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Towards 100% Renewables by 2030: Transition Alternatives for a Sustainable Electricity Sector in Isla de la Juventud, Cuba

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Abstract: Renewable Energy Sources (RES) have become increasingly desirable worldwide in the fight against global climate change. The sharp decrease in costs of especially wind and solar photovoltaics (PV) have created opportunities to move from dependency on conventional fossil fuel-based electricity production towards renewable energy sources. Renewables experience around 7% (in 2018) annual growth rate in the electricity production globally and the pace is expected to further increase in the near future. Cuba is no exception in this regard, the government has set an ambitious renewable energy target of 24% RES of electricity production by the year 2030. The article analyses renewable energy trajectories in Isla de la Juventud, Cuba, through different future energy scenarios utilizing EnergyPLAN tool. The goal is to identify the best fit and least cost options in transitioning towards 100% electric power systemin Isla de la Juventud, Cuba. The work is divided into analysis of (1) technical possibilities for five scenarios in the electricity production with a 40% increase of electricity consumption by 2030: Business As Usual (BAU 2030, with the current electric power system (EPS) setup), VISION 2030 (according to the Cuban government plan with 24% RES), Advanced Renewables (ARES, with 50% RES), High Renewables (HiRES, with 70% RES), and Fully Renewables (FullRES, with 100% RES based electricity system) scenarios and (2) defining least cost options for the five scenarios in Isla de la Juventud, Cuba. The results show that high penetration of renewables is technically possible even up to 100% RES although the best technological fit versus least cost options may not favor the 100% RES based systems with the current electric power system (EPS) setup. This is due to realities in access to resources, especially importation of state of the art technological equipment and biofuels, financial and investment resources, as well as the high costs of storage systems. The analysis shows the Cuban government vision of reaching 24% of RES in the electricity production by 2030 can be exceeded even up to 70% RES based systems with similar or even lower costs in the near future in Isla de la Juventud. However, overcoming critical challenges in the economic, political, and legal conditions are crucially important; how will the implementation of huge national capital investments and significant involvement of Foreign Direct Investments (FDI) actualize to support achievement of the Cuban government's 2030 vision?

Keywords: Isla de la Juventud; electrical power system; renewable energy; EnergyPLAN; economic analysis; 100% renewable electric system

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1. Introduction

Energy sector emissions are considered to be the major driver of human induced climate change [1]. In 2018, although the share of electricity produced from renewables grew over 7%, the continued reliance globally on fossil fuels showed the highest growth rate since 2013 and resulted in an emission increase of nearly 2% [1].

Transitioning towards Renewable Energy Sources (RES) and efficient energy management are seen globally as some of the main attributes in solving the climate crisis and utilization of fluctuating renewable energy sources is increasing world-wide. One of the main challenges, however, until recently has been the concern on how to integrate these resources into the energy systems [2–4]. Vazquez et al. (2018) state, "increased share of RES in future electrical power system brings several challenges to system planning and operation, which should be taken into account in decision making about required generation capacity and reserves, need of energy storages, control strategy and flexibility capacity of the system" [5].

The design of optimal energy mixes in combating climate change mitigation actions is, therefore, often a multicriteria decision making process. The optimization of the best fit systems are often based on multiple criteria, but mainly within two groupings: economic objectives or with a focus on techno-operational aspects [2,4].

In the recent years, renewables, especially wind and solar, have become increasingly affordable [6]. Renewable energies are also becoming increasingly competitive as they are clean and inexhaustible sources with marked differences from fossil fuels mainly because of their diversity, abundance, potential for use anywhere on the planet, and, above all, they do not produce greenhouse gases. According to International Renewable Energy Association (IRENA), solar photovoltaics (PV) have shown the sharpest cost decline over 2010–2019, at 82%, followed by concentrating solar power (CSP) at 47%, onshore wind at 40%, and offshore wind at 29%. Utility-scale solar PV electricity costs fell to USD 0.068 per kilowatt-hour (kWh) in 2019 and onshore wind to USD 0.053/kWh for newly commissioned projects. In 2019, the share of renewables in capacity expansion reached 72% and the renewable share of total generation capacity rose from 33.3% in 2018 to 34.7% [6].

A literature review shows different approaches and tools have been utilized to examine RES penetration in the energy mix. The previous research shows analysis is carried out, e.g., for examining the current systems, potential barriers of RES utilization, examining future systems and testing policy goals. Various different types of analysis tools have been used to assist long term planning of the energy sector to support decision making and the identification of current and future investment needs. The type of the tool and decisions are important and should cater for the aim of the planning exercise. Some of the most known tools according to, e.g., IRENA (2017), e.g., MESSAGE, TIMES, MARKAL, OSeMOSYS, LEAP, EnergyPLAN, WASP, and BALMORE can be suitable tools for a longer horizon planning exercises [7,8].

The energy transition studies are available worldwide in different contexts, including islands. To mention a few, Cabrera et al. (2018) found out nearly 100% RES based smart energy systems are possible in Gran Canaria [9]. Kuang et al. (2016) have studied the different RES based smart systems and their feasibility [10] and Thushara et al. (2019) have studied the Sri Lankan context of moving towards future RES based systems [11], whereas Weir (2018) has studied the role of renewable energy in the Pacific [12]. In the Caribbean region, Makhijani et al. (2013) and Chen et al. (2020) have studied energy transitions in Jamaica [13,14], Hohmeyer (2015) has analyzed 100% RES energy transition in Barbados [14], and Vazquez et al. (2018), Salazar et al. (2018), and Montes Calzadilla (2019) RES based electric systems in Cuba [5,15,16]. Mendoza-Vizcaino et al. (2016) studied nearly 80 islands from over 40 countries and the analysis shows PV and wind power are the most used renewable energy technologies on the studied islands and the integration of RE on islands (when viable) results in a fossil fuel consumption reduction and a more sustainable energy sector [17].

Cuba has been, and still is, a special case due to its isolation from international trade, mainly due to the U.S. embargo that limits the country's economic opportunities and investments in infrastructure. The U.S embargo since the 1960s has had a dramatic effect on the Cuban economic development through reduced trade and tourism, frozen bank accounts and assets, availability of goods and services, as well as movement of people [18]. Based on the United Nations' and Cuban government estimations, the U.S. financial and trade embargo has cost the Cuban economy $130 billion [19]. In the energy sector, Cuba has managed to rely on Soviet bloc countries and later Venezuela and China providing Cuba with subsidized oil and technical and financial assistance.

The Cuban government has estimated that energy and mining sector development suffered a loss over $125 million by the U.S. embargo. According to Ministry of Economy and Planning (MEP) of Cuba, the national electric utility (UNE) only exceed $16 million in losses resulting from severely influenced production and services of companies due to restrictions on manufacturers of equipment and on availability of spare parts for the production process [20–22]. This, coupled with banks being afraid of the U.S. sanctions, strangled joint venture funding from Europe and other obvious sources according to Marsh (2021) and Davis and Piccione (2017) and with most of the power generation capability still relying on old, inefficient facilities in need of upgrade, this can significantly influence the sustainable energy transition [20–22].

The Cuban energy mix is highly dependent on fossil fuels, with over 95% of generation coming from fossil fuels. The total installed capacity in Cuba was 7285 MW, of which 574 MW was renewable (8% of total installed capacity). In total, renewables account only for 4.65% (3.7% biomass, mainly from sugarcane bagasse, 0.5% hydropower, 0.2% solar photovoltaic, and 0.1% wind energy) of the total electricity production of the country [23].

Over the last decades, Cuba has been remarkably successful at revitalizing its energy sector by significantly increasing efficiency and reducing energy intensity and emissions. The current energy policy (Prospective Development of Renewable Energy Sources and the Efficient Use of Energy for 2014–2030) [24] focuses on increasing the share of renewables to 24% of the total production by 2030 through: 13 wind farms, with a total output of 633 MW; the installation of 700 MW of solar photovoltaics; 19 biomass power stations, fuelled by sugarcane and forestry biomass, with a generating capacity of 755 MW; and 74 small hydroelectric plants, with an output of 56 MW [25,26]. The main targets besides increasing the penetration rate of renewables include reducing the electricity generation costs and dependence on fossil fuels, and environmental sustainability goals. Based on the Cuban government estimates, $3.5–4.0 billion in investment (with a significant share of Foreign Direct Investments (FDI) is needed to achieve the 2030 renewable energy targets [27–31].

Although Cuba's ambitious policy goals, specific studies on energy transition from Cuba are very few. There are some recent scenario studies on the energy transitions carried out in Cuba by Montes Calzadilla (2019) on the Cuban electric system with the introduction of RES. This study shows the technical and economic feasibility up to nearly 50% RES-generated electricity. Salazar et al. (2018) and Vazquez et al. (2018) describe possible scenarios for the future development of the Cuban electricity system and the potential of integrating the intermittent energy sources in to the electric system in Cuba. However, these studies do not consider the technical challenges for the grid with high shares of RES penetration in detail.

Cuba's abundance of both solar and wind resources with an average solar irradiance of 223.8 W/m2 (5.4 kWh/m^2/day) and average wind speed at around 5.7 m/s, in the southeast above 7 m/s [32], coupled with the government promoted investments in other renewable energy sources such as biogas, forestry biomass, agro-industrial residues, and municipal solid waste offer vast opportunities towards a sustainable energy transition in Cuba [27].

The island of Isla de la Juventud is located in the southwestern part of the country with a population of approximately 89,000 inhabitants. The island has an autonomous, isolated distributed generation system with 11 diesel and fuel oil generators (with installed capacities of 35.44 MW), three solar parks with (4.2 MW), two biomass plants (with 0.5 MW), and one wind farm (with 1.65 MW) with a total installed capacity of 41.79 MW. The distributed generation systems are connected to five main 34.5 kV circuits that supply energy to the distribution substations. Currently, around 15% of installed capacity comes from renewable energy sources [33,34].

