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PV, Wind and Storage Integration on Small Islands for the Fulfilment of the 50-50 Renewable Electricity Generation Target

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Abstract: Decarbonisation in the generation of electricity is necessary to reduce fossil fuel consumption, the pollution emitted and to meet the Energy Technology Perspectives 2 °C Scenario (2DS) targets. Small islands are not exempt from this target, so this study's emphasis is placed on a 50-50 target: to reduce the fossil fuel consumption through electricity generation from Renewable Energy Sources (RES) to cover 50% of all electric demand by 2050 on small islands. Using Cozumel Island, Mexico, as a case study, this analysis will be based on three factors: economical, technical, and land-use possibilities of integrating Renewable Energy Technologies (RETs) into the existing electrical grid. This analysis is made through long-term statistical models. A deterministic methodology is used to perform time-series simulations. The selection of the best system was made on the basis of a Dimensional Statistical Variable (DSV) through primary and secondary category rankings. The presented methodology determines the best systems for capturing the initial capital cost and competitiveness of this new proposal compared with the current system of electricity generation on the Island, and can be applied to small islands as well. According to the results, all systems proposed are able to completely satisfy the renewable electricity needed by 2050 in all scenarios. From the 12 system proposals that were compared, two systems, System 2 and System 7, were chosen as eligible systems to be installed. The Levelized Cost of Energy (LCOE) result for System 2 was 0.2518 US$/kWh and for System 7 was 0.2265 US$/kWh by 2018 in the Base Scenario. Meanwhile, the Internal Rate of Return (IRR) value fluctuated from 17.2% for System 2 to 31% for System 7.

Keywords: greenhouse gas reduction; hybrid system; island electricity supply; renewable energy; renewable energy target; renewable energy technology

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1. Introduction

Renewable Energy (RE) plays an important role in the goal of reducing emissions in electricity generation. In the Small Island Developing States (SIDS), most power grids must rely on diesel generators. Even if small islands are not part of the SIDS, those that are not interconnected to large electrical systems have high operating costs, due to the dependence on expensive fuel imports [1]. Studies on the integration of Renewable Energy Technologies (RETs) into electric grids have been developed. For instance, the contribution made by Bertin and Frangi [2] that shows the potential of RETs integration into the electrical system on Guadeloupe Island. The methodology and the results shown in this document help to determine the viable potential combinations of RETs to achieve it, based on Photovoltaic (PV), Wind and flow battery technologies. Also, the data and results obtained by Meschede et al. [3] can be used as a baseline to implement the methodology shown and integrate the RETs on the islands with higher Gross Domestic Product (GDP) located in the Caribbean and South Japan, as well as in the Mariana Archipelago and Polynesia.

A similar analysis on small islands was developed, including the existing diesel generation. Some studies included the natural resource potential analysis through Geographic Information System (GIS) [4,5]. The size of a small island was determined by Blechinger et al. [4], where the GIS analysis identified approximately 1800 small islands below 100,000 inhabitants with significant renewable energy potential. Meanwhile, other studies included the analysis of the electricity excess generated after covering the electric demand [6] as a flexible load that produces desalinized water as well as drinking water. There are also studies that include an analysis of the use of pumping water—used for energy storage—as a stability solution in a hybrid renewable system for islands [7–10]. Other cases use batteries for energy storage on islands [11]. Others do not use energy storage [12] at all.

Decarbonisation in the generation of electricity is imperative in order to meet the Energy Technology Perspectives 2 °C Scenario (2DS) targets [13]. Among energy end uses, heating and cooling systems offer substantial potential for decarbonisation that so far has been largely untapped. Broad application of energy efficiency and switching to low-carbon final energy carriers (including decarbonised electricity) can push the fossil share to below 50% by 2050 with renewable energy (including renewable electricity) covering more than 40% of heating and cooling needs [14]. Every country is required to cover its electricity generation with a higher share of clean and renewable energy [15]. Table 1 shows a summary of the Paris Agreement 2015 for the emissions reductions. The first 17 countries combined emitted 77% of Greenhouse Gases (GHG) emissions in 2012, and more than 1% of the GHG emissions individually. In the table, Niue Island (country No. 141) and those listed below it contributed 0.00% of the GHG emissions individually in 2012; even so, they are committed to reducing their nearly inexistent GHG emissions and taking a path toward a net zero GHG emissions. Also, Table 1 shows the Paris Agreement signature, acceptance and ratification dates of those commitments [15,16].

For instance, one of the main objectives in the electricity system in Mexico, as well as in other countries, such as Kazakhstan [17], United Arab Emirates [18], and in Equatorial Guinea [19], is to reduce fossil fuel consumption in its electricity production and to achieve a 50% target in the generation of renewable electricity by 2050. Mexican Islands are not exempt from this target, so this study's emphasis is placed on a 50-50 target: to reduce the fossil fuel consumption through electricity production from Renewable Energy Sources (RES) to cover 50% of all electricity consumption by 2050 on small islands based on PV, Wind and flow battery technologies. According to the tropical small islands characteristics and using Cozumel Island, Mexico, localized on the Occidental Caribbean Sea, as a case study, this work will analyze the RETs integration into the existing electrical grid. Results will determine the best system for capturing the initial capital cost and competitiveness of this new proposal compared with the current system of electrical production on the Island. Remote or small island communities are particularly vulnerable to climate change impacts, and such regions are often highly dependent on imported fossil fuels to meet their electricity needs [20], so it is necessary that the results obtained through this study help those islands to install the right equipment combination to achieve sustainable solutions.

In Section 3.1 of this study, Organization of Economic Co-operation and Development (OECD) and Mexico's energy supply situation will be analysed, including the Mexican energy and electricity sector and the Peninsular Area electricity sector, which is one of the seven electric control regions in the National Interconnected System (SIN is its Spanish acronym) in Mexico. In Section 2, the methodology used to integrate the RETs into the electric grid on an island is detailed. As Cozumel Island is used as the case study, the electrical system, the RE resources and sources and the proposed systems will be investigated in Section 3.4. Also, the scenarios showing the growth in electricity and/or energy demand and predictions will be determined taking into consideration the electrical system on the island according to the main objective pointed out at the beginning of this document. This analysis will be made through long-term statistical models.

Table 1. Intended Nationally Determined Contributions (INDCs) and the Paris Agreement signature dates [15,16].

Intended Nationally Determined Contributions (INDCs)					**Paris Agreement**		
Number of parties that have submitted an INDC:		**189**	**Summary of the INDCs**	**Share of 2012 Greenhouse Gases (GHG)**	**Signature**	**Ratification**	**Entry into Force**
Share of global emissions covered by INDCs:		**99.10%**				**Acceptance (A)**	
No.	**Country**	**Date**					
1	China	30 June 2015	A peak in carbon dioxide emissions by 2030, with best efforts to peak earlier. China has also pledged to source 20% of its energy from low-carbon sources by 2030 and to cut emissions per unit of GDP by 60–65% of 2005 levels by 2030, potentially putting it on course to peak by 2027.	23.75%	22 April 2016	03 September 2016	04 November 2016
2	USA	31 March 2015	26–28% domestic reduction in greenhouse gases by 2025 compared to 2005, making its best effort to reach the 28% target.	12.10%	22 April 2016	03 September 2016 (A)	04 November 2016
3	EU	06 March 2015	At least a 40% domestic reduction in greenhouse gases by 2030 compared to 1990 levels.	8.97%	22 April 2016	05 October 2016	04 November 2016
4	India	01 October 2015	A 33–35% reduction in emissions intensity by 2030, compared to 2005 levels. Also pledges to achieve 40% of cumulative electricity installed capacity from non-fossil fuel based resources by 2030. Will also increase tree cover, creating an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent by 2030.	5.73%	22 April 2016	02 October 2016	04 November 2016
5	Brazil	28 September 2015	A 37% reduction in emissions by 2025, compared to 2005 levels, with a further indicative target of a 43% reduction in emissions by 2030.	5.70%	22 April 2016	21 September 2016	04 November 2016
6	Russia	31 March 2015	25–30% domestic reduction in greenhouse gases by 2030 compared to 1990 levels.	5.35%	22 April 2016		
7	Japan	17 May 2015	A 26% reduction in emissions on 2013 levels by 2030.	2.82%	22 April 2016	08 November 2016 (A)	08 December 2016
8	Canada	15 May 2015	A 30% reduction on 2005 greenhouse gas emissions, by 2030.	1.96%	22 April 2016	05 October 2016	04 November 2016
9	Congo	18 August 2015	A 17% reduction compared to a business-as-usual scenario by 2030.	1.53%	22 April 2016		
10	Indonesia	23 September 2015	A 29% reduction in emissions by 2030, compared to business as usual.	1.49%	22 April 2016	31October 2016	30 November 2016
11	Australia	11 August 2015	A 26% to 28% reduction in emissions by 2030 on 2005 levels.	1.45%	22 April 2016	09 November 2016	09 December 2016
12	South Korea	30 June 2015	A 37% reduction on business-as-usual emissions by 2030.	1.28%	22 April 2016	03 November 2016	03 December 2016
13	Mexico	30 March 2015	Unconditional 25% reduction in greenhouse gases and short lived climate pollutants from a business-as-usual scenario by 2030, which would rise to 40% subject to the outcome of a global climate deal. For the unconditional pledge, this means peaking net emissions by 2026 and reducing emissions intensity per unit of GDP by around 40% from 2013 to 2030.	1.27%	22 April 2016	21 September 2016	04 November 2016
14	Bolivia	12 October 2015	Ending illegal deforestation by 2020, and increasing the share of renewable energy to 79% by 2030 from 39% in 2010.	1.19%	22 April 2016	05 October 2016	04 November 2016
15	Iran	21 November 2015	A 4% cut in emissions by 2030 relative to business as usual.	1.05%	22 April 2016		
16	Saudi Arabia	10 November 2015	Expects emissions savings of up to 130 million tonnes of CO_2 equivalent in 2030, relative to business as usual.	1.05%	03 November 2016	03 November 2016	03 December 2016
17	Myanmar	28 September 2015	Increase hydropower capacity to 9.4 gigawatts by 2030, to achieve rural electrification based on at least 30% renewable sources and to increase the forested area to 30% by 2030.	1.01%	22 April 2016		
27	Kazakhstan	28 September 2015	An unconditional 15% reduction in economy-wide emissions by 2030, compared to 1990 levels.	0.70%	02 August 2016	6 December 2016	05 January 2017

