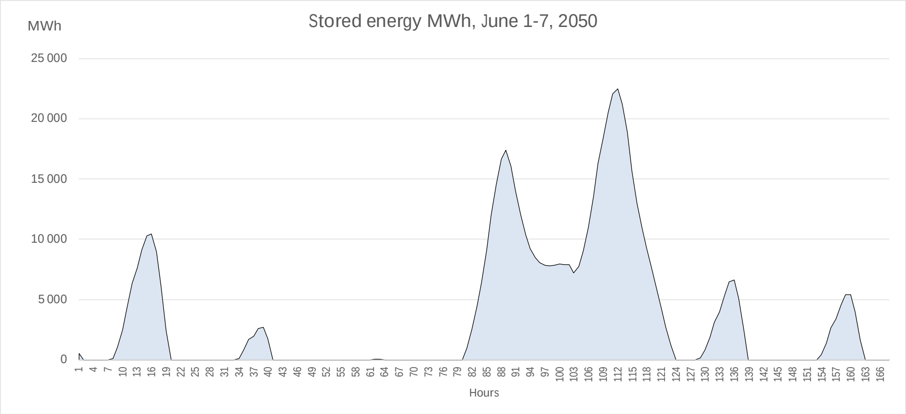
Fig. 13. Electricity supply, demand, and stored energy during January 1-7.

In the first week of June 2050, the installed renewable energy capacity, due to the low wind speed, will be insufficient to produce all the required electricity, as shown in Figure 14.

In this period, to cover the demand, it is necessary to increase production with ICEs, thermoelectrics, and gas turbines (fossil or giofuel or eFuel), and the stored energy can cover only a few hours a week.



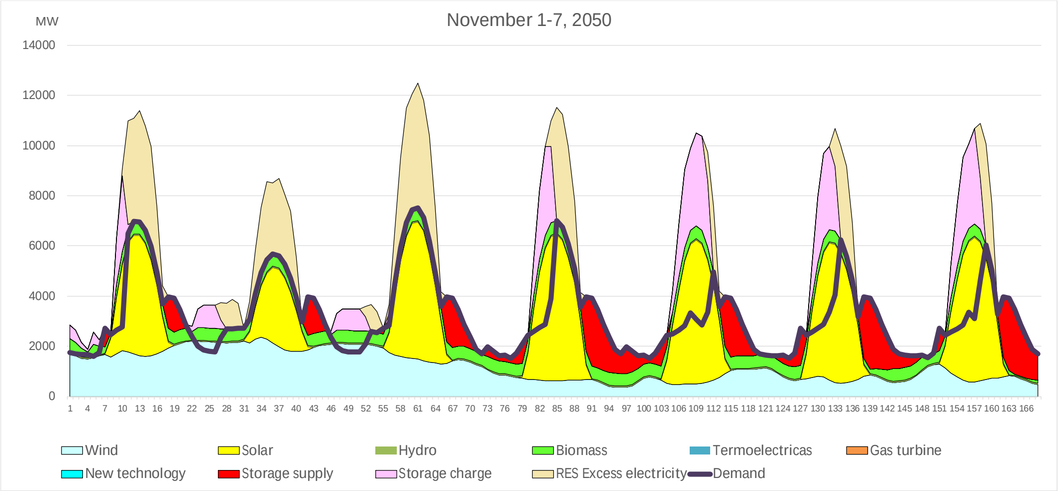
14. a)