Two recent studies have been conducted in Isla de la Juventud. Alberto Alvarez et al. (2021) modelled two technically feasible scenarios on the basis of Long-range Integrated Development Analysis (LINDA) accounting framework: 25% RES and 100% RES based electric systems. Based on the analysis, they affirm both scenarios are technically possible, however, the analysis does not indicate any financial or economic analysis of the two scenarios and, therefore, provide limited application for the needed investments [35]. Soto Calvo (2021) has examined isolated microgrid options for the community of Cocodrilo in Isla de la Juventud and the techno-economic optimization of different RES configurations compared to the existing systems. Here, the financial and economic analysis shows the existing, mainly fossil fuel based, system's total costs exceed the cost of all of the four combinations with RES introduced [36].

Isla de la Juventud was selected as a case example as it (1) shares similar characteristics of the electric power system in the main island of Cuba and (2) is an island system with smaller but similar electricity consumption patterns as in the main island of Cuba.

Cuba's (including the case study, Isla de la Juventud) energy and climate goals are closely interlinked as most of the electricity in Cuba is still produced using imported fossil fuels. The heavy reliance historically on Soviet Union and recently on Venezuela, Russia, and even China on fossil fuel supplies, coupled with cumbersome foreign investment processes, have resulted in a largely fossil fuel dominated electricity sector. However, the Cuban government has prioritized the transition towards renewables to increase energy security and independence [27,28,37].

The article utilizes the advanced energy system analysis model EnergyPlan for the analysis. The criteria in selecting the most appropriate tool prioritized the accessibility to the tool (free open access), the type of tool, future orientation, and previous studies carried out with the tool.

The article is the very first study carried out by the advanced energy system analysis model EnergyPlan in a Cuban context and the results can be representative to the general conditions of the main island of Cuba. This is crucial as Cuba is moving towards renewables and studies such as this can provide the policy makers with the much needed in-country evidence. The article will analyze the possible electricity sector transitions in Isla de la Juventud with the help of EnergyPLAN. Based on the historical provincial level data (until 2019), the article looks into five electricity sector scenarios until the year 2030: Business As Usual (BAU), Vision 2030, ARES (50% RES), HiRES (70% RES), and FullRES (100% RES).

The article looks into both techno-operational and economic analysis of the different scenarios to provide information on the future energy mix alternatives and discusses the findings in the light of the most recent research in the field. The best fit solutions are presented in economic terms to provide information for policy-making on the path to renewables in Isla de la Juventud and furthermore in the main island of Cuba.

2. Materials and Methods

This article utilizes an advanced eenergy system analysis computer model, EnergyPLAN to compare the ability of electric power system of Isla de la Juventud to introduce different shares of RES in electricity production. EnergyPLAN provides a simplified model for looking at energy systems as a whole and simulates the operation of energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors [2]. Lund et al., 2012, argue that the challenge of integrating fluctuating power from renewable energy sources in the electricity grid cannot be looked upon as an isolated issue but should be seen as one out of various means and challenges of approaching sustainable energy systems in general [38]. The simulations by EnergyPLAN allow the user to draw upon results on technical and/or economic analysis. General characteristics of the model are:

- Holistic, looking at the energy sector as a whole;
- Hourly, utilizing hourly distribution of both demand and supply;
- Yearly, providing annual analysis of the year analyzed;
- Aggregated, including both the technical and economic aspects of the energy system;

- Fast, utilizing simple programming to provide fast simulation of the input data, and
- Analytically programmed with Delphi Pascal [2].

The article uses the EnergyPLAN 14.0 version for all the different futures scenarios developed. The schematic description of the EnergyPLAN model can be seen below in Figure 1.

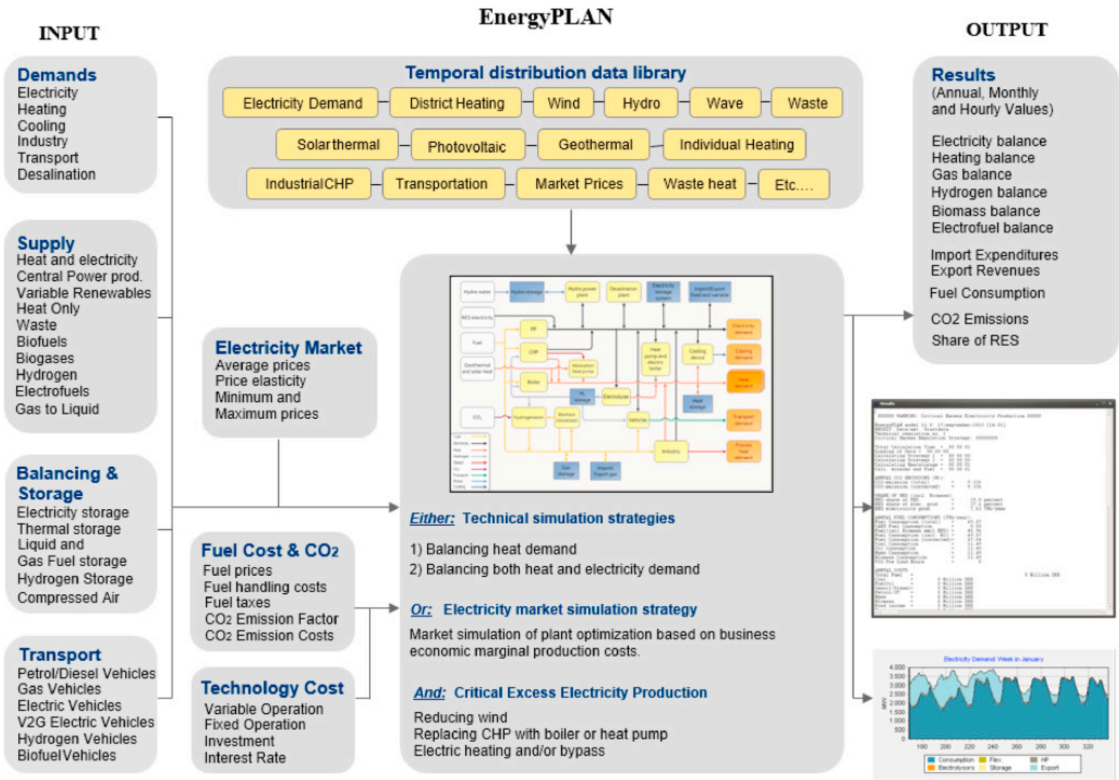

Figure 1. The schematic model of EnergyPLAN on the historical development and user inputs to define future energy demand (Reprinted with permission from Ref. [39]. Copyright 2021 Elsevier) [39].

The overall design is divided into three major parts: inputs, regulation strategies and simulation and outputs. The user inputs the demand and supply distribution data, capacities and efficiencies of the powerplants, storage options, regulation strategies and fuel costs. The user decides also on the type of analyses from economic and/or techno-operational, which can be used to simulate results on the future electricity production, share of RES, CO2 emissions, and import expenditures and export revenues.

EnergyPLAN has been utilized in around 200 scientific articles, focusing mainly on the development of high-RES scenarios at national and state level [40]. EnergyPLAN has been also used to in investigating energy transitions in various country studies such as, e.g., Finland, Germany, Ireland, Italy, Norway, Chile, and China, in islands such as Gran Canaria and Favignanan islands, and cities, regions, and even continents like Europe [39].

The data used in the modeling for the scenario analysis are obtained from the International Energy Agency (IEA) World Energy Statistics database [41], National Statistics Office of Cuba (ONEI) [42] and National Electric Utility (UNE) [43] and IRENA cost database 2019 [6]. The data inputs for future electricity growth are based partly on Cuban energy sector expert opinions and by the user. The historical data in 2019, the base year, showcases trends in economic development, electricity production and consumption, and energy use in general. The electric company at the Isla de la Juventud, National Electric Union (UNE), provides the main sources of electricity related data. Partial data have been consulted and received from existing literature and the annual load curve is user constructed simulation based on the sectoral maximum loads, typical summer and winter day loads, and the expected future electricity consumption based on the expert estimates. The sectoral composition to the GDP follows ONEI statistics and the sector shares of the total electricity consumption can be seen in ONEI's Annual Provincial summaries publicly available at UNE. All of the data have been cross-checked to represent the real data as far as possible. All the cost related data on renewable energy technologies related to investments and market prices are used from the IRENA cost database, whereas the maintenance and operation costs as well as the power plant operation parameters are based on user evaluation for the different technologies. The data sources are shown below:

- Electricity related data: Total consumption ONEI [42], daily load curve for a typical summer and winter day UNE [43], annual load curve (user defined with data from UNE [43]).
- Capacity factors, efficiencies, and parameters of technologies: expert opinions and user defined based on IRENA [6].
- Annual solar irradiation and wind speed data based on MERRA-2 satellite data [23,24].
- Cost related data: investment, operational, maintenance, and other costs: user defined based on IRENA [6].

The hourly load curves have been constructed as percentages of maximum load and modified by the author to present the actual hourly values [43]. Figure 2 illustrates the examples of typical days and weeks in January and July 2019 in Isla de la Juventud. The electricity demand is lowest in the winter months and highest in the summer (July). The electricity production shows the share of both RES (in gray) and diesel and fuel oil Power Plants, PP+ (in black), where fossil fuel based electricity production clearly dominates the electricity generation in 2019.