Table 1. *Cont.*

Intended Nationally Determined Contributions (INDCs)						Paris Agreement	
Number of parties that have submitted an INDC:		**189**	**Summary of the INDCs**	**Share of 2012 GHG**	**Signature**	**Ratification**	**Entry into Force**
Share of global emissions covered by INDCs:		**99.10%**				**Acceptance (A)**	
No.	**Country**	**Date**					
35	United Arab Emirates	22 October 2015	Increase the share of "clean energy" in the energy mix to 24% by 2021, up from 0.2% in 2014.	0.39%	22 April 2016	21 September 2016 (A)	04 November 2016
134	Equatorial Guinea	21 September 2015	A 20% reduction in greenhouse gas emissions by 2030, compared to 2010 levels, with a longer-term goal to cut emissions 50% by 2050.	0.01%	22 April 2016		
141	Niue	25 November 2015	Commits to increase the share of renewables in its electricity generation to 38% by 2020, up from 2% in 2014. This will partly be delivered through a 10% reduction in electricity demand.	0.00%	28 October 2016	28 August 2016	27 November 2016
142	Micronesia	24 November 2015	An unconditional reduction in greenhouse gases by 28% on 2000 levels by 2025	0.00%	22 April 2016	15 September 2016	04 November 2016
144	Cook Islands	20 November 2015	An 81% reduction in emissions by 2030 compared to 2006 levels.	0.00%	24 June 2016	01September 2016	04 November 2016
145	Saint Lucia	18 November 2015	Commits to a 23% reduction in emissions by 2030 compared to a business-as-usual scenario, equating to emissions reductions of 188GgCO$_2$e, with an intermediate target of a 16% reduction by 2023.	0.00%	22 April 2016	22 April 2016	04 November 2016
146	Saint Vincent and the Grenadines	18 November 2015	Unconditional 22% reduction in emissions by 2025, compared to a business-as-usual scenario.	0.00%	22 April 2016	29 June 2016	04 November 2016
148	Fiji	05 November 2015	An unconditional 10% emissions cut by 2030, compared to business-as-usual levels. Also targets 100% renewable electricity by 2030.	0.00%	22 April 2016	22 April 2016	04 November 2016
149	Antigua and Barbuda	19 October 2015	By 2030 reaching 50 megawatts of renewable power capacity.	0.00%	22 April 2016	21 September 2016	04 November 2016
151	Samoa	01 October 2015	Commits to generating 100% of its electricity from renewable energy by 2025.	0.00%	22 April 2016	22 April 2016	
154	Barbados	29 September 2015	A 44% economy-wide emissions cut in 2030, compared to business as usual. Its interim goal of 37% in 2025 is equivalent to a 21% cut relative to 2008 levels.	0.00%	22 April 2016	22 April 2016	04 November 2016
155	Cabo Verde	29 September 2015	Increasing renewable energy grid penetration, increasing energy efficiency and reforestation programmes.	0.00%	22 April 2016		
156	Dominica	29 September 2015	An 18% emissions cut by 2020, compared to 2014 levels, with cuts of 39% by 2025 and 45% by 2030 against the same baseline.	0.00%	22 April 2016	21 September 2016	04 November 2016
157	Vanuatu	29 September 2015	Moving to 65% renewable energy use by 2020 and nearly 100% renewable electricity by 2030, reducing energy emissions by 30% in 2030 compared to business as usual.	0.00%	22 April 2016	21 September 2016	04 November 2016
158	Maldives	28 September 2015	An unconditional 10% reduction in energy sector emissions by 2030, compared to business as usual.	0.00%	22 April 2016	22 April 2016	04 November 2016
159	Kiribati	26 September 2015	A conditional 13.7% by 2025 and 12.8% by 2030 reduction, compared to business as usual levels.	0.00%	22 April 2016	21 September 2016	04 November 2016
165	Marshall Islands	21 July 2015	A 32% reduction in emissions below 2010 levels by 2025, with a further indicative target to reduce emissions by 45% below 2010 levels by 2030, with a view to achieving net zero GHG emissions by 2050, or earlier if possible.	0.00%	22 April 2016	22 April 2016	04 November 2016

Works published by [21,22] were made on the basis of the SWITCH model. This is a multi-period stochastic linear programming model to minimize the present value of the cost of power plants, transmission capacity, fuel, and a per-ton carbon dioxide adder, over the course of several multi-year investment periods. The integration of renewable technology on Cozumel Island's existing electric grid, the operation and the financial cost analysed in this document were made on the basis of the HOMER simulation model [23]. This is a tool that uses two-dimensional linear interpolation through a probabilistic logic strategy using the complete enumeration method. Through this process, the software determines the optimal values of variables that the system designer controls, such as the mix of components that make up the system and the size or quantity of each variable. The optimal system or the best system configuration is the one that satisfies the user-specified constraints at the lowest total net present cost. As in the case of the SWITCH model, the HOMER simulation model uses multi-year analysis based on a time-domain simulation run at the energy-flow level with discrete time-steps of 1 h to determine the Net Present Value for a chosen configuration over a specified project lifetime [24]. More information about the HOMER model formulation is available at [25,26].

For many types of micropower systems, in particular those involving intermittent renewable power sources, a minimum one-hour time step is necessary to model the operational behavior of the system with acceptable accuracy. In a wind–diesel–battery system, for example, it is not accurate enough to know the monthly average (or even daily average) wind power output, since the timing and the variability of that power output are as important as its average quantity. To predict accurately the diesel fuel consumption, diesel operating hours, the flow of energy through the battery, and the amount of surplus electrical production, it is necessary to know how closely the wind power output correlates to the electric load. HOMER's one-hour time step is sufficient to capture the most important statistical aspects of the load and the intermittent renewable resources for the energy management of the system suitable for optimization, while dynamics and control are not analysed [27].

Other planning tools simulate power system dynamics, and optimize the capacity of renewable and fossil fuel generation technologies, storage technologies, and the transmission system, while accounting for the hourly variability of intermittent renewable generation and electricity loads. Watson et al. [28], in collaboration with the Alternative Energy Research Group, of the University of the West Indians (UWI) Mona, have developed the free Linear Optimization software, Photurgen [29], to design and analyze hybrid solar–wind systems within the Caribbean region. In this model, the historic climatological resources and instantaneous load consumption data, as shown in the daily analysis of measured load consumption, was in hourly resolution. An hourly system operation was analysed by Gils and Simon [30], considering the flexibility options and the sector linkage in a pathway to a 100% renewable energy supply for the Canary Islands. In this work, based on a back-casting approach linking the bottom-up accounting framework Mesap-PlaNet model and the high resolution power system model REMix, the authors assess the least-cost composition of generation, grid, and storage capacities in high spatial resolution, and provide an evaluation of the hourly system dispatch.

Section 4 will display the results of the arrangements proposed. A deterministic methodology is used to perform time-series simulations [6]. The selection of the best proposed hybrid system will be determined based on the Dimensional Statistical Variable (DSV) model and a linear regression analysis model, through primary and secondary category rankings [31]. Similar studies were developed using this statistical model. For instance, to predict the financial and technical performance in an off-grid renewable energy system, a linear regression analysis on the basis of this model was used [32]. On the basis of this model, in Fiji Islands, a linear regression model to estimate grid-electricity demand was considered [33]. For the energy supply on Wang-An Island, similar rank points were given for identifying the optimal integrated electricity production from RES [34]. The reduction of the CO_2 emission factor will then be indicated at the end of this Section 4. Conclusions and discussions are addressed in Section 5.

2. Methodology Plan for the Integration of Renewable Electricity Generation on Small Islands

The methodology used in this study is divided into three phases, as shown in Figure 1:

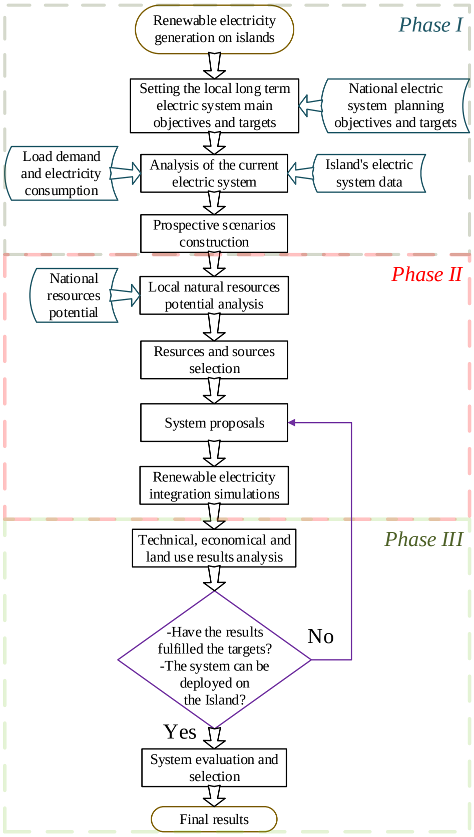


Figure 1. Methodology used to integrate the renewable electricity generation on small islands.

Phase I

A deterministic methodology is used to set up the long-term electrical system target to be achieved. Phase I is divided into:

1. Targets are set on the basis of national, regional or local energy planning objectives.
2. Development of the analysis of the island's electrical system data.
3. The results from the electrical system data analysis are used to build the prospective scenarios.

Phase II

Time-series simulations using a deterministic methodology software tool and long-term statistical models are done. In order to compare different solutions, a number of system combinations of plants based on fossil fuel and renewable resources are analysed. Phase II is divided into:

1. Local resource potential is determined according to the natural resource potential analysis.
2. The renewable energy technologies are selected and proposed.
3. Selection of the proposed hybrid energy systems.
4. Integration of the hybrid system into the island's electric grid is simulated through a deterministic methodology with a time-series simulation software tool.

Phase III

DSV and linear regression analysis models are used to determine the best hybrid system proposed on the basis of three factors: economical, technical and land-use. Phase III is divided into:

1. The results of the electrical system's operation obtained from the optimization and simulation software tool are analysed through a decision support system.
2. DSV and linear regression models are used to evaluate and validate systems that fulfil the targets and can be deployed on the island.
3. The best resultant system is chosen to be installed.

3. Study Case: Cozumel Island, Mexico

3.1. Mexico Energy and Electric Sector Status

The Total Primary Energy Supply (TPES) in 2014 was 13,699 Mtoe (million tonnes of oil equivalent), while the Global fuel consumption in 2014 was 9425 Mtoe; in the OECD, this fuel consumption was 3629 Mtoe in 2014, representing 38.5% of the total amount. The America's OECD represented 51.8% of the OECD total consumption [35]. The America's OECD was nearly 100% energy self-sufficient in 2014 [14]. The TPES is the energy production plus energy imports, minus energy exports, minus international bunkers, then plus or minus stock changes. For Mexico, in 2015, this TPES was 187.3 Mtoe, 0.37% lower than in 2014 [36].