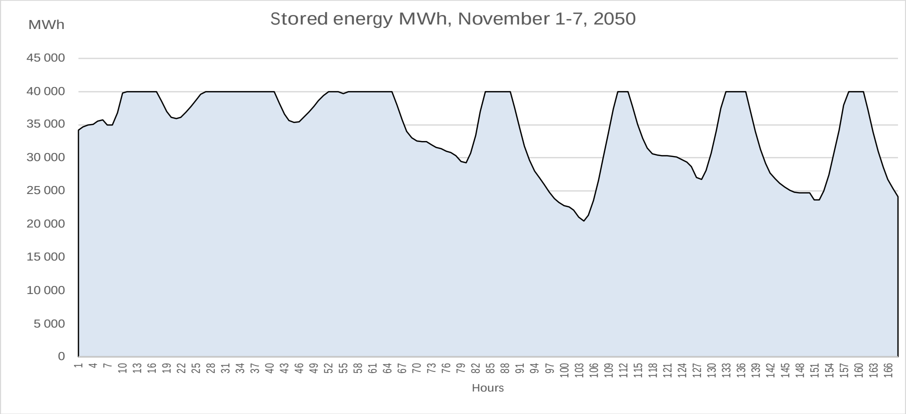
14. b)

Fig. 14. Electricity supply, demand, and stored energy during June 1-7

With increased wind speed in November, energy overproduction occurs again (see Figure 15), and excess electricity is produced when the storage is whole. This excess electricity can be used for hydrogen production.



15. a)



15. b)

Fig. 15. Electricity supply, demand, and stored energy during November 1-7

The proposal to take advantage of renewable overproduction is to generate green hydrogen using electrolyzers, the so-called Power to X principle, and use that hydrogen in multiple applications. Non-carbon hydrogen will play a key role in decarbonizing several industries whose emissions are challenging to abate, such as basic chemicals, aviation, steel production, shipping, and long-haul road transportation. In 2021, the demand for hydrogen in the world was around 94 million tons, most of it in gray hydrogen. The Boston Consulting Group (BCG), in its 2023 report, considers that by 2050, the demand for low-carbon hydrogen will soar from roughly 350 million tons per annum to 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, according to this report [25]. IRENA's World Energy Transitions Outlook sees hydrogen covering 12 percent of global energy demand and cutting 10 percent CO_2 emissions by 2050 [26].

The target of the Power-to-X (PtX) economy (see Figure 16) is to produce hydrogen and carbon-neutral hydrocarbons to replace fossil hydrocarbon products. Carbon-free hydrogen is produced by splitting water into hydrogen and oxygen by renewable electricity-powered electrolyzers and further refined to methane CH_4 and/or methanol CH_3OH by synthetizing with carbon dioxide captured directly from air or flue gases of biomass-fired thermal power plants and to ammonia, NH_3, by synthetising with nitrogen. These products can be processed further to, for instance, e-Fuels used in internal combustion engines. Energy storages play an important role in the PtX system. Hydrogen production fluctuates due to variable renewable electricity supply, but hydrocarbon synthetising processes like Fischer–Tropsch and Sabatier and Haber-Bosch for ammonia production should be operated at steady states. Thus, buffer storages are needed to smooth the fluctuating hydrogen flow to steady feed flow for refining processes.

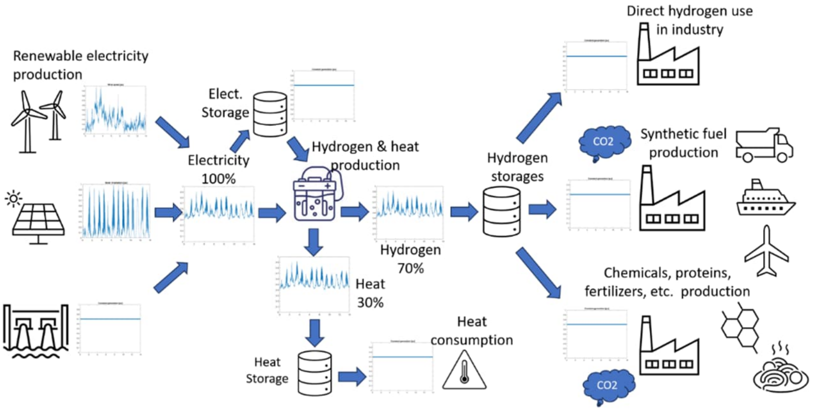


Fig. 16. Value chain of the PtX economy, where green hydrogen is produced by renewable electricity-powered electrolyzers and further processed to different carbon-neutral end products.