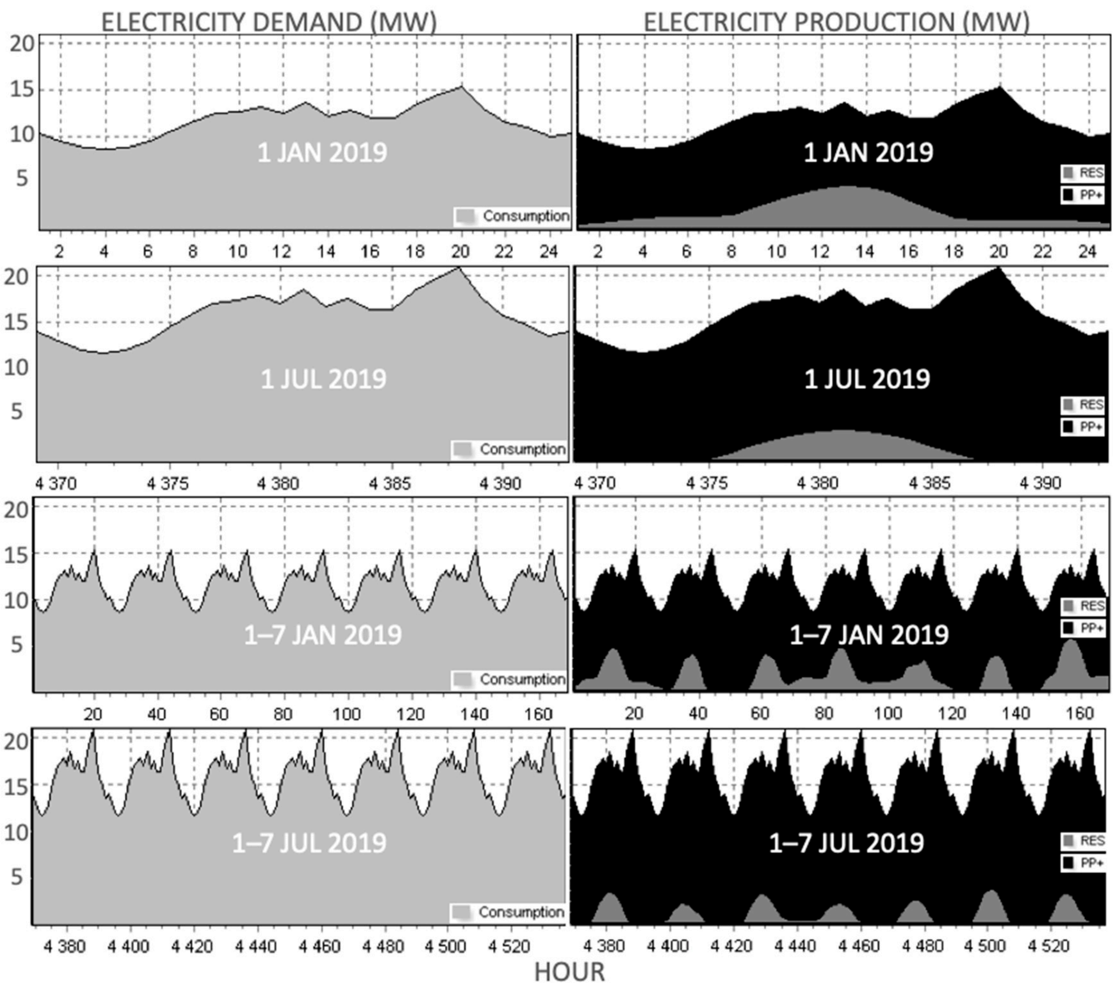

Figure 2. The daily and weekly electricity demand and production in Isla de la Juventud in January and July 2019. Data source: [43].

Figure 3 illustrates the typical weekday with sectoral electricity consumption as percentages of the maximum sectoral load in January 2019. In general, the highest sectoral shares originate from the household sector in the total electricity consumption with the highest consumption taking place in the evenings (16:00–22:00).

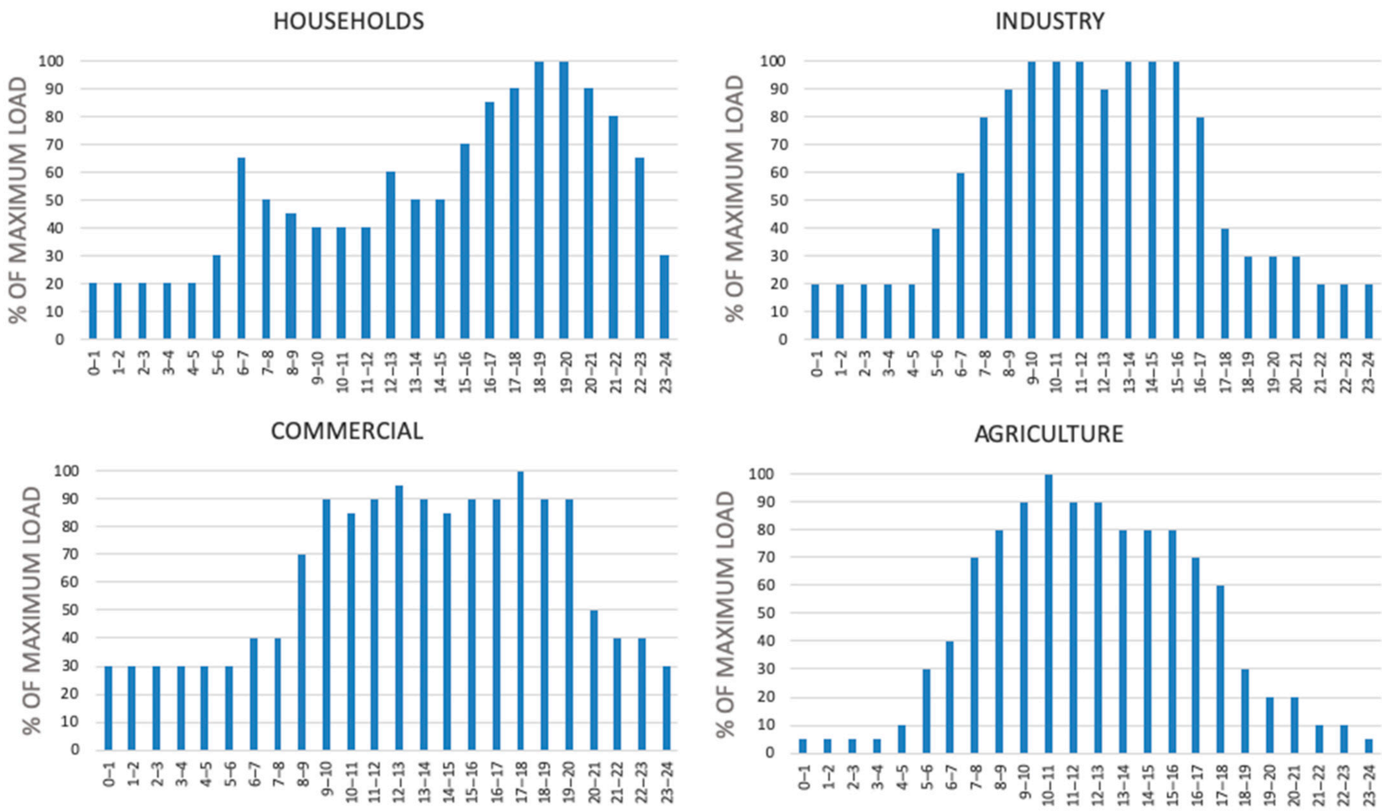

Figure 3. Load curve for sectoral electricity consumption for a weekday in January 2019 (percentage of the sectoral maximum load). Data source: [43].

The data for wind and solar radiation utilize the datasets provided the Modern-Era Retrospective analysis version 2 (MERRA 2) databases and are shown in Figures 4 and 5. Figure 6 shows the annual direct solar irradiance (kW/m^2) and wind speed (m/s) fluctuation at 50 m hub height in Isla de la Juventud. It can be seen that spring and summer months experience the lowest direct solar radiation with winter months from December to March receiving the highest direct solar irradiance. Wind speeds fluctuate throughout the year experiencing the highest wind speeds in January, February, and August/September.

