Departament d'Enginyeria Elètrica
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Doctoral Thesis

# Planning the Integration of the Renewable Energy Sources on Islands, Under the National Electric System in Mexico

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**Planning the Integration of the Renewable Energy Sources on Islands, Under the National Electric System in Mexico**

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*This thesis is specially dedicated to those how love has encourage me to give this huge step in my life. God has played the main role in the journey that life is, He gives me the strength to reach this goal and to keep me moving forward. To my big love, my partner, my girlfriend, my lover, my mate, my everything, my wife* ***Claudia****: Thank you for loving and supporting me through these wonderful 24 years together. To my son and daughter, Isaac and Ixchel, they are the motor of my life to be a better father and person. To my Mom in heaven, you taught me the most important lesson in life: not give up and never lose my faith in God. To all my family that never let me down. For the last but not for the less, to my friends here in Spain and there in Mexico, from those that are part of my family in Cozumel Island, to the new family in CITCEA and specially the new family of Regnum Christy.*

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# Summary

The electric generation systems on islands are based generally on fossil fuel. This fact and its supply make the electricity cost higher than in systems used in the continent. In this thesis, as a first part, a review of the renewable energy generation systems on islands is elaborated. To do it, 77 islands from 45 different countries were analized. This analysis will allows to know how the implementation of renewable energy sources could help these islands in developing a renewable and sustainable energy sector, including a reduction of electricity generation cost. The de-carbonising in the electricity generation 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 the emphasis of this thesis 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. 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.

As second part of the thesis, this work shows the results from a study case of the application of renewable energy technology in Cozumel Island, Mexico. This island is located in the Riviera Maya, in the Occidental Caribbean Sea. The analysis developed was made through long- term statistical models. A deterministic methodology was used to perform time-series simulations. As a first integration approaching, the simulations show that for the year 2050 a feasible integration of a system based on wind/PV can be achieved on the Island, reducing the electricity price from 0.37 US$/kWh to 0.24 US$/kWh (2050 in the Base Scenario). This result had a renewable penetration of 22.3% and does not considered a battery system or changes in the existing electric grid. With this scenario, the government will achieve its targets in renewable energy and in the reduction of the emissions of $CO_2$. This will allow reaching a sustainable electricity sector.

In a second approach, and according to the results, all systems proposed are able to completely satisfy the renewable electricity needed by 2050 in all scenarios proposed. 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 0.2401 US$/kWh and for System 7 was 0.2008 US$/kWh by 2050 in the Base Scenario. Meanwhile, the Internal Rate of Return (IRR) value fluctuated from 17.6% for System 2 to 31% for System 7, with a renewable fraction of penetration for System 2 of 56.1% and for System 7 of 56.9% by 2050 in the Base Scenario. The selection of the best system was made on the base of a Dimensional Statistical Variable (DSV) through primary and secondary category rankings. The presented proposal of three phases methodology determines the best systems for capturing the lower initial capital cost and the higher competitiveness of this new proposal compared with the current system of electricity generation on the Island, and can be applied on small islands as well.

As third part of this thesis, the analysis presents an optimization of the energy planning, a grid assessment, and an economic analysis, considering three growing scenarios (Low, Base and High) in the electricity consumption, to supply the energy demand for a hybrid power system (Photovoltaics/Wind/Diesel/Battery) on a small island by 2050. The main aim of this study is to present a four phases methodology to optimize and reduce the backup time of the battery bank, included from the hybrid power generation system selected. Also, it will compare four different battery technologies, simultaneously, without changes in the renewable energy targets settled in 50% until 2050 and without changes in the safe continuous operation of the grid. The methodology includes a grid assessment analysis to obtain a reliable, strong and safe operation response based on the grid code parameters, even in case of electric disturbance.

In the proposed four phases methodology the analysis is developed on the

basis of the use of two simulation model tools. The First simulation model tool determines the optimal values of variables that the system designer controls, such as the mix of components (Photovoltaics/Wind/Diesel/Battery) that make up the system and the size or quantity of each variable. This model uses the multi-year analysis based on a time-domain simulation run at the energy-flow level with discrete time-steps of 1 hour. The Second simulation model tool assumes all the variables and parameters on the grid as constants during the period of time analyzed. The power flow is analyzed through a programming language command script function and reflects the system response at a specific time with given specific variables and parameters. The final technical proposal and its financial analysis are obtained applying and validating this methodology on a small island, as well as, the selection of the system to be installed for the renewable electricity generation. The electric grid modifications and reinforcements through the years until 2050, according to the grid code and the renewable energy targets settled for the island's electric power system are included.

According to the results of this optimization, the lowest LCOE obtained was the system with the sensitivities applied that includes the Zn-Br flow batteries, 0.2036 US$/kWh by 2050 in the Base Scenario. Meanwhile, the Internal Rate of Return (IRR) value was 30.37% for this System, with a renewable fraction of penetration of 59%. The system analysis results were considered without the Wind Off-shore technology.

For the 100% of the renewable energy supplying the power demand PRE-Analysis, the lowest LCOE obtained including 8-3 MW Wind Off-shore turbines was 0.3006 US$/kWh by 2050 in the Base Scenario. These results are combining wind off-shore/wind on-shore/PV/Zn-Br batt/diesel, with a renewable fraction of penetration of 100%.

# Resumen

Los sistemas de generación en islas generalmente están basadas en combustible fósil. Éste hecho y su suministro ocasionan que el costo de la electricidad sea mayor que en los sistemas continentales. En esta tesis y como primera parte, se elaboró una revisión de los sistemas de generación de electricidad en las islas. Para lograr esto, se analizaron 77 islas de 45 diferentes países. Éste análisis permitirá conocer cómo la implementación de las fuentes de energía renovable puede ayudar a éstas islas a desarrollar un sector sostenible y renovable, incluyendo la reducción del costo en la generación de electricidad. La des-carbonización en la generación de electricidad es necesaria para reducir el consumo de combustible fósil, para reducir la contaminación y para lograr los objetivos propuestos en el escenario de los 2 grados en la perspectiva de las tecnologías de la energía (2DS, por sus siglas en inglés). Las pequeñas islas no están excentas de éstos objetivos, por esto, el énfasis en ésta tesis está localizado en el objetivo 50-50: reducir el consumo de combustible fósil usado en la generación de electricidad a travéz de las fuentes de energía renovable (RES, por sus siglas en inglés), y así cubrir el 50% de la electricidad demandada por las pequeñas islas para el año 2050. Éste análisis estará basado en tres factores: en el económico, en el técnico y en las posibilidades del uso de la tierra para integrar las tecnologías de energía renovable (RETs, por sus siglas en inglés) en la red eléctrica existente.

Como segunda parte de la tesis, en ésta se muestran los resultados de un caso de estudio en la aplicación de la tecnología de energía renovable en la isla de Cozumel, en México. Esta isla está localizada en la Riviera Maya, en el Mar Occidental del Caribe. El análisis desarrollado fué desarrollado a través de modelos estadísticos a largo plazo. Se ha usado una metodología determinística para realizar las simulaciones en las series de tiempo. Cómo un primer acercamiento para la integración, las simulaciones mostraron que se puede lograr para el 2050 una integración de un sistema basado en fuentes eólicas/fotovoltáicas en la isla, reduciendo el precio de la electricidad de 0.37 US$/kWh a 0.24 US$/kWh (en el escenario base para el año 2050). El resultado tuvo una penetración de la energía renovable de 22.3% sin considerar un sistema de baterías o cambios en la red eléctrica existente. En este escenario, el gobierno logrará sus objetivos en energía renovable y en la disminución de la emisión de $CO_2$. Esto permitirá lograr un sector sostenible en la electricidad.

En un segundo acercamiento y de acuerdo a los resultados, todos los sistemas propuestos pueden completamente satisfacer la electricidad renovable necesaria para el año 2050 en todos los escenarios propuestos. De los 12 sistemas propuestos que se compararon, dos sistemas, el Sistema 2 y el Sistema 7fueron elegidos como los sistemas para ser instalados. El resultado del costo nivelado de energía (LCOE, por sus siglas en inglés) para el Sistema 2 fué de 0.2401 US$/kWh y para el Sistema 7 fué de 0.2008 US$/kWh para el año 2050 en el escenario base. Mientras tanto, el valor de la tasa interna de retorno (IRR, por sus siglas en inglés) fluctuó del 17.6% para le Sistema 2 al 31% para el Sistema 7, con un factor de penetración en renovable para el Sistema 2 del 56.1% y para el Sistema 7 del 56.9% para el año 2050 en el escenario base. La selección del mejor sistema fué realizdo sobre la base de una variable estadística dimensional (DSV, por sus siglas en inglés) a través de una clasificación de categorías primaria y secundaria. La presente propuesta de metodología de tres fases determina el mejor sistema para obtener el menor costo inicial de capital y la mayor competitividad de esta nueva propuesta, comparada con el actual sistema de generación de electricidad en la isla y que también pueda ser aplicada a las pequeñas islas.

Como tercera parte de la tesis, el análisis presenta una optimización de la planeación energética, una evaluación de la red y un análisis económico, considerando tres escenarios de crecimiento (bajo, base y alto) para el consumo de electricidad y para suministrar la energía demandada por medio de un sistema híbrido de potencia (fotovoltáico/eólico/diesel/batería) en

una isla pequeña para el año 2050. El principal objetivo de este estudio es, presentar una metodología de cuatro fases para optimizar y reducir el tiempo de respaldo del banco de baterías incluídas en el sistema híbrido de generación de energía seleccionado. También comparará cuatro diferentes tecnologías de baterías de manera simultánea, sin cambios en los objetivos planteados en 50% para el año 2050, y sin cambios en la operación segura y continua de la red. La metodología incluye un análisis de la red para obtener una segura, fuerte y confiable respuesta de operación basada en los parámetros indicados en el código de red, incluso en caso de disturbios eléctricos.

En esta metodología de cuatro pasos, el análisis esta desarrollado en base al uso de dos herramientas de modelos de simulación. La primera herramienta de modelos de simulación determina los valores óptimos de las variables controladas por el diseñador del sistema, tales como la mezcla de los componentes (fotovoltáico, eólico/diesel/baterías) que conformen el sistema, o la cantidad o tamaño de cada variable. Este modelo usa el análisis multi-año basado en corridas de simulación de tiempo-dominio a niveles de flujo de energía en paso de tiempo discretos de 1 hora. La segunda herramienta de simulación asume todas las variable y parámetros en la red como constantes durante el periodo de tiempo analizado. El flujo de potencia es analizado a través de un comando de función de conteo en un lenguaje de programación y refleja la respuesta del sistema en un tiempo específico, con unos parámetros y variables específicas dadas. La propuesta final técnica y su análisis financiero son obtenidos aplicando y validando esta metodología en una isla pequeña, así como también, la selección del sistema a ser instalado para la generación de electricidad renovable. Aquí se incluyen las modificaciones y refuerzos a la red eléctrica a través de los años hasta el año 2050, realizados de acuerdo con el código de red y con los objetivos en energía renovable indicados para el sistema eléctrico de potencia de la isla.

De acuerdo a los resultados de esta optimización, el más bajo LCOE obtenido fué el del sistema que incluye las baterías de flujo Zinc-Bromine, en el cual las sensitividades fueron aplicadas y que fué de 0.2036 US$/kWh para el año 2050 en el Escenario Base. Mientras que el valor de la tasa

interna de retorno para este sistema fue del 30.37%, con una fracción de penetración de las renovables del 59%. Los resultados de los análisis fueron sin considerar la tecnología eólica fuera de costa (Off-shore).

Para el caso del PRE-análisis de cuando la energía renovable suple el 100% de la demanda de potencia, el menor LCOE obtenido incluyendo 8-3 MW turbinas eólicas Off-shore fué de 0.3006 US$/kWh para el año 2050 en el Escenario Base. Estos resultados son combinando el eólico Off-shore/eólico On-shore/fotovoltáico/baterías Zn-Br/diesel, con un factor de penetración de las renovables del 100%.

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# 1 Introduction

## 1.1 General objective

With the energetic reform that Mexican Government is experiencing today, and the expectation to have an energetic sector with more participation of clean and renewable energies, makes that be necessary have a lots of paths and tools to achieve it.

The general objective of this thesis proposal is help to fulfil the Mexican government goals in renewable energy sector and to reduce the fossil fuel consumption and its generation cost in the electricity production.

## 1.2 Specific objectives

1. Create a methodology and a tool to allow an integration of renewable energy sources on islands, within of their national electrical system, with which also can be develop future scenarios in electric sector, through the implementation of the renewable energy technology.

2. Study the holistic integration of the renewable energy, applying them to the power generation systems on islands, achieving reliability and optimization for the hybrid system, also providing a reliable, secure, rational and flexible electric system. Reducing, at the same time, the fossil fuel consumption and its generation cost in the electricity production.

3. Determine the economic and fiscal incentives models to promote the develop of renewable energy systems, and to maintain an accessible cost of the electric tariff for population, industries and services, achieving

with this, the reduction of electricity generation costs and the amount of the government budget that spends in fossil fuels consumption, through the subsidies.

## 1.3 Basic Analysis

Currently, we are already witnessing serious consequences of the global warming. Policies have been enforced to reduce the effect of these consequences. Renewable Energy (RE) seems to be one of the ways to solve the situation. These policies have focused mainly in two sectors: electricity and heating and cooling. The importance of the transportation sector has been increased recently by policy maker [75]. It is expected that in 2040 the 25% of electricity will be generated through RE. Anyway, that amount of clean energy will not be enough to avoid the 2°C temperature increase [76]. Reasons for this temperature increase include global population growth, increase of energetics consumption, power demand growth, pollutant emission and global warming. All these events have been drastically increased in the last decades and will continue their growth.

De-carbonisation in the generation of electricity is imperative in order to meet the Energy Technology Perspectives 2 °C Scenario (2DS) targets [77]. Among energy end uses, heating and cooling systems offer substantial potential for de-carbonisation that so far has been largely untapped. Broad application of energy efficiency and switching to low-carbon final energy carriers (including de-carbonised 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 [37]. Table 1.1 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 in-existent GHG emissions and taking a path toward a net zero GHG emissions. Also, Table 1.1 shows the Paris Agreement signature, acceptance and ratification dates of those commitments [37, 38].

For instance, one of the main objectives in the electricity system in

Mexico, as well as in other countries, such as Kazakhstan [78], United Arab Emirates [79], and in Equatorial Guinea [80], 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 [81], so it is necessary that the results obtained through this study help those islands to install the right equipment combination to achieve sustainable solutions.

| Intended Nationally Determined Contributions (INDCs) | | | | | | Paris Agreement | |
|---|---|---|---|---|---|---|---|
| Number of parties that have submitted an INDC: | | 189 | | | | Ratification | |
| Share of global emissions covered by INDCs: | | 99.10% | Summary of the INDCs | Share of 2012 Greenhouse Gases (GHG) | Signature | Acceptance (A) | Entry into Force |
| 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 hydro-power capacity to 9.4 gigawatt 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 1.1: Intended Nationally Determined Contributions (INDCs) and the Paris Agreement signature dates [37, 38].

| **Intended Nationally Determined Contributions (INDCs)** | | | | | | **Paris Agreement** | |
|---|---|---|---|---|---|---|---|
| **Number of parties that have submitted an INDC:** | | **189** | | | | **Ratification** | |
| **Share of global emissions covered by INDCs:** | | **99.10%** | **Summary of the INDCs** | **Share of 2012 GHG** | **Signature** | | **Entry into Force** |
| **No.** | **Country** | **Date** | | | | **Acceptance (A)** | |
| 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 renewable 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 |

Table 1.1: *Cont.*

Works published by [82, 83] 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 [84]. 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 hour to determine the Net Present Value for a chosen configuration over a specified project lifetime [85]. More information about the HOMER model formulation is available at [30, 31].

For many types of micro-power systems, in particular those involving intermittent renewable power sources, a minimum one-hour time step is necessary to model the operational behaviour 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 [86].

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. [87], 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 [88], 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 [89], 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.

Nowadays there are several renewable generation technologies for the carbon-free emission electricity production. For the small islands with less than 100,000 inhabitants [11], the integration of these Renewable Energy Technologies (RETs) is an environmentally friendly option to reduce the fuel cost of its electricity production. However, the use of the RETs in an isolated or weak electric grid, produces impacts on the grid's operation, due to the variability of the energy generation over the period of time. The nature of energy generation variability depends on the resources that are being used to supply the load. Alqurashi et al. [90] provide a technical overview of the advances in this area to solve some of these uncertainties. Maleki et al. [91] analyzed a resource and load uncertainties in a hybrid renewable energy system. In a hybrid generation system (Renewable + Diesel + Batteries), in order to supply all the energy production, the system must coordinate this renewable production with the diesel generator production to reduce the fossil fuel consumption. The network should be able to intake the renewable energy to fulfil the targets according to the agreement on the political goals of any country, region or city. An example of this, various studies from literature show that these renewable energy targets go from 50% globally in islands [11], 50% in Cozumel Island, Mexico [35], and 65% in Graciosa Island, Azores [92] to 100% in Canary Islands, Spain [89], 100% in Åland Islands, Finland [93], 100% in Cook Islands [94] and 100% in Mauritius Island [95]. The hybrid system must supply the power demand in every step of time designed with the lowest cost of production. The constraints and targets through the sensitivity analysis chosen, like cost reductions, fuel price variations, inflation rate variations and efficiency variations, can reduce the uncertainty threshold in the final decision to obtain the hybrid power system to install.

Several studies are been presented to integrate the renewable electricity generation and coordinate the energy balance and grid response for an isolated or weak electric grid in a hybrid generation system. Sigrist et al. [96], Zhang et al. [97], Obi et al. [98], Dufo-López et al. [99], Kwon et al. [100], and Szabó et al. [101] analyzed technically and economically the renewable energy integration including the energy storage system. Other studies have been developed with an emphasis in technical analysis for the renewable electricity integration, as can be seen in the work of Adefarati and Basal [102], Wijayatunga et al. [103] in Maldives Islands, Koepke and Groh [104] in Bangladesh, and Sheng et al. [105]. In this last work, the marine current turbine works together with ocean compressed energy storage. Some works propose the use of the energy storage system for the system planning, the dispatch operation, the frequency regulation and to provide the spinning reserve needed. An example of this are those studied by Shang et al. [106], Miguel et al. [107] in Madeira Island, Setas et al. [108] in Terceira Island, and Fleer and Stenzel [109]. Or simply analyzing the battery degradation process [110] or analyzing the risk in the use of the battery system (Lithium-ion) in a grid scale [111]. Finally, there are technical studies to integrate the renewable electricity generation technology with the energy storage system, madden according to the political framework and strategies for a country. Also, to develop those political frameworks and strategies, in order to achieve a better renewable generation technology integration. These works are from Taliotis et al. [112], Taibi et al. [113], Simoes et al. [114], Lin et al. [115], and Staffell and Rustomji [116]. The work of G.M. Shafiulla [117] propose the techno-economic and environmental prospects of renewable energy integration in the Capricornia region of Queensland, Australia. This work includes a load management system by which utilities can manage customer load demand efficiently.

Other similar works can be found. For example, Gan et al. [118] developed an optimization model to operate the diesel generator from a hybrid power system in an optimum way. Muruganantham et al. [119] describes the state of art in various load flow methods used to analyze the parameters of the distribution network. Therefore, the contribution of this study is a methodology for an integral energy planning, a grid assessment and an economic analysis, considering three growing scenarios (Low, Base and High) in the electricity consumption for a hybrid power system (Photovoltaics/Wind/Diesel/Battery) on a small island through time until 2050. Starting in the energy planning, this methodology establishes the initial integration of the renewable technology until the grid assessment and its safe operation and response, including the grid reinforcements through the years and the financial analysis (always fulfilling the renewable energy targets). The results in the literature reviewed partially do this, but most of them do not do it as an integral study. So, in this paper, the holistic impact of the integration of a new renewable energy technology configuration through the years on the dynamic behaviour and stability of the existing power system is systematically analyzed. The hybrid energy system analyzed deals with the energy planning and dynamic and stability simulations in an hourly time resolution through a DIgSILENT Programming Language (DPL) command script function for each year. This hourly combination can validate the energy and grid planning scenarios in the short-term dynamic simulations on frequency and voltage stability, and for a long-term planning scenarios analysis until 2050, for instance. Also, this paper has the aim to optimize and to reduce the battery bank backup time and to compare four different battery technologies. This should not present any changes in the renewable energy targets settled for the safe continuous operation of the grid. The results and response of this hybrid power system (Photovoltaics/Wind/Diesel/Battery) proposed will be compared always against the results and response of use only a fossil fuel power system (only Turbo-gas machines burning Diesel), in order to supply the electricity demand in the growing scenarios through the years until 2050.

## 1.4 Content Main Structure

In Chapter 2, a review of several proposals for the application of Renewable Energy Technologies (RETs) on islands and the integration into their electrical grids is analyzed. This chapter reviews the way Island States have approached the integration of the Renewable Energy Sources (RES) and RETs, and their combination with energy storage in the electric grids under various scenarios of power demand. To illustrating the feasibility of the application of these technologies compared with the actual fossil fuel energy technology, this analysis is applied on the base of the integration of some RETs into the electric grid in Cozumel Island, Mexico as the study case. Results indicate that, even without electricity storage Mexican government can meet its targets in the electric sector within a feasible financial proposal.

In Chapter 3, a deterministic three steps methodology is used to set up the long-term electrical system target to be achieved. This methodology sets the targets on the basis of national, regional or local energy planning objectives; develops the analysis of the island's electrical system data; uses the results from the electrical system data analysis to build the prospective scenarios. The time-series simulations are done using a deterministic methodology software tool and long-term statistical models. The local resource potential is determined according to the natural resource potential analysis. The integration of the hybrid system into the island's electric grid is simulated through a deterministic methodology with a time-series simulation software tool. Finally in this chapter, the 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.

A deterministic methodology is used to perform time-series simulations by Kaldellis et al. [120]. 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 [121]. 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 [122]. On the basis of this model, in Fiji Islands, a linear regression model to estimate grid-electricity demand was considered [123]. For the energy supply on Wang-An Island, similar rank points were given for identifying the optimal integrated electricity production from RES [124].

The four phases methodology is developed to assess an integral approach and battery optimization for the renewable energy integration and for the electric grid assessment. This methodology includes the battery backup time reduction analysis. Also, satisfy the power demand on the small island in order to fulfil the renewable energy targets and constraints for the planning scenarios of electricity consumption growing selected or developed. From a hybrid power system with batteries included, reduce the backup time from the battery bank and compare four different battery technologies simultaneously, as well. Ensures the reliability and safety of the grid's operation response according to the hourly input data in the simulations on the base of the results obtained. Ensures the stability and safety of the grid's operation response after an event that produces system instability and unbalances. Finally, obtains the minimum LCOE and the minimum NPC with the maximum NPV for the hybrid system chosen.

Chapter 5 indicate why Cozumel Island has been chosen as a typical example of an island in the Caribbean. Its characteristics of warm weather, tourism activity, the coral reefs, extensive natural areas and an environment sensitive to the climate change are typical for tropical areas. Mostly, these areas have the common characteristics of an electricity generation based on diesel or fossil fuels. The electrical system, the RE resources and sources and the proposed systems will be investigated. 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. The results of the study can be applied to other islands with similar characteristics.

In Section 7 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.

Section 7.3 will display the results of the arrangements proposed for the analysis done in Chapter 7. The reduction of the $CO_2$ emission factor will then be indicated at the end of Section 7.3.6.

Chapter 6 shows how the interconnection of Renewable Energy Technology into a Diesel Base Electric Grid is carried out, running the Cozumel electric grid's simulations. Taking into account the following conditions: a) off grid; b) no RE sources; c) power supply only with diesel turbo machines, and; d) using similar data for existing electric generators, electric loads, transformers, cables and buses.

The interconnection of energy storage into a resultant hybrid renewable energy generation grid is analized on Chapter 7. In this chapter, the simulations of the RETs integration on the Cozumel Island's grid, in combination with *diesel turbo-gas machines* and flow batteries have been done. This can be achieve employing a software tool that 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. A score was given to each system proposed, depending on their results. Systems were ranked and ordered from best to worst, considering the conditioned distribution of a specific variable.

The optimization of the renewable technology combination: Photovoltaic/Wind/Batteries/Diesel analized and selected will be carried out in Chapter 8, and its content is structured as is indicated below. This analysis will compare the use of only fossil fuel vs. the use of a hybrid system to satisfy the electric demand through three growing scenarios until 2050. This date was selected according to the National Energy Planning for Cozumel Island in Mexico. In Sections 8.3 and 8.4, the steady-state analysis and the dynamic stability analysis are elaborated, including the power system response as well. This is taking into account all the electric grid's modifications and reinforcements to be done. Then, the final complete power system will be selected as the system to be installed on the Island. By an economic analysis formulated at Section 8.5, the final Initial Capital Cost (ICC), the Net Present Value (NPV), the Internal Return Rate (IRR) and the Levelized Cost Of Energy (LCOE) for the complete power system are obtained. Section 8.5 includes the ICC of the hybrid generation system, and the ICC of the electric grid proposed and modified.

Chapter 9 was developed to indicate a pre-analysis in order to have a 100% of renewable electricity generation to satisfy the power demand until 2050. The input data to achieve this 100% of renewable energy is equal to that indicated in the previous chapters.

Discussions and results summary are addressed in Chapter 10, where the barriers, uncertainties and the lack for the access to financing can be found. Contributions and conclusions are highlighted in Chapter 11, at the end of this thesis.

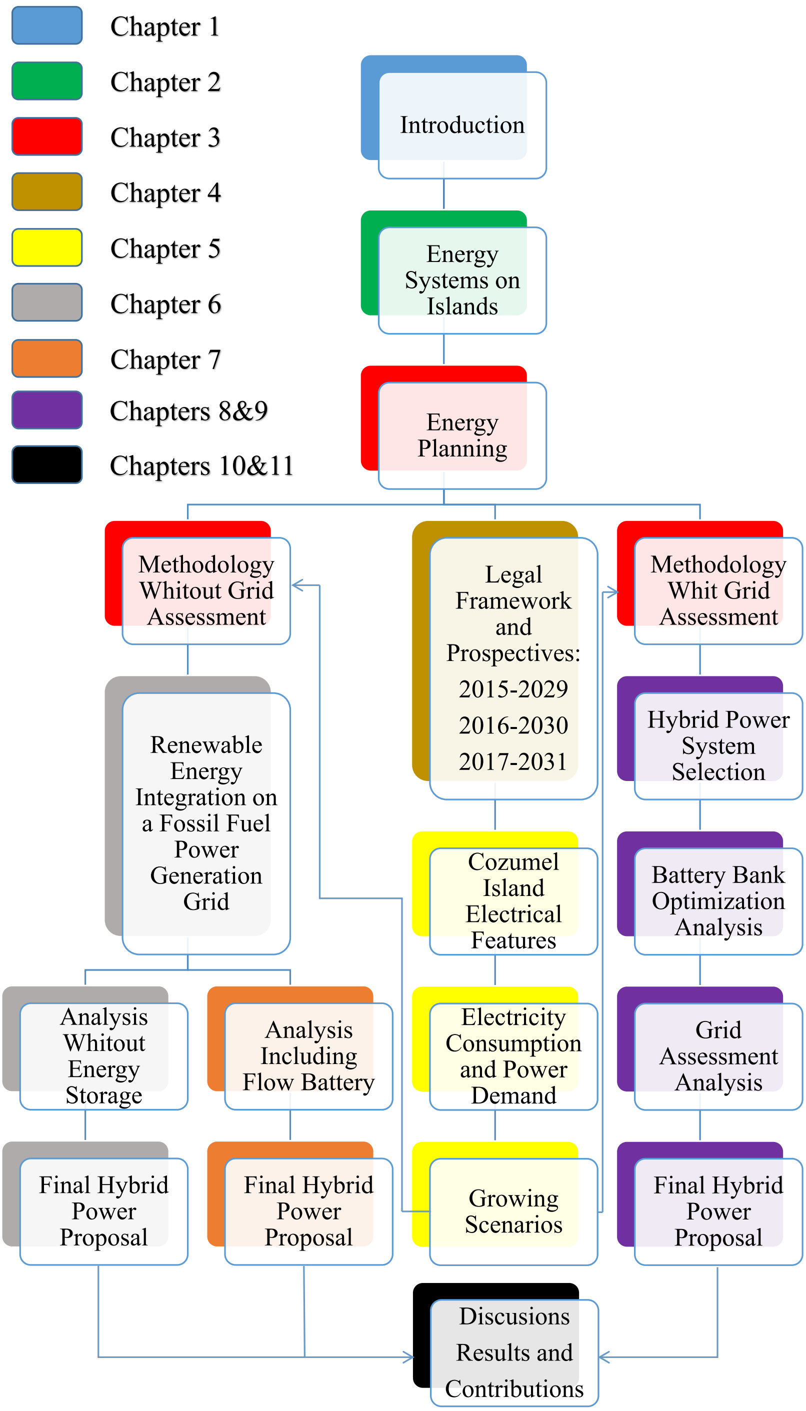


Figure 1.1: Main Structure of the Thesis Content

# 2 Energy Systems on Islands

## 2.1 Current Renewable Energy Development Globally

The 2016 year was a year with several developments on renewable energy technology integration around the world. Most of the renewable energy technologies were installed in developing countries, but mostly in China. From around 9.8 millions of employed people in this sector, PV solar and biofuels technologies are the largest numbers of jobs creators. Several cities have established new commitments to 100% renewable energy. For the third consecutive year, global energy-related carbon dioxide emissions from fossil fuels and industry were nearly flat in 2016. The increasing use of the renewable energy and the improvements in energy efficient, also the declining coal use worldwide, were the responsible for this $CO_2$ emission diminution [39].

### 2.1.1 Power

Table 2.1 shows the 2016 renewable energy indicators vs. year 2015. In hydro-power, the Renewable Global Status Report 2016 [125] reported a global total of 1,064 GW of hydro-power capacity at end-2015. The value of 1,071 GW shown in this Table 2.1 reflects the difference between end-2016 capacity (1,096 GW) and new installations in 2016 (25 GW). Differences are explained in part by uncertainty regarding capacity retirements and plant re-powering each year. Note also that the Renewable Global Status Report 2016 [125] strives to exclude pure pumped storage capacity from hydro-power capacity data. Solar hot water capacity data include water collectors only. Investment data are from Bloomberg New Energy Finance and include all biomass, geothermal and wind power projects of more than 1

MW; all hydro projects of between 1 and 50 MW; all solar power projects, with those less than 1 MW estimated separately; all ocean energy projects; and all biofuel projects with an annual production capacity of 1 million litres or more. Data for tendering/public competitive bidding reflect all countries that have held tenders at any time up through the year of focus [39]. Biofuel policies include policies listed both under the biofuels obligation/mandate Renewable Energy Support Policies and in National and State/Provincial Biofuel Blend Mandates.

| | | **2015** | **2016** |
|---|---|---|---|
| **INVESTMENT** | | | |
| New investment (annual) in renewable power and fuels | billion USD | 312.2 | 241.9 |
| **POWER** | | | |
| Renewable power capacity (total, not including hydro) | GW | 785 | 924 |
| Renewable power capacity (total, including hydro) | GW | 1856 | 2020 |
| Hydro-power capacity | GW | 10713 | 1099 |
| Biopower capacity | GW | 106 | 115 |
| Biopower generation (annual) | TWh | 464 | 507 |
| Geothermal power capacity | GW | 13 | 13.8 |
| Solar PV capacity | GW | 228 | 306 |
| Concentrating solar thermal power capacity | GW | 4.7 | 4.77 |
| Wind power capacity | GW | 433 | 490 |
| **HEAT** | | | |
| Solar hot water capacity | GWth | 435 | 459 |
| **TRANSPORT** | | | |
| Ethanol production (annual) | billion litres | 98.3 | 98.9 |
| Biodiesel production (annual) | billion litres | 30.1 | 30.11 |
| **POLICIES** | | | |
| Countries with policy targets | # | 173 | 179 |
| States/provinces/countries with feed-in policies | # | 110 | 113 |
| States/provinces/countries with RPS/quota policies | # | 100 | 103 |
| Countries with tendering/public competitive bidding | # | 16 | 37 |
| Countries with heat obligation/mandate | # | 21 | 24 |
| States/provinces/countries with biofuel mandates | # | 66 | 71 |

Table 2.1: 2016 indicators for global renewable energy [39] (adapted).