In 2015, the energy indicator (ratio of output to gross domestic supply, (PJ/PJ)) in Mexico was 0.969. This means that the energy produced was −3.1% lower than the internal energy offered to supply the consumers' activities. This value is −5.4% in relation to 2014. The national energy intensity in 2015 was 604.45 kJ/MX$ (3.9% lower than the previous year, 2014). This is the energy needed to produce one MX$ of the GDP [37]. The Human Development Index (HDI) in Mexico is very far away from the one that countries such as USA, Australia, Sweden, Japan, among others have. This indicator includes the total primary energy demand per capita, the population and the GDP per capita of each country [38].

In Mexico, from 2014 to 2015, the electricity consumption increased by 3.1%. At the end of 2014, the National Electric System (SEN is its Spanish acronym) had an electric power capacity of 65,452 MW installed. Meanwhile, at the end of 2015, this capacity was increased to 68,044 MW. The main technology to produce electricity through fossil fuels in 2015 was the combined cycle, which represented 49.29% of the total fossil fuel power generation capacity. On the other hand, the main technology to produce electricity through clean energy sources was Hydro power, which represented 64.82% of the total clean energy power generation capacity [39].

The maximum power demand and the electricity consumption will continue increasing, so it is necessary to increase the renewable power energy participation in the electricity sector in Mexico. To fulfil this electricity demand, an additional power capacity of 59,985.6 MW will be necessary by 2029. In total, 54.3% of this additional power capacity should be from clean energy sources and the remaining 45.7% from fossil fuel sources [40].

With the energy reform approved on 20 December 2013, a big step forward was made towards a competitive electric market in Mexico. The secondary laws that ensure the correct implementation of this energy reform were published on 11 August 2014. The Electric Industry Law (LIE is its Spanish acronym) defines the new electricity sector structure and the planning and control of the SEN [41].

The Mexican Government developed three future scenarios: (a) High Scenario; (b) Base Scenario; (c) Low Scenario. These three scenarios were carried out in the Development Program of the National Electric System 2016–2030 (PRODESEN is its Spanish acronym), taking the energy planning predictions in Mexico into consideration. These scenarios were made on the basis of the General Economic Policy Criteria for the Initiative of Income Law and the Federation Expenditure Budget Project (CGPE is its Spanish acronym) 2016. The macroeconomic targets and strategies that are included in these documents are the power demand, the electricity consumption, the fuel prices and the GDP among others [39].

3.2. Renewable Energy in Mexico

Mexico participated in the global renewable energy offer of 15.2 Mtoe in 2013. On average, 9% of OECD countries' energy sector consumption was through renewable sources [42]. The global participation of the renewable energy sources in the energy sector was 13.5% in 2013.

From the 70,000 MW of total power electricity generation capacity installed in Mexico, 19,000 MW are of non-fossil fuel technology [43]. Notwithstanding that Hydro power represented 64.82% of the total power capacity of clean sources in electricity generation, only 20.34% of the total electricity in 2015 was generated through these technologies [39]. To increase the RE participation, the Energy Transition Law (LTE is its Spanish acronym) demands a clean energy participation of 25% by 2018, 30% by 2021 and 35% by 2024 [44]. As a result of this clean energy increase, the CO_2 emission factor in 2000, of 0.604 tCO_2 /MWh, must be reduced by 30% by 2020 and 50% by 2050 [45]. In the Transition Strategy to Promote the Use of Cleaner Fuels and Technologies in 2016 (Estrategia de Transición para Promover el Uso de Tecnologías y Combustibles más Limpios), three targets are indicated for renewable electric generation: 35% by 2024, 37.7% (rounding up to 38%) by 2030 and 50% by 2050 [46]. Table 2 is a summary of these results and includes the targets of the RE objective: (a) generation of electricity; (b) power capacity installed and (c) CO_2 factor emission reduction. RE targets are the same regardless of the scenario under consideration.

Table 2. Targets summary of electricity generation in renewable energy (RE) for Mexico by 2050 [39,40,42,44–53].

No.	*Subject*	*Scenario*	*2018*	*2020*	*2021*	*2024*	*2030*	*2035*	*2050*
1	*Electricity generation with renewable energy sources (%)*	**High** **Base** **Low**	25.0%	30.0%	30.0%	35.0%	38.0%	40.7%	50.0%
2	*Renewable power generation capacity installed (%)*	**High** **Base** **Low**	34.6%	35.4%	35.8%	37.1%	39.7%	42.1%	50.0%
3	*Reduction of the CO_2 emission factor respect to 2000 (0.604 tCO_2eq/MWhel)*	**High** **Base** **Low**		−30.0%					−50.0%

3.3. Electricity in the Peninsular Area

The Peninsular area is one of the seven electric regional controls in the SIN [54]. The States of Yucatan, Campeche and Quintana Roo (where Cozumel Island is located) are in the Peninsular region control. The previously identified National programs included forward-looking targets in the electricity sector for the Peninsular Area. The annual average growth rate for the Peninsular Area from 2016 to 2030 is indicated in Table 3, showing the three scenarios [39].

Table 3. Peninsular annual average growth rate expected from 2016 to 2030 [39].

	Scenario		
	Low	**Base**	**High**
Electricity consumption (%)	4.7	3.8	3.3
Power demanded (%)	4.9	4.1	3.6

3.4. Cozumel Island

Cozumel Island is located in the Quintana Roo State. It has warm tropical weather throughout the year and is part of the Occidental Caribbean Sea (see Figure 2). With a surface area of 647 km^2, it had a population of 86,415 inhabitants in 2015 [55] with a density of 134 inhabitants per km^2. It is part of the second largest coral reef in the world, after the great Australian coral reef. Cozumel Island and

Quintana Roo State have an average annual temperature of 26 °C. The coolest months are December, January and February with temperatures under 22 °C. According to the Köppen–Geiger climatic classification modified by García, there are warm, sub-humid climate conditions with intermediate rainfall. A warm, humid climate with abundant rainfall in the summer is found on Cozumel Island [56].

Figure 2. Cozumel Island location [12].

3.4.1. Setting the Long-Term Electric System Target

The energy planning scenarios developed in this study are based on the data from: PSE [40]; PRODESEN [39]; The Special Program for Exploitation of Renewable Energies (PEAER is its Spanish acronym) [47]; the Climate Change General Law (LGCC is its Spanish acronym) [45]; LTE [44]; National Strategy of Climate Change (ENCC is its Spanish acronym) [48]; Energy Sectorial Program (PROSENER is its Spanish acronym) [49]; the Renewable Energy Prospective (PER is its Spanish acronym) [42]; National Strategy of Energetic Transition and Sustainable Exploitation of Energy (ENTEASE is its Spanish acronym) [50]; LIE, National Strategy of Energy (ENE is its Spanish acronym) [51]; Special Program of Climate Change (PECC is its Spanish acronym) [52]; National Program for the Sustainable Exploitation of Energy (PRONASE is its Spanish acronym) [53]; and the Transition Strategy to Promote the Use of Cleaner Fuels and Technologies of 2016 [46].

For Cozumel Island, the target is to reduce the fossil fuel consumption through electricity production from RETs to cover 50% of all electric consumption by 2050. This target is within the range proposed by [57,58]: from 15% (Antigua and Barbuda) to 100% (Dominica) for the Caribbean Islands. Therefore, the methodology used in this case study can be applied to other islands or to the SIDS.

The prospective growth rates for the electricity sector on the Island will be the same as those for the Peninsular region control, as shown in Table 3. According to this growth indicator for the three scenarios, forecasts for power demand and electrical consumption were made. These predictions were made to achieve the targets given in Table 2. The prospective electricity consumption scenarios from 2016 to 2050 on Cozumel Island (see Figure 3) were obtained from the prospective growth rates indicated in Table 3 and from the information specified in Figure 4. The prospective scenarios from 2016 to 2050 on Cozumel Island in power demand (see Figure 5) were obtained from the prospective growth rates indicated in Table 3 and from the information specified in Figure 6.

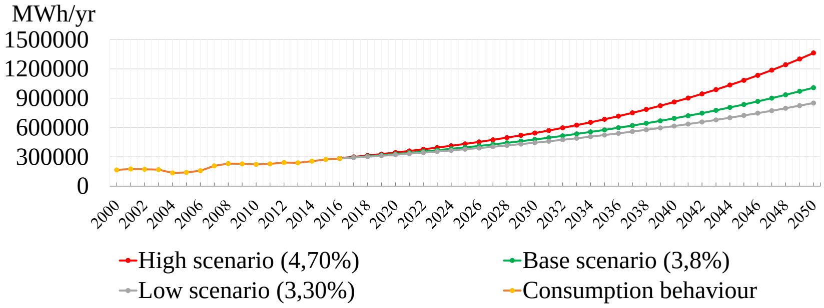


Figure 3. Electricity consumption and forecast on Cozumel Island from 2000 to 2050, based on the information from [39,55,59,60].

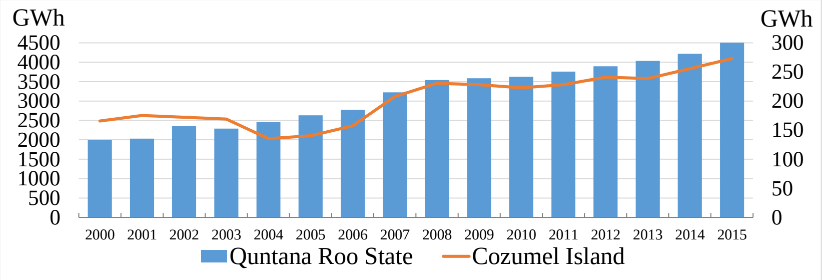


Figure 4. Electric consumption on Cozumel Island from 2000 to 2015 [59,60].

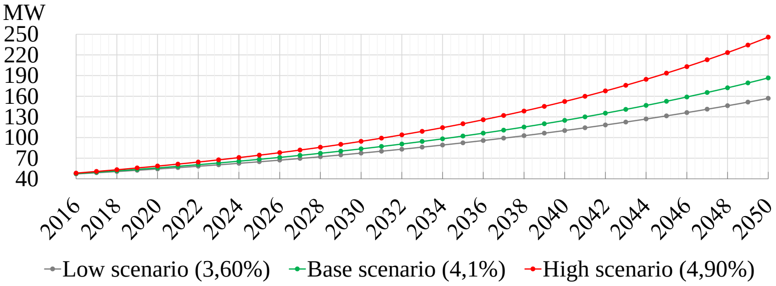


Figure 5. Forecast of maximum power demand on Cozumel Island from 2016 to 2050, based on the information from [39,55,59,60].