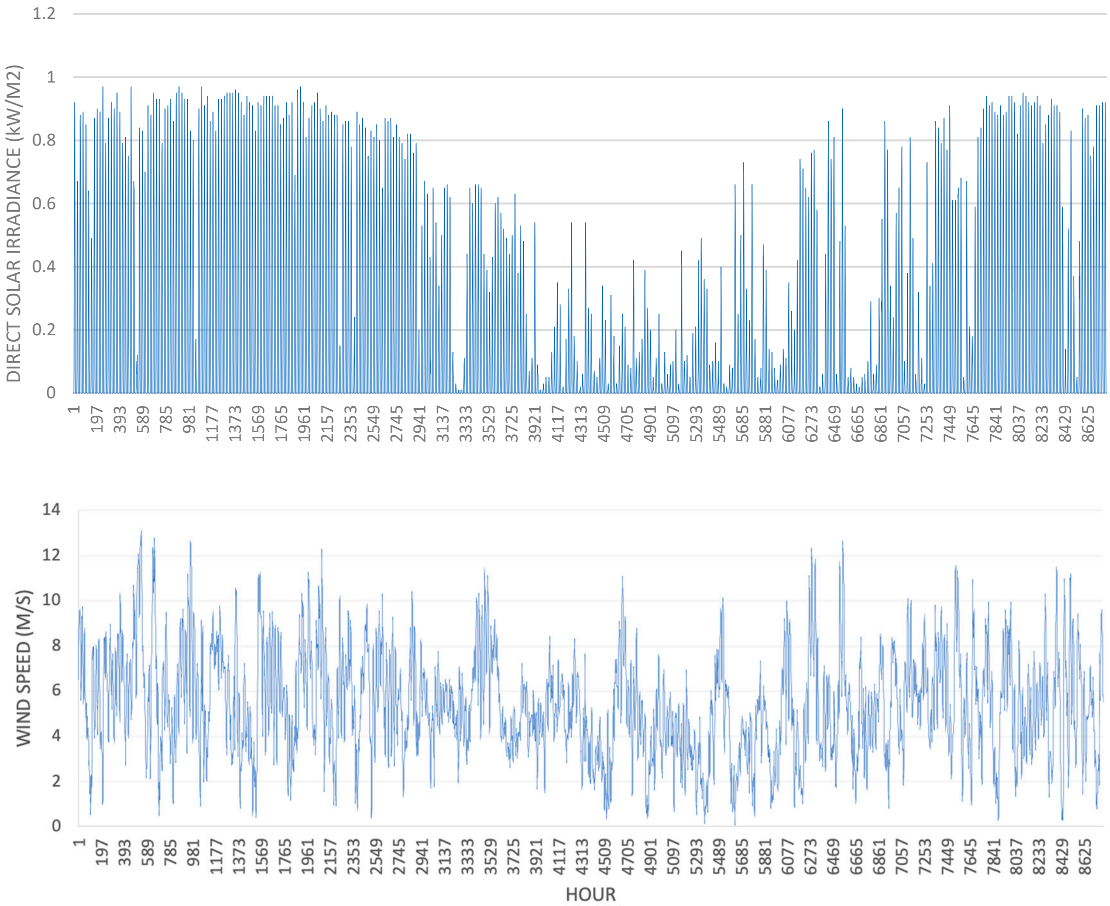

Figure 4. Hourly direct solar irradiance (kW/m²) and wind speed measurement (m/s) in 50 m hub height for 2019 in Isla de la Juventud. Source: [44,45].

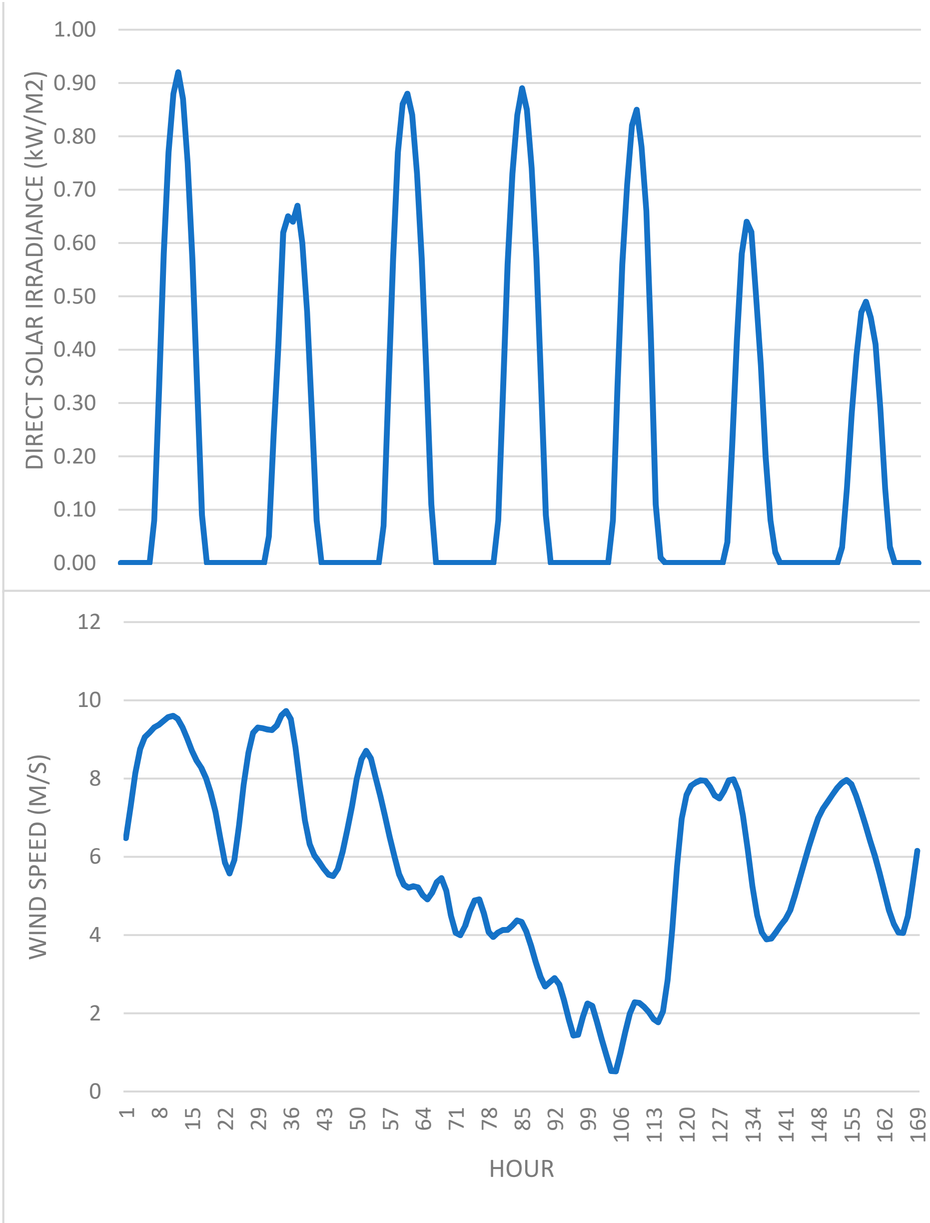

Figure 5. Example of hourly direct solar irradiance (kW/m²) and wind speed measurement (m/s) in 50 m hub height for 1–7 January 2019 in Isla de la Juventud. Data: [44,45].

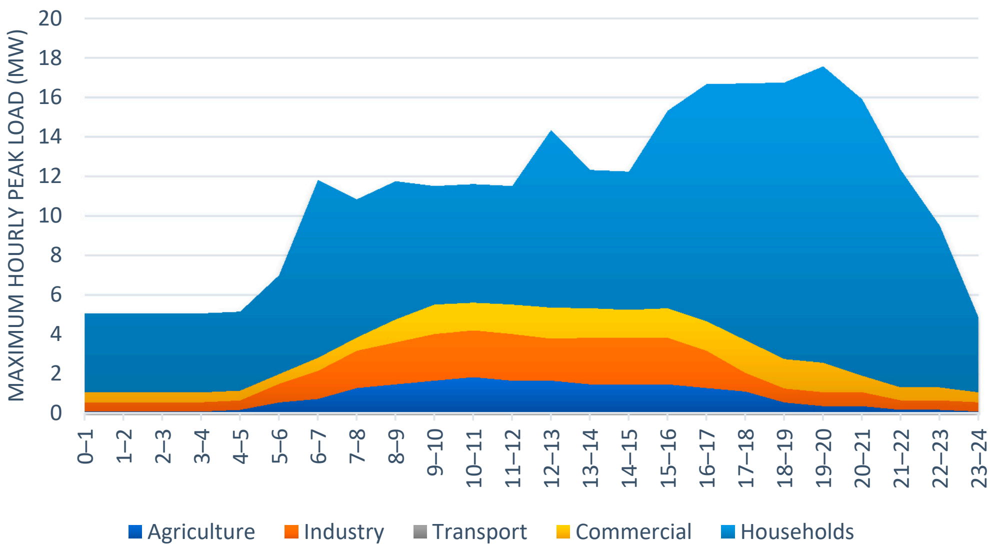

Figure 6. Hourly electricity consumption by sector in Isla de Juventud in January 2019. Data: [42].

Figure 5 shows the hourly direct solar irradiance and wind speeds for the first week of January. It can be seen that the highest solar irradiance takes place during noon time and naturally decreases towards the night until gradually increasing from morning hours. The wind fluctuation does not follow any specific trends but varies from day to day regardless of the time of the day.

The data on current electric power system represents the actual current set-up at Isla de la Juventud with a total installed capacity of 41.79 MW, [29] with:

- Eleven diesel and heavy fuel oil generators with an installed capacity of 35.44 MW, of which: four units of MAN diesel generators with a capacity of 3.85 MW (each); four units of BAZAN diesel generators with a capacity of 3.6 MW (each); three units of MTU fuel oil generators with a capacity of 1.88 MW (each). The generation system is mainly operated by the MAN generators with BAZAN providing the needed reserves and MTU generators generating for the maximum peaks;
- Three solar photovoltaic (PV) parks with a total installed capacity of 4.2 MW;
- Two biomass gasification plants with a total installed capacity of 0.5 MW;
- One wind park with a total installed capacity of 1.65 MW;
- The current share RES in the total installed capacity of the electric system at Isla de la Juventud is around 15% [34,42,43];

For the analysis with EnergyPLAN the following data were used:

- The distributional data with an increase of electricity demand by 40% up to year 2030 totaling 170 GWh with a similar load profile as illustrated in Figure 3 and solar irradiance and wind speed data (50 m hub height) from MERRA-2 satellite data [44,45];
- The expert estimated efficiencies of the electric generation plants are: diesel and fuel oil plants: 0.45; solar PV: 0.22 (capacity factor); wind: 0.30 (capacity factor); biomass: 0.30;
- IRENA cost database [6] is used for the investment, operational and maintenance costs, and interest rates and CO_2 emission costs are set to 0.

  i. Operational costs in fuels utilize global market prices excluding the costs of transportation (import and local transport). Diesel and fuel oil are set to 12 USD/GJ and biofuels at 20USD/GJ.
  ii. Investment costs of wind and solar (1473 USD/kW and 995 USD/kW), diesel and fuel oil powerplants (1000 USD/kW) with an investment period of 25 years and operation and maintenance costs of (2%, 0.1% and 2%, respectively) follow the current market prices and expert evaluations in Cuba.