### 2.1.2 Market

Bioenergy development and deployment activities continued spreading into new regions and countries, as India and Africa. Bio-power production has increased by some 6% in 2016 in European Union, Asia and in Republic of Korea. Global ethanol was stable in USA, China, India, Nigeria and South Africa. Biodiesel recovered with strong growth in Indonesia and Argentina. Biomethane grew in USA stimulated by the renewable fuel standard. In the geothermal industry, Indonesia and Turkey added 200 MW of capacity. Globally, in 2016, geothermal production was about 78 TWh, 1 TWh lees than in 2015. In hydro-power, the capacity was increased by more than 3% in China, Brazil, Ecuador, Ethiopia, Vietnam, Peru, Turkey, Lao PDR, Malaysia and India. Commercial success for ocean energy technologies remained in check due to perennial challenges. This is because the financing obstacles, high risk, high upfront costs and by the need for improved planning, consenting and license procedure. The annual market in PV solar was increased nearly 50% in 2016 respect to 2015, rising more than 31,000 solar panels installed every hour. At least 17 countries had enough solar PV capacity by year's end to meet 2% or more of their electricity demand, and several countries met far higher shares during 2016, including Honduras (9.8%), Italy (7.3%), Greece (7.2%) and Germany (6.4%) [39].

By the year's end of 2016, the global capacity in concentrating solar thermal power capacity (CSP) was more than 4.8 GW online. It was expected that 900 MW of CSP capacity was added at the end of year 2017. In these two years (2016 and 2017) the new facilities incorporated thermal energy storage, which can provide dis-patchable power to grids with high penetration of variable renewable production. In this respect, CSP is receiving increased policy support in countries with a need for energy storage, or for strong industrialization and job creation agendas, also in which count with limited oil and gas reserves and constrained power networks. For the solar thermal cooling and heating market, the year 2016 was challenging in the larger, established markets due to a number of factors, including low oil and gas prices; declining demand from home-owners, long the core market segment for the solar thermal industry; and reduced interest in solar thermal technology among installers. Many suppliers of these systems responded by successfully diversifying their portfolios for commercial clients. The use of solar thermal technologies in industry expanded quickly in Mexico and India in particular. Solar cooling systems are used increasingly in sun-rich countries to supply cooling in commercial and public buildings in conjunction with year-round solar hot water. Onshore wind power is the most cost-effective option for new grid-based power in an increasing number of markets. Offshore, about 2.2 GW of capacity was connected to grids, including the first commercial projects in the Republic of Korea and the United States, and substantial new capacity in Germany, the Netherlands and China. By year's end of 2016, more than 90 countries had seen commercial activity. At least 24 countries met 5% or more of their annual electricity demand with wind power, and at least 13 met more than 10% [39].

### 2.1.3 Energy Access

Approximately 1.2 billion people (about 16% of the global population) live without electricity, and about 2.7 billion people (38% of the global population) are without clean cooking facilities. In 2016, many countries implemented policy measures aiming to support distributed renewable energy (DRE) deployment, including dedicated electrification targets, fiscal incentives, regulations, auctions and exemptions on value-added tax (VAT) and import duties. Quality Assurance (QA) frameworks also were adopted, particularly for off-grid solar products, to reduce the sale of low-quality products on the market. New business models and technologies are accelerating access to DRE systems in the developing world. The old paradigm of energy access through grid extension alone is becoming obsolete as bottom-up customer demand is motivating hundreds of millions of households to generate their own modern energy to provide services through off-grid units or community-scale mini-grids. The most popular business models within the DRE sector in 2016 were distributed energy service companies (DESCOs) for mini/micro/pico-grids, the PAYG model for stand-alone systems, and micro-finance and micro-credit [39].

### 2.1.4 Energy Efficiency

Energy savings help renewable energy to meet a higher share of energy demand and to enter new markets. Worldwide, there is a growing recognition that energy efficiency plays a key role in reducing pollution and that it can provide multiple additional benefits, including enhanced energy security, reduced fuel poverty and improved health. Energy demand for several appliance and equipment categories also continues to rise, despite improvements in efficiency, due largely to a rapid increase in units per household, in addition to the growing number of electrified households. An increasing number of countries is setting energy efficiency targets; adopting new policies and standards, and updating existing ones; and introducing new financial incentives to channel additional funding towards energy efficiency. Policies have been the main driver of energy efficiency improvements, with innovations in technology and finance also playing important roles. Many policies attempt to harness the synergy between energy efficiency and renewable energy [39].

### 2.1.5 Policy Landscape

Policy makers continued to focus on financial incentives in the form of grants, loans or tax incentives to increase deployment of renewable heating and cooling technologies. In addition, some enacted policies designed to advance technological development. New or revised targets were adopted in all regions of the globe in 2016. Notably, at COP22 leaders of 48 developing nations committed to work towards achieving 100% renewable energy in their respective nations. Throughout the year of 2016, 117 countries submitted their first Nationally Determined Contributions (NDCs) under the Paris Agreement, and 55 of these countries featured renewable energy targets. Technology advances, falling costs and rising penetration of renewable in many countries also have continued to require that policies evolve to stimulate both deployment and integration as effectively as possible. Policies in feed-in tariffs (FITs), tendering, net metering and fiscal incentives provided support aimed at economy-wide economic development, environmental protection and national security [39].

Quantitative insights from the policy analysis are used to develop policy recommendations that support implementation of the planning analysis. Recommendations typically address the challenges of transitioning from a power system based on fossil fuels, in which costs are driven by fuel consumption, to a system dominated by renewable and in which costs are driven by upfront investments that greatly reduce fuel consumption. Additional policy concerns can be defined in advance to be addressed with dedicated quantitative analysis [1].

| **Area of policy intervention** | **Example** |
|---|---|
| Development or upgrading of grid codes | The development of harmonized European Network Codes is a good-practice example of forward-looking grid-code development with broad stakeholder participation, which can minimize costs from grid codes compliance |
| Incorporation of VRE in system operations | Red Eléctrica de España, Spain's Transmission System Operators, established a new control centre to improve management of renewable energy resources. The centre helps maximize VRE production while ensuring system reliability. |
| Optimized expansion of the grid | South Africa Government simplified the procedure of environmental impact assessment for VRE projects sited in Renewable Energy Development Zones where VRE development is considered most appropriate strategically. |
| System-friendly VRE –Location | China's FIT scheme differentiates according to resources quality, providing higher remuneration per unit of energy for areas with lower wind speeds or less sunlight. |
| System-friendly VRE –Technology mix. | Technology-specific auctions can be designed to achieve an optimal balance for the system. In South Africa, the volume of VRE procured in technology-specific auctions is set based on long-term system planning. |

*VRE: Variable Renewable Energy*
*FIT: Feed-in Tariff*

Table 2.2: Areas of policy intervention relevant to system integration of renewable [40]

In Table 2.2, the area of policy intervention is showed. This table includes some examples in each phase and layer of the power system. The policy makers should consider these interplays, identifying links and barriers between technical, institutional and economic aspects [40].

### 2.1.6 Investments Flows

Investment in renewable power and fuels has exceeded USD 200 billion per year for the past seven years. Including investments in hydro-power projects larger than 50 MW, total new investment in renewable power and fuels was at least USD 264.8 billion in 2016. Asset finance of utility-scale projects, such as wind farms and solar parks, dominated investment during the year, at USD 187.1 billion. Small-scale solar PV installations (less than 1 MW) accounted for USD 39.8 billion worldwide, representing a decline of 28%. China accounted for 32% of all financings of renewable energy, followed by Europe (25%), the United States (19%) and Asia-Oceania (excluding China and India; 11%), and the Americas (excluding Brazil and the United States), Brazil, and the Middle East and Africa accounted for 3% each. The result was that in 2016 investors were able to acquire more renewable energy capacity for less money [39].

### 2.1.7 Integration

Enabling technologies can create new markets for renewable energy in buildings, industry and transport. For example, electrification of vehicles not only reduces local air pollution, but also allows for rapidly growing renewable power technologies to displace fossil fuels in a sector where renewable other than bio-fuels previously were barred from entry. In such instances, air quality is enhanced further, along with other benefits of expanded renewable deployment. Heat pumps allow renewable power to substitute for fossil fuels in buildings and for industrial heat applications. Energy storage solutions help to balance grid-connected renewable energy supply against energy demand and to facilitate off-grid renewable energy deployment. Power systems have always required flexibility to accommodate ever-changing electricity demand, system constraints and supply disruptions, but growing shares of variable generation may require additional flexibility from the broader energy system. The increased integration of the electricity sector with thermal applications in buildings and industry and with transport is one such approach, as is increased use of energy storage [39]. High-quality Variable Renewable Energy (VRE) resources may be located in areas that lack the network to integrate them. Therefore, identification of suitable areas for VRE deployment (zoning) and their integration in transmission planning can have multiple advantages. Integrated planning may assist in identifying new lines to connect resource rich areas to the neediest load centres and in increasing the confidence of VRE developers that their assets will be put to full use, thus reducing the cost of VRE deployment [40].

The availability of wind and sun is complementary in many parts of the world: when it is windy it tends to be less sunny and vice versa. Thus, deploying both technologies in the right mix can reduce variability (from minutes to months) and impacts on the grid. Based on long-term modelling studies, it is possible to determine an optimized mix of VRE technologies. This information can then be used when putting in place and adjusting remuneration schemes for VRE plants [40].

### 2.1.8 Solution to avoid 1.5C global warming

The developing of energy roadmaps to significantly slow global warming and nearly eliminate air-pollution mortality in 139 countries was the main study of Jacobson et. al [126]. These plans call for electrifying all energy sectors (transportation, heating/cooling, industry, agriculture/forestry/fishing) and providing the electricity with 100% wind, water, and solar (WWS) power. Fully implementing the roadmaps by 2050 avoids 1.5°C global warming and millions of deaths from air pollution annually; creates new long-term, full-time jobs; reduces energy costs to society; reduces power requirements; reduces power disruption; and increases worldwide access to energy. These roadmaps were created to transform the all-purpose energy infrastructures to ones powered by WWS. The roadmaps envision 80% conversion by 2030 and 100% by 2050. WWS not only replaces business-as-usual (BAU) power, but also reduces it $\approx$ 42.5% because the work: energy ratio of WWS electricity exceeds that of combustion (23.0%), WWS requires no mining, transporting, or processing of fuels (12.6%), and WWS end-use efficiency is assumed to exceed that of BAU (6.9%). Converting may create '$\approx$ 24.3 million more permanent, full-time jobs than jobs lost. It may avoid $\approx$ 4.6 million/year premature air-pollution deaths today and $\approx$ 3.5 million/year in 2050; $\approx$ $US 22.8 trillion/year (12.7 ¢/kWh-BAU-all-energy) in 2050 air-pollution costs; and $\approx$ $US 28.5 trillion/year (15.8 ¢/kWh-BAU-all-energy) in 2050 climate costs. Transitioning should also stabilize energy prices because fuel costs are zero, reduce power disruption and increase access to energy by decentralizing power, and avoid 1.5°C global warming [126].

## 2.2 Current Renewable Energy Development on Small Islands

Small Island Developing States (SIDS) have their own peculiar vulnerabilities and characteristics. SIDS' unique and particular vulnerabilities are highlighted in "The Future We Want", adopted at The United Nations Conference on Sustainable Development (also known as Rio+20) that took place in Rio de Janeiro, Brazil in June 2012 [127] - their small size, remoteness, narrow resource and export base, and exposure to global environmental challenges and external economic shocks, including to a large range of impacts from climate change and potentially more frequent and intense natural disasters [41]. Table 2.3 shows the UN and NON-UN members of the SIDS. The SIDS Accelerated Modalities of Action (SAMOA) Pathway (Samoa Pathway) [128] adopted at the Conference addresses priority areas for SIDS and calls for urgent actions and support for SIDS' efforts to achieve their sustainable development.

Several commitments and recognitions are indicated in the *Draft outcome document of the third International Conference on Small Island Developing States* [129] in order to improve the developing on Small Islands States. For instance, point 2 of preamble indicate: *"... We reaffirm the commitments we made at United Nations conferences and summits on sustainable development: the Rio Declaration on Environment and Development, Agenda 21, the Programme for the Further Implementation of Agenda 21, the Plan of Implementation of the World Summit on Sustainable Development (Johannesburg Plan of Implementation), including chapter VII, on the sustainable development of small island developing States, and the Johannesburg Declaration on Sustainable Development, the Programme of Action for the Sustainable Development of Small Island Developing States (Barbados Programme of Action) and the Mauritius Strategy for the Further Implementation of the Programme of Action for the Sustainable Development of Small Island Developing States (Mauritius Strategy), and the outcome document of the United Nations Conference on Sustainable Development, entitled "The future we want". We further underscore that these processes are still being implemented*

| **UNITED NATIONS MEMBERS** | | | |
|---|---|---|---|
| ATLANTIC, INDIAN OCEAN, MEDITERRANEAN AND SOUTH CHINA SEA (AIMS) | | | |
| Cabo Verde | Comoros | Guinea-Bissau | Maldives |
| Mauritius | São Tomé and Príncipe | Seychelles | Singapore |
| CARIBBEAN | | | |
| Antigua and Barbuda | Bahamas | Barbados | Belize |
| Cuba | Dominica | Dominican Republic | Grenada |
| Guyana | Haiti | Jamaica | Saint Kitts and Nevis |
| Saint Lucia | Saint Vincent and the Grenadines | Suriname | Trinidad and Tobago |
| PACIFIC | | | |
| Fiji | Kiribati | Marshal Islands | Federated States of Micronesia |
| Nauru | Palau | Papua New Guinea | Samoa |
| Solomon Islands | Timor-Leste | Tonga | Tuvalu |
| Vanuatu | | | |
| **NON-UNITED NATIONS MEMBERS** | | | |
| American Samoa | Anguilla | Aruba | Bermuda |
| British Virgin Islands | Cayman Islands | Commonwealth of Northern Marianas | Cook Islands |
| Curacao | French Polynesia | Guadeloupe | Guam |
| Martinique | Montserrat | New Caledonia | Niue |
| Puerto Rico | Sint Maarten | Turks and Caicos Islands | U.S. Virgin Islands |

Table 2.3: List of Small Islands Developing States (SIDS) [41]

*and that there is a need for a more integrated approach to the sustainable development of small island developing States, with the support of the international community and all stakeholders."*; point 11 indicate: *"...We recognize that sea-level rise and other adverse impacts of climate change continue to pose a significant risk to small island developing States and their efforts to achieve sustainable development and, for many, represent the gravest of threats to their survival and viability, including, for some, through the loss of territory."*; point 16 indicate: *"... We note that small island developing States consider that the level of resources has been insufficient to ensure their capacity to respond effectively to multiple crises, and that without the necessary resources, they have not fully succeeded in building* *capacity, strengthening national institutions according to national priorities, gaining access and developing renewable energy and other environmentally sound technologies, creating an enabling environment for sustainable development or fully integrating the Barbados Programme of Action and the Mauritius Strategy into national plans and strategies.”*; point 19 indicate: *We recognize and call for the strengthening of the long-standing cooperation and support provided by the international community in assisting small island developing States to make progress in addressing their vulnerabilities and supporting their sustainable development efforts.”*; and point 22 indicate: *We reaffirm our commitment to take urgent and concrete action to address the vulnerability of small island developing States, including through the sustained implementation of the Barbados Programme of Action and the Mauritius Strategy, and we underscore the urgency of finding additional solutions to the major challenges facing small island developing States in a concerted manner so as to support them in sustaining the momentum realized in implementing the Samoa Pathway. With renewed political will and strong leadership, we dedicate ourselves to working in meaningful partnership with all stakeholders at all levels. It is in this context that the present Samoa Pathway presents a basis for action in the agreed priority areas.”* [129].

For SIDS, the limitations by their unique geography have in many ways governed access to and the successful completion of sustainable development projects. To ensure that SIDS development work stays at the top of the international agenda, as a direct follow-up to the SAMOA Pathway, the UN General Assembly decided in 2015 to establish the SIDS Partnership Framework, the first of its kind in following up and monitoring voluntary multi-stakeholder partnership agreements. There are a broad range of partnership initiatives that are advancing sustainable development of Small Island Developing States. One of these SIDS Partnership Framework programme is the SIDS lighthouses initiative (#SIDSACTION7963). In this initiative facilitated by IRENA, the Lighthouses is a joint effort of SIDS, development institutions and other partners to advance renewable energy deployment in island settings. It is a framework for action aimed at maximizing the use of indigenous, clean and plentiful renewable energy in a structured, holistic approach that takes into account medium and long-term requirements and impacts, and ensures that the requisite institutional and human capacity is in place. Small Island Developing States (SIDS) have been early supporters of renewable energy technologies to reduce the burden of high energy costs through economically viable and promising solutions to their energy challenges. The initiative is focused on activities in the areas of a) improving planning for energy transition; b) enhancing capacity and knowledge, and; c) strengthening effective project identification, structuring and implementation. At the global level, SIDS have provided strong political leadership in promoting renewable energy as a key element of the 2030 Sustainable Development Agenda and a major contribution to efforts on climate change [130]. Therefore and despite that Cozumel Island is not a SIDS member, it shares mostly their risks and difficulties, hence the solutions to solve some of those issues are the main focus of this thesis, in some way.

SIDS are disproportionally affected by weather extremes and climate change, including the increased severity of cyclones, storm surges, heavy rains, droughts, sea-level rise and ocean acidification. SIDS have demonstrated leadership in calling for action to reduce global greenhouse gas emissions while adapting to weather and climate extremes. They can also lead the way in applying weather and climate services to support vital economic sectors and vulnerable communities. The World Meteorological Organization (WMO) supports SIDS through its Programme for Least Developed Countries. It also pursues more targeted actions such as capacity-building to enhance and strengthen the capacities of SIDS National Meteorological and Hydrological Services and the development and application of science-based climate information and services in support of decision-making. WMO is now working with its partners to support increased investments in climate prediction services by all SIDS in the Caribbean, Indian Ocean and Pacific regions. Around the globe, over 50 small island nations share similar challenges in responding to the impacts of climate change as well as in cost-effectively implementing climate services because of their limited human, operational and financial resources [131].

## 2.3 Energy Planning Analysis on Small Islands

The planning analysis depends on the countries policies and frameworks, which can include accelerating renewable deployment, determining the optimal energy mix, strengthening energy security, lowering energy costs and reducing the environmental impact of energy supply. Then, the analysis maker undertakes a techno-economic analysis based on the scope of work to determine a least-cost energy system that meets the government's policy priorities [1]. This thesis uses this kind of analysis to planning the integration of the renewable energy sources on islands, under the national electric system in Mexico. This planning analysis is elaborated on the basis of the optimal technology mix to fulfill the renewable energy target in Mexico. Also, this analysis makes a grid assessment to obtain a strong and safe response of the electric grid on Cozumel Island once the renewable technologies are integrated on it. The financial analysis is the final process to obtain the lowest cost of energy and the highest value of the project. For most islands this analysis focuses on electricity generation, the activity in which renewable can have the greatest impact and where the required data is normally available. This techno-economic analysis is based on two types of models: capacity expansion, and dispatching. The capacity expansion model examines both investments in generation technologies and operational costs such as fuel and maintenance. This is to determine how to meet future demand using a least-cost mix of generation assets. This analysis normally investigates a period covering 10 to 20 years, or longer. Ideally it uses an electricity demand forecast covering every hour of the period examined. A dispatching model is then used to determine any potential operational constraints that could result in the optimal generation mix generating insufficient power to meet demand. This modelling normally covers one year, with a higher time resolution to provide more insight on operational cost impacts and to identify specific situations in which the optimal generation mix could face difficulty in meeting electricity demand [1].

Figure 2.1 shows the techno-economic analysis elaborated by International Renewable Energy Agency (IRENA) [1] in order to support the sustainable development on SIDS in their transition to a renewable-energy future. The techno-economic analysis developed in this thesis is very similar to that indicated by Figure 2.1 and the study case to validated and implemented is the Cozumel Island in Mexico. The methodology used in this thesis is indicated in Chapter 3. This methodology used in the present thesis includes a grid integration study, conducted as a separate analysis and complementing the final proposal. This study identify specific measures to address any operational issues identified by dispatching model.

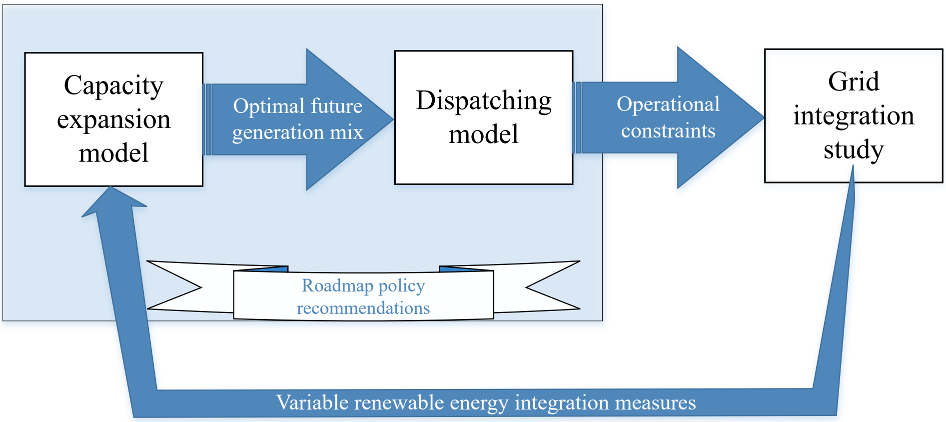


Figure 2.1: Roadmap electricity sector techno-economic analysis [1] (adapted).

Ideally the specification of any identified measures, including their costs, are fed back into the techno-economic analysis to estimate their impact on system cost and operation and determine how this affect the optimal generation mix. For smaller power systems in which the total investment required is limited, the capacity expansion and dispatching analyses can be combined. In some cases, an entire electricity system can be replaced in a single project, delivering an optimal system capable of meeting demand in all years covered by the planning analysis. For larger systems, the overall cost of reaching the optimal generation mix is often too high to be allocated to one project. In these cases, the capacity expansion model delivers a time-line detailing specific generation investments required to meet electricity demand over the period covered by the planning analysis.

The dispatching model is used to investigate the impact of each of these capacity additions, or to examine the completed optimal mix to determine any operational constraints that might require a grid study [1], as this thesis proposes. Dispatching models and grid integration studies provide detailed insights into the operational impacts and required measure for successfully integrating high shares of VRE. The study case provided in this thesis gives further insight into how VRE can be deployed on small islands.

With the growing presence of VRE, it is crucial that VRE characteristics are taken into consideration in long-term energy planning so that investments are appropriate and timely. A large-scale roll-out of VRE and flexible resources should set responsibilities, time frames, technical requirements and economic conditions for cost recovery. Integrated long-term power sector planning can also provide clear guidance to market players to align their own plans with overall system change. For example, the presence of a long-term plan enables operators of large, inflexible power plants to better determine when retrofits or decommissioning may be required [40].

## 2.4 Renewable Energy Sources on Islands

RE goal is to use an alternative energy source. The natural regeneration source capacity and quantity, in relation with its consumption, would be inexhaustible. The source's exploitation would also produce a very low environmental damage [132]. Islands around the world are, and will always be, very sensitive to the negative global warming impact, so it is necessary take action to avoid or slow down this warming. It is also very important to reduce the global emissions generated by the use of fossil fuels for electricity generation. The government subsidies keep the electricity price within reach of the general population, but this drives high expenses on their budget. The right integration of RETs will help reducing these costs.

The Table 2.4 shows the list of the islands analyzed around the world, the country to which they belong, and the inhabitants of them. Their energy systems were studied and they are indicated in this chapter. The Geographic Information System (GIS) analysis identifies 28,500 tropical islands. Of these islands, 15,900 are considered uninhabited as their average size adds up to 0.65 $km^2$ [133]. The 11% of the global population lives on islands. Approximately 2,000 islands have a between 1,000 and100,000 inhabitants [5]. 77 islands from 45 countries are analyzed in this paper. 61 of them are in tropical areas or in similar conditions and have a population range from 38 inhabitants (Pulau Ubin, Singapore) to approx. 111,000,000 inhabitants (Cuba). Of these islands, 17 are in the Caribbean Sea in 11 different countries with very similar conditions to Cozumel Island. One of the most important economic activities for these islands is tourism. All of them base their electricity generation on fossil fuel consumption. Table 2.5 shows an overview on global small island landscape in different regions around the world, including the Caribbean Sea plus the Gulf of Mexico (Blechinger et al. [42]). Meanwhile Figure 2.2 shows the total renewable production by Biomass and Hydraulic technologies on the Caribbean Region [2].

There are extensive combinations in the application of RETs on islands within the literature reviewed (Figure. 2.3). RETs included (not limited):

| **Island** | **Country** | **Inhabitants** |
|---|---|---:|
| King Island | Australia | 1,723 |
| St. Martin | Bangladesh | 4,000 |
| Barbados | Barbados | 280,000 |
| Prince Edward | Canada | 138,600 |
| Ramea Island | | 526 |
| Kinmen Island | China | 127,700 |
| Penghu | | 102,000 |
| Peng Chau | | 5,300 |
| Cook Islands | Cook Islands | 10,900 |
| Cuba | Cuba | 111,167,000 |
| Cyprus | Cyprus | 1,117,000 |
| Ærø | Denmark | 7,050 |
| Samsoe | | 3,806 |
| Mljet | | 1,111 |
| Dominic Republic | Dominican Republic | 9,445,000 |
| Federated States of Micronesia | Federated States of Micronesia | 106,000 |
| Reunion | France | 841,000 |
| Guadeloupe | | 406,000 |
| Corsica | | 322,120 |
| Greece | Greece | 11,030,000 |
| Crete | | 620,000 |
| Rhodes | | 115,500 |
| Mytilene | | 37,890 |
| Ios | | 2,024 |
| Grenada | Grenada | 109,600 |
| Haiti | Haiti | 10,000,000 |
| Hainan Island | Hong Kong | 8,700,000 |
| Aran | Ireland | 1,200 |
| Sicilia | Italy | 5,000,000 |
| Pantelleria | | 7,700 |
| Salina | | 4,000 |
| Jamaica | Jamaica | 2,900,000 |
| Kingdom of Tonga | Kingdom of Tonga | 103,000 |
| Pulau Perhentian Besar | Malaysia | 1,930 |
| Pemanggil | | 500 |
| Curazao | Netherlands | 152,760 |
| Aruba | | 102,500 |
| Bonaire | | 16,500 |
| New Zealand | New Zealand | 4,518,000 |
| Tokelau | | 1,411 |

Table 2.4: List of islands in which their energy systems were analyzed

| **Island** | **Country** | **Inhabitants** |
|---|---|---|
| Niue | Niue | 1,611 |
| Papua Nueva Guinea | Papua Nueva Guinea | 11,307,000 |
| Flores | Portugal | 1,831,000 |
| Madeira | | 268,000 |
| Azores | | 246,000 |
| Porto Santo | | 5,480 |
| Corvo | | 425 |
| Terceira | | 56,437 |
| Republic of Cabo Verde | Republic of Cabo Verde | 525,000 |
| Saint Vicente | | 100,000 |
| Republic of Fiji | Republic of fiji | 858,000 |
| Republic of Guyana | Republic of Guyana | 3,500 |
| Republic of Kiribati | Republic of Kiribati | 103,500 |
| Malta | Republic of Malta | 446,600 |
| Republic of Nauru | Republic of Nauru | 9,300 |
| Republic of Palau | Republic of Palau | 17,950 |
| Republic of Suriname | Republic of Suriname | 1,000 |
| Republic of the Marshall Islands | Republic of the Marshall Islands | 68,000 |
| Republic of Vanuatu | Republic of Vanuatu | 207,000 |
| Samoa | Samoa | 250,100 |
| Apolima | | 75 |
| Pulau Ubin | Singapore | 38 |
| Solomon | Solomon | 561,000 |
| Canary | Spain | 2,218,000 |
| Fuerteventura | | 103,000 |
| El Hierro | | 10,162 |
| Trinidad y Tobago | Trinidad y Tobago | 1,224,000 |
| Tuvalu | Tuvalu | 9,900 |
| Anguilla | United Kingdom | 13,500 |
| Puerto Rico | United States of America | 3,621,000 |
| Hawaii | | 1,375,000 |
| Rhode | | 1,053,000 |
| Oahu | | 953,000 |
| Maui Island | | 144,500 |
| St. Croix | | 50,600 |
| Tortola | | 24,000 |
| St. Thomas | | 18,000 |
| Molokai | | 7,400 |
| Lanai | | 3,102 |
| Metlakatla | | 1,375 |
| Block | | 1,051 |

Table 2.4: *Cont.*

| | Number of islands | Population (sum) millions | Ele consum (sum) GWh/yr | Ele consum (average) MWh/yr | Ele consum per capita (av) kWh/yr · cap | LCOE Diesel (average) EURct/kWh |
|---|---|---|---|---|---|---|
| **Atlantic + Arctic Ocean** | 416 | 4,150,000 | 18,270 | 43,930 | 4,400 | 36.6 |
| **Caribbean Sea +** | 105 | 1,700,000 | 5,730 | 54,550 | 3,370 | 34.2 |
| **Indian Ocean** | 232 | 2,830,000 | 2,240 | 9,670 | 790 | 38.0 |
| **Mediterranean Sea** | 104 | 1,100,000 | 3,680 | 35,390 | 3,345 | 33.2 |
| **Pacific Ocean** | 1,199 | 11,620,000 | 22,770 | 18,990 | 1,960 | 39.3 |
| **Total** | 2,056 | 21,400,000 | 52,690 | 25,630 | 2,462 | 38.0 |

Table 2.5: Global small islands overview [42].

wind power (Wind), hydro systems (Hydro), geothermal, energy recovery from biomass or crops, for example: Solid Waste (SW) and biogas used in a Combined Heat and Power system (CHP, co and tri-generation), solar thermal, photovoltaic cells (PV) and ocean energy. Smart grid technologies (SGT) with energy storage proposed have been developed with combination of: batteries, flow batteries, hydrogen ($H_2$) from electrolyzers, Fuel Cell (FC), heat storage (HS) and flywheel, among others. The Electric Vehicle (EV) is used both as load or source, depending of the power demand profile on islands. It is also used to decrease the use of fossil fuel transports. The desalinated water produced with RE excesses is stored and used in combination with hydro Pump/Turbine systems, including the information and communication technologies (ICT). In some documents, an analysis in the use of super grid connections between islands has been performed.

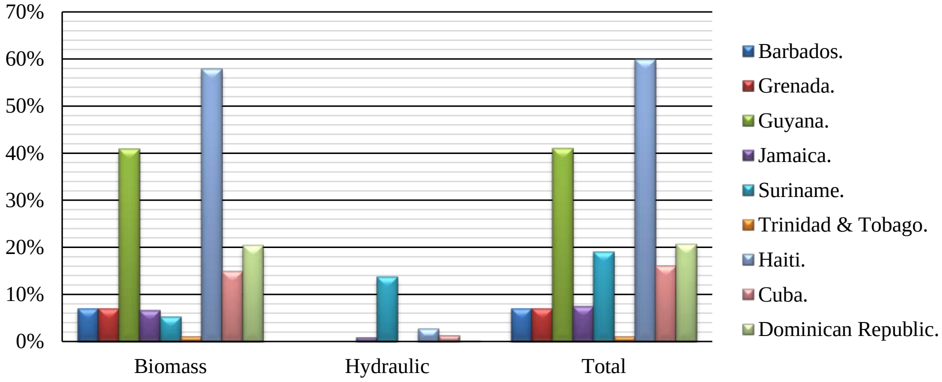


Figure 2.2: Total energy supply in the Caribbean region [2].