As a result of the analysis of the scenario, there is potential to produce green hydrogen, considering that:

- Excess electricity can be used for hydrogen production with electrolyzers;
- In this scenario, the excess electricity is 5100 MWh in 2050;
- Electrolyzers, with an efficiency between 40-50%, could produce 137 000 tons of hydrogen in 2050;
- This could be used, for instance, for production of 770 000 tons of ammonia;
- Other industrial or transportation uses.

Hydrogen can strongly impact the reactivation of processes in the Cuban industry, whose role has significantly reduced economic production since 1996, which has also impacted the reduction of industrial energy use [27]. The increase in productivity and efficiency of 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 in the Cuban economy, with, for instance, several vaccines against various bacterial and viral pathogens and the development of drugs for cancer treatment.

The agricultural and livestock sectors can also benefit from hydrogen production due to the possibility of producing fertilizers from ammonia, reducing the high cost of imported fertilizers.

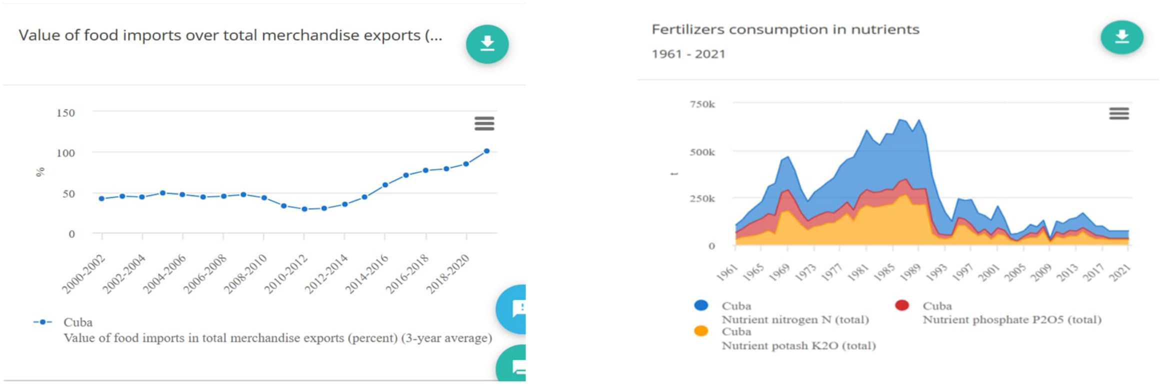


Fig. 17. Food imports and Consumption of fertilizers [28]

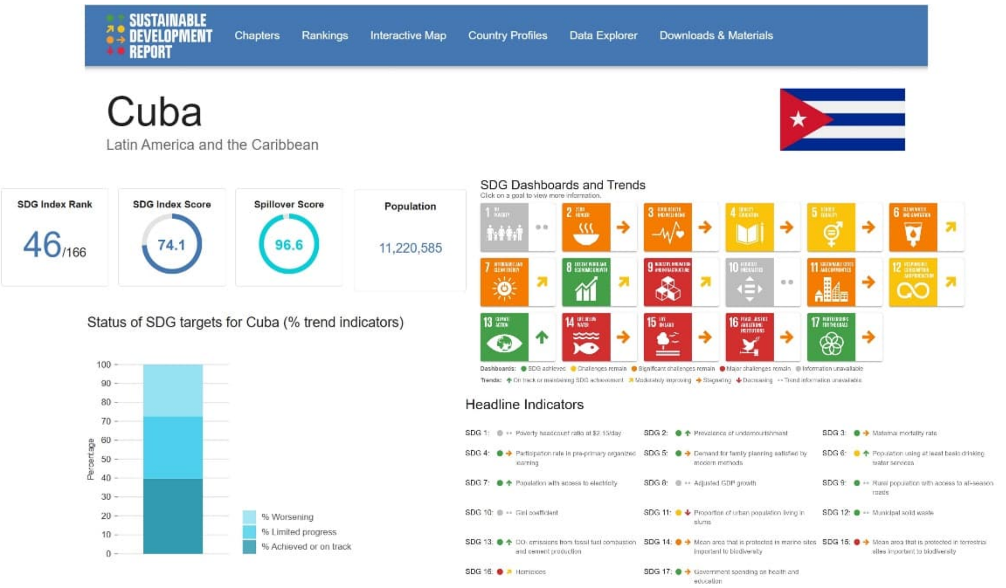
Cuban agricultural production has decreased considerably, and food imports consume practically 100% of export earnings (see Figure 17). The import and consumption of fertilizers have also decreased, which has resulted in low agricultural production.