Based on the distributional data, EnergyPLAN calculates the hourly demand and supply of the electric system for a year. The base year, 2019, provides the starting point for the user to construct future scenarios based on the projected growth in demand and allows analysis of different electric power system set-ups. The user inputs on the costs of fuels and technologies (investment, maintenance and operation and variable costs) allow different future narratives on how the development may go in the future. For data reasons the article only looks at the electricity part of the smart energy systems, although there are various possibilities to include, e.g., transport and heating/cooling in the subsequent analysis. The grid stability, residual load (hourly demand minus the hourly production by the intermittent renewable energy sources, in this case, wind and solar), and electricity excess are important factors to consider in the analysis and, therefore, the results have assumed: (1) grid stability share of 30%; ensuring 30% of the demand is generated with fast and easily controllable diesel generators to ensure inertia and frequency control of the electric system. (2) In the simulation excess production is controlled with curtailment rather than battery storage due to cost reasons; battery storage costs (with the current market prices) inflate heavily the total annual costs of the system and is, therefore, not part of the scenarios.

3. Results

The results are organized first to introduce the current situation followed by joint analysis of the five scenarios based on electricity demand growth by 40% by 2030.

- BAU 2030 scenario assumes the electricity demand growth, but does not change the energy mix or the composition of the total installed capacities in conventional or the Renewable Energy Technologies (RETs);
- VISION 2030 is based on the Cuban government vision of reaching up to 24% share of RES in the electricity production [28,30,46];
- ARES achieves a 50% share of the electricity production by RES by 2030;
- HiRES reaches up to 70% of the electricity production from RES;
- FullRES is a 100% RES based system achieving the 100% share of electricity production.

3.1. Current Situation (2019)

The analysis is based on the information provided by the national statistics office (ONEI) in its annual summary 2019 [42] and national electric utility UNE [43].

Isla de la Juventud is an isolated island system with a total installed capacity of 41.79 MW with a share of 15% from RES (6.35 MW). The total electricity consumption was approximately 119,500 GWh in 2019, with the residential sector dominating with more than two thirds of the total consumption, as can be seen in Figures 6 and 7 [42]. This is due to the low activity in other sectors (the service, industry, and agriculture sectors) similar to the structural behavior of also the main island of Cuba. Figure 6 shows the highest peak taking place in the evening (around 19:00–20:00 and Figure 7 illustrates, the highest consumption takes place during the summer months July–August while the winter months January–February experience the lowest annual demand. The expected increase in demand in high growth scenario by 2030 is set to 40%, resulting in around 170 GWh in 2030. In 2019, the share of RES in primary energy supply (PES) was under 5% (4.6) and the share in electricity production from renewables around 12% (11.6) with a total of just under 14 GWh per year (13.82) [42]. The EnergyPLAN analysis of the CO_2 emissions in 2019 results in around 95 Mton with the current electricity system, mainly due to diesel and fuel oil dominating the electricity production and transportation sector.

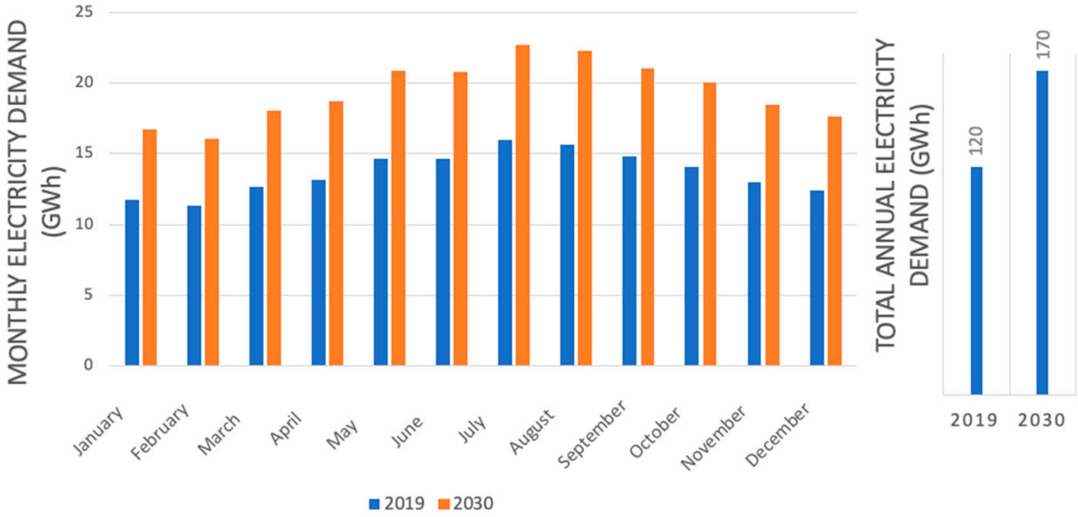

Figure 7. Total monthly and annual electricity demand in Isla de la Juventud in 2019 and 2030. Source: ONEI [42] and author defined.

3.2. Scenarios

The results are presented in five scenarios based on the user optimisation: BAU, VISION 2030, ARES, HiRES, and FullRES. All scenarios assume a 40% electricity demand growth up to 170 GWh annually and ARES, HiRES, and FullRES include a fuel switch from diesel and fuel oil to biodiesel. Below scenario parameters are discussed in detail and illustrated in Figure 8:

- BAU 2030 scenario is based on the current installed capacity, with no additional installed capacity. The installed capacities are: 35.44 MW of diesel and fuel oil generators, 4.2 MW of solar PV, 1.65 MW of wind, and 0.5 MW of biomass gasification.
- VISION 2030 scenario (RES 30%) is based on the Cuban government vision of reaching 24% share of RES in total annual electricity production and 30% share of RES in total installed capacity. In this scenario, both wind and solar PV generation capacities are increased up to 9 MW. The installed capacities for the simulation are: 35.44 MW of diesel and fuel oil generators, 9 MW of solar PV, 9 MW of wind, and 0.5 MW of biomass gasification.
- ARES scenario (RES 50%) is based on advanced introduction of RES to the current electricity mix with a target of 50% share of RES in the total annual electricity production. In this scenario, the solar PV and wind generation capacities are increased up to 23 MW and 24 M, respectively. In addition, a fuel switch from diesel and fuel oil to biodiesel increases the capacity for biodiesel generation up to 3.5W. The installed capacities for the simulation are: 31.9 MW of diesel and fuel oil generators, 23 MW of solar PV, 24 MW of wind and 0.5 MW of biomass gasification and 3.5 MW of biodiesel generators.
- HiRES scenario (RES 70%) is based on high penetration of RES to the current electricity mix with a target of 70% share of RES in the total annual electricity production. In this scenario, the solar PV and wind generation capacities are increased up to 22 MW and 28 MW, respectively. In addition, a fuel switch from diesel and fuel oil to biodiesel increase the capacity biodiesel generation up to 15.2 MW. The installed capacities for the simulation are: 20.24 MW of diesel and fuel oil generators, 22 MW of solar PV, 28 MW of wind and 0.5 MW of biomass gasification and 15.2 MW of biodiesel generators.
- FullRES scenario (RES 100%) is based on complete transition towards RES in the current electricity mix with a target of 100% share of RES in the total annual electricity

production. In this scenario, the solar PV and wind generation capacities are increased up to 20 MW and 24 MW, respectively. In addition, a fuel switch from diesel and fuel oil to biodiesel increases the capacity of biodiesel generation up to 35.44 MW. The installed capacities for the simulation are: 20 MW of solar PV, 24 MW of wind, and 0.5 MW of biomass gasification and 35.44 MW of biodiesel generators.

The total installed capacities for base year and five different future scenarios are shown in Figure 8. Only the BAU scenario does not include new installed capacity but can function with the 2019 set-up. The increase in total installed capacity in Vision 2030 is 12.15 MW, i.e., 29% increase, in ARES 41.1 MW, i.e., 98% increase, in HiRES 44.15 MW, i.e., 106% increase, and in FullRES 38.15 MW, i.e., 91% increase due to the increased RES based total installed capacity compared to the base year of 2019.

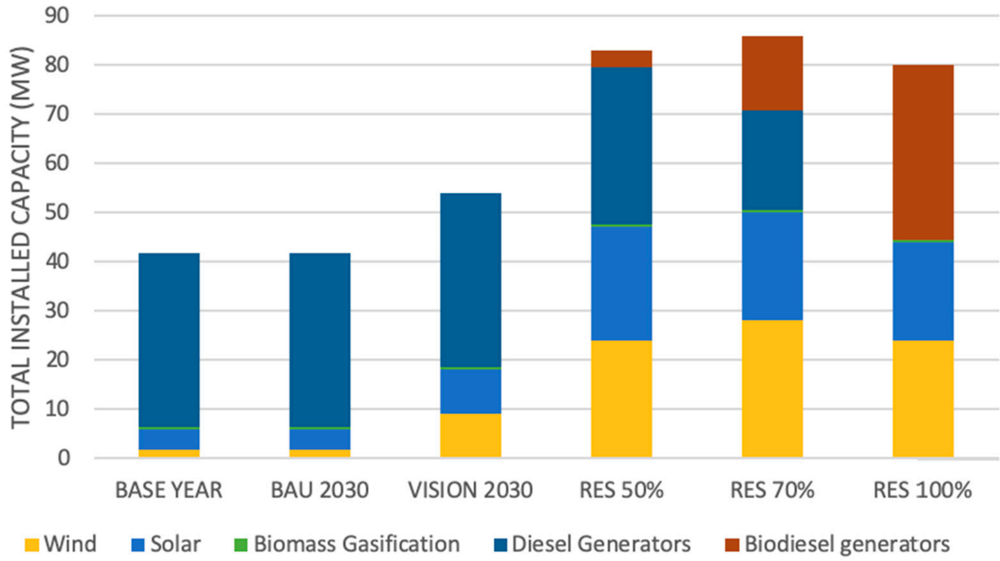

Figure 8. Total installed capacity (MW) in 2019 and in the future scenarios by 2030.