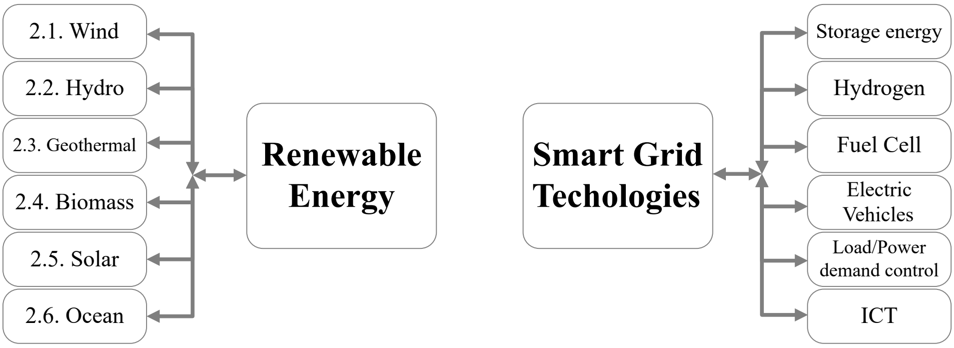


Figure 2.3: Combination of RET, RES and SGT, and their application on islands.

Finally, there is a combination in the use of fossil technologies with oil, natural gas (NG) and diesel, as backup or as part of the whole electric system.

### 2.4.1 Wind

Wind power is used for electricity generation through the kinetic energy transformation in to a rotational mechanical movement, being limited only by the Betz's Law and the wind turbines efficiency. Wind power obtained in Ærø Island, Denmark, in 2001, 20.5 GWh was supported by 7.2 MW wind farm, accounting for 57% of the island's total electricity [134]. For the islands in [8, 43, 134, 135], wind power has been considered for electricity production: a) Cape, 3,800 kW eolic turbines; b) USA, Hawaii and Puerto Rico, where Oahu counts with 600 MW, Lanai with 600 MW and Molokai with 400 MW, and for St. Thomas, Tortola, St. Croix and Puerto Rico, 3.7 GW of wind potential could be exploited; c) Anguilla, where a comparative simulation of 6 wind turbines was made of 1.25 MW (Falcon) and 6 of 0.75 MW (Unison) was performed to a total of 5.95 GWh/y and 3.3 GWh/y respectively, and; d) Curacao, where in the 80's the 5% was 3 MW and in 2000 was 9 MW, from the 226 MW installed, and in Aruba, 30 MW was 13% and will add 30 MW of wind for a total of 149 MW installed. In Block Island, in Rhode Island, USA, five 6 MW wind turbines array were installed interconnected with a 34.5 kV submarine cable from site to mainland. It is expected to generate approximately 125.5 GWh/y to supply electricity to near 17,200 households [136].

### 2.4.2 Hydro

Hydro-power converts the kinetic energy from water to mechanical energy using a turbine with a generator. It is considered as renewable energy if the water cycle is a continuous cycle [137]. For example, the Caribbean area [43] has 32.8 MW installed and 4% of its total consumed energy is through hydro energy. Suriname and Trinidad & Tobago have a system close to 4.7% from renewable energy sources. Dominican Republic, Haiti and Cuba have achieved an impressive 22.8% [2]. Flores Island, Portugal, has an installed capacity of 1.5 MW of hydro for an electricity production of 4.45 GWh/y (39% in 2007). This could be increased with 3.14 MW of small hydro [138].

### 2.4.3 Geothermal

It is the heat flow energy coming from the internal part of earth to the surface. Due the huge quantity of heat within the earth's nucleus, this kind of energy represents practically an inexhaustible source of energy [139]. Papua New Guinea accounts with 6 MWe installed [2], Greece has 5.4 MWe [140] and Pantelleria, Italia, has an install capacity of 2.5 MWe (46% of Island consumption) [141].

### 2.4.4 Biomass

Every matter from biological source, except those stored in geological formations like fossil fuels, is known as biomass [142]. For its distribution on earth, biomass is a very common source of energy in the planet. For its photosynthesis activity in plants (direct) and animals (indirect), it is a very sophisticated form of storage of solar energy. Therefore it is a renewable primary energy source [137]. The main application of this technology is described below. Generally it is used in combination with another RETs (section 2.8, hybrid systems).

In New Zealand, where the RE was the 38% of primary energy in 2010 and biomass, the solar thermal energy supplied the 20% of the energy produced. Maui Island, November 2012, had a 16 MW electricity generation plant from sugar-cane bagasse, providing the 4.5% of the Island energy [143]. In the Island of Crete, there is a 166 kW biogas plant combined with another RETs. In Cape the biomass is used for heating [134]. The Peng Chau Island in China has an electricity generation potential from biomass of 370 kW, but for the damage caused to its natural areas, this is non-viable [144]. At the end of 2011, the Sicilia Island in Italy, had 5.8 GW of fossil fuel technology installed, consisting in 730 MW hydro, 866 MW PV, 1.68 GW wind and 54 MW in biomass. This combination was configured to a fixed electricity production of 50 MW of biomass, and the frequency control was made through hydro technology [145].

### Solid Waste (SW)

The SW is an energy vector from biomass. Due to its chemical composition, Carbon/Nitrogen ratio and humidity content, biogas can be obtained from its organic fraction. Thermal energy can be obtained through the burned matter content [137]. This biomass vector can be produced from municipal, residential, industrial, commercial and others sources of waste. The energy obtained from Municipal Solid Waste (MSW) is around the 30% with a Cost of Energy (COE) of 0.04 US$/kWh. Mytilene, a city in the north of the Aegean Sea, can produce 9,400 ton of MSW with a 2.25 MWe capacity. In total, the Greece Islands of the north of the Aegean Sea, could produce 1.25% of the total of electricity required for a maximum of 3.1 MW of electricity and 2.9 MW of heat [140]. Peng Chau Island, China, with a measure of 1.4 kg by person produced, and considering a 30% of efficiency and a calorific value of 2,200 kcal (2,559 kWh) per kg of MWS, could have an electricity generation capacity of 270 kW [144]. Kinmen Island, China, with 18 ton of Residential Waste Solids (RWS) of the 50.68 ton total of MWS, could generate 11,070 kWh/day [44].

### Biogas

Generally biogas is a bio-fuel in a gas state obtained from biomass, through a biological way by anaerobic digestion or fermentation of its organic matter [146]. In some cases, biogas is part of hybrid systems, indicated in section 2.8. In Samsoe, Denmark, bio-gas from MWS is enough to supply the 100% of the primary energy needed on the Island [147]. In Canada, in Prince Edward Island, bio-gas is used for electricity generation with an operation cost of 0.02 US$ per kWh. Production is 116,565 kWh per year, with a 14.4 kW equipment capacity [148].

## 2.4.5 Solar

One of the main ways for solar energy conversion for human benefit is thermo-electric conversion to electricity, using the photovoltaic effect to produce electricity. Another key form of solar energy conversion is the production of heat, which is the easiest application of solar energy [149]. The main application of this technology is described below. Generally it is used in combination with another RETs (section 2.8, hybrid systems).

### Photovoltaic (PV)

The conversion of solar energy to electricity in PV systems is due to the continuous excitation of the electrons across an n-p junction. This is done by the sunlight in the photovoltaic cell [150]. On islands with a few inhabitants the use of PV systems with batteries are enough to supply the electricity needs. They are commonly used in combination with another RE source. The use of only PV systems in Pulau Perhentian Besar Island, Malaysia, is presented like an answer for the 1,500 fisherman houses [151]. The rest of PV systems used on islands can be found in section 2.8.

### Thermal

In the Caribbean, the Solar Water Heating (SWH) technology is used mainly for water heating and in the air conditioning of buildings [2]. There are 3.7 $m^2$ of solar thermal panel per capita installed in Ærø Island, Denmark, covering 26,800 $m^2$ in three districts, serving 2,070 households [134]. In the Canary Islands is mandatory that the new domestic buildings have SWH. In 2012, the energy saved was 8.5 GWh. Cyprus counts with the highest heaters quantity per capita in the world, 1 $m^2$ per capita and approximately 90% of privately owned dwellings, 80% of the apartments and 50% of the hotels were equipped with SWH by 2007. In 2010, in New Zealand, the biomass together with solar thermal contributed for 20% of the energy [147]. In the Aran Islands, Ireland, the solar thermal energy replaced the fossil fuel for heating [152]. The Penghu Island, Taiwan, had a total of 1,000 houses and an area of 6,400 $m^2$ of heaters from 2011 to 2015. In 2016 the energy saved will reach 8.4 TWh and in 2026 is expected to reach 19 TWh [153]. In 2009, 102,666 SWH systems (300 L equivalent) operated in Reunion Island, France. The total area of solar collectors installed reached 410,664 $m^2$ to produce 154 GWh. Household SWH systems could save 1,167.7 GWh of electricity per year. For commercial and institutional buildings 22,796 $m^2$ have been installed, saving 13.7 GWh [154]. In Pulau Ubin Island, the thermal equipment used together with other renewable technologies equipment gave, as results, that the second case will be the most viable option in a long term. This, despite that the third case is the most saving case obtained. The Figure 2.4 shows the technology combination and the Primary Energy Savings (PES) obtained [3].

### 2.4.6 Ocean

There is an extraordinary potential of energy conversion from energy harnessed in the ocean to produce electricity, coming from tidal range, wave, currents, thermal gradients and salinity gradients [132]. The most used of this RESs is in combination with another RETs in the literature reviewed, as the following sub-sections show.

#### Tidal combined with wave and solar

In Peng Chau Island a tidal energy generation was proposed, according with [144]. In wave energy generation capacity 200 buoys of 40 kW each were

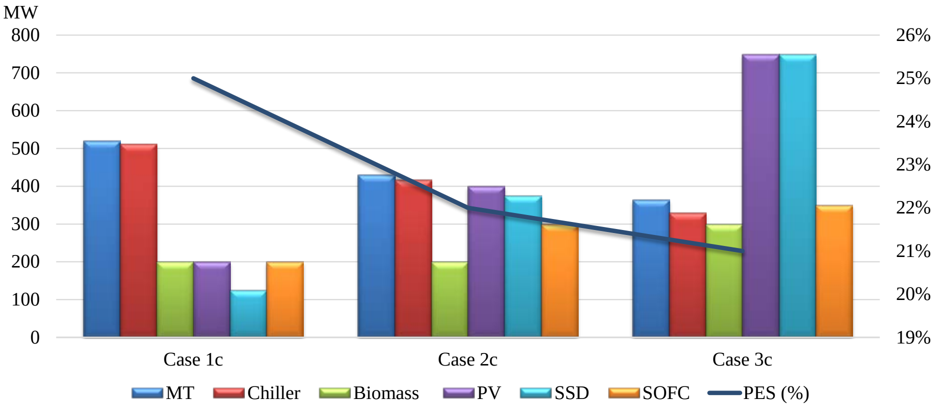


Figure 2.4: Combination of Micro-Turbine (MT), Absorption Chiller, Biomass, PV, Solar Sterling Dish (SSD), and Solid Oxide Fuel Cell (SOFC) technologies, including the results for the Primary Energy Savings (PES) in a tri-generation renewable technology comparative for Pulau Ubin Island, Singapore [3].

proposed, for a total of 2.8 MW installed. In Wave/Solar with 70 buoys were proposed for a total of 1 MW of generation capacity installed.

### Wave combined with wind

In Fuerteventura Island, a Wind/Wave combination using the coastal wave model SWAN (Simulating WAve Nearshore) has been simulated, proposing 7 arrangements of 6 MW wave and 7 MW wind offshore capacity, for a total of 91 MW capacity installed [155]. Wave energy in Aran Islands has a potential of 192 GWh/y with 22 MW installed [152]. For the year 2015, the Canary Islands, Spain, has determined that 30% of the electricity generation should be supplied by RES, and a wave energy of 50 MW generation capability [156].

### Ocean Thermal Energy Conversion

In Reunion Island, France, the proposal is through ocean thermal energy conversion, using cold water from deep seawater (1,000 m and 5 °C) and the surface water (between 25 °C and 28 °C) as hot spring. It foresees a 10 MW plant for 2014 with a potential of 130 MW for 2030 [154] [33].

### 2.4.7 Energy Storage

The RES intermittency in electricity generation creates a high unbalance risk to the whole electrical system of any place. For example, when windless hours come and PV generation is not enough to supply the power demand, energy storage is the green solution. Other solution could be to run the reserved fossil fuel equipment for isolated systems. This energy storage can be done with electromechanical systems, as well as with thermal and chemical systems. The hydrogen storage systems is a chemical system and has an enormous potential to store and supply a huge quantity of energy, because its fuel transformation in the future [150].

Table 2.6 shows multiple energy storage services and their applications and main uses. The ability of energy storage technologies to offset demand and absorb excess generation makes them in principle an ideal complement to variability in VRE output and energy demand. Storage options span a large array of technologies with different cost and performance characteristics. This makes them suited differently to the range of services electricity storage can provide. Currently, the vast majority of electricity storage deployed globally is pumped hydro storage, but battery technologies such as lithium-ion or flow batteries are also increasingly common. No single application would require the entire storage capacity continuously. Therefore, storage can provide additional services at the same time. This would increase the profitability of such investment option, if there is an appropriate regulatory framework. To enable that, policy makers need to remove existing barriers, for example adjusting minimum bidding size in reserve markets, where batteries are often excluded due to small size [40].

#### Batteries and RETs

For Pemanggil Island, Malaysia, an integration simulation was made of 30 kW of wind, 45 kW diesel and batteries with a 40 kW converter and charge system of 20 kWp of demand and 202 kWh per day [45]. The International

| | Application | Description |
|---|---|---|
| Generation | RE integration bulk | Time-shift RE output to optimise for grid integration and minimize curtailment |
| | RE integration ramp | Optimize short-term RE output to improve power quality and avoid imbalances |
| | Frequency control | Maintain supply and demand balance via power increases/decreases with different response patterns |
| Network operation | T&D deferral | Defer upgrades to network infrastructure |
| | T&D congestion | Avoid re-dispatch and local price differences due to risk of overloading existing infrastructure |
| | Black start | Restore power plant operations after network outage without external power supply |
| | Voltage support | Maintain voltage levels across networks via reactive power supply/reduction |
| Behind the meter storage | Peak power supply | Reduce demand supplied by the network during peak hours to reduce network charges |
| | Back-up power | Provide power during network failure to ensure power quality and availability |
| | Renewable energy self-consumption | Maximize usage of self-generated power and minimize exports to the network |
| | Bill management | Shift energy consumption from high-tariff to low-tariff periods to reduce energy charges |
| Market | Energy arbitrage | Purchase power in low-price periods and sell in high price periods on wholesale or retail market |

T&D = *transmission and distribution.*

Table 2.6: Qualitative description of energy storage services in the power system [40]

Renewable Energy Agency (IRENA) [46] presented a series for storage solutions for diverse Islands such as: a) Apolima, Samoa, with 13.5 kW of PV and Lead-acid batteries. b) Bonaire Island, in the Caribbean, with 11 MW of wind, 14 MW of diesel, nickel batteries type SMRX of 3 MW, 640V, 1,320 Ah. (845 kWh) to serve to 12 MW of power demand. c) King Island, Tasmania, with 2.45 MW of wind, 100 kW of PV and a vanadium redox battery system with 68,000 l of electrolyte for a capacity of 200 kW and 800 kWh, with a short time response of 400 kW, in addition to a diesel system as backup and complement. d) Republic of Kiribati, with Household-sized PV/lead-acid batteries systems. It considered the installation of 270 domestic arrays of 100 W PV with a capacity of 140 Ah in batteries. e) Metlakatla, Alaska, combined 3.3 MW of diesel machines with 4.9 MW of hydro. It has installed 1 MW in batteries since 1997. Jarry et al. [157] have done a study about RE in Reunion Island, France, with 1 MW of sodium sulphurs battery in 20 modules of 50 kW, 7.2 MWh, 1.2 MW of charge, and 1 MW of discharge, combined with 2 MW of PV and 10 MW of wind.

### Flywheel, Electrical Vehicles (EVs) and RETs

In Flores Island, Portugal, the EV's was studied as substitute of conventional vehicles and as energy storage. It was combined with the integration of 0.6 MW of wind, 1.5 MW in hydro and 2.3 MW of diesel supported by a flywheel, simulating loads and demands within an increasing scenario of 1.5%, 3% and 4.5% from 2007 to 2013 [138]. In Aran Islands [152] EV was included for storage and control energy.

### Electrolyser, $H_2$ and Fuel Cell and RETs

Generally when a $H_2$ production from an electrolyzer exists, it is used in fuel cells. It can also be used like fuel for transportation or for thermal machines in some cases. This production can be stored. Commonly this $H_2$ is produced by RE sources. A pilot plant in Porto Santo Island, Azores, has a 75 kW electrolyzer unit, 300 kWh of $H_2$ storage, 25 kW FC and 1.1 MW of wind farm [134]. Figure. 2.5, refers to Porto Santo, 100% renewable with 25 MW of wind turbines and nearly 20 MWp of solar PV installed. An electrolyzer unit of 11 MW doubles the peak and a FC covers the peak of 5.5 MW [4]. In Mljet, Denmark, eighteen scenarios have been modelled and the outcomes are optimized for maximal penetration of renewable energy. Terceira, Portugal, has a project for the installation of a geothermal energy unit of 12 MW. For 2025, they propose changing the transport to $H_2$. Malta has a fossil fuel, RE and hydrogen storage scenario for the transportation sector. This $H_2$ is produced from wind and solar sources and will satisfy 5% of the transportation energy demand in 2015. In Ramea Islands, Canada, a RE project was made with $H_2$ and FC. In 2004 they installed 6 wind turbines of 65 kW each, increasing 3 wind turbines of 100 kW each, combined to a 162 kW electrolyzer unit, three $H_2$ storage tanks of 1,000 $m^3$ of capacity and five $H_2$ thermal generators for a total of 250 kW [46]. The use of a hybrid system like Solid Oxide Fuel Cell (SOFC)/$H_2$/Tri-generation proposed [3] for Palau Ubin Island in Singapore, with a SOFC (200-350 kW) fed with $H_2$ from an electrolyzer unit. In Corvo Island a methodology was created to correctly integrate the energy flows with a RE penetration scenario of 30% and another with 100% of RE penetration, where 50% of the year 100% of RE can be obtained, including the $H_2$ storage [158]. In Saint Vicente, Cape, the obtaining of a RE integration was simulated with $H_2$ to supply the 30% of the electricity consumption on the Island, and the 50% of the required water for people with 3 wind turbines of 350 kW each [7].

### 2.4.8 Hybrid Systems

The intermittency in the energy production of the renewable sources has implications for the electrical system. If it reaches high production levels, the system controls must disconnect these renewable sources. There are several combinations of RETs applied to serve the power demand and the electricity consumption around the Islands States (Figure. 2.6). These combinations sometimes are bounded for the following reasons: A) Government budget. B) Land restrictions and environmental regulations. C) The objectives acquired by governments in intergovernmental panels. D) As part of a sustainable development main plan on the islands. E) To correctly balance the electrical system. F) A research project to demonstrate the correct RETs integration into an electric grid is feasible.

For example, in Corsica, Guadeloupe and Reunion Islands, it reached in 2012 more than 30% of electricity penetration in the grid (34%, 34% and 35%, respectively) with many problems, so a smart grid was proposed to solve this problem [157]. An overview in the Azores Archipelago shows that the total electricity consumption in 2002 was 600.8 GWh, and 43% of this energy was obtained with clean energy sources [134]. In the Caribbean, an hybrid system was proposed (Figure. 2.7) taking into account the diesel Price in 0.6 Euros/l with an annual increase of 3%, a machine efficiency

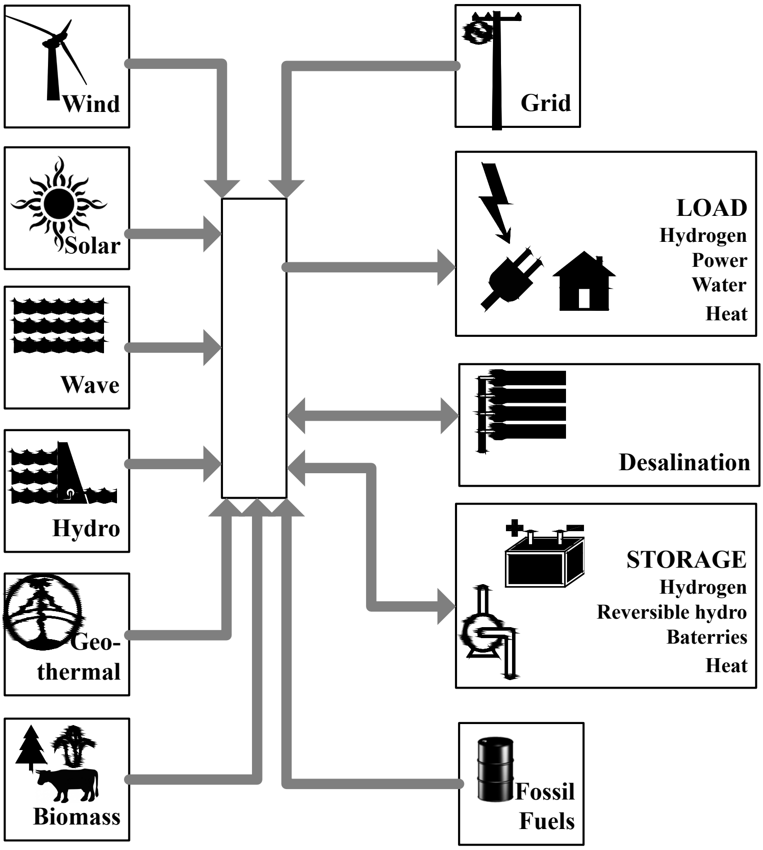


Figure 2.5: The H2RES model version 2.8 used for Porto Santo, Mljet, Terceira, Malta and Ramea Islands [4] (adapted).

of 25%-35%, a battery efficiency of 85%, 10 years of life, a c-rate of 1:6 kW/kWh, a 30% flywheel of RE and wind [42].

In St. Martin Island, Bangladesh, an hybrid system PV/Wind/Battery/Diesel is simulated for 80 existing houses with 10 kW of PV, 10 kW of diesel, 3 kW of wind, 12 kW converter capacity and 104 batteries [159]. The combination of Wind/PV/NG/Hydro/Grid was simulated in Hainan Island, China, with 720 MW of hydro, 4.5 GW of wind, 600 MWp of PV, 1 GW with NG, 600 MW with submarine wire for grid connection (Figure. 2.8) [6]. In Kinmen Island, China, the integration of Wind/PV/Biogas/Tidal system was simulated, where were considered PV from 100 W to 1 kW for houses, and

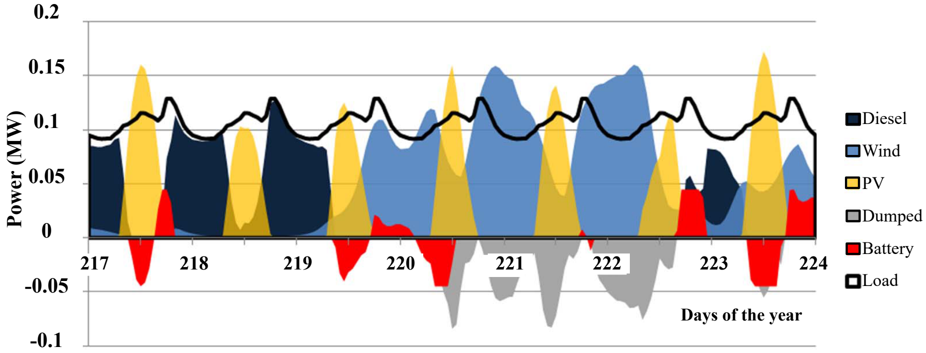


Figure 2.6: Energy power flow diagram based in a RE integration on an hybrid system [5] (adapted).

from 1 kW to 1 MW for government offices and street lighting, for a total of 2,033 kWp, with 520 units of 10 kW of Wind distributed [44]. Rhodes Island, Greece [160], considered WP-PSSs (wind powered pumped storage systems) including diesel contribution. Pulau Ubin Island, Singapore, integrated micro turbines (MT) for a tri-generation system, single effect absorption chiller (Abs), Biomass co-generation plant (BCP), PV, SSD, SOFC, Mechanical Chiller (MC), Auxiliary boiler (aux), using a TRNSYS 17 simulation tool (Transient System Simulation Program) [3].

Greece has a combination of a pump storage system of 3.8 MW and 2.4 MW of wind [134]. Corvo Island has a Wind/Pump system to obtain the 70% of electricity from RE. Their goal is to achieve the 100% from RE with Wind/Hydro/Pump [158]. For Sicilia Island, Italy, it has been simulated an addition of a Pump/Turbine station of 580 MW to stabilize the whole electrical system in case of fault, as happened in May 2011 [145]. In El Hierro, Spain, there is a 500,000 $m^3$ upper water storage and a 150,000 $m^3$ lower water storage in combination with Wind/Pump/Turbine for a total of 210 MWh with 2 pipes (Figure. 2.9), 6 pumps of 0.5 MW and 2 of 1.5 MW to 6 MW and 4 Pelton turbines of 2.83 MW, 11.5 MW wind and 11.18 MW with diesel machines to backup [161].

In Penghu Island, Taiwan, [153], a new methodology was developed to

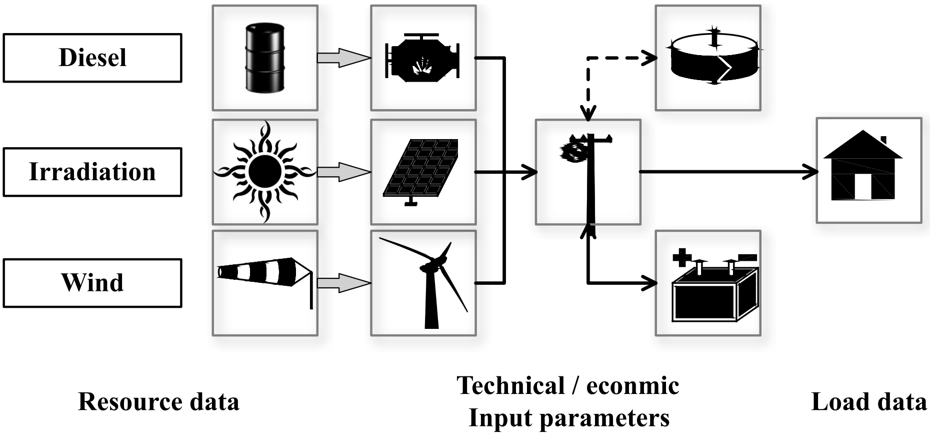
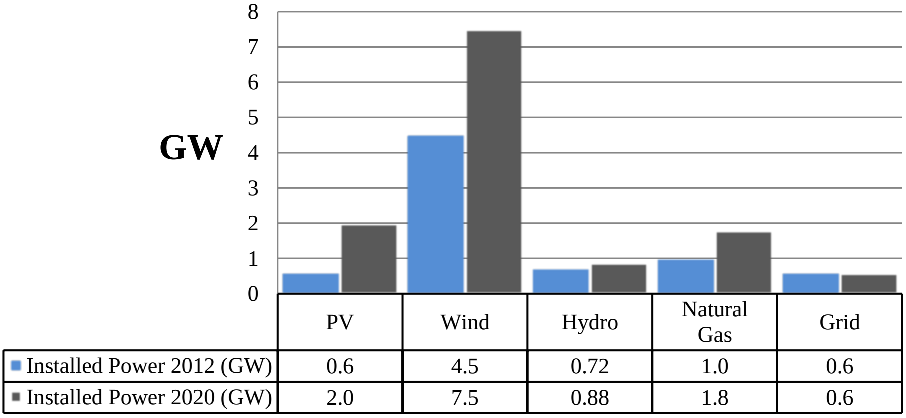


Figure 2.7: Basic scheme of an hybrid system for the Caribbean zone.

accomplish the government energy politics. In Salina Island, Italy, [162] simulations were made with axial wind turbines of 1.5 kW, and a development potential of 1,908 turbines for a 2,422 MWh/y. In the France's Corsica, Reunion and Martinique Islands, PV/Wind systems were proposed to optimize with meteorological algorithms the grid integration supported by batteries, 2 MW of PV and 10 MW of wind [157]. The Oahu Island, Hawaii, have a combination of 1,471 MW steam-oil, 185 MW steam-coal, 99 MW wind, 164 MW of PV, 73 MW from MSW and 120 MW from thermal biodiesel, for a total capacity of 2,112 MW installed, trying to add 400 MW of wind production capacity connected with High Voltage Direct Current submarine wire (HVDC), 200 MW in Lanai Island and 200 MW in Molokai Island and add 760 MW of PV too [163]. Jarry et al. [157] developed a study about RE in Guadeloupe Island, France, combining 50 MW Pump/Turbine of salt water, wind and solar thermal.

In Saint Vicente, Cape [7], as there is no fresh water available in the Island, the proposed solution considered the use of desalinated water in the pumping and hydro station to later be supplied to the population. A hybrid desalinated water system was simulated with 17 $m^3$ per capita, executed with 6 inverse osmosis machines. This system has a 7,800 $m^3$/day production fed by 8 wind turbines of 850 kW each with the construction of a 30,000



| | PV | Wind | Hydro | Natural Gas | Grid |
|---|---|---|---|---|---|
| ■ Installed Power 2012 (GW) | 0.6 | 4.5 | 0.72 | 1.0 | 0.6 |
| ■ Installed Power 2020 (GW) | 2.0 | 7.5 | 0.88 | 1.8 | 0.6 |

Figure 2.8: Results of the modelling of a power supply system in Hainan Island, China [6] (adapted).

$m^3$ desalinated water storage. There is also an analysis to storage 50,000 $m^3$ desalinated water, linking it up with a Pump/Turbine system, to reduce the electricity rejection from 45% to 9% in 2030, using the H2RES model (Figure. 2.10). In this work, regarding the maximization of the RES, the supply system reached 71%, with 65% of wind and 6% of hydroelectricity. In 2020, for scenarios 7 and 9, and with an hourly intermittent energy penetration of 100%, the percentage of desalinated water produced with wind can reach 75% and 59% respectively. In Ios Island, Greece, a desalinated water system was simulated with a capacity of 30 $m^3$/h and 230,000 $m^3$ of storage. A desalinate equipment with a capacity of 2,000 $m^3$/day and 5 kWh/$m^3$ is also considered, in combination with 8 MW of pump and 7.5 MW turbines, including 660 kW of wind, increasing to 16.2 MW in a near future [164]. Whereas in Pantellería Island, Italy, [141] it was studied how to integrate the RE with an electricity production of 11,600 MWh/y based in a desalinated water production of 800,000 $m^3$/y (27% of the electricity required).

In 2001, Madeira Island, Portugal, produced 16% of its electricity with a combination of Hydro/Wind, saving 25 Mlt of oil and 15 klt of diesel [134]. In the Pacific area, 31% of electricity is produced through hydro [2]. Metlalaka, Alaska, has 4.9 MW of hydroelectric system capacity, combined

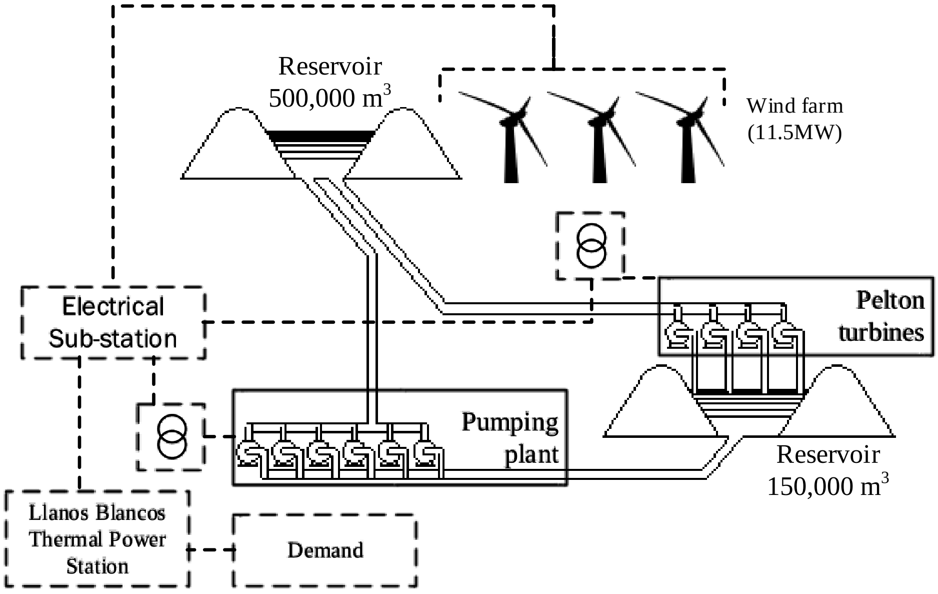


Figure 2.9: Hybrid system in El Hierro Island, Canary Islands, Spain (adapted)

with diesel generator (3.3 MW) and battery storage (1 MW) since 1997 [46]. Biogas from biomass and waste were taken for CHP, in Reunion Island, France, where it reached 1.95 TWh/y of co-generated energy and 1.28 TWh/y of electricity for a total of 3.11 TWh/y of the energy obtained [154]. CHP production is used in Cyprus and in the Canary Islands, Spain, the CHP contributed with a portion of the 2,268 MWe of capacity installed. The same case was reproduced in Samsoe Island, Denmark. Due to its biogas production, CHP can be used supplying 70% of the Island's heat consumption with this system [147]. Pulau Ubin Island, China, proposed a Combined Cooling Heating and Power (CCHP) or tri-generation, with micro turbines (MT), single effect absorption chiller (Abs) for cold and heat management, a biomass co-generation plant (BCP), SSD and a SOFC system [3].