SuWi and Doughnut Economic result

In the Sustainable Development Reports, where compliance with the SDGs by most countries can be seen, Cuba appears in 46th place out of 166 countries (Figure 18).

We carried out a Sustainability Window analysis to assess Cuban development concerning three pillars of the Green Economy: (i) Low carbon development, (ii) resource efficiency, and (iii) social inclusion (see [12], where the methodology of SuWi is explained). We have utilized different indicators in the analysis to compare their ease of use and provide a broader view of the development of the green economy.

In this research, different indicators have been used. The Sustainable Society Index (SSI) [30 -31], together with the SDG database [29], was the primary data source for the analysis. We have used the raw data from the SSI database and similar data from the SDG indicators.



Cuba

Latin America and the Caribbean

SDG Index Rank: 46/166

SDG Index Score: 74.1

Spillover Score: 96.6

Population: 11,220,585

Headline Indicators

SDG 1: Poverty headcount ratio at $2.15/day
SDG 2: Prevalence of undernourishment
SDG 3: Maternal mortality rate
SDG 4: Participation rate in pre-primary organized learning
SDG 5: Demand for family planning satisfied by modern methods
SDG 6: Population using at least basic drinking water services
SDG 7: Population with access to electricity
SDG 8: Adjusted GDP growth
SDG 9: Rural population with access to all-season roads
SDG 10: Gini coefficient
SDG 11: Proportion of urban population living in slums
SDG 12: Municipal solid waste
SDG 13: CO_2 emissions from fossil fuel combustion and cement production
SDG 14: Mean area that is protected in marine sites important to biodiversity
SDG 15: Mean area that is protected in terrestrial sites important to biodiversity
SDG 16: Homicides
SDG 17: Government spending on health and education

Fig. 18. Cuba. Updated information on the status of compliance with the SDGs [29].

In addition, we have used [5] statistical data for GDP, [32] data for the Human Development Index, [33] data on energy and CO_2 emissions, and [34] data on education. The SSI dataset integrates Human, Environmental, and Economic well-being indicators to form a more comprehensive view of development. Similar Sustainability Window analyses have been conducted using several SSI and other database indicators. We can visualize sustainability in a doughnut form when the pairwise results, the quantified Sustainability Window, of all the social and environmental indicators pairs are arranged in a radial diagram (see [35]). The data used in the analysis covers 2006–2016, for which the SSI data is available.

The strong criterion for environmental sustainability is defined as the situation where the environmental stress does not increase (see [36 - 38]). Strong sustainability means that, for instance, CO_2 emissions should not increase. This analysis also utilizes the weak sustainability criterion, which states that the environmental stress per GDP should not increase. Weak sustainability means that, for instance, the CO_2 emissions divided by GDP does not increase. The weak sustainability criterion can be used in this case because, for instance, Cuba's CO_2 emissions per capita are very low. The criterion for social sustainability in this analysis is that social welfare should increase. It is also possible to carry out the SuWi analysis using absolute targets for environmental stress (for instance, 1.8 tons of CO_2 emissions per capita) and social well-being if such absolute criteria can be defined.

In this analysis, we have used the following indicators, listed in Table 2, to illustrate the method:

Table 2. Indicators used in the construction of the doughnut model for Cuban development.