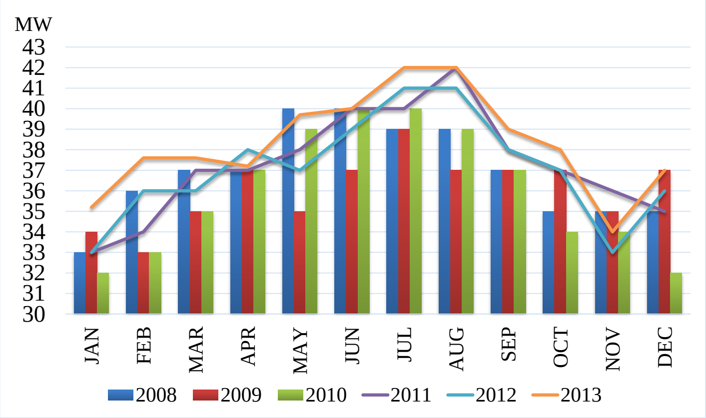


Figure 6. Maximum power demand on Cozumel Island from 2008 to 2013 [59].

3.4.2. Analysis of the Current Electric System

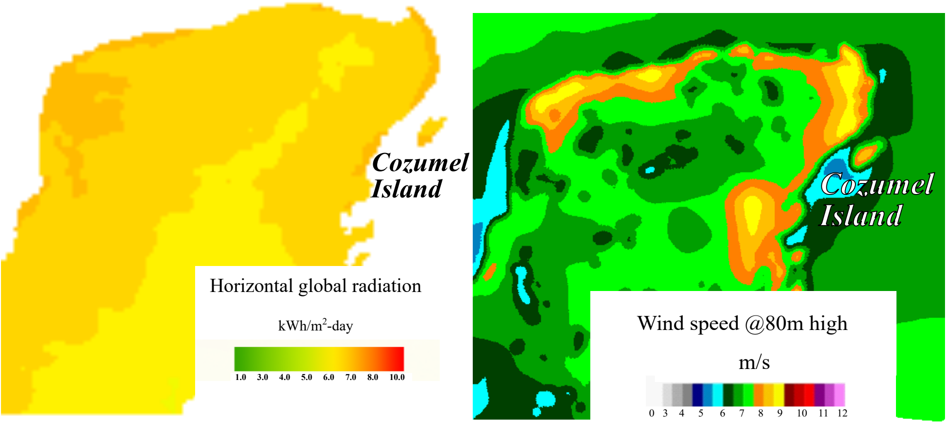
Currently, the electricity generation on the Island depends solely on *diesel turbogas machines* (single cycle gas turbines burning diesel). There are three *diesel turbogas machines*: (1) W Diesel 19.2 MVA, (2) M Diesel 17.5 MVA and (3) GE Diesel 45.2 MVA. These machines are used to support the peak demand on the Island, and in some cases to supply part of the electricity demand on the North part of the State. The Island has a submarine interconnection cable to provide the electricity needed. In case of a wire fault, the *diesel turbogas machines* support the power demand. Through this submarine cable connection from the Riviera Maya node to the Cozumel node, the electricity can flow in both directions.

The maximum power demand fluctuates between 41 MW in 2011 and 44 MW in 2014 (see Figure 6). The maximum power generated on the Island covers the electric demand, but sometimes the electricity excess production flows to the main land (Riviera Maya node) [59]. The electricity consumption on the Island in 2015 was 272.97 GWh, 6.77% higher in regard to 2014 [37]. Figure 4 indicates the electricity consumption behavior from 2000 to 2015 [59,60].

The hourly power demand seasonal profiles for Cozumel Island were based on the information from [39,40,55,59,60]. This information will be used in the hourly electrical operation simulations of the electrical grid. This way, the projections of maximum power demand and electricity consumption were developed from 2016 to 2050.

3.4.3. RE Potential on Cozumel Island

The RE potential in the Yucatan Peninsula and Cozumel Island was obtained from the INERE [61] and CONABIO [62] Website tool through a Geographic Information System (GIS), from the RES statistical and geographic database. Figure 7a,b show the Horizontal global radiation and the wind speed @80m, respectively, of the RE resources' potential on the Yucatan Peninsula and Cozumel Island. According to this information of the RE resources' potential, PV and Wind technologies have been selected to develop this potential on the island.



(**a**) (**b**)

Figure 7. Atlas for RE potential in the Peninsula Area [61,62]. (**a**) Renewable Electricity generated and RE fraction; (**b**) RE capacity installed and on-shore surface used.

3.4.4. Renewable Energy Sources Selection

The environmental impact of land use in the selection of RETs is important due to the damage that can affect the selected site. Protected natural areas play a major role in the restrictions of RE sites [63]. Multiple arrangements of the RETs selected in the previous subsection have been considered in this study, on the basis of a minimum land impact that does not represent an environmental risk. This includes on-shore and off-shore wind combined with/without PV on unused land on the Island (see Table 4). The land where these systems can be deployed is common land, which has already been impacted by livestock and agricultural uses, but to this day is idle land. Cozumel common land covers 145,068 Hectares (Ha). Of this surface area, 15,347 Ha are for agricultural use and 129,721 Ha are unused land [64]. This unused land is not entirely idle land. It is divided into many smallholdings. Therefore, in order to impact the minimum quantity of land used for each system and to achieve the targets indicated, twelve different system proposals were selected. The use of off-shore turbines in combination with on-shore and/or PV will be considered (see Table 4).

Table 4. Systems proposed for the hybrid system simulations.

Technology Type	**PV**	**Wind**	**Wind**	**Wind**	**Wind**	**Wind**	**Wind**	**Wind**
Company	Generic	GoldWind	Wind to Energy	Sany	EWT	EWT	EWT	Enercon
Power curve type		III B	III A	S	III B	III B	III B	I A
Capacity	333.33 kW	2.5 MW	3 MW	2 MW	250 kW	500 kW	900 kW	7.5 MW
Model		GW121	W2E 132	SE11520	DW 54/250	DW 54/500	DW 54/900	E-126 135
Place to install	On-shore	On-shore	Off-shore	On-shore	On-shore	On-shore	On-shore	Off-shore
System 1	√	√						
System 2	√	√	√					
System 3	√		√		√			
System 4	√		√			√		
System 5	√		√				√	
System 6			√					
System 7	√			√				
System 8								√
System 9	√				√			
System 10	√					√		
System 11	√						√	
System 12	√							
All systems include:		W Diesel	M Diesel	GE Diesel	Turbogas Diesel	EnerStore 50 kWh	EnerSection Converter	
*Only for years 2021, 2024, 2030, 2035 and 2050		√	√	√	*	√	√	

Figure 8 shows a preliminary feasible option for the 5 Ha of land surface: a combination of 2, 2.5 and 3 MW on-shore wind turbines with 333.33 kW of PV. The size has been agreed between owners and local agrarian authorities, taking into account external restrictions such as land used for the production of drinkable water and other agricultural activities. In this land size, and to avoid wind turbulence from the wooded area of the jungle (8–10 m tree high), the minimum distance and the surface roughness length have been considered [65]. To avoid shadowing, due to the position of the sun on the horizon in the PV panels area, the minimum distance from obstacles or trees has also been considered. Figure 8 represents a basic scheme of the land size available for each PV-Wind combination. It does not mean that this scheme is a restricted surface configuration to be applied.

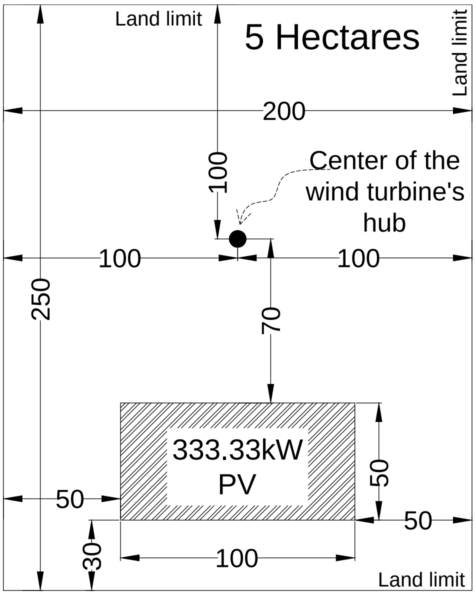


Figure 8. PV and wind turbine combination on a proposed 5 Ha area of land (dimensions are in meters).

3.4.5. RETs System Proposals and Its Combination with Diesel and Flow Batteries

Rules and controls in the electricity sector exist to maintain the reliability of the grid when the generation plants are integrated into it. The grid code is the interconnection rules and controls for the RETs or any generation sources at the moment they are integrated into the electrical system, keeping the reliability and stability of the electrical grid. To make this possible, this code has the minimum or maximum control and protection parameters. The code depends on the country in which the RETs are going to interconnect. For instance, the grid code for large-scale photovoltaic power plants (LS-PVPPs) and very large-scale PVPPs (VLS-PVPPs) connected to the transmission system vary according to the country's grid code, as indicated by [66]. In this study, the grid code parameters have been considered accomplished, according to the existing one in the SEN. Therefore, the control, protections and demand response are outside the scope of this proposal.

The simulations of the RETs integration on the Cozumel Island's grid, in combination with *diesel turbogas machines* and flow batteries have been done through the HOMER®software tool [23] and using its modified standard models included in this electronic tool. HOMER®uses a two-dimensional linear interpolation through a probabilistic logic strategy using the complete enumeration method. Through this process, the software determines the optimal values of variables that the system designer controls, such as the mix of components that make up the system and the size or quantity of each variable. The optimal system or the best system configuration is the one that satisfies the user-specified constraints at the lowest total net present cost [27,67].

The technology selected for these simulations is indicated in Table 4. The topology and the renewable electrical system of the grid in this study are shown in Figure 9, including the current generation and main transformation system. The equipment selected for these simulations was: Generic PV system; GOLD WIND turbine machines (121/2.5 MW) type IIIB [68]; WIND to ENERGY turbines (132/3 MW) type IIIA [69]; SANY wind turbines (SE11520 2 MW) type S [70]; EWT turbine machines (DW54/250 kW, DW54/500 kw, DW54/900 kW) type IIIB [71]; and ENERCON wind turbine (E-126 135 7.5 MW) type IA [72]. These proposed systems have considered the existing *diesel turbogas machines* and one additional *diesel turbogas machine* (named: *Turbogas Diesel*). This new machine will be added only when the power demand exceeds the existing generation capacity, including the 6% reserve margin. The years in which this new *diesel turbogas machine* will be added are 2021, 2024, 2030, 2035 and 2050. The ideal energy model for the flow batteries was used and the quantity of flow batteries (EnerStore50, from ZBB ENERGY CO. [73]) in order to achieve 2 hours of backup power was proposed. The Kinetic Battery Model to determine the amount of energy that can be absorbed by or withdrawn from the storage bank each time step [74] was used. The AC/DC converter (EnerSection Converter, from ZBB ENERGY CO. [75]) was dimensioned, considering the 2 hours of backup time from batteries on a full discharge time. This backup time is considered as the time that allows a *diesel turbogas machine*, starting from a cold point, to supply the electricity needed in that moment, as well as to minimize the fossil fuel generation and to maintain the reliance of the system. As shown in Figure 10, in the first 8 h of 2018 in the Base Scenario, the RES and batteries supply the power demand while the *diesel turbogas machine* runs. However, between 47 h and 71 h, the fossil fuel generation is imperative, because there is no RE production and the batteries are discharged. It is important to remark that these electrical simulations on the electric grid of Cozumel Island were done in an off-grid mode. This operation allows the system to supply the electricity through fossil fuels for several hours when the renewable sources are not producing and the batteries are discharged. The system runs inversely when batteries are fully charged and renewable sources are producing enough electricity to supply the demand completely. In these two cases, fossil fuels and renewable energy supply the electricity demanded by the system. Because of this, the capacity installed must be much bigger than the power demand, having a 6% reserve margin.