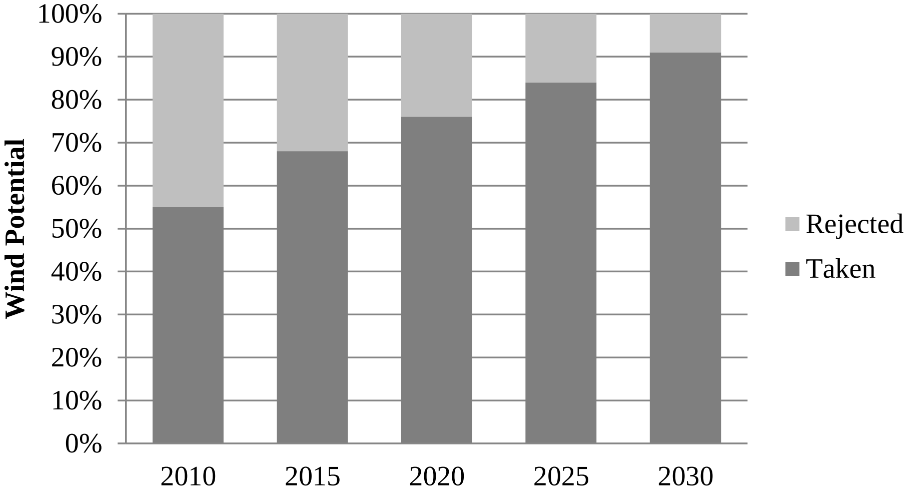


Figure 2.10: Wind potential taken and rejected in S. Vicente for the BAU scenario [7] (adapted).

### 2.4.9 Super grid for islands

Currently, a great challenge for the islands electric sector is the integration of massive intermittent energy resources. A possible solution is the inter-island network for bulk transmission, enabling networks to share centralized renewable power generation by the interconnection between countries and/or Islands States [165]. USA [8] reported a super grid connection analysis between the Islands of St. Thomas, Tortola, St. Croix and Puerto Rico, exploiting the 3.7 GW of wind potential to supply the electricity for the whole Caribbean zone in an interconnected way through submarine cable. Meanwhile, in Hawaii, the Hawaii Clean Energy Initiative (HCEI) consider the inter-islands connection between Oahu, Molokai, Lanai and Maui islands, exploiting around 1,200 MW of Wind peak, shown in the Figure 2.11. The Greek Islands analyzed (north of the Aegean Sea) in three prefectures, Samos, Chios and Lesbos, and five regional units, Chios, Ikaria, Lemnos, Lesbos and Samos, the RE integration vs. super grid to the continent, with CSP, a COE of 0.125 Euros/kWh and a maximum capacity to be installed of 21.6 MW. This array supplies the 4.1% of the electricity to the grid together

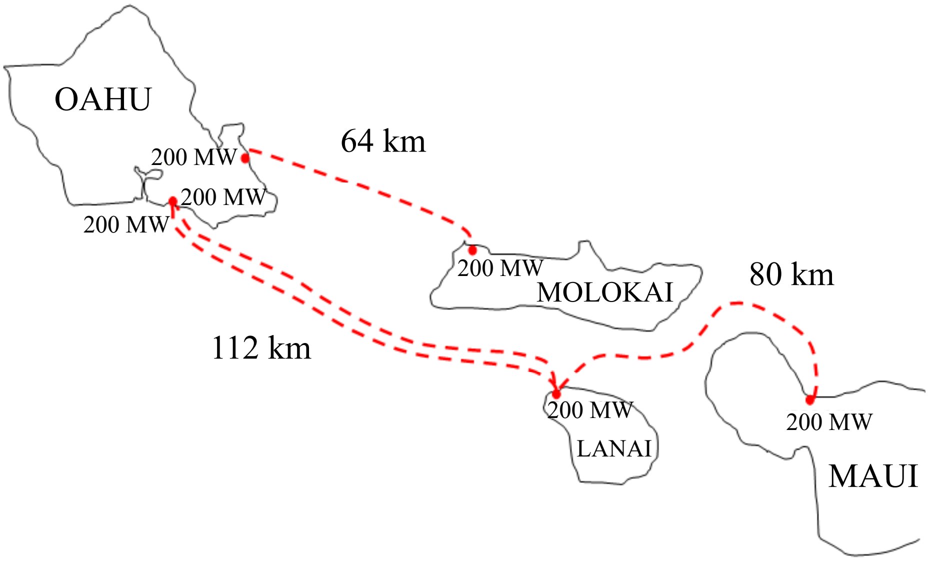


Figure 2.11: Potential cable landing points and inter-island routes for the Hawaii Clean Energy Initiative (HCEI) [8] (adapted)

with PV [140].

## 2.5 Cost of energy by renewable energy integration to the grid through some islands

The use and the implementation of RETs is so beneficial, it would expected to have it scattered all over the world. But when a nuclear plant produces electricity for less than 0.01 US$/kWh, and in a coal power plant for 0.035 US$/kWh, it is very difficult for an electric utility to make investments in wind technology, for example with an electricity production of 0.12 US$/kWh or 0.16 US$/kWh for a PV power plant [150]. The cost analysis is very important to make the right decisions and choose the correct RET combination for the electricity supply, and also to show how it can save in fossil fuel consumption and reduce this electricity cost.

In Hainan Island, China, it is estimated the reduction of COE will decrease from 0.074 US$ in 2010 to 0.051 US$ in 2020. This is based in the reduction of the RETs and because 80% of the electricity production comes from coal, with an electricity increase from 12 TWh in 2010 to 21.5 TWh in 2020, using: COE = TAC / Eu, where TAC (Total Annualized Cost) and Eu (Energy, useful) [6]. In Pemanggil Island, Malaysia, an hybrid project was developed with Diesel/Wind to supply electricity with a power demand of 202 kW/day, including energy storage and decreasing the COE from 1.008 US$ kWh to 0.686 US$ kWh [45]. Some results from the analysis of the value of COE on the islands by the integration of RETs for the electricity production are indicated in Table 2.7. In this table, the COE is indicated before and after RETs integration on islands. These COE reductions are the results of diminishing the fossil fuel consumption, as a mechanism to improve the current electric system to a distributed renewable energy system.

| Island/Region | Initial | Final |
|---|---|---|
| **Aruba** | $ 0.260/kWh | $ 0.013/kWh (Wind) |
| **Atl. & Arctic Oceans** | € 0.259/kWh | € 0.152/kWh |
| **Barbados** | $ 0.294/kWh | $ 0.051/kWh (SWH) |
| **Caribbean Sea** | € 0.255/kWh | € 0.168/kWh |
| **Curazao** | $ 0.355/kWh | $ 0.028/kWh (Wind) |
| **Grenada** | $ 0.341/kWh | $ 0.283/kWh (PV) |
| **Hainan Island** | $ 0.074/kWh (2010) | $ 0.051/kWh (2020) |
| **Indian Ocean** | € 0.239/kWh | € 0.098/kWh |
| **IRENA (Model Island Case, 2012)** | $ 0.539/kWh | $ 0.424/kWh (Diesel-PV-Storage) |
| **Jamaica** | $ 0.265/kWh | $ 0.078/kWh (Wind) |
| **Kinmen Island** | NT$ 11-14/kWh (2010) | NT$ 7.26-9.24/kWh (2020) |
| **Mediterranean Sea** | € 0.277/kWh | € 0.222/kWh |
| **Pacific Ocean** | € 0.281/kWh | € 0.179/kWh |
| **Pemanggil Island** | $ 1.008/kWh (2014) | $ 0.724/kWh (Diesel-Bat 2014)<br>$ 0.686/kWh (Diesel-Wind 2014) |
| **Portugal (Imaginary Island)** | € 0.15/kWh | Model 1: € 0.105/kWh (Waste/Hydro/Wind/Grid)<br>Model 2: € 0.047/kWh (Waste/Hydro/Wind/Storage/Grid)<br>Model 3: € 0.250/kWh (Waste/Hydro/Wind/Biomass/Solar/EV Storage/Grid) |

Table 2.7: LCOE analysis on islands [6, 43–48].

## 2.6 RETs and RES discussion

PV and Wind power is the most used RETs on the islands reviewed, but mostly in combination with another RETs and SGTs, to achieve a feasible and viable application of these technologies. All results show that the integration of RE on islands (when viable), results in a reduction of fossil fuel consumption. Due to the characteristics of each island, not all RETs can be deployed. It will depend of several conditions, such as environmental, economic, political, regulatory and/or social-cultural aspects. A universal methodology must be developed in order to achieve an efficient integration of the RETs, taking into account the basic issues of this kind of technologies and sources.

Is important to remark that only a few papers of all the literature reviewed have indicated that the incorporation of some RETs are infeasible [44, 141, 144, 162], due to the natural protected areas and the damage that could cause. As a consequence, the size of these technologies has been reduced, replacing them by a hybrid system with Fossil/RETs. In this work, all the RETs proposed in the simulations were placed on areas already impacted to achieve the minimal environmental impact in their integration. The pre-selected areas for RETs site were agreed in consensus by environmental specialist, land owners and government delegates, in an illustrative form.

## 2.7 Computer Tools for Energy Planning

### 2.7.1 EnergyPLAN tool

EnergyPLAN simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. It is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. The model is used by many researchers, consultancies, and policy-makers worldwide. This is possible due to the key focus on sharing the model during its development. For example, the model has a user-friendly interface, it is disseminated as a free-ware, there is a variety of training available including our forum, and existing models are already available for many countries. The EnergyPLAN model has been used in hundreds of scientific publications and reports, which are presented in the case studies section [166].

The model is an input/output model. General inputs are demands, renewable energy sources, energy plant capacities, costs and a number of optional different simulation strategies emphasizing import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption, import/exports and total costs including income from the exchange of electricity. Design and analysis of large and complex energy systems at the national level and under different technical simulation strategies. In this analysis, input is a description of energy demands, production capacities and efficiencies, and energy sources. Output consists of annual energy balances, fuel consumptions and $CO_2$ emissions [167].

Further analysis of trade and exchange on international electricity markets. In this case, the model needs further input in order to identify the prices on the market and to determine the response of the market prices to changes in import and export. Input is also needed in order to determine marginal production costs of the individual electricity production units. The modelling is based on the fundamental assumption that each plant optimizes according to business-economic profits, including any taxes and $CO_2$ emissions costs. The Market economic simulation strategy is based on a short-term marginal price market model similar to the NordPOOL market design, so it focuses solely on bids to the electricity market while minimizing short-term electricity consumer costs and minimizing short-term district heating costs. As a result, this simulation strategy only uses variable costs and does not optimize based on the long-term costs of different energy supply technologies. Furthermore, it only optimizes the supply side of the energy system, and not the demand side (although the user can manually change the demand and analyze the resulting impact of a market economic simulation). While mathematically it is possible using the price elasticity feature in EnergyPLAN to simulate 100% renewable energy scenarios using this current market design, represented by the market economic simulation, this may not accurately represent how future energy supply and demand markets should be designed. Today's markets are primarily designed for dispatchable plants, whereas 100% renewable energy systems will most likely depend on very high levels of non-dispatchable renewable energy. Therefore, using the technical simulation strategy is typically more accurate at simulating energy systems with very large penetrations of intermittent renewable energy, which in combination with the cost data for the technologies, makes it possible for the user to identify least cost solutions over their total lifetime [167].

Calculation of feasibility in terms of total annual costs of the system under different designs and simulation strategies. In such case, inputs such as investment costs and fixed operational and maintenance costs have to be added together with lifetime periods and an interest rate. The model determines the socio-economic consequences of the productions. The costs are divided into: (1) fuel costs; (2) variable operational costs; (3) investment costs; (4) fixed operational costs; (5) electricity exchange costs and benefits, and; (6) possible $CO_2$ payments [167].

### 2.7.2 H2RES tool

H2RES is a balancing tool that simulates the integration of renewable energy into energy systems. The model is developed by the Instituto Superior Técnico, Lisbon and the Faculty of Mechanical Engineering and Naval

Architecture at University of Zagreb, Croatia in 2000. Ten versions of the model have been released to date but the number of users is not monitored. The H2RES model balances the hourly time series of water, electricity, heat, and hydrogen demand, appropriate storage, and supply over any user-defined period. The model has been specifically designed to increase the integration of renewable sources and hydrogen into island energy-systems which operate as stand-alone systems. It can also serve as a planning tool for single wind, hydro or solar power producers or it can be used for planning of larger power-systems. The model considers all forms of thermal generation except nuclear power, and all renewable technologies except tidal power. Also, all storage and conversion technologies are considered by H2RES except compressed-air energy-storage, but only hydrogen vehicles are simulated in the transport sector. The desalination of water is also considered by H2RES as this is often used on island systems. To simulate wind, solar and hydro, wind velocities, solar radiation and precipitation data are obtained from the nearest meteorological station. This raw meteorological data is in-putted into the H2RES program and the output is simulated from the appropriate renewable-energy technology [168].

The biomass module of H2RES takes into account the feedstock information, the desired mix of feed stocks, conversion processes (combustion, gasification and digestion) and desired output production (power, heat or combined heat and power). Biomass module is set to follow the heat load and it generates electricity as by-product. The biomass module is designed to utilize the available resource so that there is enough biomass in storage to supply demand. This is a major factor when dealing with isolated systems as they cannot afford to run out fuel. The geothermal module functions as base load, where the installed power generates electricity for the system continuously, except when it is in maintenance. To simulate the electricity sector, the load module is used. It is based on a given criteria for the maximum acceptable intermittent and renewable electricity in the power system, integrates a part or all of the available renewable output into the system and either stores or discards the rest of the renewable/intermittent output. The sequence of sources in supplying of demand could be easily set up according to criteria. Excess renewable-electricity can be stored in a pumped-hydro facility, batteries or as hydrogen, used for some non-time critical loads (deferrable loads), and used for desalination. If there is still unsatisfied electricity load it is covered by fossil fuels blocks or by the mainland grid if such a connection exists. Financial calculations are not completed in H2RES® but this area is currently under development [168].

### 2.7.3 RETScreen tool

RETScreen is a Clean Energy Management Software system for energy efficiency, renewable energy and co-generation project feasibility analysis as well as ongoing energy performance analysis. The RETScreen Clean Energy Project Analysis Software is a decision support tool developed with the contribution from government, industry, and academia. It was originally developed in 1996 by Natural Resources Canada. The software, provided free-of-charge from, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs). The software (available in multiple languages) also includes product, project, hydrology and climate databases, a detailed user manual, and a case study based college/university-level training course, including an engineering e-textbook [70, 168, 169].

Fundamental to RETScreen is a comparison between a “base case”, typically the conventional technology or measure and a “proposed case” i.e. the clean energy technology. RETScreen is ultimately not concerned with the absolute costs, but rather the costs of the proposed case that are in excess of those for the base case. In the RETScreen Software, the energy benefits are the same for both the base case and the proposed case. If, for example, a proposed on-grid wind farm generates 50,000 MWh per year, then this compared to 50,000 MWh of electricity from conventional sources available through the grid. On the other hand, the costs will not, in general, be the same for the base case and the proposed case: typically, the proposed case will have higher initial costs and lower annual costs (i.e. savings). Thus RETScreen’s analysis task is to determine whether or not the balance of costs and savings over the life of the project make for a financially attractive proposition. RETScreen's greenhouse gas emission reduction analysis adheres to this same analysis approach. RETScreen can analyse up to a 50-year time-horizon in monthly or yearly time-steps. The software can be applied to any energy system, ranging from individual projects to global applications. In addition the model considers all sectors of the energy system except the transport sector. RETScreen uses a five-step analysis for every model: (1) The Energy Model: User enters location of the energy project, the type of system used in the base case, the technology for the proposed case, the loads (where applicable), and the renewable energy resource (for RETs). RETScreen then calculates the annual energy production or energy savings. All thermal generation and renewable technologies can be accounted for using RETScreen. However, the only storage device considered is BES, and it cannot model any hydrogen or transport technologies. (2) Cost Analysis: User enters the initial, annual, and periodic costs for the proposed case system as well as credits for any base case costs that are avoided in the proposed case (alternatively, the user can enter the incremental costs directly). (3) Greenhouse Gas (GHG) Analysis (optional): Determines the annual reduction in GHG emissions stemming from using the proposed technology in place of the base case technology. (4) Financial Summary: User specifies financial parameters related to the avoided cost of energy, production credits, GHG emission reduction credits, incentives, inflation, discount rate, debt, and taxes. From this, RETScreen calculates a variety of financial indicators (e.g. net present value, etc.) to evaluate the viability of the project. (5) Sensitivity & Risk Analysis (optional): Identifies how uncertainty in the estimates of various key parameters may affect the financial viability of the project [70, 168].

### 2.7.4 LEAP

LEAP (Long-range Energy Alternatives Planning) is an integrated modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy, which is developed by the Stockholm Environment Institute. It is usually used to analyze national energy-systems, and it is free to qualified users in developing countries but there is a cost for OECD based users [168]. LEAP is an integrated, scenario-based modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks. In addition to tracking GHGs, LEAP can also be used to analyze emissions of local and regional air pollutants, and short-lived climate pollutants (SLCPs) making it well-suited to studies of the climate co-benefits of local air pollution reduction [170].

LEAP functions using an annual time-step, and the time horizon can extend for an unlimited number of years (typically between 20 and 50). LEAP supports a number of different modelling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modelling. On the supply side, LEAP provides a range of accounting and simulation methodologies for modelling electric sector generation and capacity expansion planning. This also allows for the incorporation of data and results from more specialized models. LEAP's modelling capabilities operate at two basic conceptual levels. At one level, LEAP's built-in calculations handle all of the "non controversial" energy, emissions and cost-benefit accounting calculations. At the second level, users enter spreadsheet-like expressions that can be used to specify time-varying data or to create a wide variety of sophisticated multi-variable models, thus enabling econometric and simulation approaches to be embedded within LEAP's overall accounting framework. LEAP does not currently support optimization modelling, although this capability is currently being developed in conjunction with the IAEA in Vienna. Overall, LEAP can simulate all sectors and all technologies within an energy system. LEAP also includes a scenario manager that can be used to describe individual policy measures. These can then be combined in different combinations and to create alternative integrated scenarios. The resulting scenarios are self-consistent story lines of how an energy system might evolve over time. LEAP displays its results as charts, tables and maps which are user-defined and can be exported to Excel or PowerPoint: these include fuel demands, costs, unit productions, GHG emissions, air-pollutants, and more. Usually, these results are then used to compare an active policy scenario versus a policy neutral business-as-usual scenario [168].

### 2.7.5 energyPRO

energyPRO is a complete modelling software package for combined techno-economic design, analysis, and optimization, of both fossil and biofueled co-generation and tri-generation projects as well as wind power and other types of complex energy-projects. It is developed and maintained by the company EMD International A/S in Denmark, and over 50 versions have been released over the past 20 years. With energyPRO it can model, optimize, simulate and analyze all kinds of energy plants in existing systems or greenfield energy projects. The software optimizes the operation of the modelled system in accordance to all preconditions such as weather conditions, technical properties of the different units, maintenance costs, fuel prices, taxes, subsidies, etc. The analytical optimization methodology provides a fast and powerful tool for strategic energy planning, optimization of distributed energy systems, basis for investment decisions, system integration, sustainable change processes etc. energyPRO enables to: (a) calculate the optimal operation of an energy plant; (b) make detailed investment analyzes; (c) model industrial co-generation and tri-generation; (d) simulate energy plants participating on different electricity markets, and; (e) analyze the interaction between separate energy plants [168, 171].

The energyPRO model is specifically designed for a single thermal or CHP power-plant investigation. It can model all types of thermal generation, renewable energy and energy storage to complete this analysis. However, it only models the electricity and district heating sectors. The analysis is carried out using a 1-minute time-step for a maximum duration of 40 years (which represents the typical lifetime of power plant). In addition, the energyPRO model accounts for all financial aspects also such as fuel prices, fuel handling costs, investment costs, operation and maintenance costs as well as environmental costs [168].

### 2.7.6 WASP

The WASP (Wien Automatic System Planning Package) model permits the user to find an optimal expansion plan for a power generating system over a long period and within the constraints defined by the planner, which is maintained by the IAEA (International Atomic Energy Agency) [168]. In order to meet the needs of electricity planners and following the recommendations of the Helsinki symposium, development of a new version of WASP was initiated in 1992 with the co-operation of some Member States (Hungary and Greece). Advisory group and consultancy meetings on the subject convened during 1992–1996 focused on identifying necessary enhancements to the model and appropriate methodological approaches to address the new issues. Like its predecessors, the current WASP-IV version is designed to find the economically optimal expansion policy for an electric utility system within user specified constraints. It utilizes probabilistic estimation of system production costs, unserved energy costs, and reliability, linear programming technique for determining optimal dispatched policy satisfying exogenous constraints on environmental emissions, fuel availability and electricity generation by some plants, and the dynamic programming method for optimizing the costs of alternative system expansion policies [172].

In WASP the optimum expansion plan is defined in terms of minimum discounted total costs. Each possible sequence of power plants that could be added to the system (expansion plan or expansion policy) and that meets the selected constraints, is evaluated by means of a cost function composed of: capital investment costs, fuel costs, operation and maintenance costs, fuel inventory costs, salvage value of investments and cost of energy demand not served. The entire simulation is carried out using 12 load duration curves to represent each year, for up to a maximum duration of 30 years. As a starting point, WASP requires representation of the existing system defining the technical, economic and environmental characteristics of all existing power plants: note that only the electricity sector is considered. These characteristics include: plant capacities, minimum and maximum operating levels, heat rates, maintenance requirements, outage rates, fuel and operation costs, emission rates, etc. Conventional fossil-fuel, nuclear and biomass power plants can be simulated. In addition wind, wave, tidal and hydro power can be considered as well as PHES. For the given yearly future demand for electricity, it explores all possible sequences of capacity additions that will match this demand and at the same time satisfy all the constraints. The constraints can be based on achieving a certain level of system reliability, availability of certain fuels, build-up of various technologies, or environmental emissions. The sequences of capacity additions are first screened and those that satisfy the constraints, called feasible configurations for expansion of the system, are selected. The operation of a system for all these configurations is then simulated using a probabilistic simulation technique, which takes into account the failure probabilities of the plants and produces unit dispatch schedules to meet the given load. Available units are dispatched according to their marginal production costs. The generation, fuel requirement and environmental emissions of each unit are calculated and checked against any limitations imposed externally. Finally, a dynamic programming algorithm traces the optimal sequencing of capacity additions [168].

### 2.7.7 HOMER® tool

HOMER® (Hybrid Optimization Model for Multiple Energy Resources) is a user-friendly micro-power design model developed in 1992 by the National Renewable Energy Agency in USA, who have released 42 versions of the program. HOMER® simulates and optimizes stand-alone and grid-connected power systems comprising any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, micro-turbines, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads (by individual or district-heating systems). The simulation considers a 1 year time-period using a minimum time-step of 1 minute. It performs a sensitivity analyzes which can help the analyst to do what-if analyzes and to investigate the effects of uncertainty or changes in input variables. The objective of the optimization simulation is to evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability [24, 30, 31, 84, 168, 173].

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 [86, 174].

### 2.7.8 MATLAB®, Technical Computing

Millions of engineers and scientists worldwide use MATLAB® to analyze and design the systems and products transforming our world. MATLAB® is in auto-mobile active safety systems, interplanetary spacecraft, health monitoring devices, smart power grids, and LTE cellular networks. It is used for machine learning, signal processing, image processing, computer vision, communications, computational finance, control design, robotics, and much more. The MATLAB® platform is optimized for solving engineering and scientific problems. The matrix-based MATLAB® language is the world's most natural way to express computational mathematics. Built-in graphics make it easy to visualize and gain insights from data. A vast library of prebuilt toolboxes lets you get started right away with algorithms essential to your domain. The desktop environment invites experimentation, exploration, and discovery. These MATLAB® tools and capabilities are all rigorously tested and designed to work together. MATLAB® helps you take your ideas beyond the desktop. You can run your analyzes on larger data sets, and scale up to clusters and clouds. MATLAB® code can be integrated with other languages, enabling you to deploy algorithms and applications within web, enterprise, and production systems [175].

Key Features:

- High-level language for scientific and engineering computing.
- Desktop environment tuned for iterative exploration, design, and problem-solving.
- Graphics for visualizing data and tools for creating custom plots.

- Apps for curve fitting, data classification, signal analysis, control system tuning, and many other tasks.
- Add-on toolboxes for a wide range of engineering and scientific applications.
- Tools for building applications with custom user interfaces.
- Interfaces to C/C++, Java®, .NET, Python, SQL, Hadoop, and Microsoft® Excel®.
- Royalty-free deployment options for sharing MATLAB® programs with end users.

### 2.7.9 Power Factory (DiGSILENT) tool

PowerFactory is a leading power system analysis software application for use in analyzing generation, transmission, distribution and industrial systems. It covers the full range of functionality from standard features to highly sophisticated and advanced applications including windpower, distributed generation, real-time simulation and performance monitoring for system testing and supervision. PowerFactory is easy to use, fully Windows compatible and combines reliable and flexible system modelling capabilities with state-of-the-art algorithms and a unique database concept. Also, with its flexibility for scripting and interfacing, PowerFactory is perfectly suited to highly automated and integrated solutions in your business applications. The calculation program DIgSILENT PowerFactory , is a computer-aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization. “DIgSILENT” is an acronym for “DIgital SImuLation of Electrical NeTworks”. DIgSILENT Version 7 was the world’s first power system analysis software with an integrated graphical single-line interface. That interactive single-line diagram included drawing functions, editing capabilities and all relevant static and dynamic calculation features [25, 176].

Use of a single database, with the required data for all equipment within a power system (e.g. line data, generator data, protection data, harmonic data, controller data), means that PowerFactory can easily execute all power simulation functions within a single program environment - functions such as load flow analysis, short-circuit calculation, harmonic analysis, protection coordination, stability analysis, and modal analysis. Although PowerFactory includes highly-sophisticated power system analysis functions, the intuitive user interface makes it possible for new users to very quickly perform common tasks such as load flow and short-circuit calculations. The functionality purchased by a user is configured in a matrix-like format, where the licensed calculation functions, together with the maximum number of buses, are listed as coordinates. The user can then, as required, configure the interface and functions according to their requirements. Depending on user requirements, a specific PowerFactory license may or may not include all of the functions described in this manual. As requirements dictate, additional functionality can be added to a license. These functions can be used within the same program interface with the same network data. Only additional data, as may be required by an added calculation function, need be added [25, 176].

PowerFactory incorporates a comprehensive list of simulation functions, including the following:

- Load Flow Analysis, allowing meshed and mixed 1-,2-, and 3-phase AC and/or DC networks.
- Low Voltage Network Analysis.
- Short-Circuit Analysis, for meshed and mixed 1-,2-, and 3-phase AC networks.
- Harmonic Analysis.
- RMS Simulation.
- EMT Simulation.
- Eigenvalue Analysis.

- Model Parameter Identification.
- Contingency Analysis.
- Reliability Analysis.
- Generation Adequacy Analysis.
- Optimal Power Flow.
- Distribution Network Optimization.
- Protection Analysis.
- Network Reduction.
- State Estimation.

## 2.8 Selecting the computer tools for the energy planning and grid assessment on small islands

The properly software tools used to integrate the renewable energy on a fossil fuel generation grid, and the grid assessment to obtain a strong and safe grid response, must define the approaching strategy of the renewable targets to fulfil. According to the country, region or city policies, it can establish the legal framework to the sustainable development in the integration of the renewable power system on small islands.

So, in this thesis, the holistic impact of the integration of a new renewable energy technology configuration through the years on the dynamic behaviour and stability of the existing power system is systematically analyzed. Also, this thesis has the aim to optimize and to reduce the battery bank backup time and to compare four different battery technologies. This should not present any changes in the renewable energy targets settled for the safe continuous operation of the grid. The results and response of this hybrid power system (Photovoltaic/Wind/Diesel/Battery) proposed will be compared always against the results and response of use only a fossil fuel power system (only Turbo-gas machines burning Diesel), in order to supply the electricity demand in the growing scenarios through the years until 2050. As this integral analysis cannot be done with only one technical computer tool, the decision of select more than one is pointed below.

In case of the renewable energy integration it has selected the HOMER® software tool, in order to compare the use of only fossil fuel power system vs. an hybrid generation system [24, 30, 31, 84, 173]. 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. 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 hour to determine the Net Present Value for a chosen configuration over a specified project lifetime. The RETScreen Clean Energy Project Analysis Software is used to validate and to compare the HOMER® software tool results and to integrate, in the financial analysis, the detailed costs of the grid, electricity prices, the engineering works and fiscal taxes [70].

For the grid assessment, the MATLAB® [175] program was used to simulate the current electric grid on Cozumel Island and to run the Newton Raphson algorithm in a simple power flow. This will help to validate the mathematical section used in the initial power flow calculus in the DIgSILENT PowerFactory software tool [25, 176]. The DIgSILENT PowerFactory software tool is used to analyze the hybrid power system, which deals with the energy planning and dynamic and stability simulations in an hourly time resolution through a DIgSILENT Programming Language (DPL) command script function for each year. This hourly combination can validate the energy and grid planning scenarios in the short-term dynamic simulations on frequency and voltage stability, and for a long-term planning scenarios analysis until 2050, for instance [25, 176].

# 3 Methodology for Energy Planning in Small Islands

## 3.1 Three phases methodology plan

The proposed methodology in this study is to set up the long-term electrical system targets to be achieved and with the use of a DSV and linear regression models to evaluate and validate them, and is divided into three phases, as shown in Figure 8.1:

### 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:

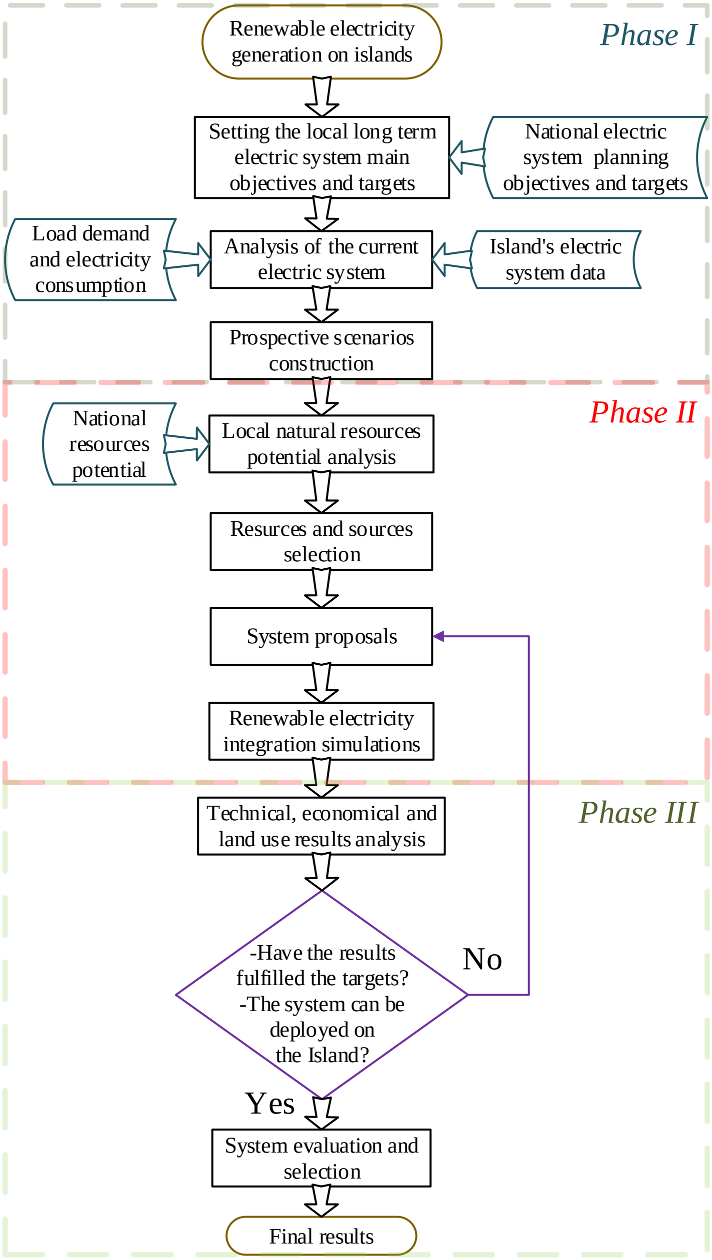


Figure 3.1: Methodology used to integrate the renewable electricity generation on small islands.