Social indicators		Environmental indicators		Economic
Food	Sufficient Food	Forest	Biodiversity forest area	GDP
Drink	Sufficient to Drink	Conservation	Biodiversity protected area	
Edu	Education	Water	Renewable Water Resources	
HLY	Healthy life years	Consu	Consumption of global hectares	
Gend	Gender equality	Energy	Energy use	
Inc	Income distribution	Intens	Energy savings	
Emp	Employment	CO_2	Greenhouse gases	
Soc inc	Social inclusion	Ren energy	Renewable energy	
HDI	Human Development Index	Organic	Organic farming	
EduPT	Education Pupil-Teacher ratio	Sanitation	Safe sanitation	

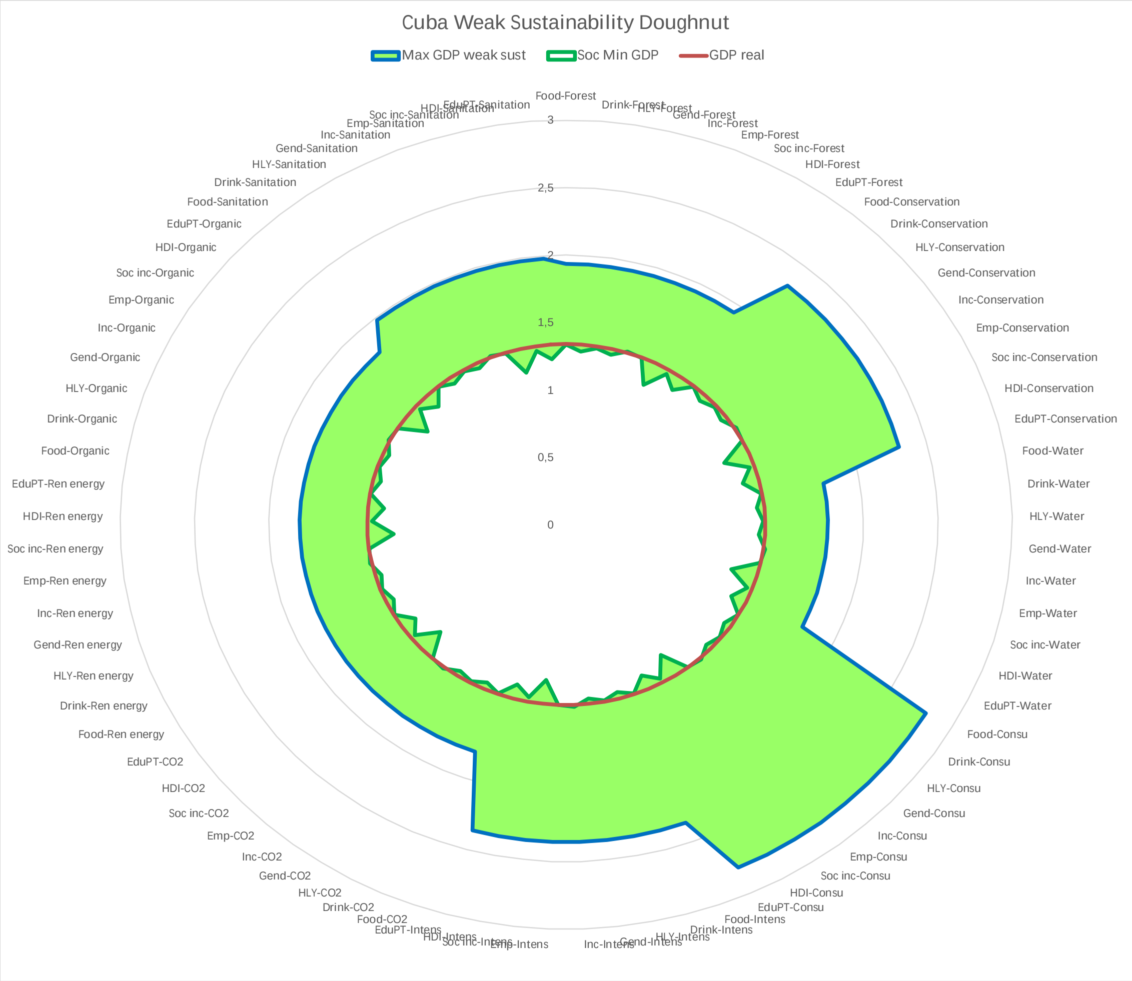


Figure 19. *Doughnut model for weak sustainability* analysis of Cuban development in 2006-2016. *Blue line* indicates the maximum economic development to fulfill the environmental sustainability criteria, and the *green line* indicates the minimum economic development to fulfill the social sustainability criteria. The *red line* indicates the real GDP growth level during the analyzed period. *Green area, sustainability doughnut illustrates the possible area for sustainable development.*