RES penetration shares as percentages of primary energy supply and electricity production are shown in Figure 9. In BAU 2030, RES account for 15% of the total installed capacity and 8% of the total annual electricity production, in VISION 2030 34% and 25%, in ARES 62% and 50%, in HiRES 76% and 70%, and in FullRES 100% and 100%, respectively. It has to be noted, however, that FullRES is producing more than 100% of the share in the electricity production due to excess generation that can be seen also in Figure 10.

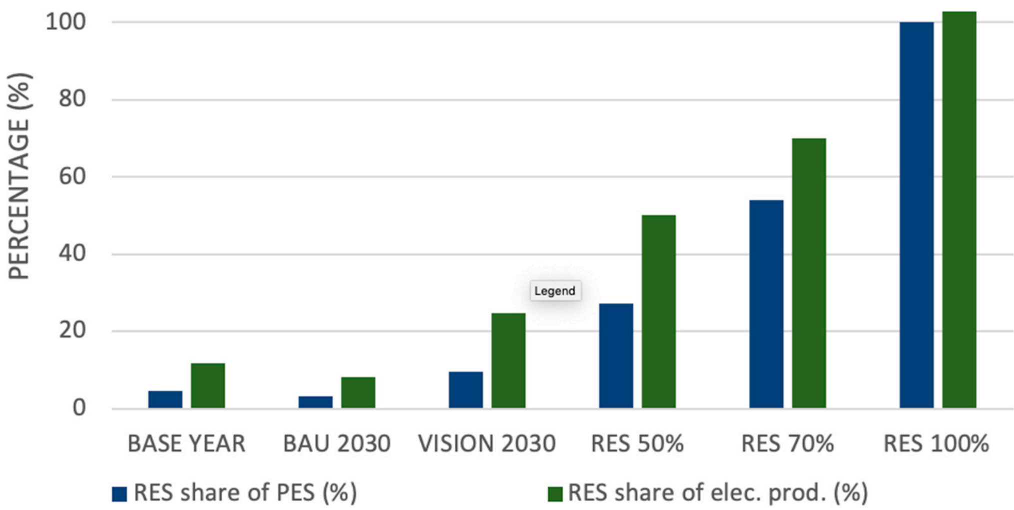

Figure 9. Renewable energy penetration rate (%) of primary energy supply in electricity production (PES) and share of electricity production 2019 and for the five scenarios by 2030.

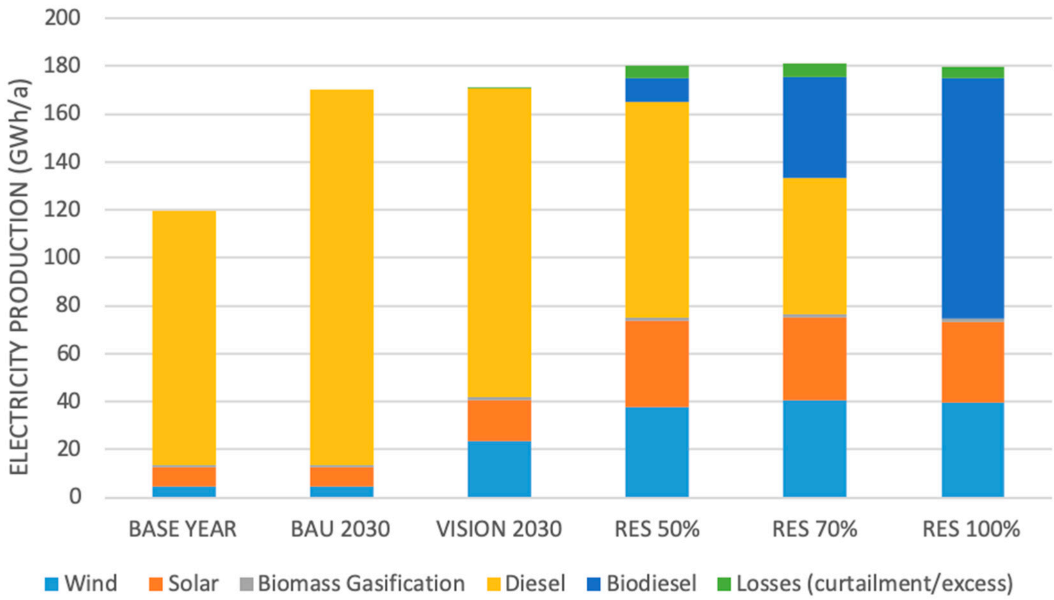

Figure 10. Annual electricity production (GWh) for base year and future scenarios.

Figure 10 shows the annual electricity production for 2019 and the five future scenarios. In BAU 2030, we see the increased utilisation of diesel generators (existing capacity) to match the increasing demand whereas VISION 2030, ARES, HiRES, and FullRES show increased electricity production from renewables and share of excess production that equals the amount of losses regulated by curtailment. The excess production has been minimised to decrease the total annual costs of the system. Battery storage or pumped hydro storage are not economically viable with the current costs, however, the excess production could be stored and harnessed in the future not only for consumption but also for the grid stability, should the global costs come down.

Figure 11 illustrates the electricity production by the share of both RES (in gray) and diesel and fuel oil Power Plants, PP+ (in black) in BAU 2030, VISION 2030 whereas Power Plants, PP+ (with black) with biofuel are employed in ARES, HiRES, and FullRES scenarios with a 10%, 43%, and 100% of biofuel share, respectively. Figure 11 shows the increase of RES based production and decrease of the conventional fossil fuel based generation.

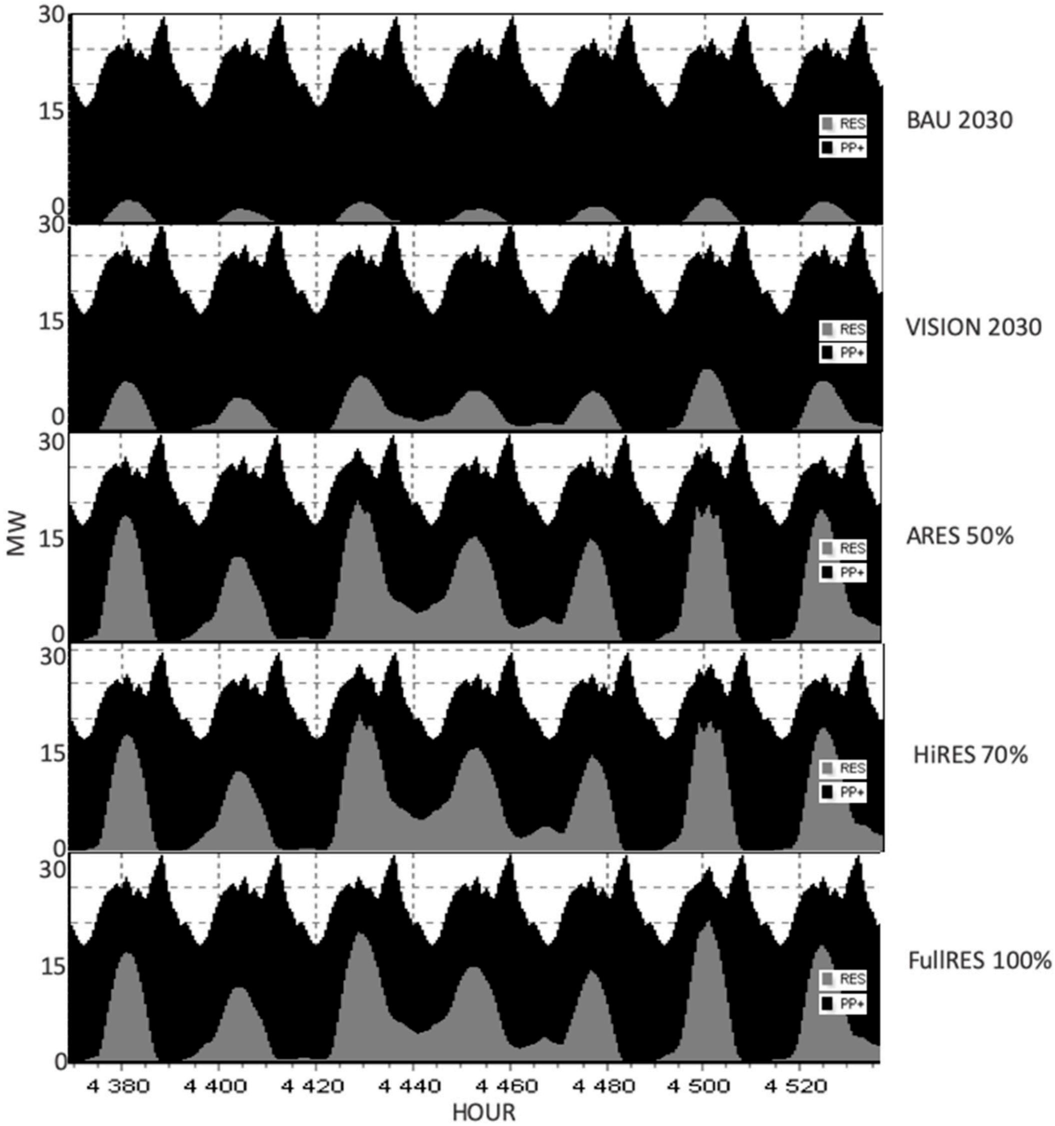

Figure 11. Electricity production capacity with different sources in July 1–7 2019 in Isla de la Juventud. (RES (in gray) and Power Plants, PP+ (in black) with 100% diesel and fuel oil in BAU 2030 and Vision 2030 and 10%, 43%, and 100% of biofuel share in ARES, HiRES, and FullRES, respectively).