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.

Chapter 6 uses and applies this methodology.

## 3.2 Four phases methodology plan

As the Small Island Development States (SIDS) or Countries are become more renewable in the energy consumption or production, as the Paris Agreement-Status of Ratification shows [177], their national legal framework includes the renewable energy targets to be fulfilled until 2020, 2030 or 2050, for instance. So, this methodology is developed in four phases to assess an integral approach and battery optimization for the renewable energy integration and for the electric grid assessment. The hybrid power system analyzed will supply the electric demand through the years until 2050 (Phase 1). The time-varying profile of load and renewable generation will be compared against the use of only fossil fuel and will analyze the advantages of their integration on the grid. In Phase 2, as result of the simplified system operation analysis (power flow), the electric grid will be modified or reinforced, in order to maintain the system parameters according to the grid code. At this point, the electric system response has to be good enough to fulfil the grid code parameters selected, even in case of disturbance and faults in the grid. As part of Phase 3, these faults and disturbances will show how strong the electric grid response is, if the grid shows weakness in the response, the modifications will improve this response. In Phase 4 the economic analysis for the hybrid power system will be performed, including in the final ICC the cost of the electric grid modifications or reinforcements.

The methodology used to assess a strong grid response when the renewable energy generation is integrated in a small island power system is indicated in Fig. 3.2. This methodology includes the battery backup time reduction analysis. In the methodology proposed, the data marked in a *italic* and **bold** format is the particular data input chosen for this specific study case. To use this methodology on other small islands, just use the specific data from the small island and substitute them in the italic and bold format spaces.

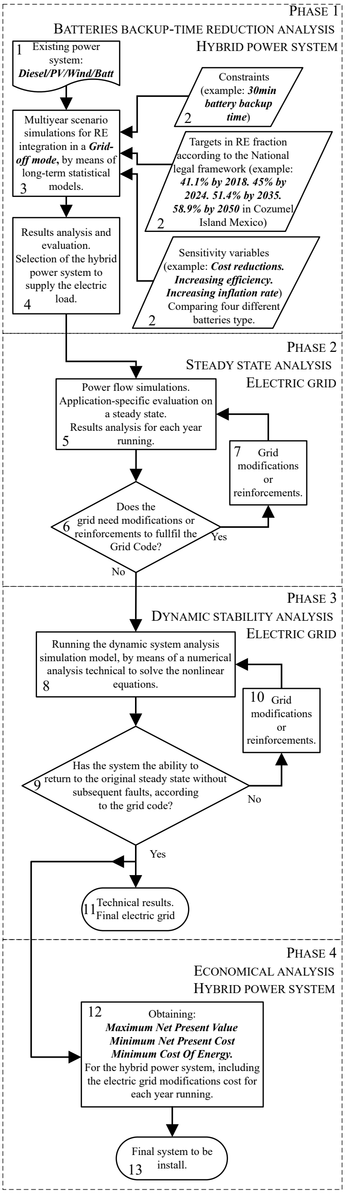


Figure 3.2: Methodology to analyze the integration of the renewable electricity generation and the electric grid response on a disconnected small island, comparing four different batteries type and reducing their battery backup time.

### 3.2.1 PHASE 1 (Renewable electricity integration and batteries backup-time reduction analysis)

Objective: Satisfy the power demand on the small island in order to fulfil the renewable energy targets and constraints for the planning scenarios of electricity consumption growing selected or developed. From a hybrid power system with batteries included, reduce the backup time from the battery bank and compare four different battery technologies simultaneously, as well.

STEP 1. Selection of the initial hybrid system ***(Photovoltaics / Wind / Diesel / Battery)*** to analyze and optimize its operation and results.

STEP 2. In this step, the input data to determine the simulation parameters and constrains for the hybrid system analysis to be done in STEP 3 is uploaded. For example: a) A minimum backup time according to the grid code selected of ***30 min*** from a cold start to a synchronization running for a diesel machine. b) A Renewable Energy Fraction (REF) integrated in the electric grid of ***41.1% by 2018, 45% by 2024, 51.4% by 2035, and 58.9% by 2050***. This example is in accordance with the National legal framework in Mexico, that includes the renewable energy targets to be fulfilled until 2050. c) A sensitivities variables applied, like ***a cost reductions, an increasing efficiency, and an increasing inflation rate***. All this comparing four different batteries type to determine the best performance with the minimum operation cost, using ***Ion-Lithium, Lead-Acid, Vanadium flow redox, and Zinc-Bromine flow redox***.

STEP 3. By means of a long-term statistical model, a deterministic methodology is used to perform time-series simulations. This analysis is made considering the electric system in a grid-off mode or disconnected. In this step, the energy planning and the growing scenarios are developed or selected. For this case, the selection of the growing scenarios applied are those analyzed and presented by Mendoza-Vizcaino et al. [35]. The three growing scenarios are: a) ***Low Scenario***; b) ***Base Scenario***, and; c) ***High Scenario***; in the four key years: ***2018, 2024, 2035 and 2050*** in the electricity consumption and power demanded were taken in consideration from this study.

STEP 4. Regarding the ***minimum LCOE, the minimum Net***

***Present Cost (NPC), and the maximum NPV*** the analysis and the results evaluation are made to choose the hybrid generation system to be installed on the Island.

### 3.2.2 PHASE 2 (Steady-state analysis)

Objective: To ensure the reliability and safety of the grid's operation response according to the hourly input data in the simulations on the base of the results obtained in Phase 1.

STEP 5. In this stage, the power flow simulations are executed. The electric system responses must be within a functional range, in order to establish the most suitable operation configuration to keep a reliable, safe and strong grid. The signals to be monitored can be the voltage, the angle, the current flow, the reactive and active power, among others. The power flow analysis of an electric system gives enough information about the grid state in the present time and can use this analysis to have a future operation planning of the system [176].

STEP 6. In this stage, the analysis of the results from STEP 5 is carried out, this analysis can detect weakness on the grid or a fault on the limits response according to the grid code selected. Therefore, the suggested solution and alternatives or reinforcements to do, while considering monthly and/or yearly load increase or decrease [176] will be done in STEP 7. The working loop between STEP 5 (power flow), STEP 6 (results analysis) and STEP 7 (grid modifications or reinforcements) will be repeated until the parameters of the grid's operation response and requirements of the grid code selected will be complimented. If the results fulfil the grid code parameters selected, it must go to STEP 8 (PHASE 3).

STEP 7. In this stage, the changes or suggested solutions and alternatives of reinforcements to do on the electric grid are integrated on it. These changes determine the base of calculus to run the simulations in the new power flow analysis (STEP 5) to obtain the most suitable operation configuration of the grid (STEP 6).

### 3.2.3 PHASE 3 (Dynamic stability analysis)

Objective: To ensure the stability and safety of the grid's operation response after an event that produces system instability and unbalances.

STEP 8. This analysis is done with the results of the final system chosen in STEP 6. The power system stability depends on the system response in a presence of a short-circuit or by the effects of frequency and voltage values under the varying load or sources conditions. These effects will increase if the supply sources are conforming mostly by renewable energy sources due to its own nature variability. In this document, the dynamic analysis is done so the power system must be able to return to a steady-state after disturbances and to ensure a voltage stability and a frequency stability [178].

STEP 9. As result of the stability analysis, and if the system returns to a steady-state correctly, the procedure will follow STEP 11. If it does not, then the electric grid must be modified to obtain the most suitable operation configuration in STEP 10.

STEP 10. In this stage, the changes or suggested solutions and alternatives of reinforcements to do on the electric grid are integrated on it. These changes will determine the base of calculus to run the simulations in the stability analysis and obtain a stronger and reliable grid operation response.

STEP 11. The final hybrid power system is shown and this technical results will be the system chosen to install on the Island. Therefore, the economic data obtained from this final system is used together with the economic results from STEP 4 to have a final economical proposal. In PHASE 4, the economic analysis is detailed.

### 3.2.4 PHASE 4 (Economical analysis)

Objective: To obtain the minimum LCOE and the minimum NPC with the maximum NPV for the hybrid system chosen.

The investment must be able to produce enough profits in order to give back the same amount of the initial capital plus a return flow during the project lifetime [179]. This gives reliability and safety to the investment even in the case of severe affectations produced from the natural conditions of the renewable facility's site.

STEP 12. The NPV is the present value of the discounted future cash flow at the end of the project lifetime. This value gives the cash flow saved in comparison with the base case, affected by the capital recovery factor. The more value resulted, the more attractive the investments will be.

STEP 13. The final hybrid power system, including the electric grid, is presented to be installed on the Island as result of the complete analysis done.

# 4 Legal Framework on Small Islands and Mexico

## 4.1 Current Legal Framework Status on Small Islands

Since 2011, the United Nations (UN) has activated the Small Island Developing States program (SIDS). One of its goals is to reduce the great expenses governments have as consequence of the intensive use of fossil fuels on islands. Taking into account the vulnerability and the small size of the islands, it is extremely urgent to: take advantage of RE potential, develop energy efficiency and enforce the SIDS program for a sustainable development (see Figure 4.1) [180]. Development is not possible without energy, and a sustainable development is not possible without a sustainable energy [9].

Inside its Ten-Year Framework of Programmes on Sustainable Consumption and Production Patterns (10YFP), the UN also promotes the Sustainable Tourism Programme. The reason for promoting this program is that tourism can deplete natural resources, leading to water shortages, loss of biodiversity and land degradation. Tourism also contributes to climate change and pollution growth. As example of this energy deploying in every Caribbean Island, in Barbados, the air conditioning is the mains driver of electricity consumption (see Figure 4.2) [10]. Without proper management and protection of the environment and without investing in greening the sector, ecosystems and thousands of magnificent species will suffer, among other impacts, especially on islands[181].

Global actions and programs enforced to reduce global warming and environmental damage have increased the use of renewable energy grids (commonly call micro-grids). This takes place in suburban areas, rural zones

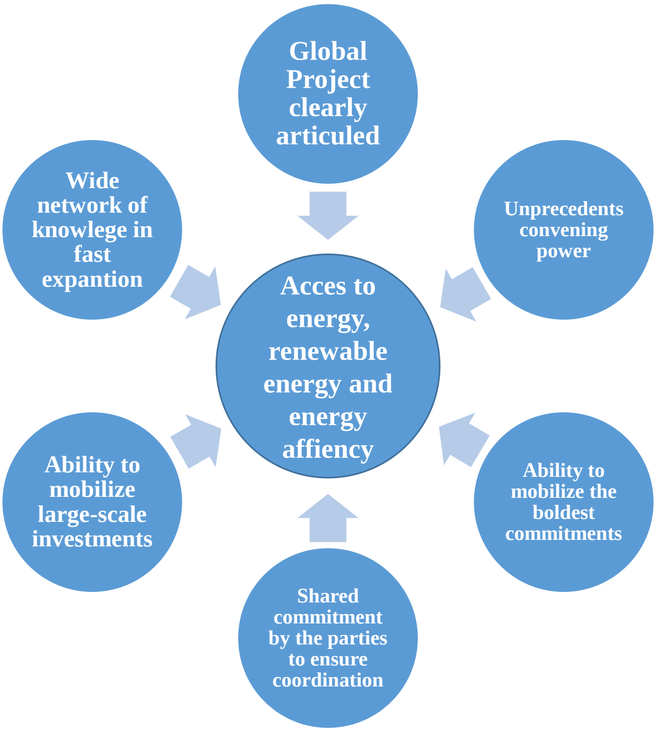


Figure 4.1: Value proposition of United Nations (UN) initiative: Sustainable Energy for All (SE4All) [9].

or small Island States. These micro-grids, combined with the Information and Communication Technologies (ICT), have activated the distributed renewable energy economy [75].

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 [182]. Studies on the integration of Renewable Energy Technologies (RETs) into electric grids have been developed. For instance, the contribution made by Bertin and Frangi [183] that shows the potential of RETs integration into the electrical system on Guadeloupe

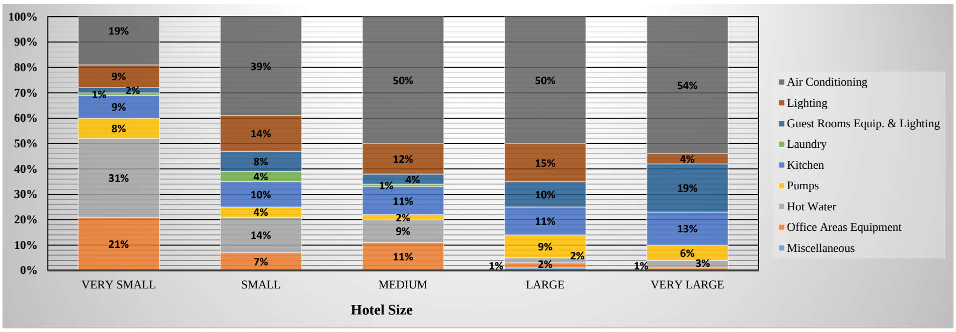


Figure 4.2: Electricity consumption in the hotel sector of Barbados, by hotel size. [10].

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. [184] 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) [11, 12]. The size of a small island was determined by Blechinger et al. [11], the Figure 4.3 shows results from the GIS analysis. It was 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 [120] as a flexible load that produces desalinated 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 [164, 185–187]. Other cases use batteries for energy storage on islands [188]. Others do not use energy storage [19] at all.

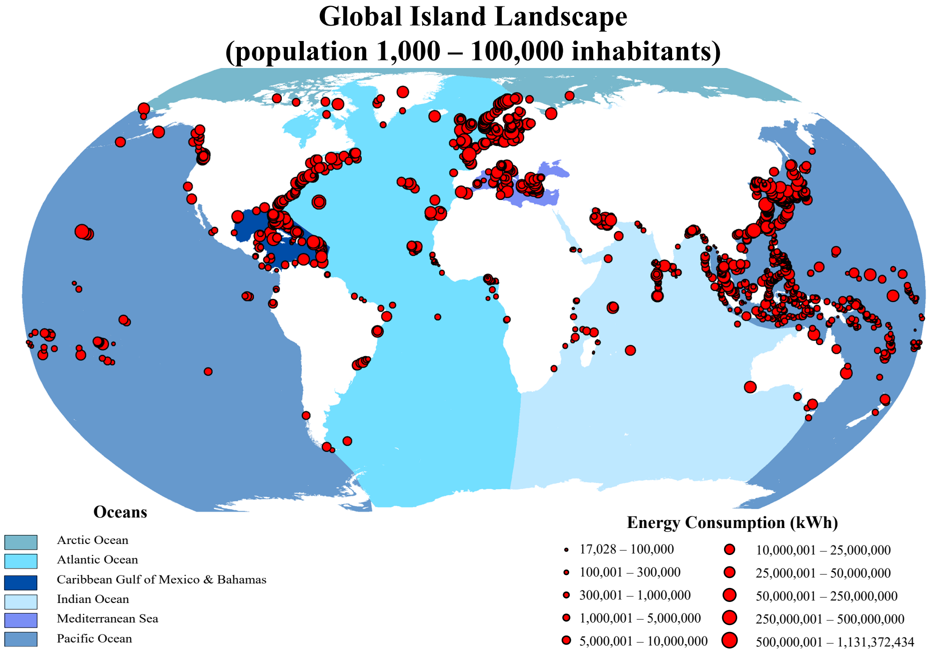


Figure 4.3: GIS analysis identified approximately 1800 small islands below 100,000 inhabitants with significant renewable energy potential [11, 12].

## 4.2 Legal Framework for the Renewable Energy Development in Mexico

### 4.2.1 Renewable Energy Policy in Mexico

In Mexico, the Secretary of Tourism has developed a sustainable tourism program. This program pretends to generate a sustainable development in the tourist activities, raising this way the quality of life of the inhabitants [189]. This measure is supported by UNWTO and aims to maximize the environmental profits, minimizing the environmental damages [190]. Aligned to this target is the goal of the Secretary of Energy indicated in the Energy Sector Prospects 2014-2028 (PSE, for its Spanish acronym), published in 2014 and in the same document dated 2013-2027 [63]. These two documents were created through the Energetic Transition and Financing for the Renewable Energy Improving Law (LAERFTE, for its Spanish acronym) and the Climate Change General Law (LGCC, for its Spanish acronym). In a first scenario, the national electric power demand must be supplied by 35% of clean technologies in 2024. In a second scenario, an alternative expansion of the electric sector must accomplish 35% of electricity generation based on non-fossil fuel in 2027. Also, in this second scenario, the limit for fossil fuels electricity generation must be 65% in 2024, 60% in 2035 and 50% in 2050. Under the actual prospect (PSE 2014-2028) the RE generation will reach about 28.2% of the national electricity generation in 2018, 28.5% in 2024 and 41.4% in 2028 [64].

Within Mexico's National Development Plan 2013-2018 (PND, for its Spanish acronym) the Renewable Energy Improving Special Program (PEAER, for its Spanish acronym) was developed [65]. It was indicated in this document an intermediate target: to have by 2018 a 34.6% of the electricity generation capacity installed by clean energy sources. Another another target by 2018 was to have an electricity generation of clean energy sources equal or higher than 32.8%. All these governmental objectives are summarized in Table 6.1.

### 4.2.2 Mexico energy and electric sector status

There is a world commitment to reduce $CO_2$ emissions. Countries are looking for a change in their energy market composition. The participation of renewable energy in the electric sector will help ensuring their natural resource sustainability and reducing the fossil fuel impacts and their price volatility [49].

Globally, 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 9,425 Mtoe; in the OECD, this fuel consumption was 3,629 Mtoe in 2014, representing 38.5% of the total amount. The America's OECD represented 51.8% of the OECD total consumption [15]. The America's OECD was nearly 100% energy self-sufficient in 2014, as Figure 4.4 shows [13, 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 [191].

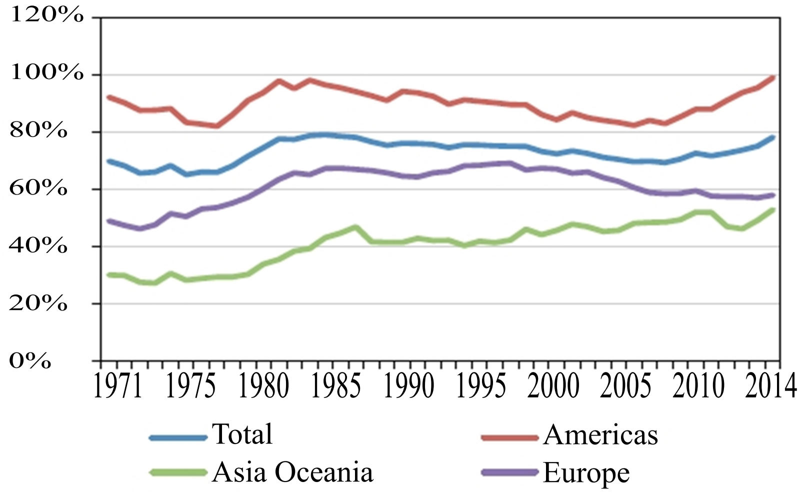


Figure 4.4: OECD energy self-sufficiency in 2014 [13]

The global energy landscape is changing quickly as result of the economic shifts and the technological improvements. Figure 4.5, Figure 4.6 and

Figure 4.7 show the TPES (toe, ton of oil equivalent/kUS$), the electricity generation (GWh) and the RE production (Gigatoe) for Mexico, the OECD, other countries and Global production [13–15].

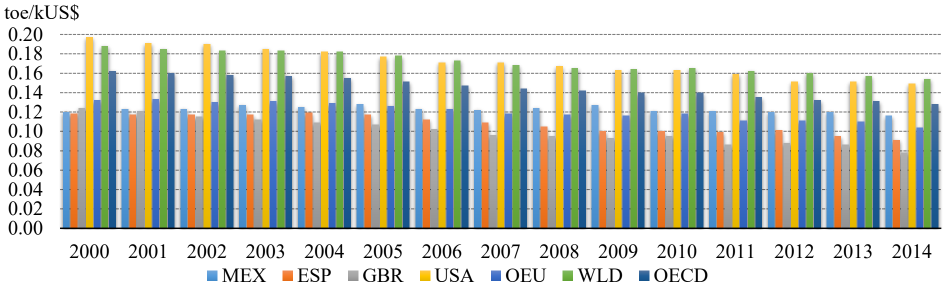


Figure 4.5: TPES in toe/kUS$ for global, OECD, Mexico and others countries from 2000 to 2014 [13–15]

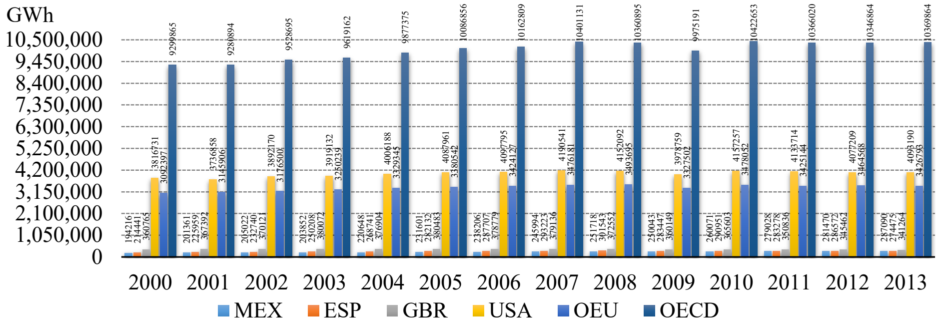


Figure 4.6: Electricity generation in GWh for global, OECD, Mexico and others countries from 2000 to 2013 [13–15]

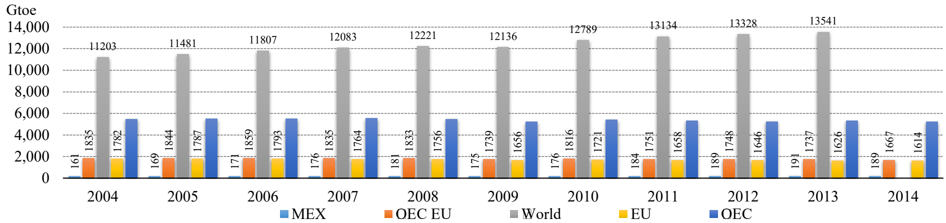


Figure 4.7: Renewable production in Gigatoe for global, OECD, Mexico and others countries from 2004 to 2014 [13–15]

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 [192]. 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 [193].

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 (see Figure 4.8). 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, as it can see in Figure 4.9. 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 [16], as it can see in Figure 4.10. The National electricity production in Mexico is indicated in Figure 4.11 for 2014 and 2015 [16].

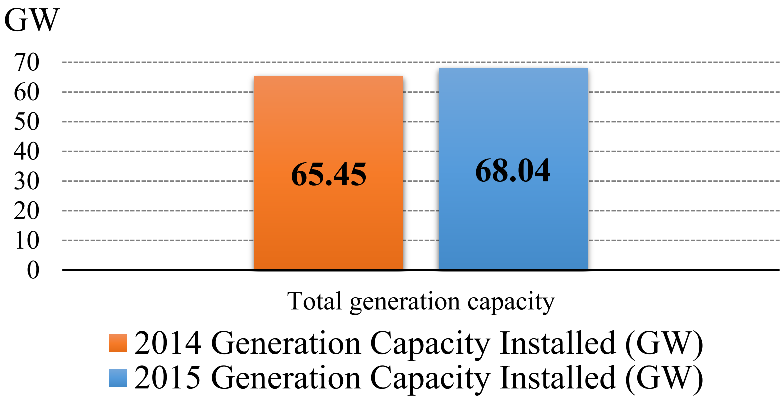


Figure 4.8: Electricity generation capacity installed in 2015 [16]

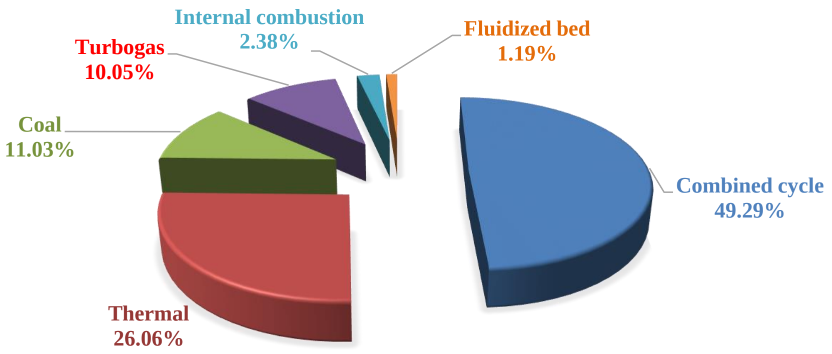


Figure 4.9: Composition of the conventional (fossil fuel) power capacity installed in 2015 [16]

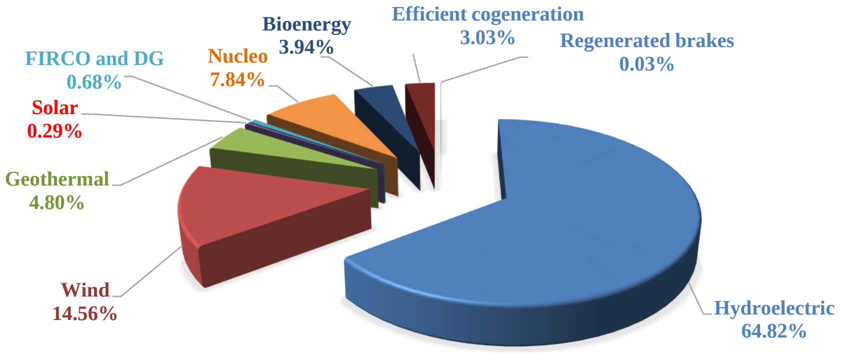
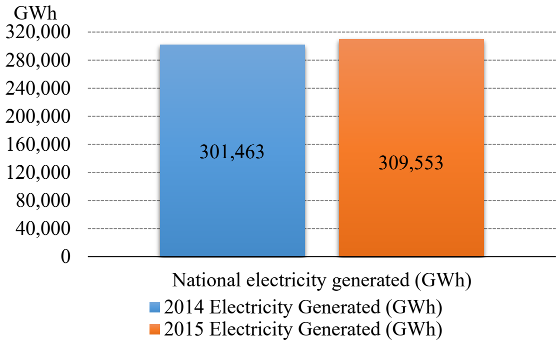
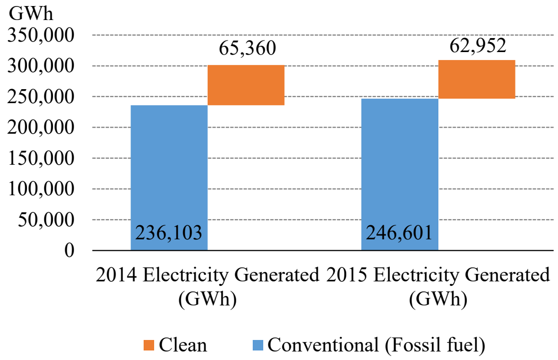


Figure 4.10: Composition of the clean energy (non-fossil fuel) power capacity installed in 2015 [16]

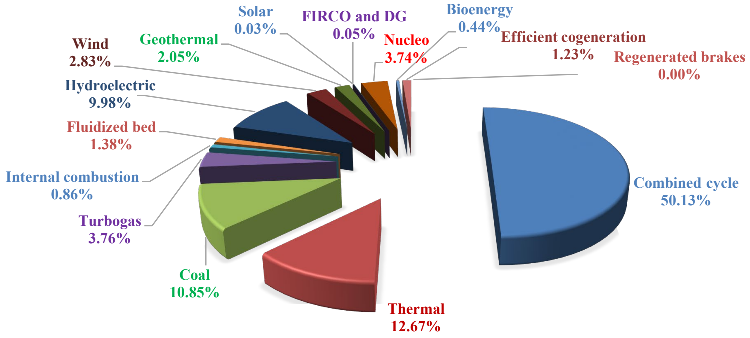
The maximum power demand and the electricity consumption will continue increasing, so it is necessary to increase the renewable power energy participation in the electricity sector in Mexico. The electric sector growth is directly related with the GDP (Figure 4.12). The prospective growth for the electric sector was determined by the GPD prospective growth, the energy indicator, the population increase and the fossil fuels prices (Macro-data, [16]). 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%



(a) Electricity generated.



(b) Electricity geerated with clean and conventional sources.



(c) Composition of the electricity generation technology installed.

Figure 4.11: Electricity generation characteristics in Mexico for 2014 and 2015 [16].

from fossil fuel sources [49].

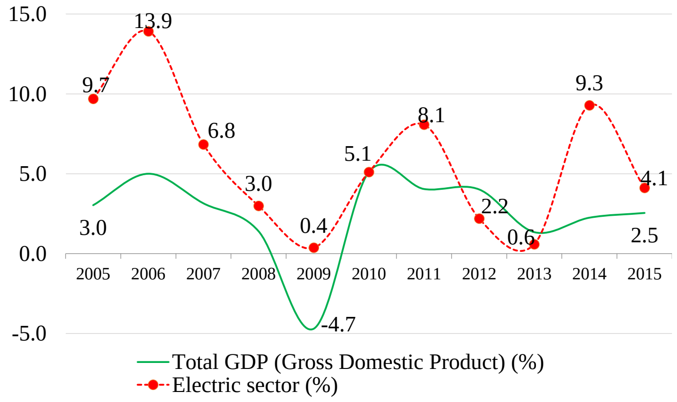


Figure 4.12: Electric sector growth vs. gross domestic product (GDP) growth in Mexico [16]

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 [194].

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 [16].

### 4.2.3 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 [17]. The global participation of the renewable energy sources in the energy sector was 13.5% in 2013. In Figure 4.13 the per capita consumption, the energy intensity, and for the sizes of the spheres, the percentages of the RE in their electricity production in 2013 are indicated [17].

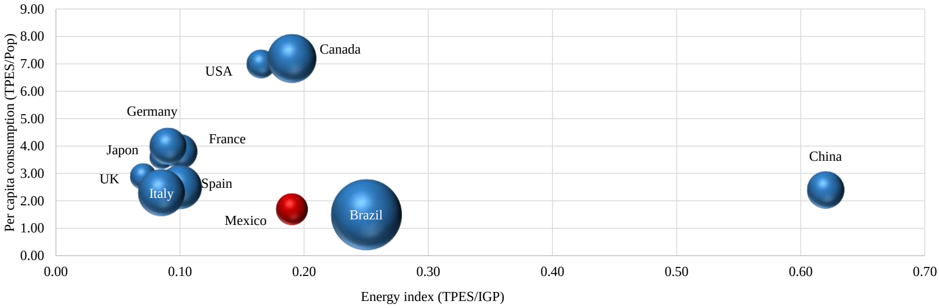


Figure 4.13: Energy intensity, per capita consumption and sphere size related to the percentage of the RE participation in their electricity production in 2013 [17]

There is an enormous potential in RE in Mexico. The National Inventory of Renewable Energy (INERE, for its Spanish acronym) [18], indicate that the proved and probable renewable electric generation potential is 100,278 GWh/yr. This amount of energy was 33% from the total electricity generated in 2014. Only PV generation represented 35% of this 2014 generation. The feasible potential on renewable energy is 195,278 GWh/yr. The solar power has an infinite potential for development, according to INERE [17, 18]. Figure 4.14 shows this RE potential in Mexico.