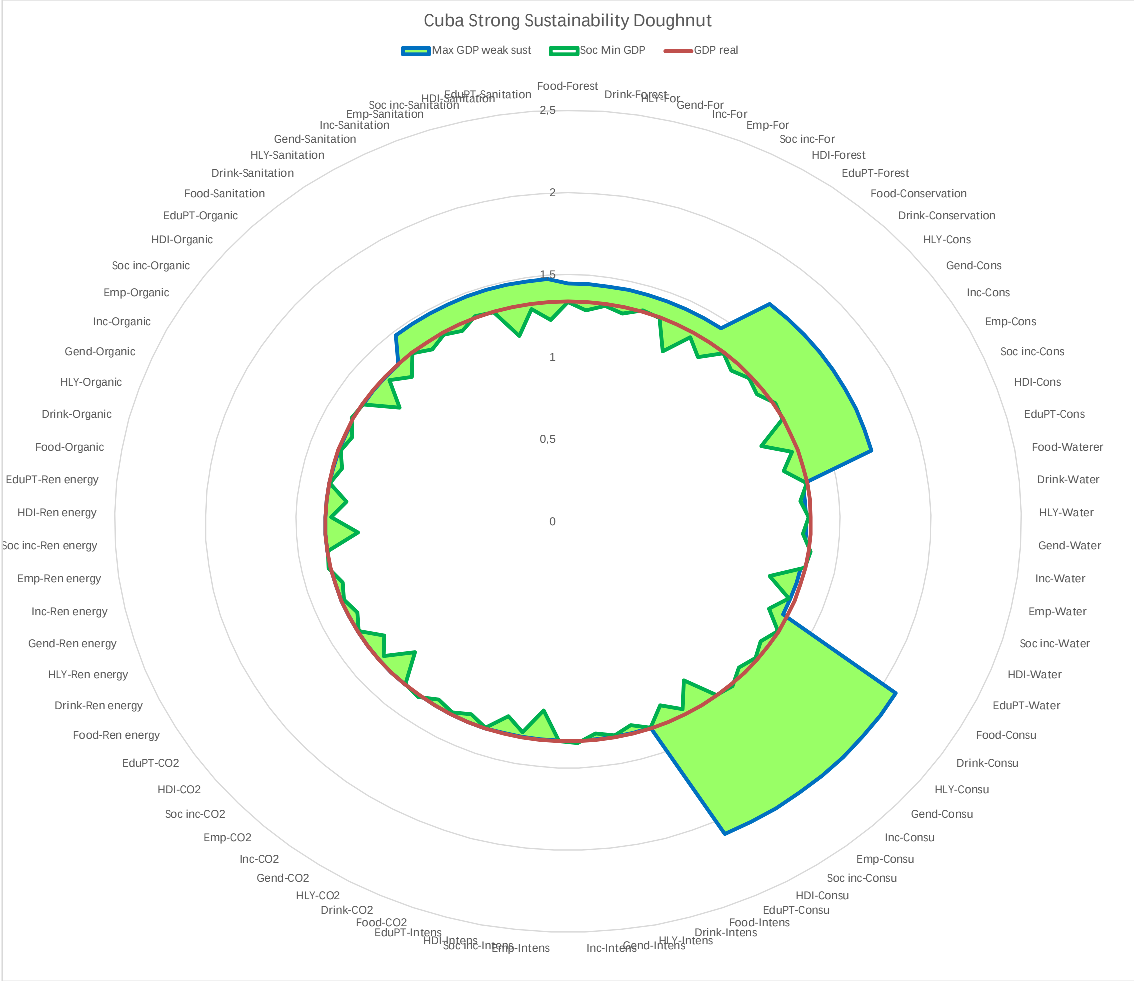


Figure 20. *Doughnut model for strong sustainability* (absolute reduction in environmental stress) analysis of Cuban development in 2006-2016. The *blue line* indicates the maximum economic development to fulfill the strong environmental sustainability criteria and the *green line* indicates the minimum economic development to fulfill the social sustainability criteria. The *red line* indicates the real GDP growth level during the analyzed period. *Green area, sustainability doughnut illustrates the possible area for sustainable development.*

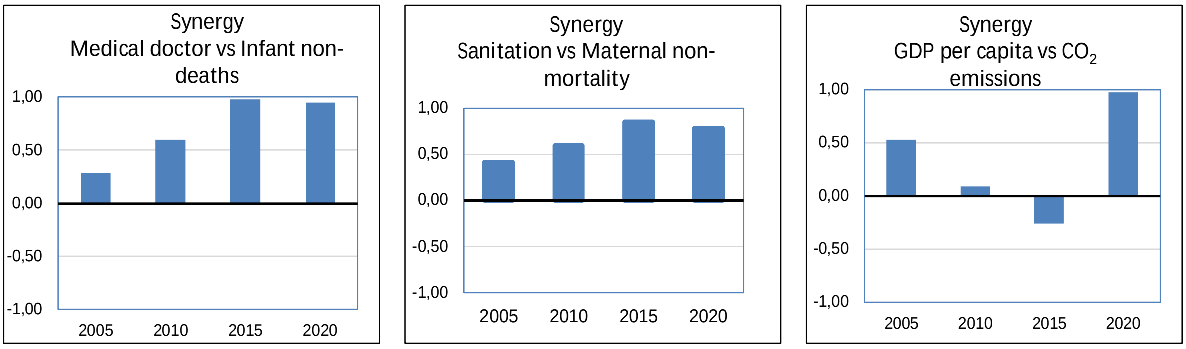
Sustainability Window (SuWi) method provides a novel approach for analyzing sustainability simultaneously in social, environmental, and economic dimensions in a quantitative way. The simultaneous analysis in different dimensions provides possibilities for comprehensive analyses where the interactions between different sectoral developments are revealed, and the problematic areas can be detected. This makes it possible to consider the policy responses in sectors of the economy and direct interventions in the areas where they are most urgently needed. The possibilities to analyze development in different policy areas simultaneously can lead to more balanced policies and timely actions compared to one sector analyses.

The developed quantitative illustration of the *Doughnut Economy* provides a new visualization of the development. It clearly illustrates the problematic areas of development and can be utilized as a method for communication of the complex development problematique. The visualization is crucial when the policy planning includes actors from different areas and backgrounds to receive feedback from larger stakeholder groups.

Synergy method applied.

In the following text, we show how synergy analysis can provide additional information on the interlinkages of development processes in different domains for planning purposes. The sectoral interlinkages are often very strong due to numerous value chains in the production and non-material connections.

The synergies in the following figures are calculated based on the changes in the used SDG indicators from the base year 2000. Figure 21. a) shows quite an obvious synergy between the availability of medical doctors and the survival of infants. Figure 21. b) shows a result of safely managed sanitation service and maternal survival rate. Investments in medical care and sanitation clearly have a positive impact on healthy life of the population. Figure 21. c) is, however, quite interesting, showing considerable synergy between GDP per capita and CO_2 emissions for 2000-2005, but very low and negative synergy for 2000-10 and 2000-15. Then again, the synergy seems very strong for 2000-2020. This indicates changes in the production system, which is not linearly linked to economic output.