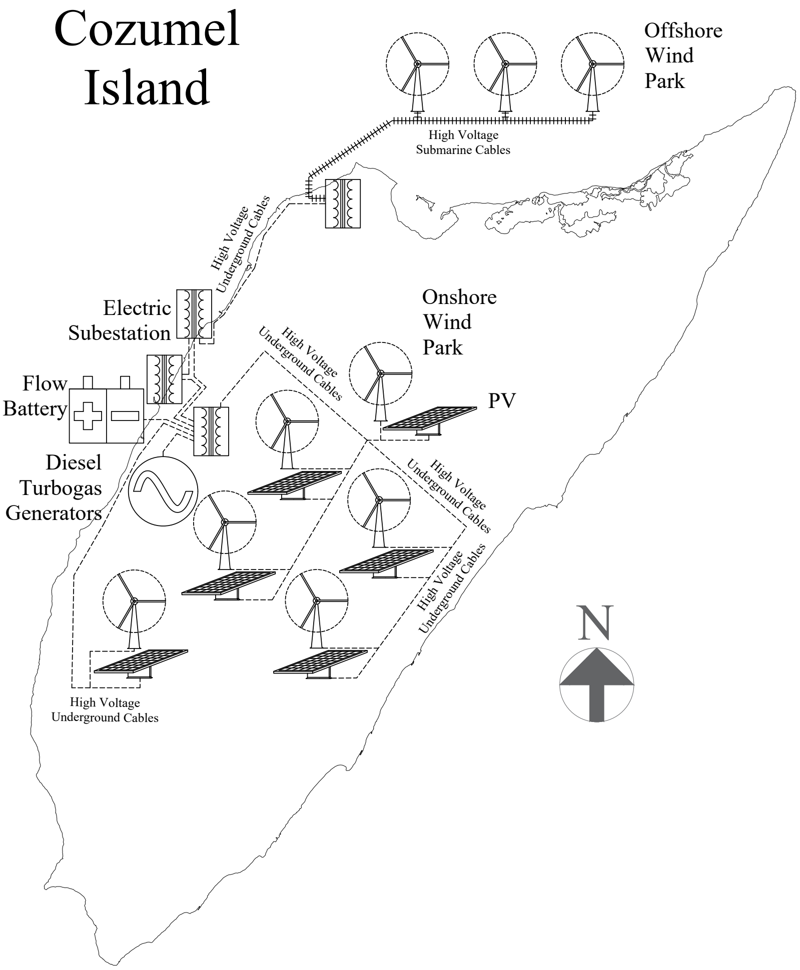


Figure 9. Topology and renewable electricity system, including the current generation and main transformation system, proposed for Cozumel Island.

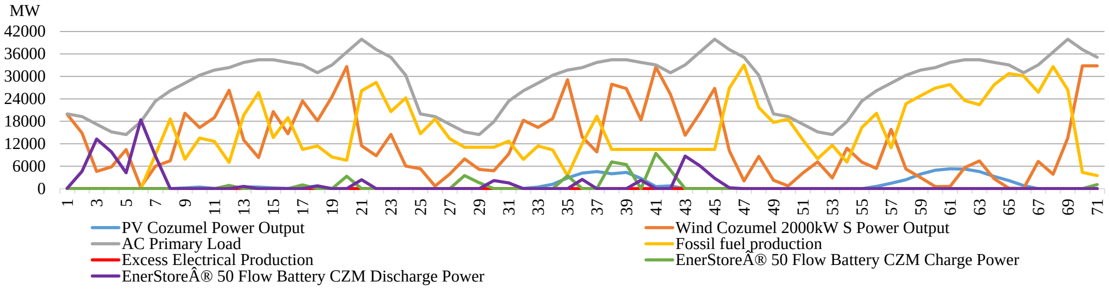


Figure 10. Operational curve for System 7 in the Base Scenario for Cozumel Island by 2018.

The elements included in each system belong to a series of direct combinations between 333.33 kW in PV with one wind turbine in a 5 Ha surface area for on-shore (see Figure 8), considering the low wind profile resource using wind turbines with a type III-B (GW121-2.5 MW; DW-54/250 kW; DW-54/500 kW; DW-54/900 kW) and S (SE-115/2 MW) power curve. For off-shore, two turbines—type III-A (W2E-3 MW) and I-A (E-126-7.5 MW) power curve—were placed at a separation distance nine times their height in the same prevailing wind direction, and five times their height perpendicular to the direction of the prevailing wind. This was to avoid the presence of a wake effect and the wind production reduction [65]. Figure 9 shows the proposed topology of the electric grid in combination with the existing equipment on the Island. Only one system (System 12) was selected on the basis of PV, considering a surface area of 1.5 Ha/MW of peak capacity installed. The Figure 11 shows the total land surface affected by 2050 in the Base Scenario, by each of the 12 systems proposed. For instance, System 9 will need 2005 Ha and System 2 will need 175 Ha on-shore and 1140 Ha off-shore.

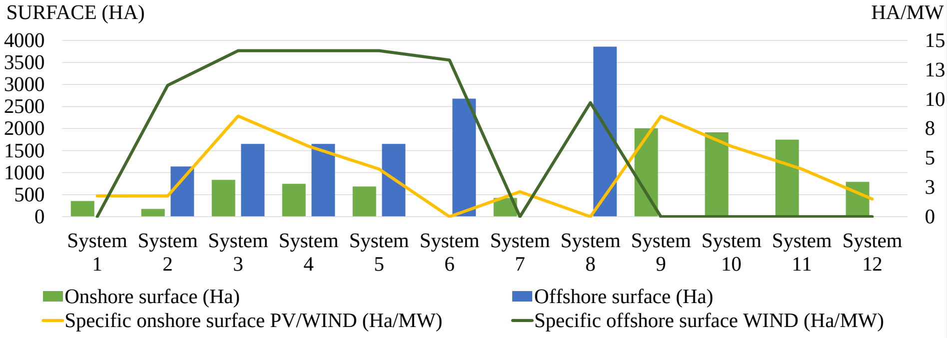


Figure 11. Results of on-shore and off-shore surface area used by each system on Cozumel Island for 2050 in the Base Scenario.

4. Results

4.1. Previous Essential Information

The basic considerations to develop the economic proposal on Cozumel Island (see Table 5) were made based on data from PRODESEN [39], PRE [42], International Energy Agency (IEA) [13,76,77], Sandia National Laboratories [78], and from the Department of Energy (DOE, USA) [79]. The average diesel cost was obtained from the World Bank Website [80] and from PRODESEN. The capital cost of the equipment, O&M, and other economic considerations from the Mexican Government's report were used in these simulations. The Renewable Energy Certificates' (CEL is its Spanish acronym) economic inputs were not considered. The results obtained were: the generation capacity of fossil fuels and renewable energy; the electricity generated; the LCOE; the capital cost; the Internal Return Rate (IRR); the payback time, among others. In addition to these results obtained through HOMER®tool, other results were obtained: the surface area used; the CO_2 emissions emitted and avoided; the specific electricity generated by each system; the reserve margin; the targets in contrast to each concept shown in Table 6, inter alia. These results are for the 12 defined systems proposed in this study (see Section 3.4.5). Two lifetime data for the PV and wind technologies have been chosen in the sensitivity parameters: 25 years and 12.5 years. This is due to the risk of a hurricane during the lifetime of the project as indicated at the end of Section 4.3. Wind resource data used in the simulations was compared, obtaining a high similarity with the data obtained from Figueroa-Espinoza and Paulo Salles [81]. Technical results are included in Section 4.2. Economic results are indicated in Section 4.3. System selection is shown in Section 4.4. After the system selection, analysis of the best system was conducted, as discussed in Section 4.5. Finally, the emission factor reduction results are shown in Section 4.6.

Table 5. Economic and financial parameters for the technologies used in the simulations

Concept	**Unit**	**Diesel**		**Wind**		**PV**	**Flow Batteries**
		Current	**New**	**On-Shore**	**Off-Shore**		**(Bulk Storage)**
Capital Cost	$/kW	0	620	1600	4500	1346	484
	$/kWh						238
Remplacement Cost	$/kW	620		1600	4500	1346	
O&M	$/kWh-year			0.025			0.0005
	$/h	0.0042					
	$/kW					19	4.50
Diesel price	$/L	1					
Lifetime	year	25					
Discount Rate	%	10					
Inflation Rate	%	3					
Real Discount Rate	%	6.8					
Diesel start cost	$/year	1241					
Currency	US $	2016 constant					
Operating Reserve	%	6					
Random Variability of electric load	%	0					

Table 6 shows the electricity generation and the power demand expected for the Island. Considering the existing 68.82 MW fossil fuel generation, the Table 6 also includes the electricity generation composition in RE and fossil fuel and the minimum and maximum power capacity composition to be installed [59]. Data in Table 6 is based on the targets for Cozumel Island, indicated in Table 2. Points 1 and 2 in Table 6 represent the forecast data according to the prospective growth from Figures 3 and 5. Points 3 and 4 show the minimum data for the RE results. Figures 12 and 13 indicate the results for these points in RE, contrasting them with their targets. Points 5 and 6 show the maximum fossil fuel data for the results. Point 5 was always fulfilled in regard to the maximum fossil fuel production. Point 6 was never accomplished, because the fossil fuel always supplied the demand when there was not enough RE production. In some hours during the year (2021 in the Base Scenario), the power demand was higher than the installed fossil fuel power capacity. This resulted in the addition of a new fossil fuel generator from this year until 2050 (named: *Turbogas Diesel*), including the 6% of the reserve margin. Point 7 shows the maximum emission factor to fulfil the emission factor reduction regarding the one calculated for 2000 (see Figure 22 in Section 4.6). Point 8 is the maximum reserve margin to be considered in the power capacity installed. It is important to note that this 6% in the reserve margin was never accomplished, because the most restrictive of all targets in RE was the emission factor reduction (see Figure 14). Whereas the electricity generation targets for RE and the power capacity installed were achieved, the fulfilment of the factor emission reduction target implicated an increase in the RE generation capacity (see Figure 13).

Table 6. Forecast of the electrical system of Cozumel Island to be fulfilled with the simulation results until 2050.