From the 70,000 MW of total power electricity generation capacity installed in Mexico, 19,000 MW are of non-fossil fuel technology [195]. 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 [16]. To in-

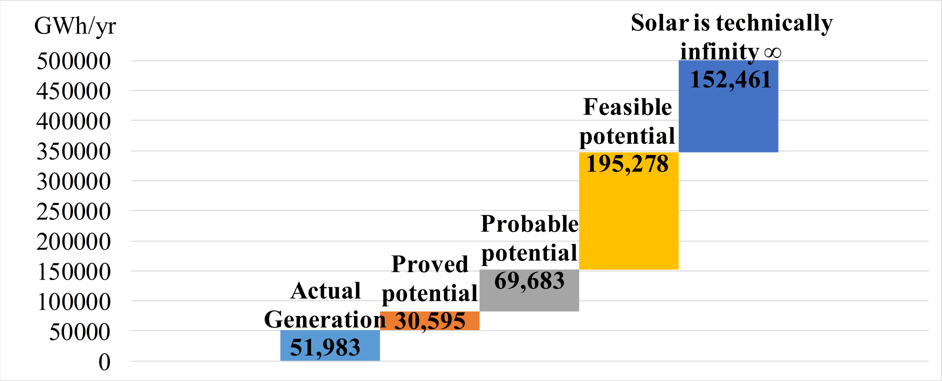


Figure 4.14: Proved, probable and feasible renewable electric generation potential for Mexico in 2014 [17, 18]

crease 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 [50]. 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 [51]. 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 [52]. Table 4.1 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.

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

Table 4.1: Targets summary of electricity generation in renewable energy (RE) for Mexico by 2050 [16, 17, 49–59].

## 4.3 Electric Sector in the Peninsular Area

The Peninsular area is one of the seven electric regional controls in the SIN [61]. 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 4.2, showing the three scenarios [16].

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

Table 4.2: Peninsular annual average growth rate expected from 2016 to 2030 [16].

The Peninsular perspective of growth in power demand is shown in Figure 4.15 and the Peninsular perspective of growth in electricity consumption is shown in Figure 7.1 [16].

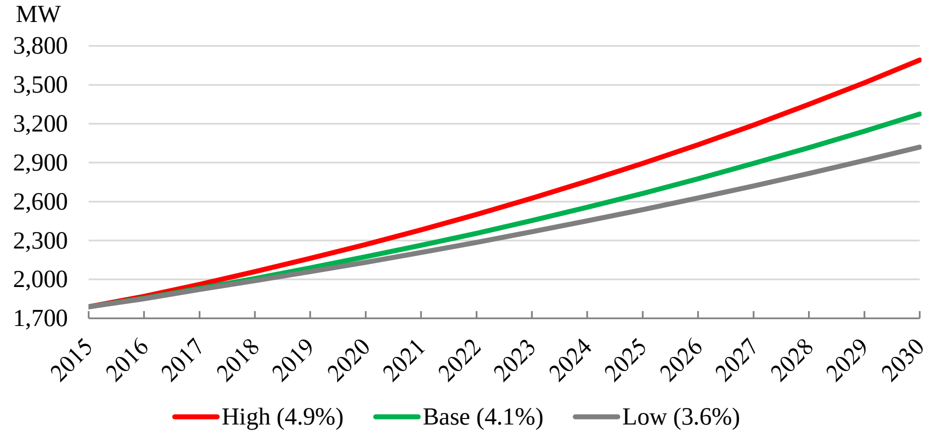


Figure 4.15: Forecast in maximum power demand from 2015 to 2030 in the Peninsular regional control for the three growing scenarios: (1) High Scenario, (2) Base Scenario and (3) Low Scenario [16]

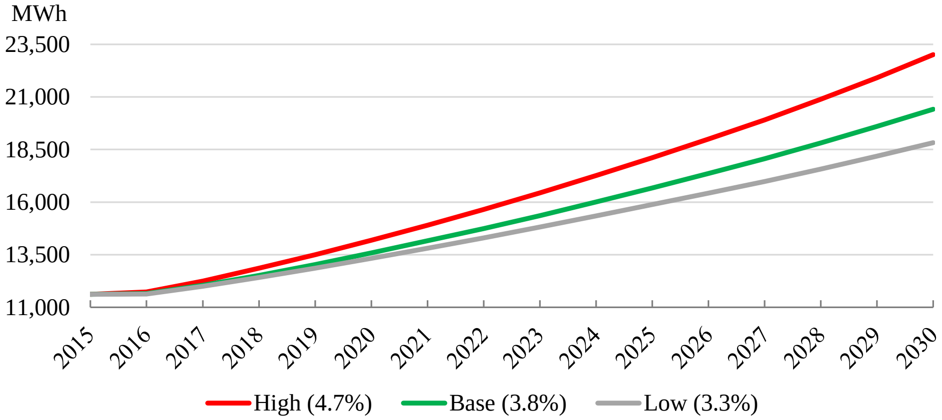


Figure 4.16: Forecast in electric consumption from 2015 to 2030 in the Peninsular regional control for the three growing scenarios: (1) High Scenario, (2) Base Scenario and (3) Low Scenario [16]

## 4.4 Legal Framework for the Renewable Energy on Cozumel Island

The local objectives for RE in Cozumel Island are nearly non-existent. The document that makes a few references about them is the Municipal

Development Plan 2013-2016 (PMD, for its Spanish acronym) [196]. Because of the lack of specific objectives in Cozumel Island, the Peninsular area objectives in renewable energy will be taken (Table 6.1) as reference. Note: for national security confidential reasons, all data of power demand, electricity generation capacity and electric grid features on the Island are reserved. This information has been estimated from the published data in [21, 60, 63–65]. Even so, we believe these data considerations do not modify the validity of the results obtained.

# 5 Study case: Cozumel Island

## 5.1 Cozumel Island, México

Not all RETs should be considered on small islands, this due of their geographic characteristics, natural protected areas, sensitive environment, like coral reefs, cultural and historic heritage, and limitations in the use of land for commercial and industrial developments. The specific RETs have to be chosen with a well-defined methodology, taking care of all factors that can cause the project to fail or can generate major environmental damage.

Cozumel Island has been chosen as a typical example of an island in the Caribbean. Its characteristics of warm weather, tourism activity on the coral reefs, extensive natural areas and an environment sensitive to the climate change are typical of tropical areas. These areas have common characteristics, with electricity generation based on diesel or fossil fuels. Having into account that locally there is not a specific governmental strategy to develop the RETs, the main goal of this proposal is to prove that an integration of RETs can accomplish the following target: to have clean electricity in the Island in the future. This development would help to make Cozumel Island a renewable and sustainable place to live and visit for the good of the community and the world. In this sense, the results of the study can be applied to other islands with similar characteristics.

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 5.1). Cozumel's coral reef is part of the second world's largest coral reef and it is aimed to attempt tourism. With a surface area of 647 km$^2$, it had a population of 86,415 inhabitants in 2015 [28] 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 [197].

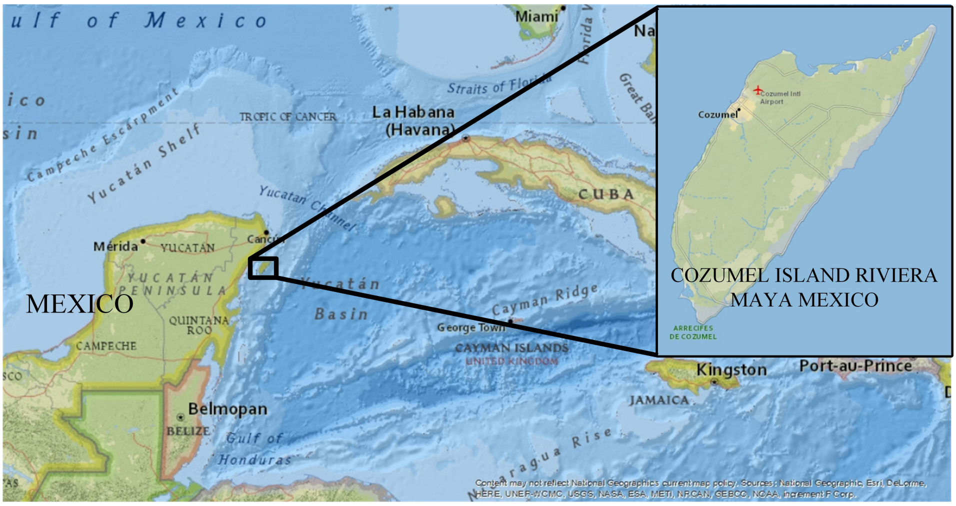


Figure 5.1: Cozumel Island location [19].

The electrical system in this exercise will be simulated “off-grid”, as in case of a hurricane presence or an interconnected submarine wire failure. Tourism is a key business element for most of the islands reviewed in this paper and can be the tool for achieving a sustainable future growth. Currently tourism is the number one growing sector, contributing with 9% of the global gross domestic product, providing one of every 11 jobs and being the 6% of global exportations. According to the United Nations World Tourism Organization (UNWTO), in 2030 there will be 1.8 billion of tourists globally every year. In another hand, tourism provides 5% of $CO_2$ global emissions. So if this activity does not grow in a sustainable way, it could generate a serious environmental damage [181].

## 5.2 Cozumel Island's Electric System Characteristics

The Island has a continental wire connection through a submarine cable from the Riviera Maya node (Playa del Carmen city) to the Cozumel node. The electricity flows in both directions, as it can be seen in Table 5.1. Figure 5.2 shows the monthly power demand through the years 2008-2013. As a consequence of the 2008 global financial crisis, the power demand dropped, in contrast with 2009's power demand, which was clearly upward. Although there was a small increase, in 2013 the power demand was stabilized [20]. In Figure 5.2, the power demand decrease in 2012 vs. 2011 was caused by the sanitary crisis of the A (H1N1) influenza epidemic. Combined with the global financial crisis and according to the information from the Secretary of Tourism, the amount of visitors in that year to Cozumel Island were fewer than in 2011 [198].

| | **2011** | **2012** | **2013** | **2014** |
|---|---|---|---|---|
| **Maximum Power Generated (MW)** | W.D.* | 46 | 39 | 43 |
| **Maximum Power Demanded (MW)** | 42 | 41 | 42 | 44 |
| **Electricity Consumed (GWh)** | 228 | 240 | 250 | 261 |
| *** W.D.= Without Data.** | | | | |

Table 5.1: Cozumel Island's electrical main features [20, 21, 60]

Table 5.1 indicates the maximum power demanded and generated. It also indicates the electricity consumed from 2011 to 2014, showing an increase in the maximum power demand of 4.57% in 2013 compared to 2012. Figure 5.3 shows the electricity consumption for the Quintana Roo State and for Cozumel Island from 2000 to 2014 [21]. Meanwhile, Figure 5.4 indicates the electricity consumption behavior from 2000 to 2015 [20, 22]. These values combined with the values of Figure 5.2 helped to develop the power demand seasonal profile (data were obtained from [20–23]). With these data, the hourly power demand seasonal profile was elaborated and used in the simulations of Cozumel Island's electric grid (Figure 5.5 and Figure 5.6).

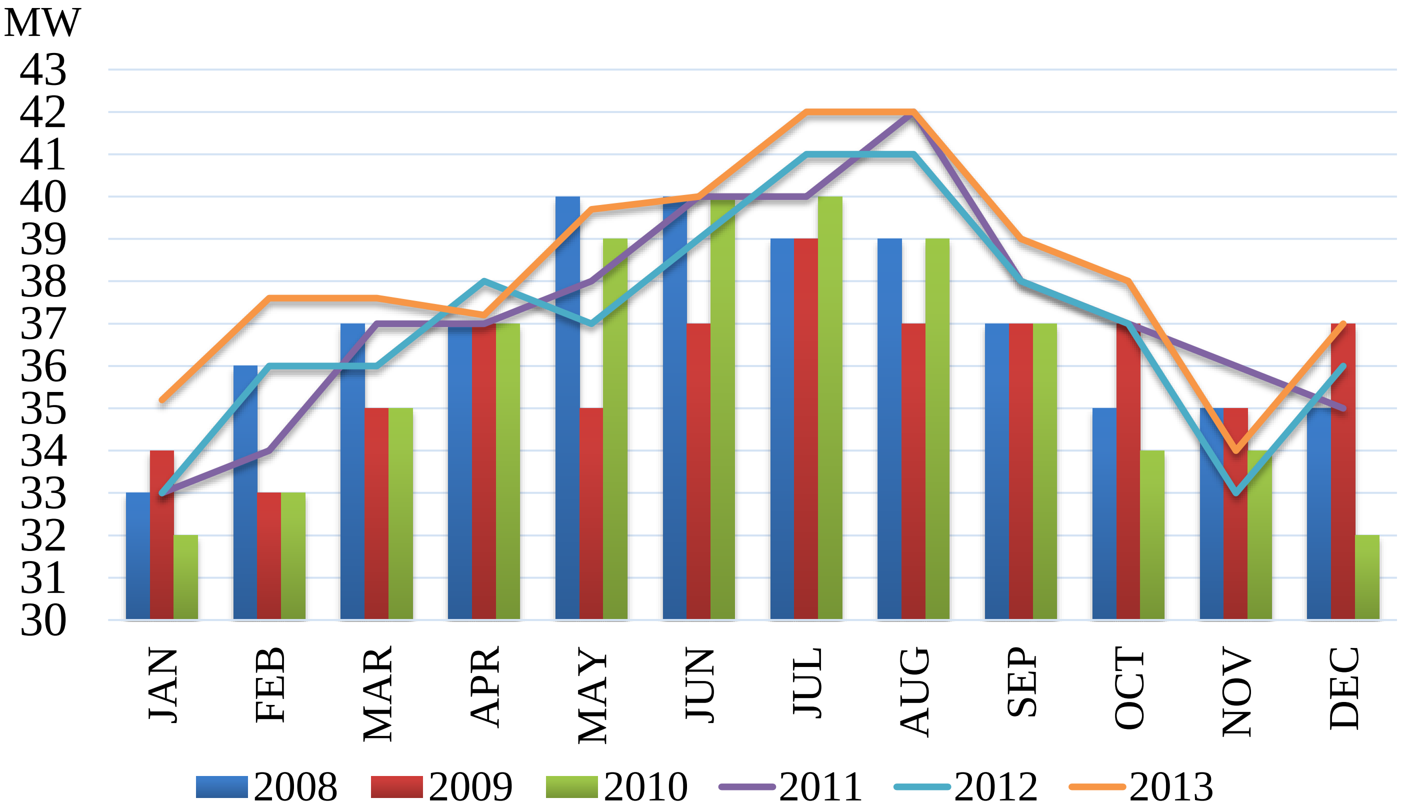


Figure 5.2: Cozumel Island's maximum power demand [20] [62].

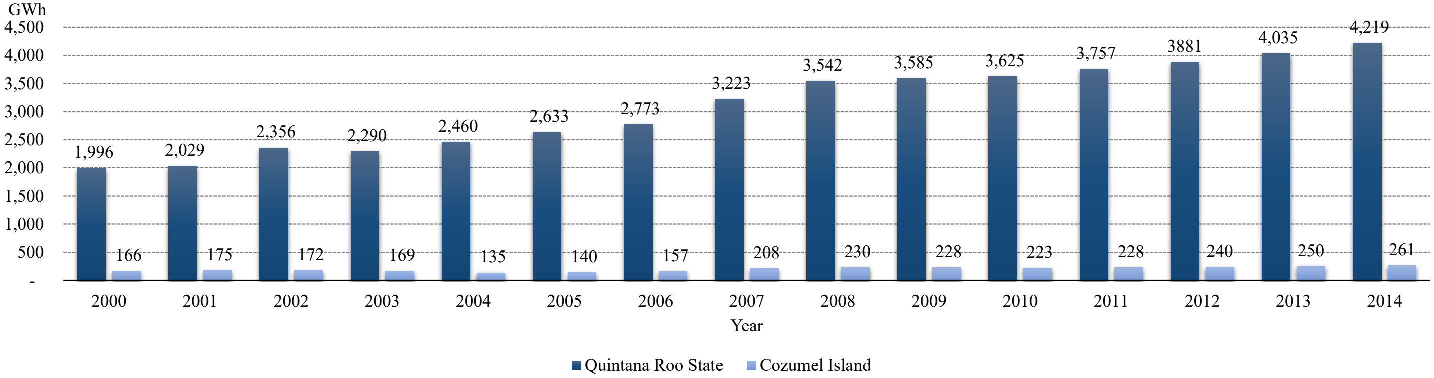


Figure 5.3: Electricity consumption for the Quintana Roo State and for Cozumel Island from 2000 to 2014 [21].

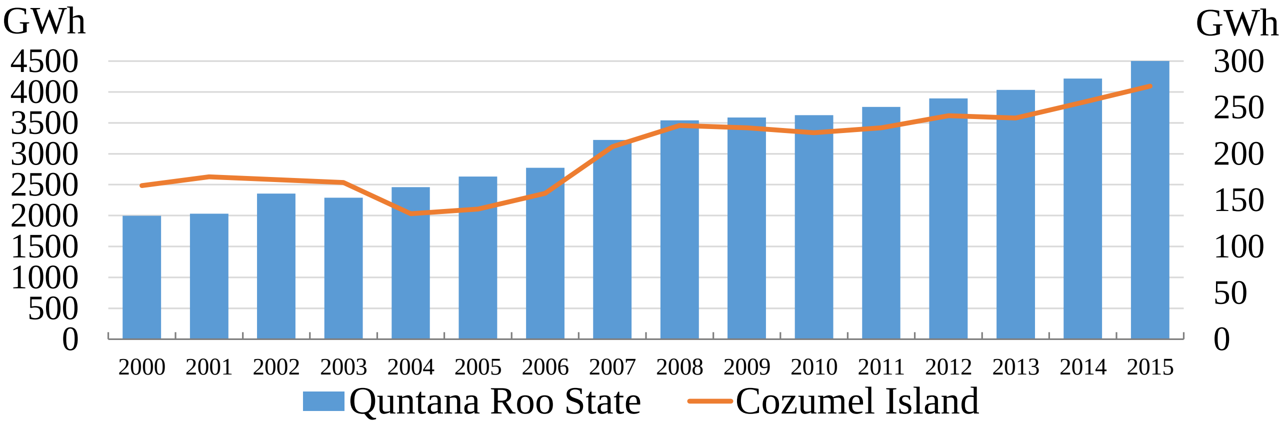


Figure 5.4: Electricity consumption on Cozumel Island from 2000 to 2015 [20, 22]

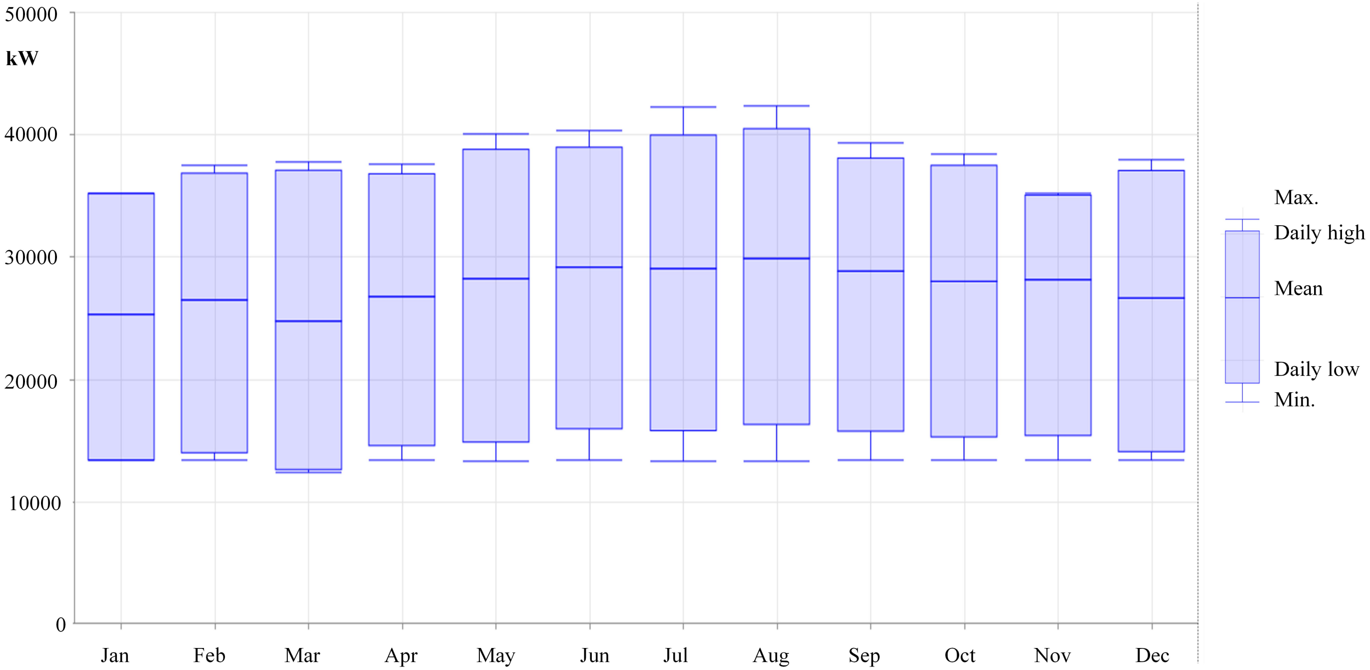


Figure 5.5: Cozumel Island's Power Demand Seasonal Profile in 2013 [20, 21, 23, 24].

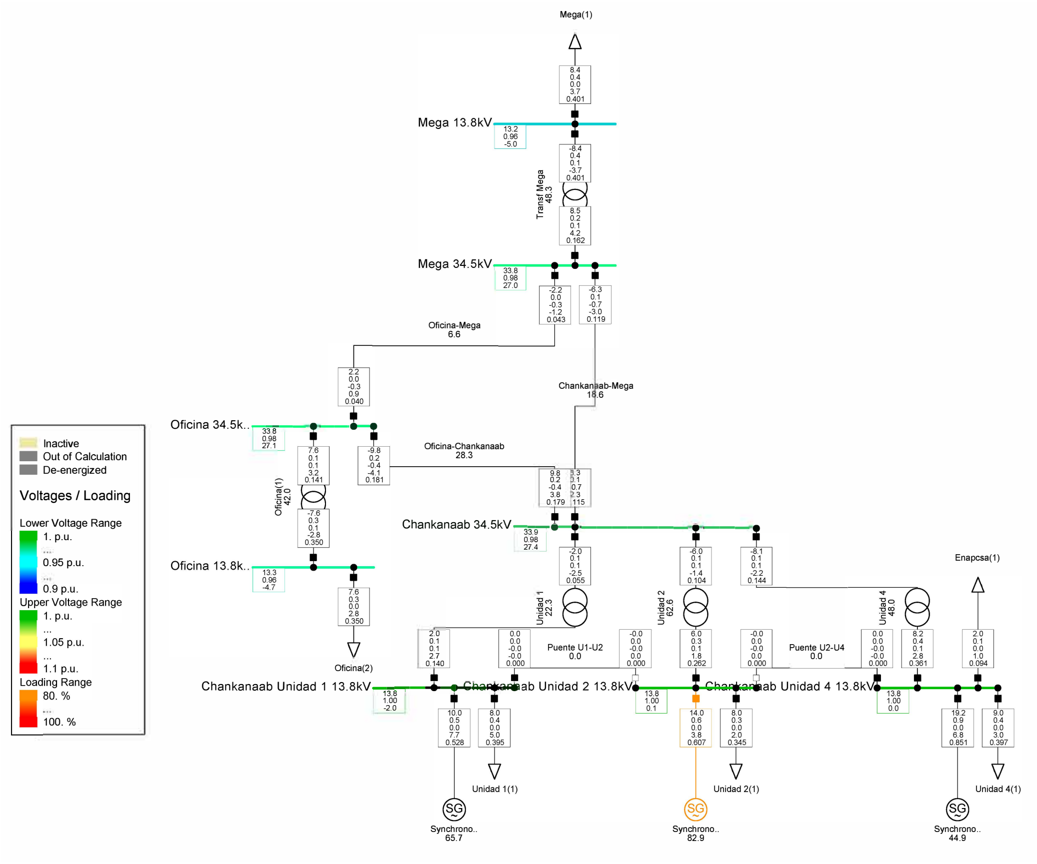


Figure 5.6: Grid-off simulation without RE sources, also without communication and control systems [20, 21, 25].

## 5.3 Analysis of the current electric system

Currently, the electricity generation on the Island depends solely on *diesel turbo-gas machines* (single cycle gas turbines burning diesel). There are three *diesel turbo-gas 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 turbo-gas 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.

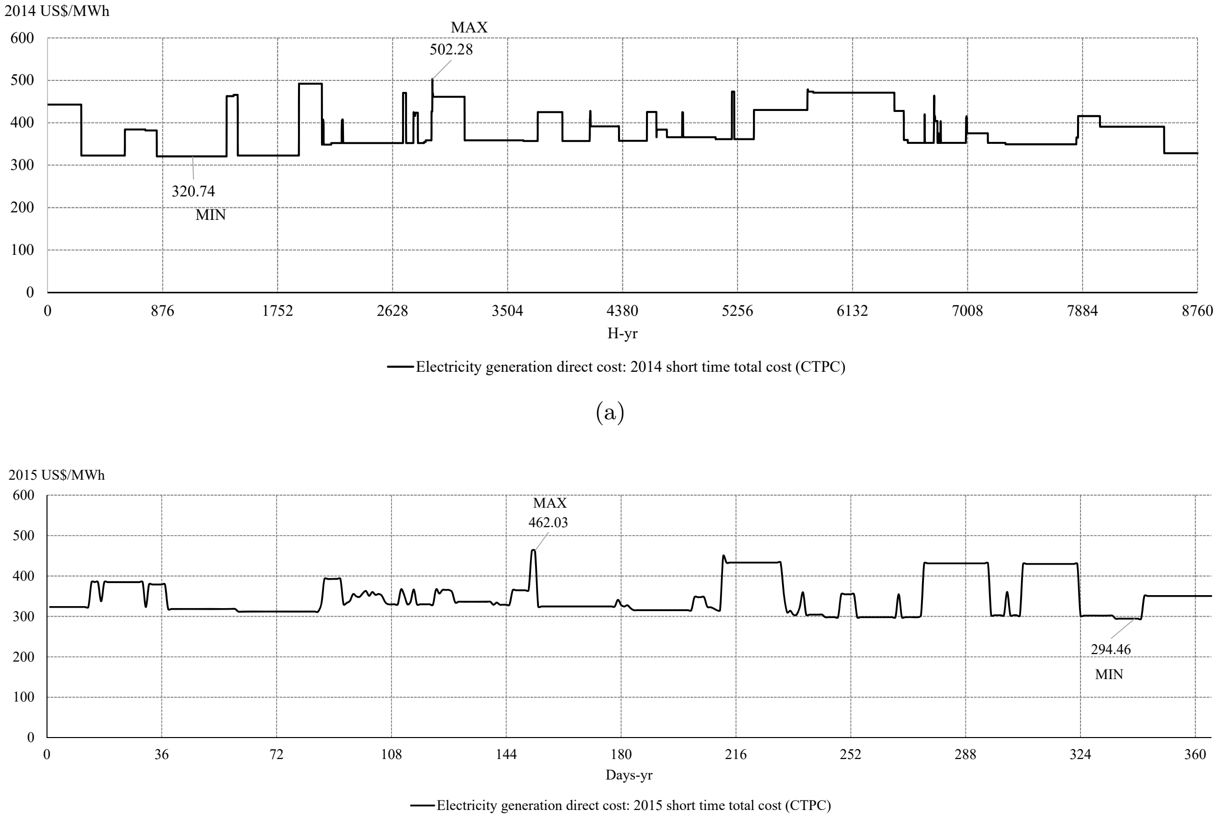
The maximum power demand fluctuates between 41 MW in 2011 and 44 MW in 2014 (see Figure 5.2). The maximum power generated on the Island covers the electric demand, but sometimes the electricity excess production flows to the main land (Riviera Maya node) [20]. The electricity consumption on the Island in 2015 was 272.97 GWh, 6.77% higher in regard to 2014 [192]. Figure 5.4 indicates the electricity consumption behaviour from 2000 to 2015 [20, 22].

The hourly power demand seasonal profiles for Cozumel Island were based on the information from [16, 20, 22, 28, 49]. 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.

The cost of electricity generation considered for the financial scenarios was based on turbo-machines that burn diesel. Its average was within the range from 312.34 $US/MWh to 472.44 $US/MWh (2013 exchange rate average of 12.77 $MX/$US) in 2013. The current generation system on Cozumel Island are used to supply the peak demand and in emergency cases. According to the government utility reports, the electricity generation cost for that period of time of peak demand in 2014 is indicated on Fig. 5.7a. Its average was within the range from 320.74 $US/MWh to 502.28 $US/MWh (2014 exchange rate average of 13.30 $MX/$US) in 2014. This year 2015, the CTCP price was within the range from 294.46 $US/MWh to 462.03 $US/MWh (2015 exchange rate average of 15.87 $MX/$US). Fig. 5.7b shows the 2015 CTCP daily. Is important to remark that this CTCP, will be considered as the hourly production cost in order to have a comparative analysis of the Levelized Cost of Energy (LCOE), for the Cozumel Island's electricity generation system [20, 26, 27]. Fig. 5.7 shows that the 2015 CTCP is less than the 2014 CTCP, this is because the $MX/$US average exchange rate considered. In 2014, the $MX/MWh of the CTCP was less than in 2015 (See Table 5.2).

| | MX$ | |
|---|---|---|
| | MAX | MIN |
| 2014 CTCP | 6,498.60 | 4,262.06 |
| 2015 CTCP | 7,149.11 | 4,750.50 |

Table 5.2: MX$/MWh CTCP for 2014 and 2015 in Cozumel Island [20, 26, 27]



(a)

(b)

Figure 5.7: Short time total cost (CTCP) (**a**) 2014 hourly; (**b**) 2015 daily [20, 26, 27].

According to the growth prospective for the electric sector in Mexico, and considering the diesel prices fluctuations over the time until 2050, the results in the electricity generation costs in Cozumel Island from 2014 to 2050 are indicated in the Figure 5.8 (in US$/MWh) [20, 26, 27]. This generation costs are taking into account the diesel turbo-gas technology currently running to supply the power demand on the island. Likewise, Table 5.3 shows the growth prospective for main fossil fuel prices to the electricity production from 2015 until 2030 in Mexico [61], but if we assume that this growing trend keeps its way, it can be valid used the diesel price growing tendency to build the Figure 5.8.

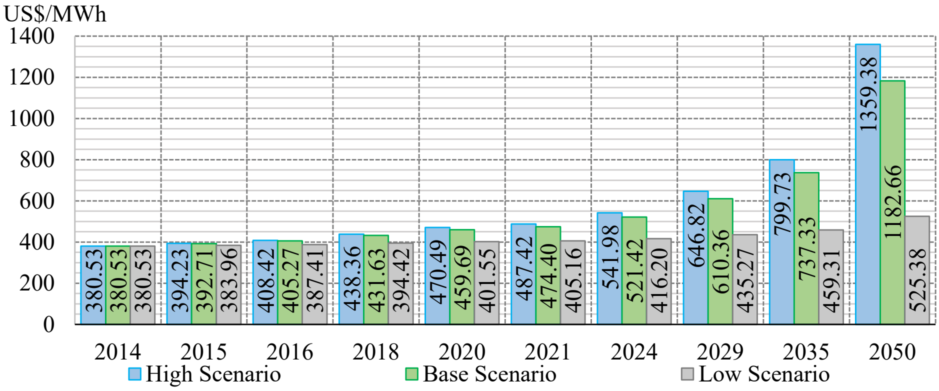


Figure 5.8: Growth perspective graph of the electricity generation cost from 2014 to 2050 on Cozumel Island with a fossil fuel generation system (based on data from [20, 26, 27]).

| **Scenario** | **Low** | **Base** | **High** |
|---:|:---:|:---:|:---:|
| Coal | 3.6 | 3.8 | 4.2 |
| Fuel Oil | 2.3 | 5.0 | 10.2 |
| **Diesel** | **0.9** | **3.2** | **3.6** |
| Natural Gas | 2.2 | 2.6 | 5.4 |
| Liquefied Natural Gas | 3.0 | 3.3 | 2.0 |

Table 5.3: Growth perspective indicators for main fossil fuels prices to electricity generation in Mexico from 2014 to 2030 [61].