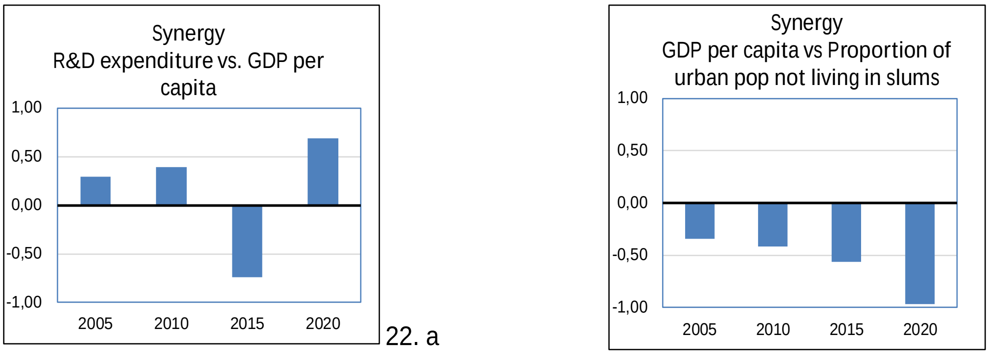


21. a 21. b 21. c

Figure 21. Synergy between Medical doctors per 10 000 population vs. survival of infants (21. a). Synergy between the proportion of the population using a safely managed sanitation service vs. Maternal survival (21. b). Synergy between GDP per capita vs. CO_2 emissions (21. c).

Figure 22. a) shows the synergy between the expenditure on research and development and GDP per capita. This result indicates the important role of research and development work and scientific innovations for promoting economic development.

Economic growth does not, however, always yield positive results in all spheres of life if the planning processes cannot allocate resources in all required areas. Figure 22. b) is an illustration of this. 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.



22. a 22. b

Figure 22. Synergy between the research and development expenditure as a proportion of GDP and GDP per capita (22. a). Synergy between GDP per capita and the proportion of the urban population not living in slums (22. b)

The above examples illustrate how synergy analysis can provide important additional information about the multiple interlinkages of different activities in societies. It can be integrated into other planning tools to provide a more comprehensive view of changes. Using SDG indicators in the synergy analysis adds important elements of sustainability to the analysis framework.

CONCLUSIONS

The construction of a 100% renewable scenario in Cuba by 2050, using the LINDA model, demonstrates that achieving this objective is possible by applying appropriate policies, with more investment, with the application of energy savings and efficiency measures.

It is also important to introduce energy storage and the production of green hydrogen. Hydrogen can be used the production of e-Fuels, which can be used in the electricity generation to replace fossil fuel use. The production of green hydrogen will also allow for expanding the link between the different sectors of the economy, mainly with agriculture and industry.

Based on this future renewable scenario, assessing how the policies and measures applied influence sustainable development and compliance with the SDGs is important.

The simultaneous analysis in different dimensions that the Sustainability Window allows offers possibilities for comprehensive analyzes that reveal the interactions between different sectoral developments and detect problem areas, providing a framework for policy responses in sectors of the economy and direct interventions in the areas that need it most urgently. Analyzing developments in different policy areas simultaneously can lead to more balanced policies and timely actions compared to analyzes of a single sector.

The developed quantitative illustration of the Donut Economy provides a new visualization of development that clearly illustrates problem areas and can be used to communicate the complex development problem. Visualization is crucial when policy planning includes actors, decision-makers and stakeholders from different areas, allowing for more participatory planning.

Synergy analysis can provide additional information on the multiple interrelationships of different activities in societies. The various components of sustainability can be interrelated by using SDG indicators in synergy analysis. Finally, this method can be integrated with other planning tools to provide a more comprehensive view of what can happen when implementing measures to improve societal well-being.

This is why the use of models and tools such as Sustainability Window (SuWi), Doughnut Economy, and Synergy analysis are important to have a broad vision of sustainable development.

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