Figure 12 shows the annual fuel consumption in 2019 and for the five scenarios modeled by 2030. In 2019, BAU 2030 and VISION 2030 scenarios biofuels were not considered besides small amount from biomass gasification due to accessibility and availability of biodiesel. In the ARES, HiRES, and FullRES biofuels were included (based on the plans of the Cuban government in national biofuel production in the near future) gradually to displace fossil fuels and to assure grid stability. The results show the decrease of oil consumption as the shares of RES increase gradually. It should be noted that the biofuel share is growing to partially replace oil consumption.

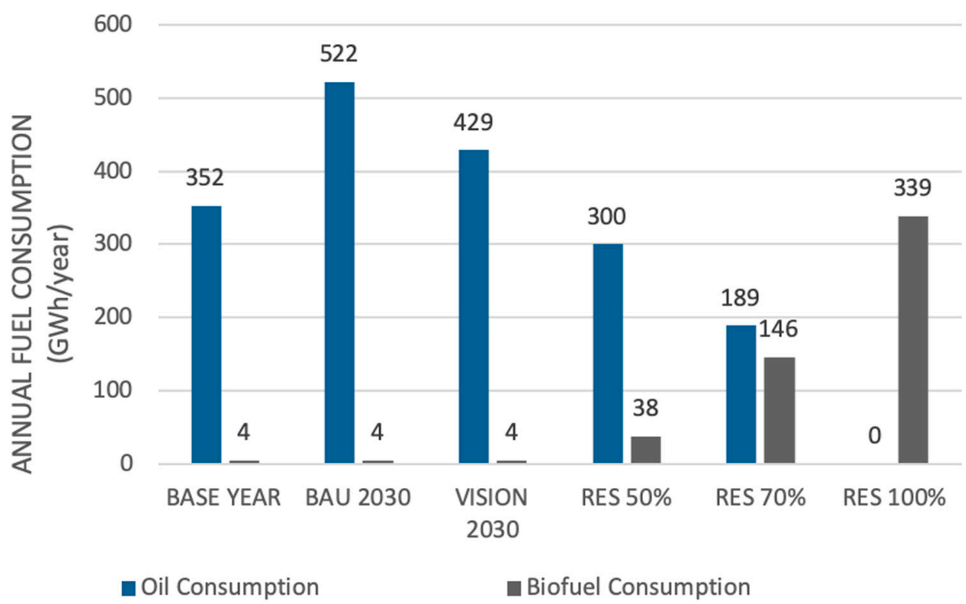

Figure 12. Annual fuel consumption (GWh/year) for base year 2019 and five scenarios by 2030 in Isla de la Juventud.

Figure 13 illustrates the CO_2 emissions in 2019 and for the five scenarios modeled by 2030. It can be seen that CO_2 emissions naturally decrease as the system transitions towards RES with the replacement of fossil fuels. The life cycle emissions (e.g., transportation) of the fuels have not been estimated and, therefore, may not represent the real situation especially in cases of imported fossil and biofuels. Use of biofuels also assumes the resources are renewed at a sustainable pace and, thus, are zero net emissions alternatives.

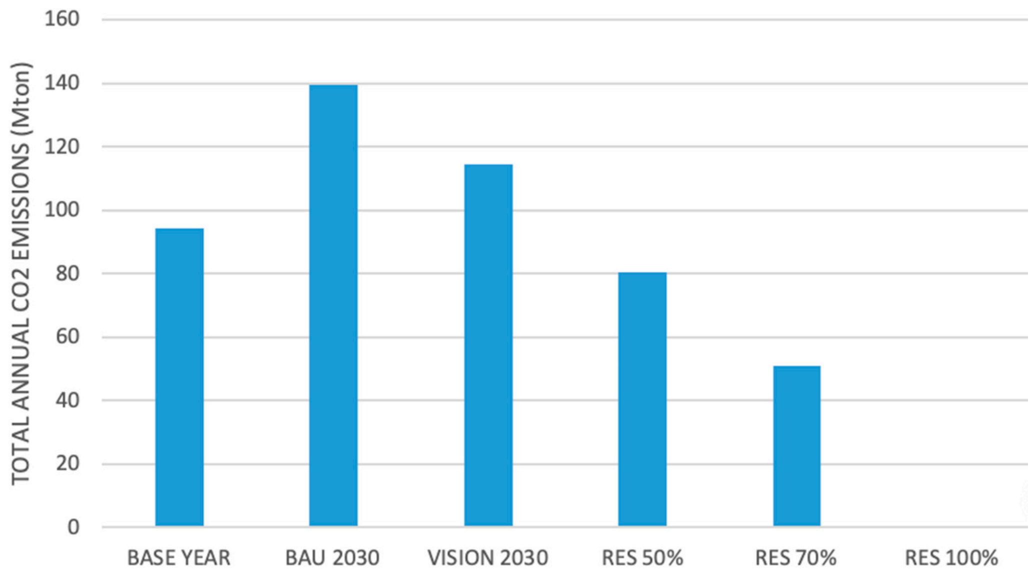

Figure 13. Total annual CO_2 emissions in 2019 and in 2030.

The total annual costs (MUSD) are shown in Figure 14. The highest total annual costs can be observed in the FullRES scenario, followed by the BAU 2030 scenario. The highest annual investment costs are found in HiRES and ARES whereas the highest variable costs take place in BAU 2030 and FullRES scenarios due to high shares of oil and biofuel consumption, respectively. The analysis indicates that even up to 70% RES based systems are still more cost-efficient than relying on the current generation practices. However, the analysis assumes biofuels can be interchangeably used in the current diesel and fuel oil units and, thus, includes no new investments taking place to retrofit the current set-up for the use of biofuels.

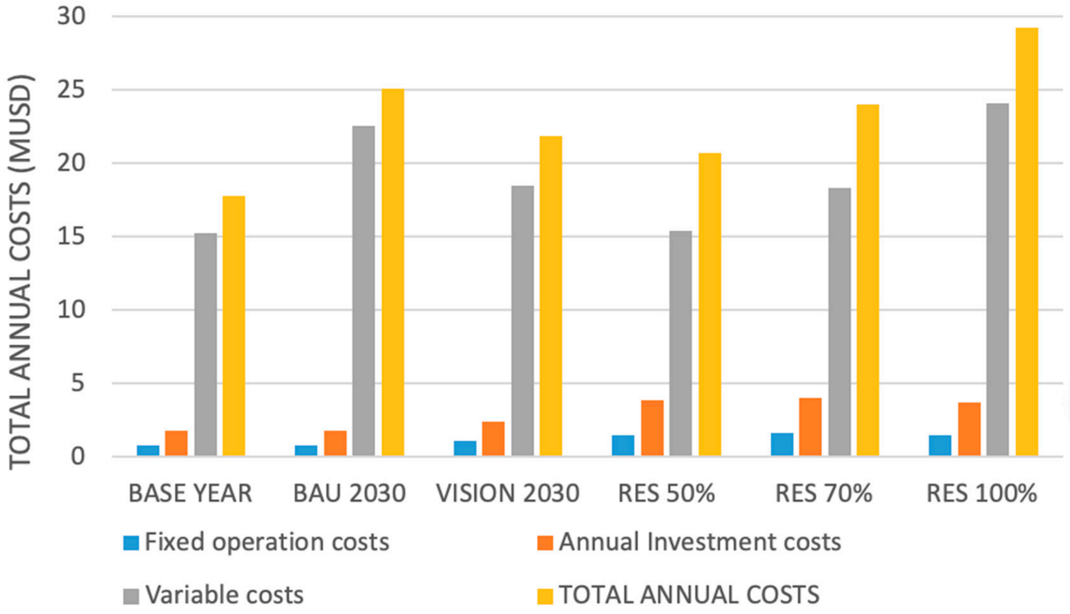

Figure 14. Total annual costs (MUSD) in 2019 and in 2030.

3.3. Summary of the Scenario Results

The results are summarized in Table 1. All the scenarios are technically possible and can support the Cuban government's 2030 goals. The high shares of RES are also economically and technically viable solutions and can provide the electricity demand in a reliable way with the current electricity infrastructure as a back-up. This would also enable energy independence and security of Isla de la Juventud to rely on their local resources, conditional on the availability of local biofuels. The CO_2 emissions also naturally decrease as the share of RES increases. Excess production that in some scenarios take place can be regulated with curtailment, however, should storage options be available and affordable, it could contribute to grid stability and support in meeting the peak demands.

Table 1. Scenario inputs and summary of results.

Scenarios		BAU 2030	VISION 2030	ARES	HiRES	FullRES
RES share (%) of Electricity Production		8%	25%	50%	70%	100%
Installed capacity (RES)	Solar	4.2 MW	9 MW	23 MW	22 MW	20 MW
	Wind	1.65 MW	9 MW	24 MW	28 MW	24 MW
	Biomass	0.5 MW	0.5 MW	0.5 MW	0.5 MW	0.5 MW
	Biofuel	-	-	3.5 MW	152 MW	35.44 MW
Installed capacity (conventional)	Diesel/ Fuel Oil	35.44MW	35.44 MW	31.9 MW	20.24 MW	-
Additional installed capacity		-	12.15 MW	41.1 MW	44.15 MW	38.15 MW
Share of increase in installed capacity		-	29%	98%	106%	91%
% RES of installed capacity		15%	34%	62%	76%	100%
Total Annual Costs (MUSD)		25.1	21.9	20.7	24	29.3
Total investment Costs (MUSD)		43.2	58.7	98.2	99.7	91.8
CO_2 emissions		139 Mton	115 Mton	81 Mton	51 Mton	0 Mton
Electricity production		170 GWh	171 GWh	175 GWh	176 GWh	175 GWh
Electricity consumption		170 GWh	170 GWh	170 GWh	170 GWh	170 GWh

4. Discussion

This section evaluates the results of the analysis against recent studies in other island systems and discusses some of the most important challenges in achieving the RES based electric power system. At the end, limitations and further studies are discussed based on the experiences of this article.