## 5.4 Setting the Long-Term Electric System Target

The energy planning scenarios developed in this study are based on the data from: PSE [49]; PRODESEN [16]; The Special Program for Exploitation of Renewable Energies (PEAER is its Spanish acronym) [53]; the Climate Change General Law (LGCC is its Spanish acronym) [51]; LTE [50]; National Strategy of Climate Change (ENCC is its Spanish acronym) [54]; Energy Sectorial Program (PROSENER is its Spanish acronym) [55]; the Renewable Energy Prospective (PER is its Spanish acronym) [17]; National Strategy of Energetic Transition and Sustainable Exploitation of Energy (ENTEASE is its Spanish acronym) [56]; LIE, National Strategy of Energy (ENE is its Spanish acronym) [57]; Special Program of Climate Change (PECC is its Spanish acronym) [58]; National Program for the Sustainable Exploitation of Energy (PRONASE is its Spanish acronym) [59]; and the Transition Strategy to Promote the Use of Cleaner Fuels and Technologies of 2016 [52].

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 [199, 200]: 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 4.2. 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 4.1. The prospective electricity consumption scenarios from 2016 to 2050 on Cozumel Island (see Figure 5.9) were obtained from the prospective growth rates indicated in Table 4.2 and from the information specified in Figure5.4. The prospective scenarios from 2016 to 2050 on Cozumel Island in power demand (see Figure 5.10) were obtained from the prospective growth rates indicated in Table 4.2 and from the information specified in Figure 5.2.

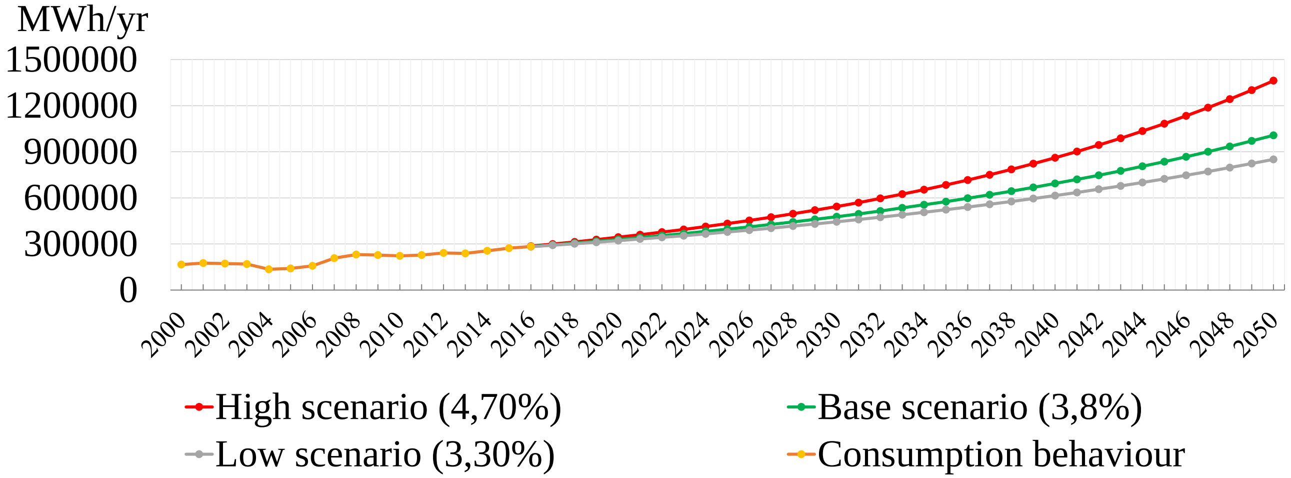


Figure 5.9: Electricity consumption and forecast on Cozumel Island from 2000 to 2050, based on the information from [16, 20, 22, 28]

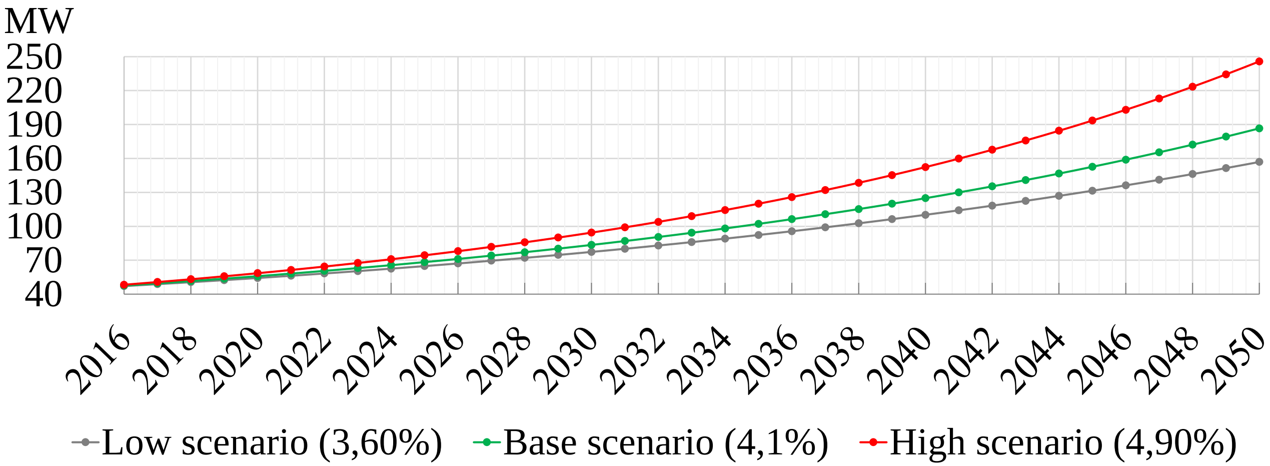


Figure 5.10: Forecast of maximum power demand on Cozumel Island from 2016 to 2050, based on the information from [16, 20, 22, 28]

The growing perspectives values indicated for 2016 and 2017 show a data difference between both tables, even so, the data selected to do the simulations in this work were those indicated by the Table 5.4. This table shows the electric sector growing perspectives values used to develop the ***Low Scenario***, the ***Base Scenario*** and the ***High Scenario*** for ***Cozumel Island from 2018 to 2050*** in 2016 [16].

Cozumel Island's Electric Sector
Growing Perspectives (%/yr)

| | SCENARIO | | |
|---|---|---|---|
| | LOW | BASE | HIGH |
| Power Demand | 3.6 | 4.1 | 4.9 |
| Electricity Consumption | 3.3 | 3.8 | 4.7 |

Table 5.4: Electric Sector Growing Perspectives for Cozumel Island in 2016 [16]

Table 5.5 shows the electric sector growing perspectives values used to develop the ***Low Scenario***, the ***Base Scenario*** and the ***High Scenario*** for ***Cozumel Island from 2018 to 2050*** in 2017 [62].

Cozumel Island's Electric Sector
Growing Perspectives (%/yr)

| | SCENARIO | | |
|---|---|---|---|
| | LOW | BASE | HIGH |
| Power Demand | 3.2 | 3.8 | 4.5 |
| Electricity Consumption | 3.3 | 3.8 | 4.5 |

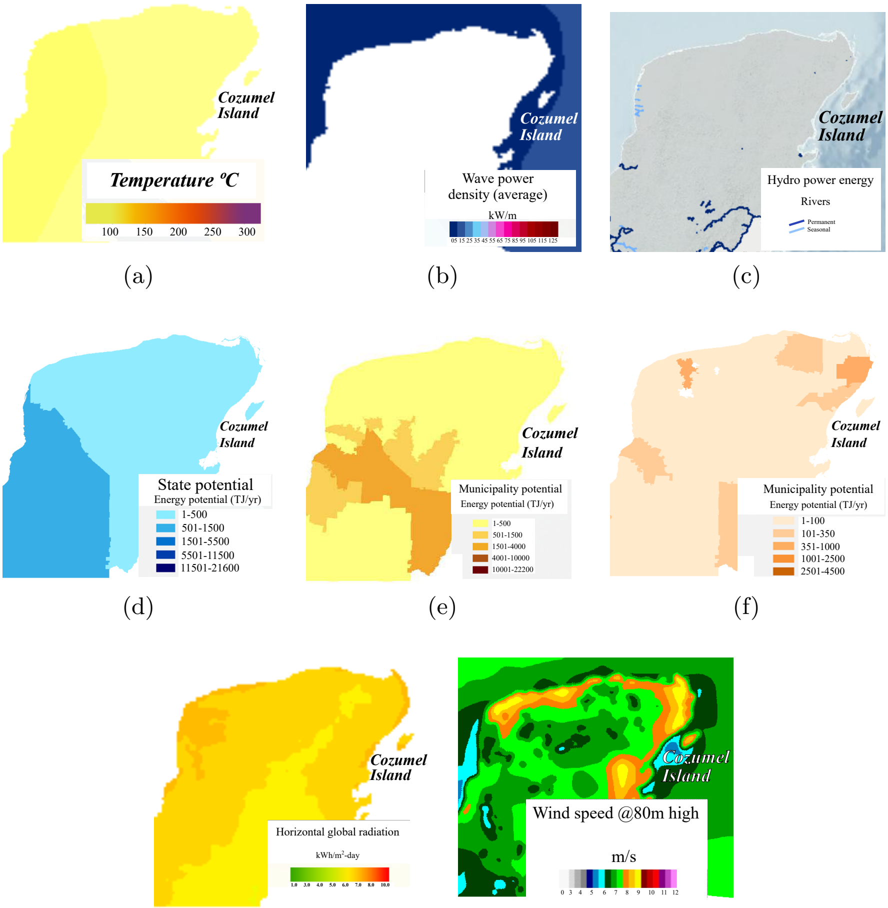
Table 5.5: Electric Sector Growing Perspectives for Cozumel Island in 2017 [62]

Reducing the electricity generation cost for the electric system on Cozumel Island

## 5.5 RE potential on Cozumel Island

The RE potential in the Yucatan Peninsula and Cozumel Island was obtained from the INERE [18] and CONABIO [29] Website tool through a Geographic Information System (GIS), from the RES statistical and geographic database. Figure 5.11 shows the Atlas for RE potential on Yucatan Peninsula and Cozumel Island: (a) Geothermal; (b) Ocean energy; (c) Hydro; (d) Biomass energy; (e) Agricultural and forestry waste energy; (f) Municipal Solid Waste (MSW) energy; (g) Horizontal radiation, and; (h) Wind velocity @80m high [18, 29]. According to this information of the RE resources' potential, PV and Wind technologies have been selected to develop this potential on the island.

Even if the specific place selected to install the renewable technology has the potential to develop them, Mexico has federal laws and state laws to protect natural areas (see Figure 5.12. The natural protected areas by federal laws in the north part of Quintana Roo State are shown in Figure 5.12a (including Cozumel Island, Map 2.1). Meanwhile, Figure 5.12b shows the natural protected areas by state laws in the north part of Quintana Roo State (including Cozumel Island, Map 2.2). The limits pointed in these natural protected areas laws will determine the right land selected to place the RETs on the island [18].

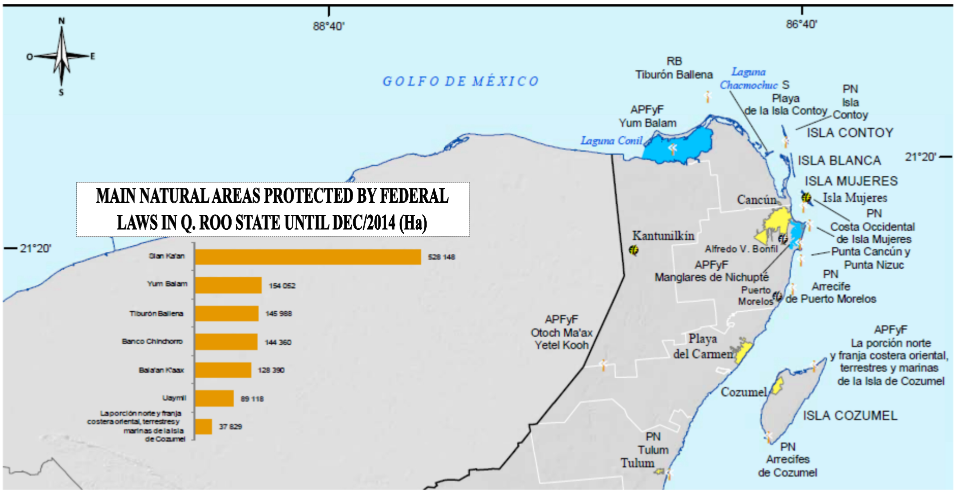


(a) (b) (c)

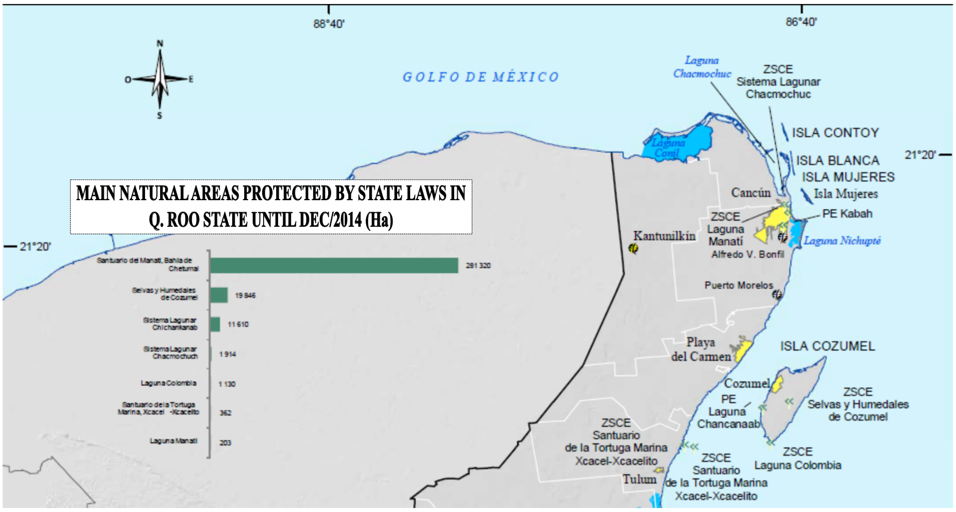
(d) (e) (f)

(g) (h)

Figure 5.11: Atlas for RE potential in the Peninsula Area. (a) Geothermal. (b) Ocean energy. (c) Hydro. (d) Biomass energy. (e) Agricultural and forestry waste energy. (f) Municipal Solid Waste (MSW) energy. (g) Horizontal radiation. (h) Wind velocity @80m high [18, 29].



(a) Federal protected natural areas for the North of Quintana Roo State (including Cozumel Island).



(b) State protected natural areas for the North of Quintana Roo State (including Cozumel Island).

Figure 5.12: Federal laws and state laws protecting natural areas (land sizes in Hectares) in the north part of Quintana Roo State and Cozumel Island [18].

## 5.6 Renewable energy integration on Cozumel Island in Mexico

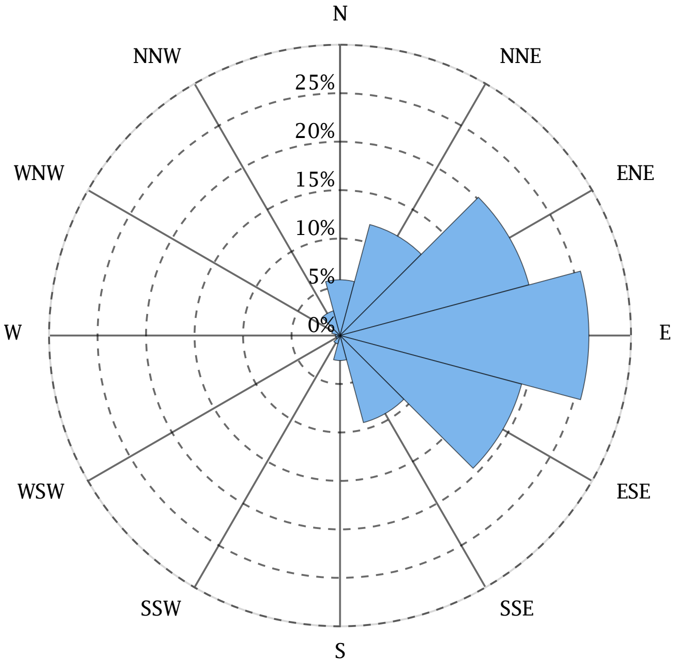
The RE integration on small islands helps in the de-carbonizing goal for the electricity generation, meanwhile reducing the cost of the fossil fuel spent to supply the electric demand of the electric grid on it. The intermittent production of electricity from Renewable Energy Sources (RES) over the time, produce some uncertainties in the total electricity production. To keep the balance of the system between the renewable energy production and the energy consumption, the fossil fuel generation and the energy storage must be coordinated to guarantee the power system stability. The analysis presented in this paper is done on the base of a hybrid power system already presented by [35] on a small Caribbean island. Currently, there is not a RES supplying electricity into the electric grid on Cozumel Island, so this work takes the results and data used by [35] to reduce the backup time of the battery bank proposed from 2 h to 0.5 h according to the Mexican Grid Code (MGC) [201]. This is done so, in case of a renewable electricity production variation, it is necessary that the system keeps the reliability on the grid, and the battery bank must support the grid balance, while the diesel turbine starts and synchronizes on it. Also, the targets in the $CO_2$ emission reduction, which determine the REF to integrate to the electric grid for each year and scenario, are used.

## 5.7 Previous essential information

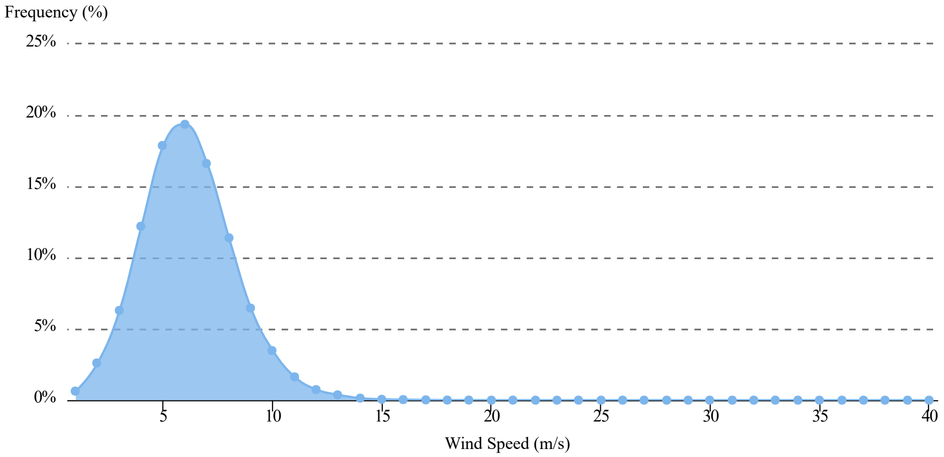
All the previous analysis are including the REF factor target fulfilment settled in STEP 2. The wind speed data was obtained from the US Renewable Resource Data Center for the specific area of the WIND site and from INERE and CONABIO [18, 29–32]. Figure 5.13 shows the wind data resources for the island. The Photovoltaic (PV) production is calculated according to the solar radiation incident on the PV array and it was obtained from NASA's Surface Solar Energy Data Set for the specific area of the PV site and from INERE and CONABIO [18, 29–31, 202].

The storage energy brings safety to the response of the system in case of unbalance between load and generation. It can supply the lack of electricity in the grid according to the size and parameters of the battery bank designed. It can also store the excess electricity production from the overproduction of the RETs or from the minimum electricity production settled on the fossil fuel machine parameters [106–109]. The power needed to design the minimum size of the battery bank, the maximum power charging and discharging of the battery bank vary according to the specific battery type selected. The backup time or the battery autonomy depends, initially from the technology's characteristics and its control responses [30, 31].

The ratio between the total power generation capacity (kW) and the battery bank capacity (kW) define the number of batteries to install and to obtain the autonomy or the final backup time in hours. To keep the battery charging power and discharging power capacity ratio, the converter must be designed in a relation of 1:1 regarding the battery bank capacity. Depending on the battery type and its operation efficiency, the number of batteries will be modified in order to have the minimum backup time required.



(a) Wind rose direction @50 m for Cozumel Island.



(b) Frequency of wind data @50 m for Cozumel Island.

Figure 5.13: Wind resources for Cozumel Island [18, 29–32].

# 6 Interconnection of Renewable Energy Technology into a Diesel Base Electric Grid

## 6.1 Cozumel Electric Grid's Simulations

The power flow simulation of Cozumel Island's electric grid has been done using standard models included in the DIgSILENT® Power Factory v15.1 program [25] and running the Newton Raphson algorithm, by using the Matlab® program [175] to validate the results of this flow load. Using 2013 data from Table 5.1 and Figure 5.2 (in order to achieve the stability of the system), the system has been simulated with the following conditions: a) off grid; b) no RE sources; c) power supply only with diesel turbo machines, and; d) using similar data for existing electric generators, electric loads, transformers, cables and buses. The next step was to accomplish the targets shown in Table 6.1 based in the LAEFRTE and LGCC laws, and in the programs PND and PEAER. For the selected years, the chosen RETs in Cozumel Island through the HOMER® version 3.2 [24] and RETScreen® programs [70] were integrated. The results obtained allowed the achievement of the governmental objectives. The financial data of the project was obtained by these programs as well.

The MATLAB [175] program was used to simulate the actual electric grid on Cozumel Island and to run the Newton Raphson algorithm in a simple power flow. This simulation package is a widely used tool for energy system analysis and also applies to islands. Matthew Dornan and Frank Jotzo applied empirical data in a custom-built stochastic simulation model in order to assess the economic impacts of renewable technology investments in Fiji's electricity grid. Through a Monte Carlo sampling approach in the Matlab software package, the modelling results indicated that investment in renewable technologies in Fiji is generally beneficial from both a cost and risk mitigation perspective, although the impacts of different technologies were not the same [203]. K. Shivarama Krishna and K. Sathish Kumar investigated a hybrid system with PV and fuel cell technology. The power generated from the fuel cell was used to support the photovoltaic generation. A grid connected to PV-fuel cell hybrid system was modelled in the MATLAB/Simulink environment. In this system, using real data from a commercial PV module, a 160 W power PV module was developed. A 5 kW fuel cell was designed to support the hybrid system DC bus. The authors considered a 30 kW wind/solar hybrid system along with Energy Storage System (ESS), which was modelled in the MATLAB/Simulink environment. Results showed STATCOM was able to enhance the transient voltage stability of the system [204]. Vikas Khare, Savita Nema and Prashant Baredar, in their review of solar-wind hybrid renewable energy system, made a summary of modelling methods of solar/wind HRES, where the long term simulation model of HRES was carried out with MATLAB/Simulink. Hydrogen production was simulated with MATLAB/Simscap. MATLAB/Simulink/Labview was used for the identification and simulation of HRES [205]. Ranjeeta Khare and Yogendra Kumar, in their work for obtaining optimal sizing of PV-wind-battery-diesel IHRES in Bhopal (India) for the optimization methodology, used a process for optimization of a simple genetic algorithm by the MATLAB program. The m-file coding was done for all technique ie. SGA, PSO, TLBO, ITLBO, MOL and hybrid MOL-TLBO [206]. M. Reyasudin Basir Khan, Razali Jidin and Jagadeesh Pasupuleti, as part of their previous paper “Optimal combination of solar, wind, micro-hydro and diesel systems based on actual seasonal load profiles for a resort island in the South China Sea”, treated the data in meteorological extrapolation based on a linear extrapolation technique using MATLAB software, in order to fill the missing data in the meteorological data acquired [207].

## 6.2 Fulfilment the Targets

Mexican Government has the need to achieve the targets settled on the energetic scenarios in RE and electric fields. It also needs to decrease pollutants emissions. The main goals were structured in five key years (2018, 2020, 2024, 2035 and 2050) through the three GROWING SCENARIOS called: HIGH, BASE AND LOW. They have been gathered in 3 work lines (Table 6.1): work line 1) decrease the greenhouse gases emissions ($CO_2$); work line 2) increase the power capacity installed and the electricity generation through RETs, and; work line 3) decrease the fossil fuel percentage participation in the electricity generation. Table 6.1 indicates the main objectives in RE for Mexico's electric system.

| | | | **SCENARIOS** | | |
|---|---|---|---|---|---|
| **Work Lines** | **2018** | **2020** | **2024** | **2035** | **2050** |
| **Line 1: fossil fuel percentage decreasing in electricity generation** | | | 65% fossil fuels used for electricity production | 60% fossil fuels used for electricity production | 50% fossil fuels used for electricity production |
| **Line 2: RE electricity generation and capacity installed** | 24.9% of electricity generated with RE<br>34.6% of electricity generation capacity with clean and RE | 35% of electricity generation from clean energy sources | 35% of electricity generation from clean energy sources | 40% of electricity generation from clean energy sources | 50% of electricity generation from clean energy sources |
| **Line 3: decrease of greenhouse emission ($CO_2$)** | | 30% decrease of greenhouse emission respect to 2000 | | | 50% decrease of greenhouse emission respect to 2000 |

Table 6.1: Summary of the achievement of the objectives in three working lines. Three different scenarios and five key years for the electricity generation with RE, the reduction of the fossil fuels participation and the diminution of the greenhouse emissions in Mexico [23, 54, 56, 63–69].

## 6.3 Renewable technology integration on a current fossil electric grid

Considering the targets in Table 6.1 and with the expected growth of gross domestic product, the increase of the electric power demand that Cozumel Island should experiment could be determined, as well as the electricity that has to be supplied with the new RE sources to be installed for the future scenarios. In 2013, the amount of electricity consumed in Cozumel Island was 6.19% (250 GWh) from a total of the State of Quintana Roo (4,035 GWh). For Cozumel Island, this value represented a 3.96% growth compared to 2012 and was similar to the State's growing percentage [22]. The growing percentage in 2014 compared to 2013 was 4.57%. Following this growing trend, the total electricity need it in the future scenarios can be determined. The 2013 Energy Balance published by the Secretary of Energy [208] indicates a national increasing in the energy consumption of 2.3% and of almost 1% in electricity consumption compared to 2012. This growing trend is similar to Cozumel Island's.

Considering the last information and knowing that Cozumel Island has an actual generation capacity of 68.82 MW diesel technology installed [20], it can be determined the goals in Table 6.1 will be achieved if the data in Table 6.2 (specific objectives for Cozumel Island) is accomplished. Table 6.2 indicates the growth the electric system will have, as well as the actual electric system features. The objectives to be accomplished for the future scenarios in Cozumel Island are also included in Table 6.2.

The results obtained by HOMER® [24] and RETScreen® programs [70] show details about generation capacity, electricity generated, LCOE, technology cost and return period. These results cover the data Table 6.2 indicates. All the outcomes in these five scenarios are shown in Table 6.3. The cost of the kWh paid by the government used in the financial part was the *short time total cost* (CTCP, for its Spanish acronym) or the marginal cost for the year of 2013. The costs of the renewable technologies were considered with the same year prices [20, 71, 209].

The RETScreen® program was used to calculate the amount of electricity

| | **SCENARIOS** | | | | |
|---|---|---|---|---|---|
| | **2018** | **2020** | **2024** | **2035** | **2050** |
| **Electricity to be consumed in Cozumel (GWh):** | 312 | 341 | 408 | 668 | 1305 |
| **Maximum power demand (MW):** | 53 | 57 | 69 | 112 | 220 |
| **Objectives to be Fulfilled:** | | | | | |
| **Max. fossil fuel electricity generation (MW):** | | | 45 | 67 | 110 |
| **RE electricity to be generated (GWh):** | 78 | 120 | 143 | 267 | 653 |
| **RE generation capacity to be installed (MW):** | 24 | 24 | 24 | 45 | 110 |
| **Pollutant emissions ($CO_2$) compared to 2000:** | | -30% | | | -50% |

Table 6.2: Objectives to be fulfilled in $CO_2$ emissions, power capacity, electricity generation and RE required for Cozumel Island. Using a growing factor of 6.19% in electricity consumption and an increasing factor of 4.57% in power demand [20, 22].

generated by Wind and PV power combined with diesel generation, without grid optimization and without energy storage. The same program was used to calculate the financial part. The HOMER® program was used to make seasonal power demand profiles (Figure 5.5) and the power demand capacities of RES, with an optimal technical array of the system. In both cases, it was done without considering communication and control systems and without energy storage.

According to the HOMER® program, the LCOE results for the year 2013 were 0.36 $US/kWh, without RETs, equal to the average cost used as the energy cost in Cozumel Island for the same year, obtained from [20]. Table 6.3 indicates the LCOE results of each scenario. The configurations of each electric system chosen provide an optimum and technical integration of the RETs, through the optimization software listed above.