No.	*Subject*	*Scenario*	*2018*	*2020*	*2021*	*2024*	*2030*	*2035*	*2050*
1	*Electricity consumed (GWh/year)*	High	313.3	343.4	359.6	412.7	543.7	684.0	1362.2
		Base	305.3	328.9	341.4	381.9	477.6	575.5	1007.0
		Low	300.9	321.1	331.7	365.6	444.2	522.5	850.4
2	*Maximum power demand (MW)*	High	53.2	58.5	61.4	70.9	94.4	119.9	245.8
		Base	51.6	55.9	58.2	65.6	83.5	102.1	186.6
		Low	50.6	54.3	56.3	62.6	77.3	92.3	156.9
3	*Electricity generation with renewable energy sources (GWh/year)*	High	78.3	103.0	107.9	144.3	206.5	278.3	681.1
		Base	76.3	98.7	102.4	133.5	181.4	234.1	503.5
		Low	75.2	96.3	99.5	127.9	168.7	212.6	425.2
4	*Renewable power generation capacity installed including 6% of reserve margin (MW)*	High	19.5	22.0	23.3	27.8	39.8	53.5	130.3
		Base	18.9	21.0	22.1	25.8	35.2	45.5	98.9
		Low	18.6	20.4	21.4	24.6	32.6	41.2	83.2
5	*Electricity generation with fossil fuel sources (GWh/year)*	High	235.0	240.4	251.7	268.4	337.2	405.7	681.1
		Base	229.0	230.3	239.0	248.3	296.2	341.4	503.5
		Low	225.7	224.8	232.2	237.8	275.5	310.0	425.2
6	*Fossil fuel power generation capacity installed including 6% of reserve margin (MW)*	High	36.9	40.1	41.8	47.3	60.3	73.6	130.3
		Base	35.8	38.3	39.6	43.8	53.4	62.7	98.9
		Low	35.1	37.2	38.3	41.7	49.4	56.7	83.2
7	*Reduction of the CO_2 emission factor respect to 2000 (0.604 tCO2eq/MWhel)*	High Base Low	0.433	0.423 (−30%)	0.418	0.404	0.378	0.357	0.302 (−50%)
8	*Reserve Margin (%)*	High Base Low				6%			

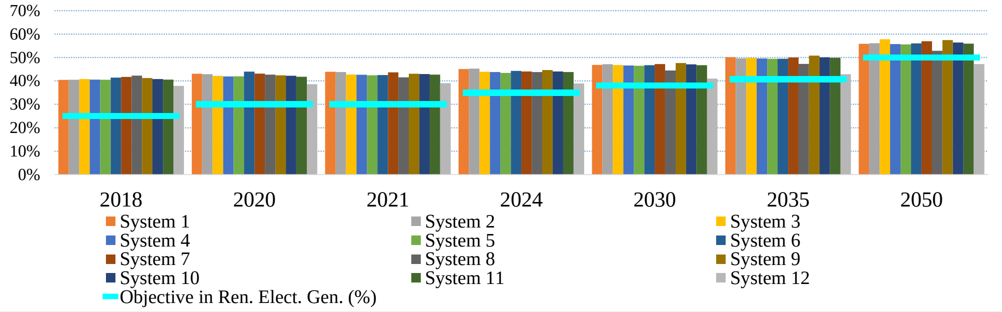


Figure 12. Results of renewable electricity generated vs. its objective for each system in the Base Scenario.

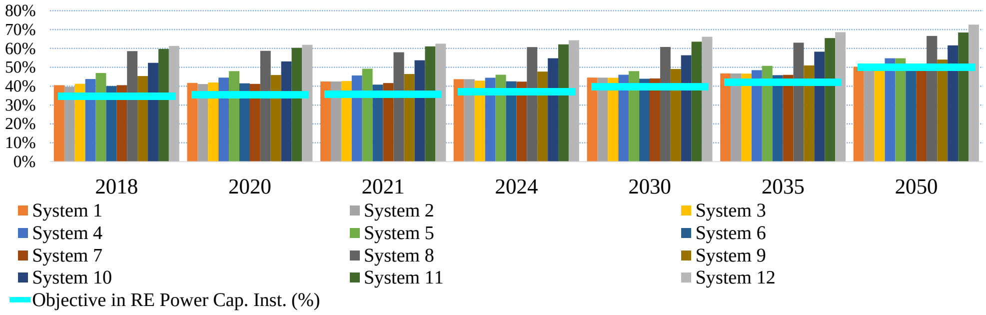


Figure 13. Results of total renewable power capacity installed vs. its objective for each system in the Base Scenario.

4.2. Technical Results

In accordance with the RE targets, Table 7 shows the results for each system proposed for 2050 in the Base Scenario. The quantity of on-shore and off-shore wind turbines is included in combination with PV, in some cases. For all systems proposed, the diesel generation, the flow batteries and the converter are always present.

Figure 11 shows the surface area used on-shore and off-shore for each system in the Base Scenario in 2050, as an example. Figures 12–14 show results of renewable electricity generated, renewable power capacity installed and the reserve margin in comparison with their targets for the 12 systems in the seven key years. In Figure 14, the Mexican Government projects a 6% reserve margin, according to the result from: $RM = [(\sum i + jCI - DB)/DB] \times 100$. Where RM is the reserve margin, $i + jCI$ is the existing and projected power capacity installed and DB is the power demand [54]. Considering only the power capacity installed on the Island, this 6% is not enough to achieve the required power capacity generation in RE and fossil fuel to supply the electricity consumption needed in time, as Figure 14 shows. The system is oversized and the reserve margin results will be out of the target indicated by the Mexican Government. Comparing the three scenarios' results (Low, Base and High), similarities can be found, but the amount of electric data changes. This means that topology and technologies included in the 12 systems proposed never change. Only the power demand, the electric consumption and the capacity of the system elements change. The RE generation capacity data will change in direct proportion to these variations. In the Low Scenario, the data diminishes and in the High Scenario the data increases in relation with the Base Scenario.

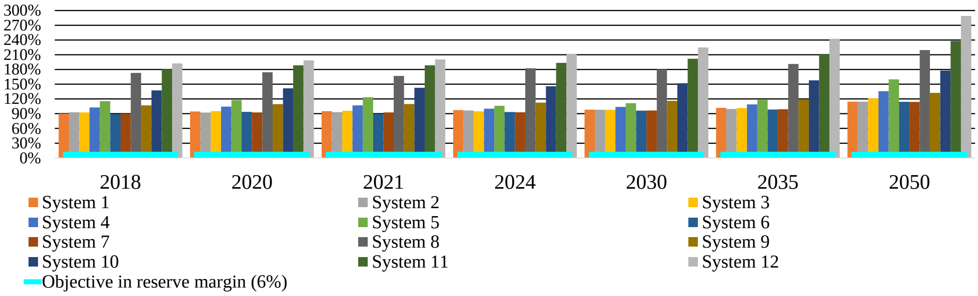


Figure 14. Results of reserve margin vs. its objective for each system in the Base Scenario.

Table 7. System results for electric generation for 2050 in the Base Scenario.

	PV (MW)	GW121 Quantity	W2E 132 Quantity	SE11520 Quantity	DW 54/250 Quantity	DW 54/500 Quantity	DW 54/900 Quantity	E-126 135 Quantity	W Diesel (MW)	M Diesel (MW)	GE Diesel (MW)	Turbogas Diesel (MW)	EnerStore 50 kWh Quantity	EnerSection Converter (MW)
System 1	23.7	71							16.32	14	38.5	130	5130	128.25
System 2	11.7	35	34						16.32	14	38.5	130	5130	128.25
System 3	55.7		39		167				16.32	14	38.5	130	5130	128.25
System 4	49.7		39			149			16.32	14	38.5	130	5130	128.25
System 5	45.7		39				137		16.32	14	38.5	130	5130	128.25
System 6			67						16.32	14	38.5	130	5130	128.25
System 7	30.4			85					16.32	14	38.5	130	5130	128.25
System 8								53	16.32	14	38.5	130	5130	128.25
System 9	134.4				401				16.32	14	38.5	130	5130	128.25
System 10	127.7					383			16.32	14	38.5	130	5130	128.25
System 11	116.7						350		16.32	14	38.5	130	5130	128.25
System 12	527.0								16.32	14	38.5	130	5130	128.25

4.3. Economic Results

The LCOE generated for each selected piece of generation equipment, including the existing *diesel turbogas machines* and the new one, are indicated in Table 8. The LCOE resultant of each system is the average cost per kWh of useful electrical energy produced by the systems indicated in Table 9 (25 years and 12.5 years of lifetime project). The Net Present Cost (NPC) and the O&M are also indicated according to their lifetime (25 years or 12.5 years). Table 9 also shows the Initial Capital Cost (INV), the Discounted Price Value (DPV), the Internal Return Rate (IRR) and the Discounted Payback time as common results. The simulations developed were based on fossil fuels, the prices of which were not increased.

Table 8. Levelized Cost of Energy (LCOE) resultant for each piece of selected generation equipment for every scenario and key years.

Generation Equipment	LCOE (US$/kWh) 25 Years Lifetime Project	LCOE (US$/kWh) 12.5 Years Lifetime Project	Generation Equipment	LCOE (US$/kWh) 25 Years Lifetime Project	LCOE (US$/kWh) 12.5 Years Lifetime Project
PV	0.09	0.13	DW 54/900 kW	0.12	0.16
GW121/2.5 MW	0.06	0.08	E-126 135 7.5 MW	0.25	0.34
W2E 132/3 MW	0.14	0.19	W Diesel	0.23	0.23
SE11520 2 MW	0.06	0.08	M Diesel	0.23	0.23
DW 54/250 kW	0.06	0.07	GE Diesel	0.23	0.23
DW 54/500 kW	0.08	0.11	Turbogas Diesel	0.25	0.25

On 24 September 2015, the production cost in the peak period (from 6 p.m. to 11 p.m. approx.) was 0.351 US$/kWh on Cozumel Island [59,82]. In this study, the result obtained for this production cost was 0.230 US$/kWh for the existing *diesel turbogas machines*, and 0.251 US$/kWh for the new machine using a diesel price of 1 US$/L [37,80] (see Table 8). Results obtained in this study are very far from the ones reported by the Mexican government. For instance, in the first energy auction closed on 30 March 2016, the average electricity price from clean sources was 0.04748 US$/kWh + CEL [39]. However, in the second long-term electric auction, preliminary results published on 22 September 2016, the average electricity price from clean sources was 0.03347 US$/kWh + CEL [83].

Table 9. Economic results for the systems with a projected lifetime of 25 years and 12.5 years by 2050 in the Base Scenario.