The goal of the article was to identify the best fit and least cost options in transitioning towards 100% electric power system in Isla de la Juventud, Cuba. The article analyses future alternatives to fossil fuel based electricity generation in Isla de la Juventud as a proxy to the main island of Cuba. Isla de la Juventud was selected as a case example as it (1) shares similar characteristics of the electric power system in the main island of Cuba and (2) is an island system with smaller but similar electricity consumption patterns as in the main island of Cuba.

The results show high shares of RES are possible both technically and economically in Isla de la Juventud; up to 100% share of RES in the electricity production. This should, however, be coupled with the local economic, political, and legal conditions enabling opportunities to actualize this transition through significant involvement of national and foreign capital investments. The abundance of renewable energy sources coupled with decreasing costs of especially wind and solar power can provide energy independence and security while also being cost-efficient in Isla de la Juventud. With the current market prices provided by IRENA, it can be seen that electricity systems with even up to 70% of RES (e.g., HiRES scenario) can be more feasible in financial terms (total annual costs) when compared to the current fossil fuel based systems (approx. 5–17% less). There are various studies on island energy systems transitioning towards 100% RES (e.g., [9–18]). In many of the studies in the Caribbean region, e.g., Barbados [15,47], Jamaica [13,14], and Cuba, [5,15,17] it has been found that the transition towards RES is not only possible but economically attractive due costs related to fossil fuel imports. Although the pricing system of petroleum products and imports in Cuba cannot be fully comprehended due to cumbersome trade agreements such as "oil for doctors" [48–50] and highly subsidized fuel prices and electricity tariffs [27], it can be shown that with a market priced fossil fuel imports Cuba's electricity generation costs exceed ARES and HiRES scenarios in this study. Although this finding echoes the regional research findings in the Caribbean with high RES systems becoming more economically viable, the distortion in the pricing circumstances mentioned above have to be taken in to consideration when calculating the real costs of the systems and scenarios.

The inclusion of biofuels in the mix can both offset the fossil fuel based emissions but provide enhanced system stability as the intermittent sources such as wind and solar are integrated into the grid. The use of biofuels is supported by the Cuban government plan to increase the use of biomass for electricity production nationally [51]. However, the use of biomass is somewhat contested in the literature due to its real GHG reduction potential. Jacobson (2014) and Giuntoli et al. (2016) question the real greenhouse gas mitigation potential of biofuels in their studies and argue that carbon neutrality largely depends on the type of bioenergy and scale of deployment and the effects of burning of biomass through aerosols and clouds on the climate [52,53]. The IEA Bioenergy task force (2020) discusses the use of biomass especially in relation to forests stating that the increased use of forests could lead to lower carbon stock and carbon sequestration. Regeneration and ensuring carbon uptake capacity in the forest is, therefore, crucial although biomass utilization for energy could also incentivize the better management of the forests [54]. Sterman et al. (2018) also comment on the regeneration aspect stating that in the short term, immediate impact of substituting wood for coal is an increase in atmospheric CO_2 and the payback times for carbon debt could go beyond 100 years and "assuming biofuels are carbon neutral may worsen irreversible impacts of climate change before benefits accrue" [55]. Similarly, Searchinger et al. (2018) state treating wood for bioenergy as a carbon-free fuel would greatly increase the atmospheric carbon for decades [56]. Field et al. (2020) argue that net greenhouse gas mitigation benefit of biofuel pathways is "controversial due to concerns around ecosystem carbon losses from land use change and foregone sequestration benefits from alternative land uses" [57]. Evidently, the biomass use for energy needs to follow sustainable practices to be considered "net zero" or "carbon neutral", unfortunately the literature shows there are dangers of "jumping" into use of biomass with climate targets in mind [54–57].

In the Cuban context, and based on the evaluation above the justification for including biomass in the scenarios resulted from (1) increased energy security and independence: linking the strategy of promoting biomass by the Cuban government to decrease dependency on fossil imports and, thus, increasing energy security and independence with national sources from energy; (2) technical reasons: utilizing the existing infrastructure of fast responding diesel and fuel oil plants that could be substituted by biofuels and, thus, assuring grid stability with the high penetration of intermittent energy sources; (3) cost-efficiency: the energy storage options in the Isla de la Juventud are in practice only batteries (with the absence of hydropower or potential location to pumped hydro-storage). This option, however, is very expensive compared to substitution by biofuels (even when biofuel prices are valued in the upper range of the market prices) and, thus, not considered in this article. However, the use should focus on sustainable practices and utilizing the wastes or residues instead of cultivation merely for bioenergy. In Cuba, there are various possibilities to utilize the wastes and residues, e.g., from the sugar industry, forest waste, cooking oils among others. Additionally, on degraded lands there could be options of utilizing, e.g., marabu (*Dichrostachys cinerea*) to replace fossil fuel based electricity. According to Sagastume Gutiérrez et al. (2018), biomass-based electricity could reduce up to 81% of the greenhouse gas emissions compared to those of 2012 and could reduce the costs of electricity generation up to 30% [58].

The growing concern about climate change drives the global transition towards non-fossil based energy systems. Cuba is no exception in this regard and the government vision is aiming at 24% share of RES in the electricity production by 2030. With the current share of only 4% renewables and the decades long dependence on the imports of oil and petroleum products from Russia and Venezuela after the collapse of Soviet Union in the 1990s, this is an ambitious task.

The results also show clear benefits in reducing CO_2 emissions, even to zero net emissions with the change of the electricity generation towards renewables, which is one of the Cuban climate change mitigation priorities. In the country's Nationally Determined Contributions to UNFCCC, Cuba is committed to avoid the emission of an estimated 30.6 million kilotons of carbon dioxide equivalent (ktCO2eq) through its energy system transformation [59]. Although the total greenhouse gas emissions are equal to roughly 0.1% of the total global emissions and 3.7 tons of CO_2 equivalent per capita, which is well below the average global, the move towards more renewables can show especially to the largest emitters an example of decreasing the climate impact through energy sector transformation [60]. The advantages of biomass utilization in the energy sector also support Cuba's climate mitigation and sustainable development goals as stated by, e.g., Bravo Hidalgo [51].

As discussed in the introduction, the impact of the U.S. embargo cannot be ignored in the case of Cuba. The previous U.S administration imposed even stricter sanctions to trade with Cuba, thus, adversely affecting the foreign banks' and investors' willingness to engage with Cuba. This has put a halt on gradual opening of trade partners such as the European Union and China that have in the recent years been especially promising for the energy sector [61,62]. This is very much needed as the Cuban government foresees 3.5–4 billion USD investments needed for the transition towards sustainable electric power systems [27]. To exceed the 24% share of RES, the investment requirements grow inevitably. Furthermore, these sanctions have had a direct effect due to restrictions on manufacturers of equipment and availability to spare parts for the production process in the energy sector [21,22].

Analyzing sustainable electricity on technological and economic attributes provides only a starting point towards sustainable and smart energy systems. Many scholars have proposed in their previous research to examine holistically the whole energy system instead of focusing on a single sector (e.g., electricity) (e.g. [2]). By integrating transport, heating and cooling with the electricity sector, energy storage and conversion through batteries or heat storages can increase the efficiency of the system [38,39]. This article, however, focused only on an economic analysis of the technological alternatives to showcase that transitioning to RES in electricity generation not only makes sense but also is economically feasible.

The main challenges in the energy and electricity sector transformation are financial, with the expectation of large private foreign investments fueling the transition. Legal framework and legislation in Cuba were implemented to allow foreign investments since 2014 onwards. However, with the existing challenges of cumbersome and slow project approval processes, limited access to financing and credit quality of UNE (national electricity utility) there have been only partial success in implementing the Vision 2030 plan. This coupled with an outdated grid, lack of motivation and qualified staff, lack of available data, the government's limited access to foreign currency, and limited ability to access international banks etc., have further put-off the interested investors [27].

5. Conclusions

The article shows a sustainable energy and electric power systems transition is possible in Isla de la Juventud. The scenarios developed with EnergyPLAN software show high penetration of RES is possible and even more economically viable than a reliance on the current fossil fuel based electricity generation. Cuba is at the crossroads between sustainable and unsustainable energy choices, and while the government has taken an encouraging leap towards RES, the implementation of the vision is yet to be seen. Here future oriented multicriteria decision making with an abundance of alternative paths will highly benefit when selecting the right energy mix to cater for local, national, and international requirements. The modelling and simulation exercises here have a strong role to play and EnergyPLAN can definitely provide decision makers with evidence on the least-cost options. It is equally important to make sure an enabling environment is in place for both the local and international investors to support Cuba in reaching sustainable energy futures. A sustainable energy road map, with a clear implementation plan coupled with adequate resources is critical in this quest.

The article focuses on the electricity sector and does not provide economic implications/analysis of the whole system. Rather, the focus is put on the financial feasibility of high RES introduction compared to the conventional electricity system. Recommendations for future work include a thorough SWOT analysis (strengths, weaknesses, opportunities, and threats) to identify the bottle necks and advantages in various areas covering political, economic, social, technological, environmental, and cultural (PESTEC) aspects of the energy transformation. The cost-benefit analysis of the whole energy system of Cuba would be a crucial step in identifying the balance of benefits from the emergence of the renewable sources and costs related to adapting to it. Only then the real value of renewable energy transition could be evaluated. In detail, focus should be put upon the investment frameworks, risk guarantees, subsidies and tariff and agreement processes, project approval, implementation and support mechanisms, legal and regulatory environments, policy and plan formulation processes, social and cultural motivation and incentives and entrepreneurship in energy, and environmental and climate benefits of the renewables, etc. [27].

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