	Common Results				25 Years Lifetime			12.5 Years Lifetime		
	Initial Capital Cost (INV) (US$M)	Discounted Present Value (DPV) (US$M)	Internal Return Rate (IRR) (%)	Discounted Payback (year)	LCOE (US$/kWh)	Net Present Cost (NPC) (US$B)	Operation & Maintenance (O&M) (US$M)	LCOE (US$/kWh)	Net Present Cost (NPC) (US$B)	Operation & Maintenance (O&M) (US$M)
System 1	439	1,113	30.1	4.0	0.1926	2.3	157	0.2042	2.4	169
System 2	**738**	**816**	**17.6**	**6.9**	**0.2175**	**2.6**	**157**	**0.2401**	**2.9**	**180**
System 3	791	818	16.9	7.1	0.2173	2.6	152	0.2419	2.9	177
System 4	836	711	15.3	8.0	0.2263	2.7	157	0.2525	3.0	184
System 5	908	636	13.9	9.1	0.2324	2.8	157	0.2613	3.1	187
System 6	1,028	521	12.0	11.7	0.2422	2.9	157	0.2754	3.3	191
System 7	**436**	**1,152**	**31.0**	**3.8**	**0.1893**	**2.3**	**154**	**0.2008**	**2.4**	**166**
System 8	1,912	−465	3.9	16.1	0.3246	3.9	166	0.3904	4.7	232
System 9	464	1,123	29.2	4.1	0.1920	2.3	154	0.2045	2.4	167
System 10	601	967	22.1	5.6	0.2049	2.4	156	0.2225	2.7	173
System 11	784	769	16.5	7.3	0.2214	2.6	157	0.2457	2.9	181
System 12	832	509	13.0	9.8	0.2434	2.9	175	0.2695	3.2	201

Table 10 shows Tropical Storms and Hurricanes in Quintana Roo State from 1901 to 2015. This table was made according to the data from Gómez Ramírez and Álvarez Román [84] and the Hurricane Research Division [85]. In this table, two categories are indicated: (a) From Tropical Storm wind forces (less of 119 km/h) to Hurricane Category 2 wind forces (154–177 km/h) and (b) from Hurricane Category 3 wind forces (178–208 km/h) or higher [86]. As can be seen in Table 9, a major Hurricane (Category 3 or higher) in a 25-year lifetime project can affect the economic results shown in the 12.5-year lifetime project cost. If the major hurricane happens before the payback time has been reached, or two or more times within its lifetime project, these proposals could be economically infeasible

Table 10. Tropical Storms and Hurricanes in Quintana Roo State from 1901 to 2015 [84,85].

	1901	1909	1916	1931	1933	1938
From Tropical Storm to Hurricane category 2	√	√		√	√ √	√
Hurricane category 3 or higher			√			
	1942	1944	1955	1967	1971	1974
From Tropical Storm to Hurricane category 2		√				
Hurricane category 3 or higher	√		√ √	√	√	√
	1975	1988	2003	2005	2007	2008
From Tropical Storm to Hurricane category 2			√	√ √	√	√ √
Hurricane category 3 or higher	√	√		√ √	√	
	2010	2011	2012	2013	2014	2015
From Tropical Storm to Hurricane category 2	√	√	√	√		
Hurricane category 3 or higher						

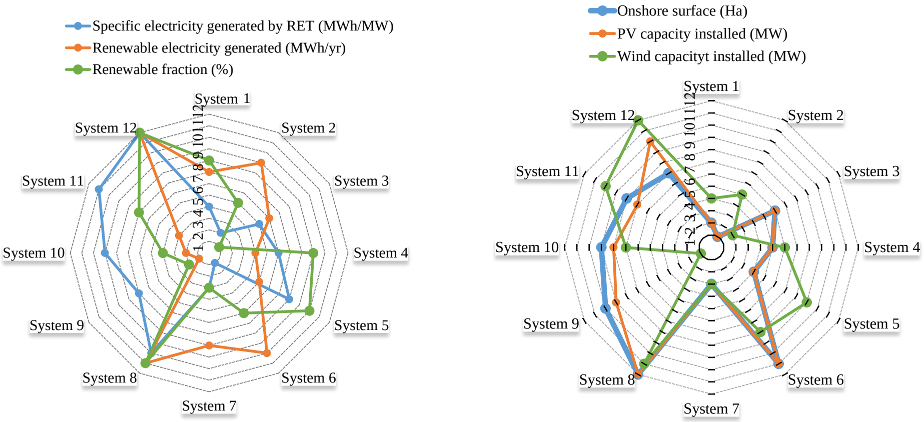
4.4. System Selection

From all system proposed, two have been selected to represent the results for the other two scenarios: Low Scenario and High Scenario. On the base of a DSV model through primary and secondary category rankings and through a decision support system and an applied spreadsheet tool, the selection analysis of the best system proposed was made. A score was given to each system, depending on its results. Systems were ranked and ordered from best to worst, considering the conditioned distribution of a specific variable. A 12-point score was given to the best result for each specific variable analysed. On the other hand, a 1-point score was given to the worst result for the same specific variable analysed.

For instance, the specific RE generated for each capacity unity proposed (MWh/MW) for all systems. In this case, the best system is the one with more electricity production (MWh) over less capacity installed (MW). The winner is System 6 in the Base Scenario for 2050 (see Figure 15). For the economical results, the same selection methodology was used and it is illustrated in Figure 16. The ranking positions of the system results are indicated in Table 11. The overall results are considered as the main category, while the economical, technical and land use results are considered as secondary categories. Through the Minitab®Statistical Software [87], these results have been validated.

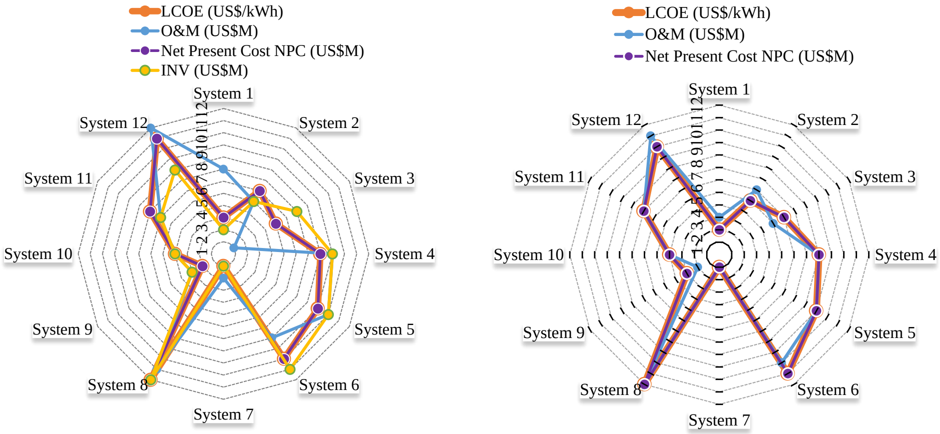
Table 11. Results for 2050 in the Base Scenario in ranking and points for the analysed systems.

	Main Category		**Secondary Categories**					
	Overall Points and Ranking Obtained		**Economical Points and Ranking Obtained**		**Technical Points and Ranking Obtained**		**Land-Use Points and Ranking Obtained**	
	Points	**Rank**	**Points**	**Rank**	**Points**	**Rank**	**Points**	**Rank**
System 7	1223	1	787	1	375	2	61	4
System 1	1158	2	724	3	364	3	70	2
System 9	1100	3	752	2	327	5	21	10
System 2	954	4	484	6	386	1	84	1
System 10	916	5	628	4	260	8	28	9
System 3	803	6	401	7	348	4	54	6
System 11	789	7	540	5	214	10	35	8
System 4	680	8	311	9	308	6	61	4
System 5	599	9	249	10	281	7	69	3
System 12	457	10	319	8	96	11	42	7
System 6	414	11	175	11	225	9	14	11
System8	189	12	90	12	92	12	7	12



(**a**) (**b**)

Figure 15. Technical evaluation results by system, from best (1) to worst (12) in 25-year lifetime on Cozumel Island for 2050 in the Base Scenario. (**a**) Renewable Electricity generated and RE fraction; (**b**) RE capacity installed and on-shore surface area used.

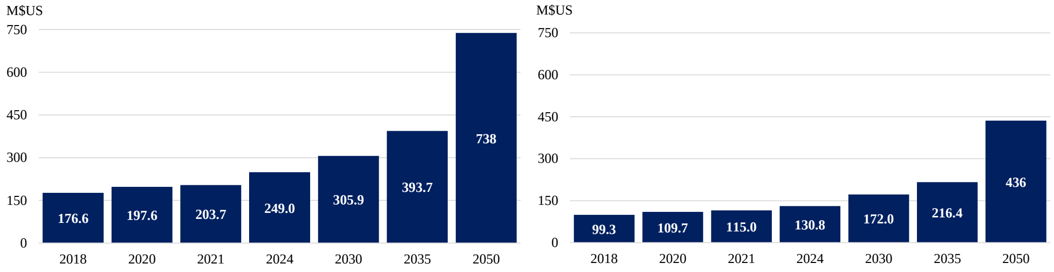


(**a**) (**b**)

Figure 16. Economical evaluation results by system, from best (1) to worst (12) on Cozumel Island for 2050 in the Base Scenario. (**a**) Levelized Cost of Energy (LCOE), Operation and Maintenance (O&M), Initial Capital Cost (INV) and Net Present Cost (NPC) for 25-year lifetime; (**b**) LCOE, O&M and NPC for 12.5-year lifetime.

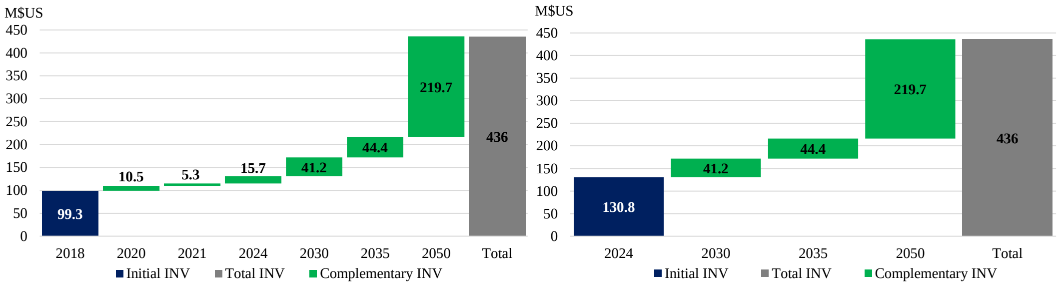
4.5. Selected System Analysis

Considering the previous results, System 7 (2 MW/333.33 kW Wind/PV) and System 2 (2.5 MW/333.33 kW Wind/PV + 3 MW off-shore wind) have been selected. The economic results for both are indicated in Table 9 and Figure 17. In this Figure 17, the investments will be made depending on the year chosen to start the project. It will not be a yearly investment. Figure 18 (System 2) and Figure 19 (System 7) indicate the initial capital investment for 2018 and 2024. They also show complementary investments that need to be made in order to have the required equipment capacity installed to reach the RE targets in the following years. Figures 18 and 19 (left side for both) show the initial capital investment to develop in 2018. The right sides of both show the initial capital investment to develop in 2024. Likewise, in view of the fact that implementing RE-integrated projects can last from 3 to 15 years [55], this study has considered 7 years of implementation. This would happen if, in 2017, the application process for the RE-integrating project is started before the Energy Regulatory Commission (CRE is its Spanish acronym) in Mexico. It is important to clarify that the timing of the investment takes into account the total cost of the project during the project lifetime, i.e., total cost by 2050 in the Base Scenario for System 2 (Figure 17a) will be 738 M$US, but if we choose to start the investments in 2024, the investment will be 249 M$US.



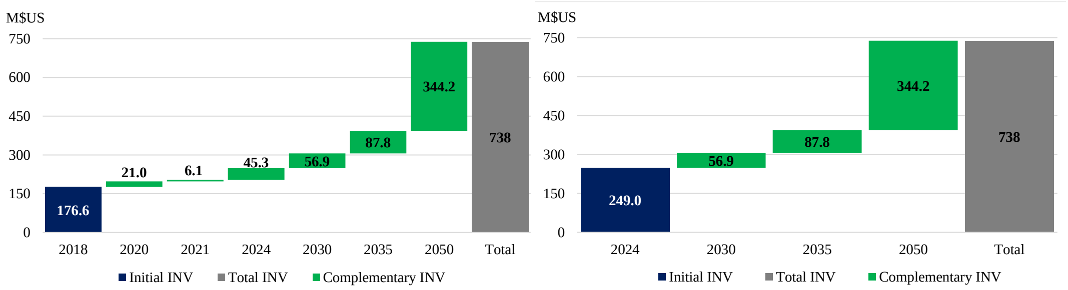
(**a**) (**b**)

Figure 17. The results are the investments needed depending on when the project starts. These amounts are calculated on the basis of the money invested in 2016 in US$M. (**a**) Investments for System 2 in the Base Scenario; (**b**) Investments for System 7 in the Base Scenario.



(**a**) (**b**)

Figure 18. After the project begins, each year shows a complementary investment that needs to be made until 2050. These amounts are calculated on the basis of the money invested in 2016 US$M. (**a**) Investments for System 2 starting in 2018; (**b**) Investments for System 2 starting in 2024.



(**a**) (**b**)

Figure 19. After the start of the project, each year shows a complementary investment that needs to be made until 2050. These amounts are calculated on the basis of the money invested in 2016 US$M. (**a**) Investments for System 7 starting in 2018; (**b**) Investments for System 7 starting in 2024.

A comparison of the results between Systems 2 and 7 is indicated in Figures 20 and 21 in the Base Scenario. The values of Internal Return Rate (IRR) and the discounted payback are compared in Figure 20. The values of the LCOE for each system are compared in Figure 21. The relative frequency results of the power discharge from the batteries for 2018 in System 7 for the Base Scenario showed that 89.2% of the time, over one year, the power discharge goes from 0 MW to 1 MW, and only 0.228% of the time does it reach the full power discharge. In future works, the results by complementary methodologies, such as cost minimization methodology or multi-criteria methodology, will be analysed. Also, the use of analytical programmed energy system tools and linear programming optimization models can provide more data in cost and energy storage optimization [88,89].

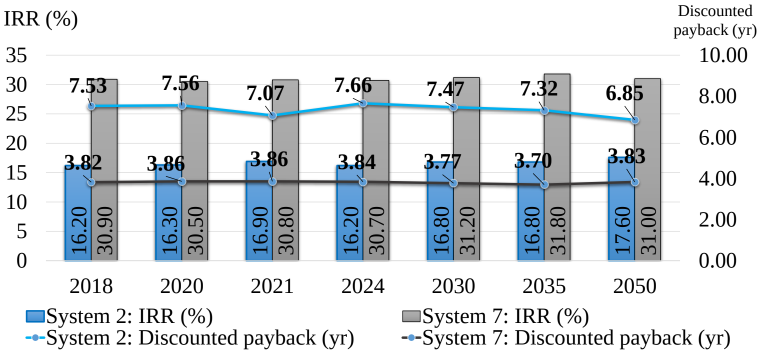


Figure 20. Comparison of economic results in Internal Return Rate (IRR) and Payback time between System 2 and System 7 in the Base Scenario.

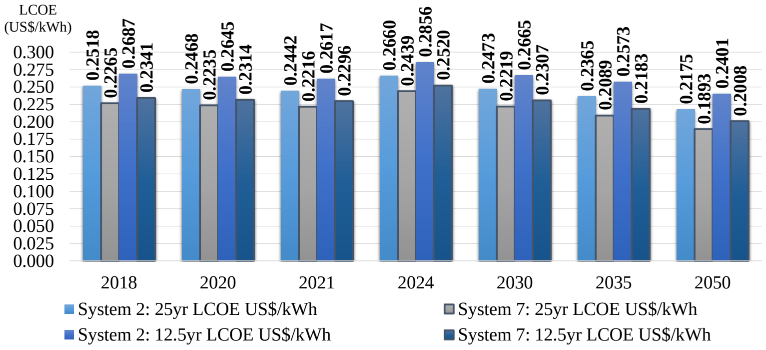


Figure 21. Economic results comparison in Levelized Cost Of Energy (LCOE) for 25-year and 12.5-year lifetime between System 2 and System 7 in the Base Scenario.

4.6. Emission Factor Reduction Results

The results of the CO_2 factor emission reduction for each MWh produced through electricity generation are indicated in Figure 22 in the Base Scenario for 2050, as an example. In Table 6, point 7 specifies the minimum factor of this emission to achieve the goals in this matter. The amount of CO_2 emissions in the 2000 for an electricity generation of 165,638 MWh on Cozumel Island was 100,095 tCO_2eq [60]. The emission factor in that year was 0.6043 tCO_2eq/MWh. In 2014, this emission factor dropped to 0.454 (−24.87% respect to 2000) [90]. In 2018, 2020, 2024, 2030, 2035 and 2050, the minimum emission factor was used, as indicated in point 7 of Table 6.

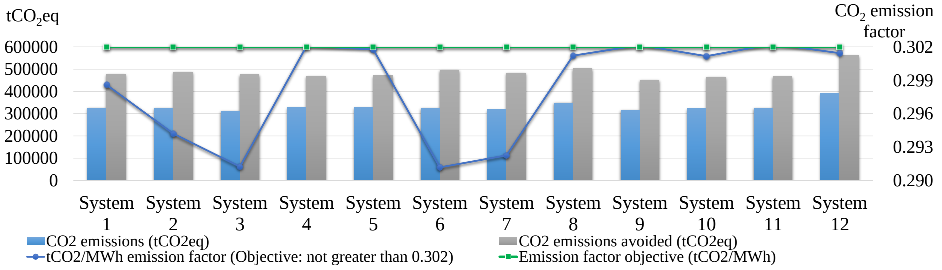


Figure 22. Results in CO_2 emissions emitted and avoided by each system and emission factor vs. their objectives on Cozumel Island for 2050 in the Base Scenario.

5. Conclusions and Discussion

To fulfil the 50-50 energy target on a small island—using Cozumel Island, Mexico, as a case study—in order to reduce the fossil fuel consumption through electricity generation from renewable energy sources to cover 50% of all electric consumption by 2050, 12 system proposals were compared and two systems were chosen. Focusing on their overall results, Table 7 shows the quantity of the equipment selected to achieve this target. Meanwhile, Table 9 shows the LCOE for all the systems analysed.

All systems proposed are able to completely satisfy the renewable electricity needed by 2050 in all scenarios. The differences between them were evaluated and two systems, System 2 and System 7, were chosen as eligible systems to be installed. Table 11 shows the ranking points. For System 7, the most important criteria were the overall and the economical results. The criteria used to choose System 2 were land use and technical results. System 7 (Rank 1) had an initial capital cost of 99.3 US$M by 2018 and System 2 (Rank 6) had an initial capital cost of 176.6 US$M (Figure 17). System 7 (Rank 4) had an on-shore impact of 223 Ha and System 2 (Rank 1) had an on-shore impact of 91.9 Ha, and an off-shore impact of 1140 Ha (Figure 11). Figure 21 shows the LCOE results from the two selected systems. According to the targets, input data and operational assumptions and constraints, the economic results shows that System 7 is the best system, with a lower LCOE of 0.1893 US$/kWh by 2050 in the Base Scenario. On the other hand, and also according to the targets, input data and operational assumptions and constraints, the land-used results show that System 2 is the best system, with a lower land surface of 25 Ha used by 2018 and 175 Ha by 2050 in the Base Scenario.

According to System 7, by 2018, in the Base Scenario, by reducing the battery backup time to 1 h, the initial capital cost (INV) was reduced from 99.3 USM$ to 81 USM$ and the LCOE dropped from 0.2265 US$/kWh to 0.2214 US$/kWh. Without batteries, the INV was 62.1 USM$ and the LCOE was 0.2188 US$7kWh. In this scenario and year, for System 7, the cost of each hour of backup with flow batteries was close to 20 USM$/h-backup time.

Each presented simulation includes a sensitivity analysis with a 25-year and 12.5-year lifetime for the PV/Wind technologies. In spite of the 12.5-year lifetime considered, the IRR was maintained above the 13.5% reported by the Mexican government for authorised and presented RE projects. As the results in this paper indicate, the IRR value fluctuated from 17.2% for System 2 to 31% for System 7. The sensitivity analysis was conducted on the basis that one major hurricane would strike the RE plant. If the major hurricane happens before the payback time has been reached, or two or more times within its lifetime project, this proposal could be economically infeasible (Figure 20). It is important to remark that these economic analyses were conducted without capital cost reductions through time. The main objective in this study was to formulate an approach to the investment needed according to the increase in RE and the fulfilment of the targets indicated at the beginning of this work. The report elaborated by the European Commission in the Joint Research Centre, through the Institute for Energy and Transport, contains an assessments of energy technology reference indicators. It is aimed at providing independent and up-to-date cost and performance characteristics of the present and future European energy technology portfolio projections for 2010–2050. As an example of these capital cost reductions, the fixed PV capital cost could be reduced by 58.6% by 2050 in relation to the 2014 prices in the high CAPEX consideration [91]. This study used the worst case scenario with no cost reductions.

The decision to choose to construct the final system relies on broad-based political support by the highest authority, because the decision includes risks in terms of the feasibility and sustainability of renewable energy development [57]. The methodology used in this case study can be applied to others small islands or to the SIDS for planning island electricity systems that will achieve low emission targets in their electricity generation.

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