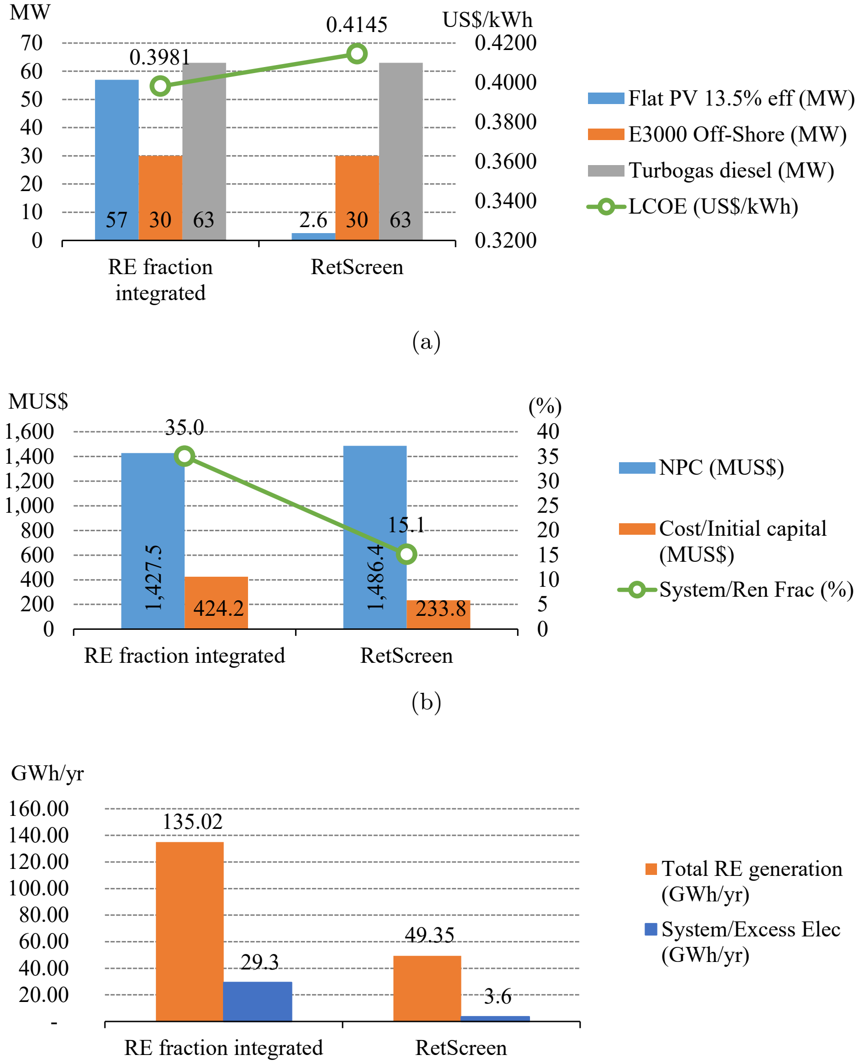
For the RetScreen results, the data obtained showed only a limited power capacity installed and its electricity generation. This limit is the renewable electricity target for the five key years. The fulfillment of the renewable electricity fraction target integrated to the grid in a real running

| | **Power demand (MW)** | **Capacity installed (MW)** | **Energy generated (GWh)** | **Total project cost M$US** | **LCOE ($US/kWh)** | **Return period (Years)** | **Capital repayment time (Years)** | **Cost-benefit relation** |
|---|---|---|---|---|---|---|---|---|
| **2018 Scenario** | | | | | | | | |
| **Wind** | 30.0 | 30.0 | 57.3 | 255.7 | 0.37 | 3.6 | 2.5 | 3.3 |
| **Photovoltaic** | 2.6 | 2.6 | 22.6 | | | | | |
| **Diesel** | 27.8 | 63.0 | 234.7 | | | | | |
| **2020 Scenario** | | | | | | | | |
| **Wind** | 30.0 | 30.0 | 57.3 | 284.6 | 0.32 | 2.6 | 1.3 | 6.4 |
| **Photovoltaic** | 17.4 | 17.4 | 152.1 | | | | | |
| **Diesel** | 28.3 | 67.0 | 134.7 | | | | | |
| **2024 Scenario** | | | | | | | | |
| **Wind** | 30.0 | 30.0 | 57.3 | 315.6 | 0.32 | 2.2 | 1.1 | 8.0 |
| **Photovoltaic** | 25.1 | 25.1 | 220.3 | | | | | |
| **Diesel** | 34.3 | 79.0 | 134.1 | | | | | |
| **2035 Scenario** | | | | | | | | |
| **Wind** | 30.0 | 30.0 | 57.3 | 438.0 | 0.33 | 1.6 | 0.7 | 11.9 |
| **Photovoltaic** | 54.9 | 54.9 | 480.7 | | | | | |
| **Diesel** | 57.5 | 130.0 | 134.9 | | | | | |
| **2050 Scenario** | | | | | | | | |
| **Wind** | 60.0 | 60.0 | 114.7 | 941.9 | 0.24 | 1.6 | 0.7 | 12.1 |
| **Photovoltaic** | 125.3 | 125.3 | 1,085.5 | | | | | |
| **Diesel** | 108.9 | 260.0 | 115.5 | | | | | |

Note: Financial and energetic calculation conditions that Table 6.3 includes:
1. Cost of equipment and O&M were not considered for existing diesel turbo machines
2. Result show the hybrid system diesel/wind/PV integrated to the grid
3. This paper takes in consideration prices and exchange rates for the year 2013 [26] [84]
4. The technology cost was taken from CFE [20] [62], Energy Regulatory Commission (CRE, for its Spanish acronym) [209] [82] and IEA [71] [83]
5. This exercise was based as an off-grid system
6. Emission factor was obtained from Programa GEI Mexico [72] [86]
7. It was considered what government paid to the little producer of electricity for each GWh injected into the grid in 2013, based in the marginal cost (CTCP, for its Spanish acronym) incurred [20] [62]
8. This is until the Energy Regulatory Commission and the Secretariat of Finance and Public Credit (SHCP, for its Spanish acronym) determined the energy costs in the new SPOT market that begins in 2018

Table 6.3: Project cost, RE capacity to be installed, LCOE and electricity generation results [20, 22, 24, 70, 71].

simulation is carried out through HOMER® program. The results differ from those obtained through RetScreen, and are shown in the Fig. 6.1. This comparative figure is made to illustrate the fact that the electric system can have the minimum capacity installed of renewable technology, or can have the minimum renewable electricity produced to fulfill the renewable targets. Even so, the most important data result is the renewable fraction integrated on the electric grid. In a renewable technology integration simulation, takes into account the hourly production from wind and solar production, for this case, and the hourly power demands of the electric system. This is the main difference indicated on the two concepts from Figure 6.1: (1) RetScreen results (just to fulfil the renewable target), and (2) The real integration of the renewable electricity into the electric grid (Ren Frac).



(a)

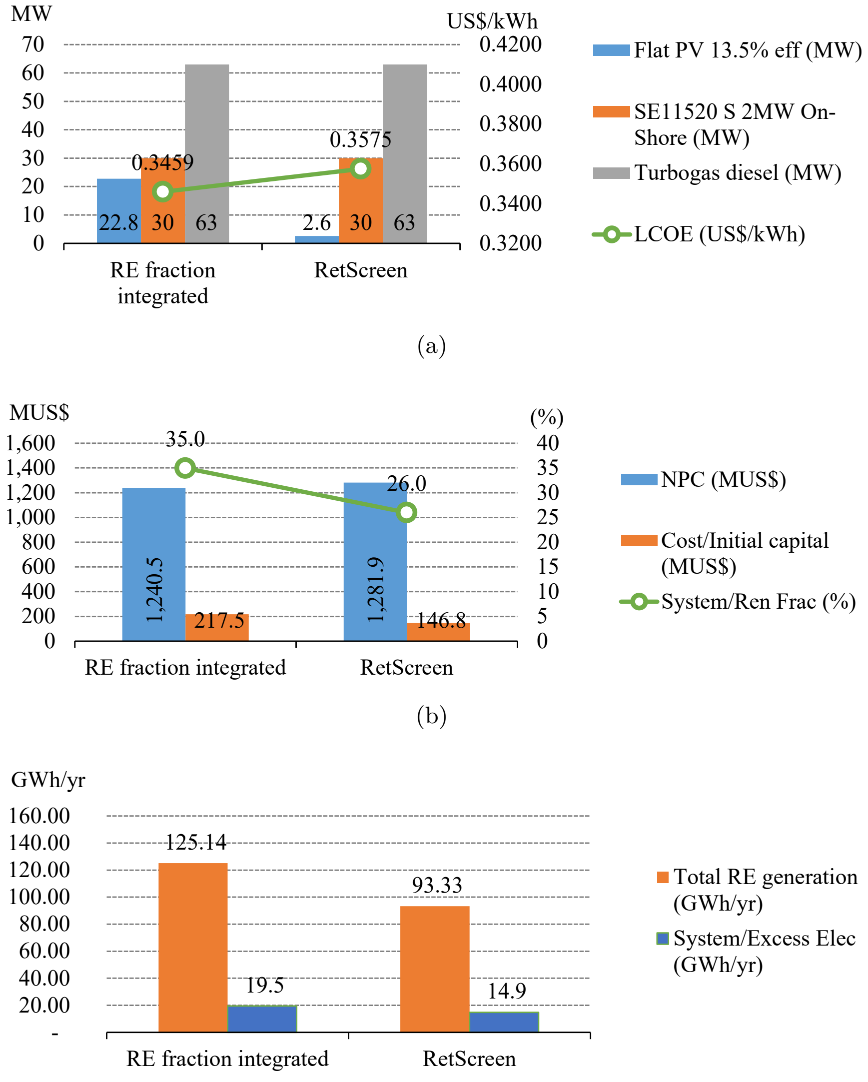
(b)

(c)

Figure 6.1: Results obtained after running simulations with data from RetScreen. Generic flat PV panels and Off-shore Enercon Wind Turbine [33]. (**a**) Generation capacity installed and LCOE results; (**b**) Net Present Cost (NPC), Initial Capital Cost and renewable fraction; (**c**) Total renewable generation and electricity excess.

Moreover, Figure 6.2 shows the same running simulations done for the electric system in Cozumel Island. The only difference was that the Off-shore Enercon Wind Turbine [33] was substituted by the On-shore SANY Wind Turbine [34] with a low wind speed power production curve. This special power curve for low wind speed achieves more electricity production from those turbines with a medium wind speed equipment, as the Off-Shore Enercon 3 MW considered has.

More details in the technology selection and integration on the electric grid for the Cozumel Island will be found in the next Chapter 7, Chapter 8 and Chapter 9.



(a)

(b)

(c)

Figure 6.2: Results obtained after running simulations with data from RetScreen. Generic flat PV panels and On-shore SANY Wind Turbine [34]. (**a**) Generation capacity installed and LCOE results; (**b**) Net Present Cost (NPC), Initial Capital Cost and renewable fraction; (**c**) Total renewable generation and electricity excess.

## 6.4 $CO_2$ Emission

One of the government aims is to reduce the amount of $CO_2$ emissions by electricity generation for future years compared with the year 2000. The value in the year 2000 for $CO_2$ emissions by electricity generation of 165,638 MWh in Cozumel Island [22] were 100,095 $tCO_2$eq. This result was reached using an emission factor of 0.6043 $tCO_2$eq/MWh for the 2000 year. In 2013 this emission factor dropped to 0.4999 (-17.28% compared to 2000) [72]. For the years 2018, 2020, 2024, 2035 and 2050 a 0.525 emission factor was used [72]. The emission reduction due to the integration of RETs is indicated in Table 6.4. In this table, it was considered that the current emission factor does not change in time for this exercise. Columns 5 to 7 indicate the emission reductions through electricity generated with RE, as well as the results compared to the base year. Columns 2 to 4 indicate the emissions of $CO_2$ through the electricity generated only with diesel generators based on a current emission factor.

| | **ONLY DIESEL GENERATION** | | | **HYBRID GENERATION** | | |
|---|---|---|---|---|---|---|
| **YEAR** | **Electricity generated with diesel (GWh)** | **Total pollutant emission of $CO_2$ (kton)** | **Pollutant emissions compared to year 2000** | **Decreasing emissions of $CO_2$ by RE integration (kton)** | **New pollutant emissions of $CO_2$ (kton)** | **New pollutant emissions compared to year 2000** |
| **2000** | 166 | 100 | 0% | | | |
| **2013** | 250 | 125 | 25% | | | |
| **2018** | 312 | 164 | 64% | 42 | 121.92 | 22% |
| **2020** | 341 | 179 | 79% | 110 | 69.27 | -31% |
| **2024** | 408 | 214 | 114% | 146 | 68.71 | -31% |
| **2035** | 668 | 350 | 250% | 282 | 67.99 | -32% |
| **2050** | 1,305 | 685 | 585% | 636 | 48.94 | -51% |

Table 6.4: Reducing $CO_2$ emissions compared to year 2000 ($ktCO_2$eq.) through the RETs integration in Cozumel Island [20, 22, 72].

# 7 Interconnection of Energy Storage into an Hybrid Renewable Energy Generation Grid

## 7.1 Renewable Energy Sources Selection

Three scenarios were carried out in the Development Program of the National Electric System (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, for its Spanish acronym). 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.

The maximum power demanded and the electricity consumed for each year and scenario analyzed for Cozumel Island are shown in Fig. 7.1. The REF to be integrated on the electric grid for each year and scenario analyzed is indicated in STEP 2 of the four phases methodology plan. Figure 7.2 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 [210]. 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

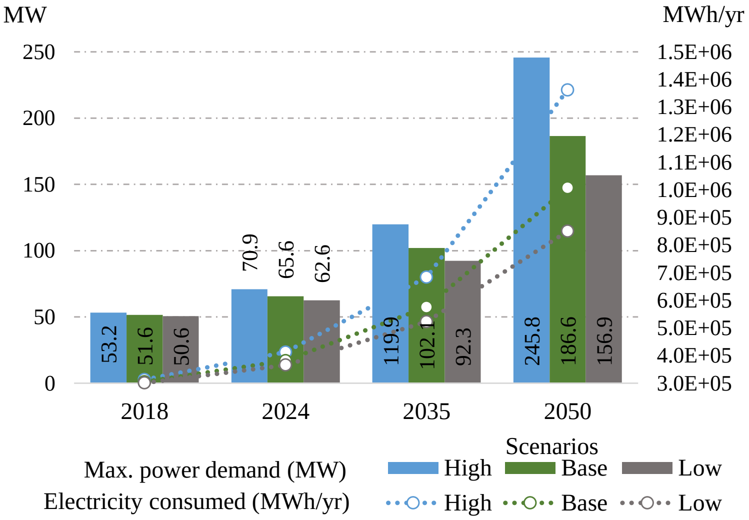


Figure 7.1: Maximum power demanded and electricity consumed for each year and scenario analyzed for Cozumel Island [35].

has also been considered. Figure 7.2 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.. Meanwhile, Fig. 7.3 shows the topology and the renewable electric system of the grid used, including the current generation and main transformation system [35].

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 [211]. 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 7.1). 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 [212]. This unused land is not entirely idle land. It is divided into many

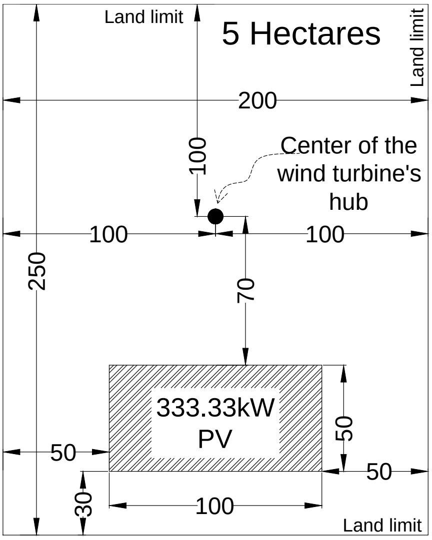


Figure 7.2: PV and wind turbine combination on a 5 Ha of the land size proposed (dimensioning in meters) [35].

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 7.1).

The results obtained by [35] present the System 2 and System 7 as the systems to be installed on the Island, from the technical and economical perspective, respectively. This proposal combines the 2 MW On-Shore Wind Turbine from System 2, the 3 MW Off-Shore Wind Turbine from System 7 and the PV system joined with the battery bank (see Fig. 7.3). Table 7.1 shows the composition of System 2 and System 7 and the final combination to use in this study case.

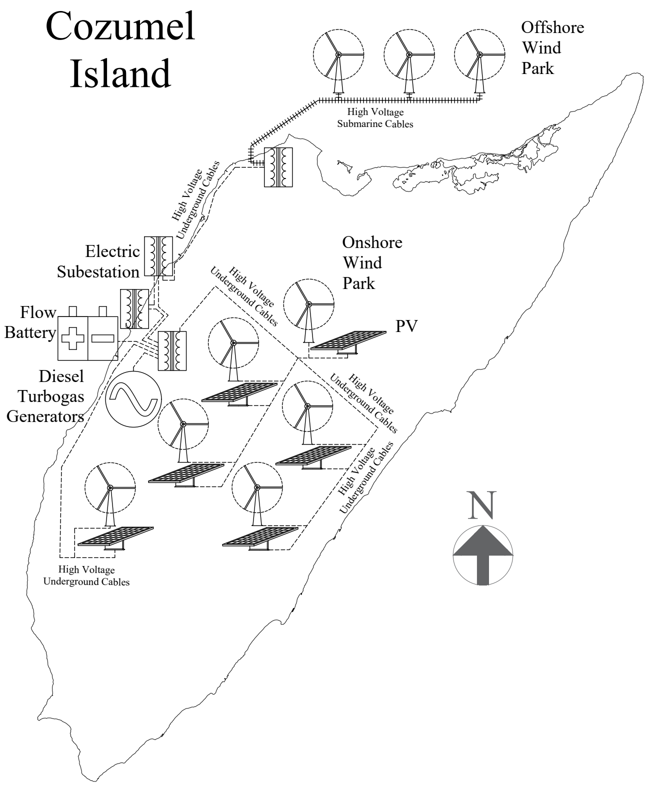


Figure 7.3: Topology and renewable electric system, including the current generation and main transformation system, proposed for Cozumel Island [35].

## 7.2 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

| **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 | Turbo-gas Diesel | EnerStore 50 kWh | EnerSection Converter | |
| *Only for years 2021, 2024, 2030, 2035 and 2050 | | √ | √ | √ | * | √ | √ | |

Table 7.1: Systems proposed for the hybrid system simulations

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 [213]. 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 turbo-gas machines* and flow batteries have been done through the HOMER®software tool [84] 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 [86, 174].

The equipment selected for these simulations was: Generic PV system; GOLD WIND turbine machines (121/2.5 MW) type IIIB [214]; WIND to ENERGY turbines (132/3 MW) type IIIA [215]; SANY wind turbines (SE11520 2 MW) type S [34]; EWT turbine machines (DW54/250 kW, DW54/500 kw, DW54/900 kW) type IIIB [216]; and ENERCON wind turbine (E-126 135 7.5 MW) type IA [33]. These proposed systems have considered the existing *diesel turbo-gas machines* and one additional *diesel turbo-gas machine* (named: *Turbo-gas 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 turbo-gas 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. [217]) 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 [218] was used. The AC/DC converter (EnerSection Converter, from ZBB ENERGY CO. [219]) 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 turbo-gas 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 7.4, in the first 8 h of 2018 in the Base Scenario, the RES and batteries supply the power demand while the *diesel turbo-gas 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.

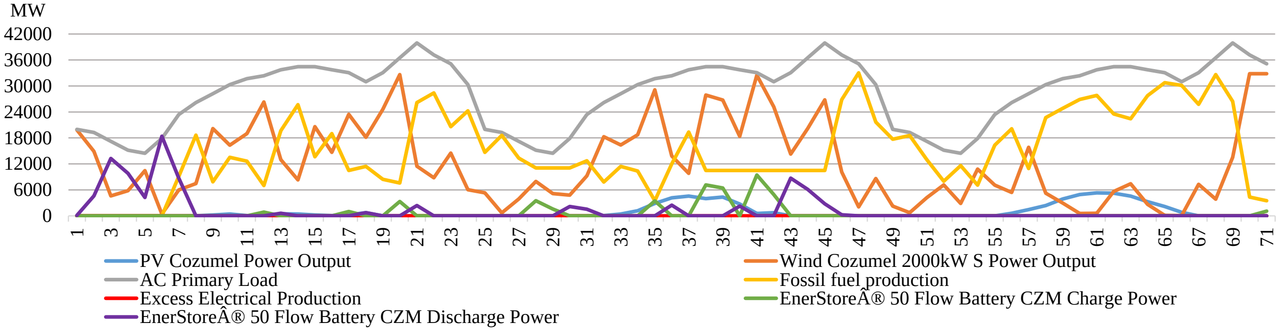


Figure 7.4: Operational curve for System 7 in the Base Scenario for Cozumel Island by 2018.

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 [210]. 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 7.5 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.

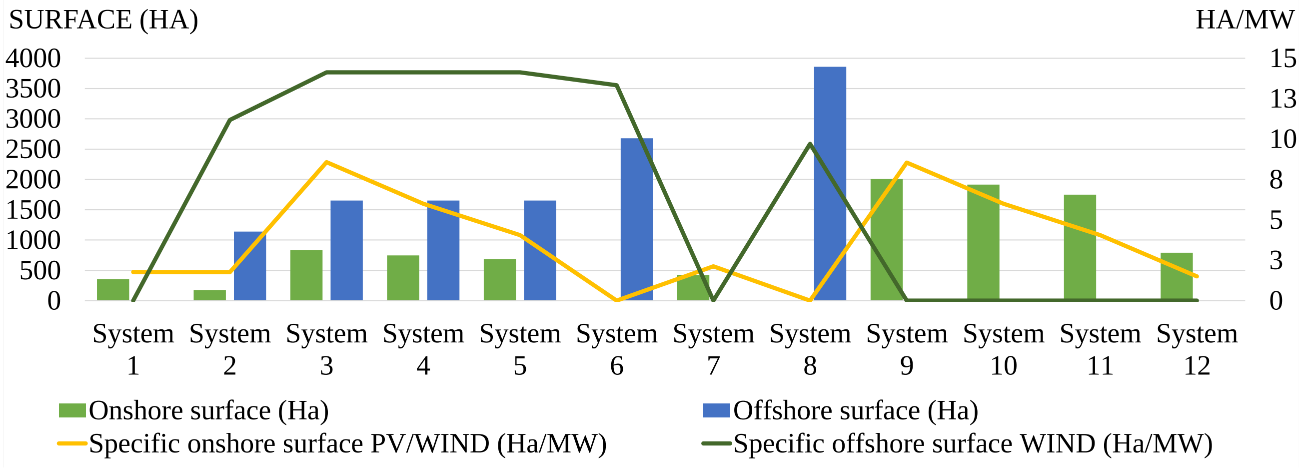


Figure 7.5: Results of on-shore and off-shore surface area used by each system on Cozumel Island for 2050 in the Base Scenario.

## 7.3 Results

### 7.3.1 Previous Essential Information

The basic considerations to develop the economic proposal on Cozumel Island (see Table 7.2) were made based on data from PRODESEN [16], PRE [17], International Energy Agency (IEA) [77, 220, 221], Sandia National Laboratories [222], and from the Department of Energy (DOE, USA) [223]. The average diesel cost was obtained from the World Bank Website [224] 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 7.3, inter alia. These results are for the 12 defined systems proposed in this study (see Section 7.2). 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 7.3.3. Wind resource data used in the simulations was compared, obtaining a high similarity with the data obtained from Figueroa-Espinoza and Paulo Salles [225]. Technical results are included in Section 7.3.2. Economic results are indicated in Section 7.3.3. System selection is shown in Section 7.3.4. After the system selection, analysis of the best system was conducted, as discussed in Section 7.3.5. Finally, the emission factor reduction results are shown in Section 7.3.6.

Table 7.3 shows the electricity generation and the power demand expected for the Island. Considering the existing 68.82 MW fossil fuel generation, the Table 7.3 also includes the electricity generation composition in RE and fossil fuel and the minimum and maximum power capacity composition

| 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 |
| Replacement 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 7.2: Economic and financial parameters for the technologies used in the simulations

to be installed [20]. Data in Table 7.3 is based on the targets for Cozumel Island, indicated in Table 4.1. Points 1 and 2 in Table 7.3 represent the forecast data according to the prospective growth from Figure 8.5 and Figure 8.6. Points 3 and 4 show the minimum data for the RE results. Figure 8.12 and Figure 8.18 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: *Turbo-gas 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 7.16 in Section 7.3.6). 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 8.19). 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 8.18).

| ***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<br>Base<br>Low | 0.433 | 0.423<br>(−30%) | 0.418 | 0.404 | 0.378 | 0.357 | 0.302<br>(−50%) |
| *8* | *Reserve Margin (%)* | High<br>Base<br>Low | | | | 6% | | | |

Table 7.3: Forecast of the electrical system of Cozumel Island to be fulfilled with the simulation results until 2050.

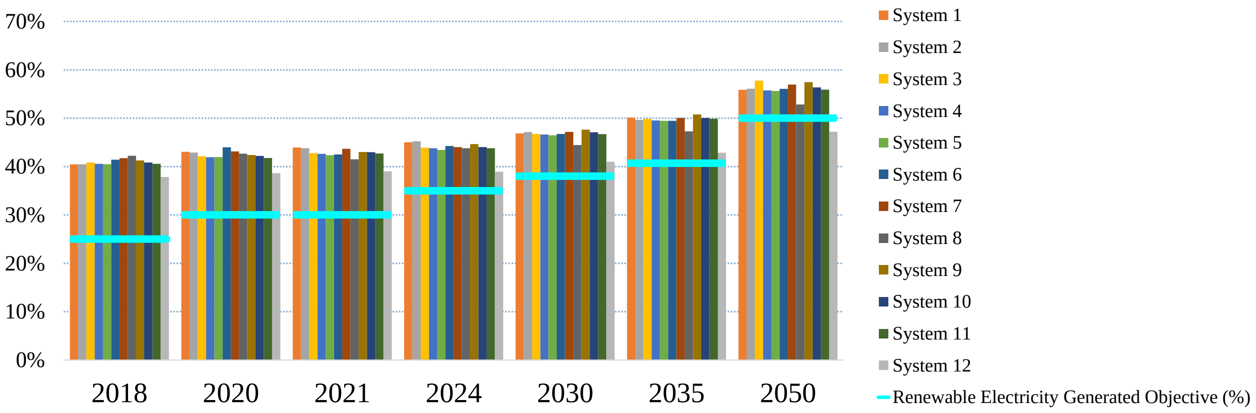


Figure 7.6: Results of renewable electricity generated vs. its objective for each system in the Base Scenario.

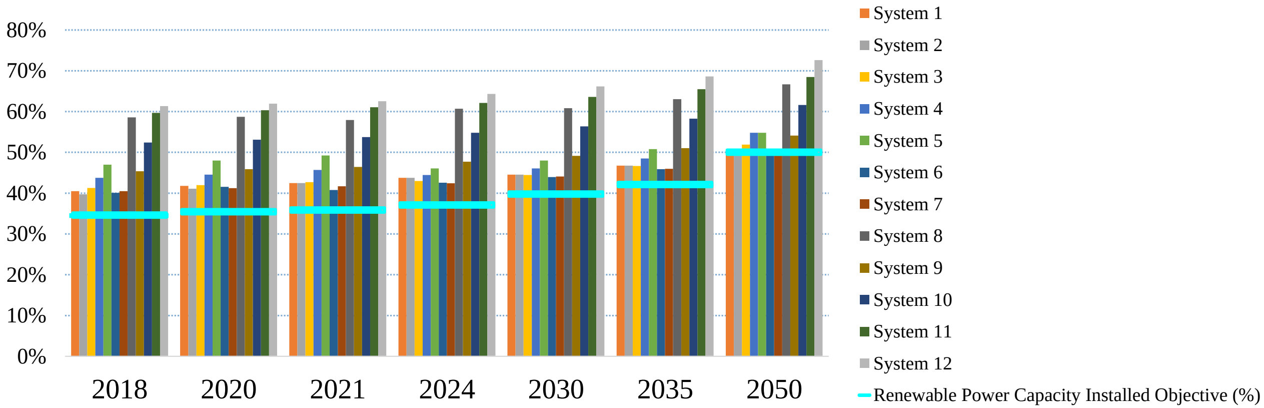


Figure 7.7: Results of total renewable power capacity installed vs. its objective for each system in the Base Scenario.

### 7.3.2 Technical Results

In accordance with the RE targets, Table 7.4 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.

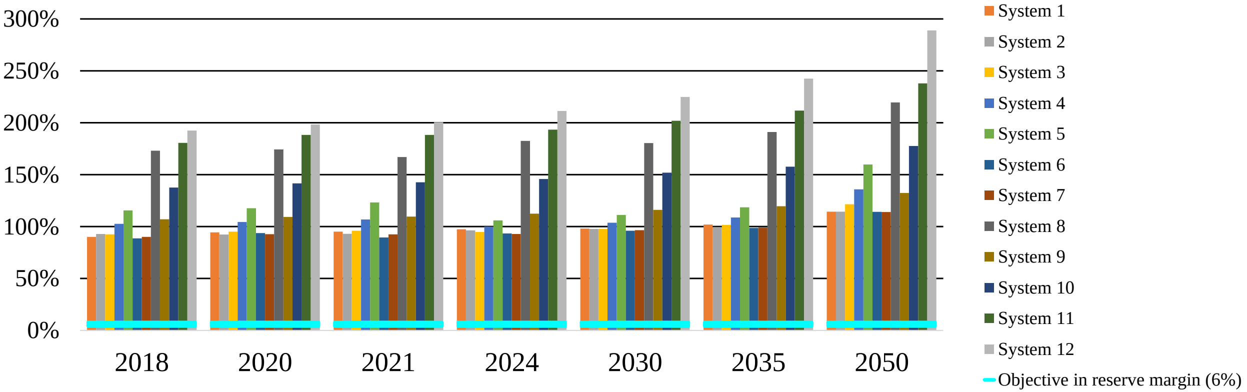


Figure 7.8: Results of reserve margin vs. its objective for each system in the Base Scenario.

Figure 7.5 shows the surface area used on-shore and off-shore for each system in the Base Scenario in 2050, as an example. Figure 8.12, Figure 8.18 and Figure 8.19 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 8.19, 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 [61]. 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 8.19 shows. The system is oversized and the reserve margin results will be out of the target indicated by the Mexican Government.

| | 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 |

Table 7.4: System results for electric generation for 2050 in the Base Scenario.

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.

### 7.3.3 Economic Results

The LCOE generated for each selected piece of generation equipment, including the existing *diesel turbo-gas machines* and the new one, are indicated in Table 7.5. The LCOE resultant of each system is the average cost per kWh of useful electrical energy produced by the systems indicated in Table 7.6 (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 7.6 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.

| **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 | Turbo-gas Diesel | 0.25 | 0.25 |

Table 7.5: Levelized Cost of Energy (LCOE) resultant for each piece of selected generation equipment for every scenario and key years.

On 24 September 2015, the production cost in the peak period (from 6 p.m. to 11 p.m. approx.) was 0.351 US$/kWh on Cozumel Island [20, 226]. In this study, the result obtained for this production cost was 0.230 US$/kWh for the existing *diesel turbo-gas machines*, and 0.251 US$/kWh for the new machine using a diesel price of 1 US$/L [192, 227] (see Table 7.5). 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$/kWh + CEL [16]. However, in the second long-term electric auction, preliminary results published on 22 September 2016, the average electricity price from clean sources was 0.03347 US$/kWh + CEL [228].

| | **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 7.6: Economic results for the systems with a projected lifetime of 25 years and 12.5 years by 2050 in the Base Scenario.

Table 7.7 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 [73] and the Hurricane Research Division [74]. 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 [229]. As can be seen in Table 7.6, 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

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

Table 7.7: Tropical Storms and Hurricanes in Quintana Roo State from 1901 to 2015 [73, 74].

### 7.3.4 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 8.8).

For the economical results, the same selection methodology was used and it is illustrated in Figure 7.10. The ranking positions of the system results are indicated in Table 7.8. 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 [230], these results have been validated.

| | **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 |

Table 7.8: Results for 2050 in the Base Scenario in ranking and points for the analysed systems.

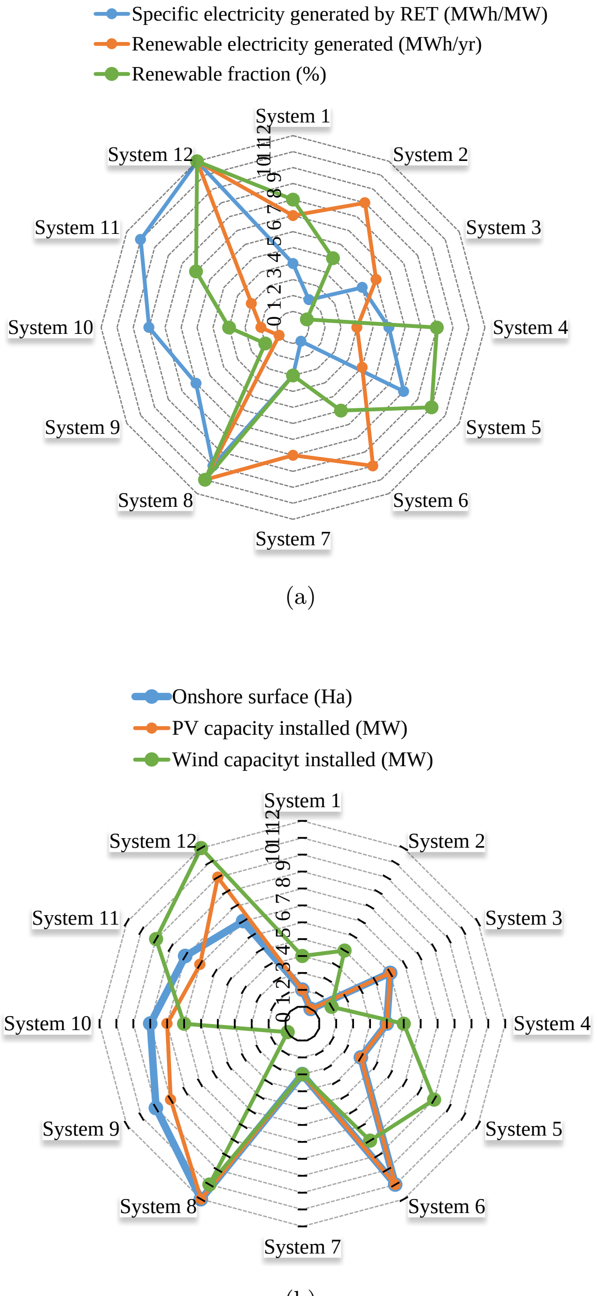
### 7.3.5 Selected System Analysis

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 7.6 and Figure 7.11. In this Figure 7.11, the investments will be made depending on the year chosen to start the project. It will not be a yearly investment. Figure 7.12 (System 2) and Figure 7.13 (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. Figure 7.12 and Figure 7.13 (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 [28], 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 7.11a) will be 738 M\$US, but if we choose to start the investments in 2024, the investment will be 249 M\$US.

A comparison of the results between Systems 2 and 7 is indicated in Figure 7.14 and Figure 7.15 in the Base Scenario. The values of Internal Return Rate (IRR) and the discounted payback are compared in Figure 7.14. The values of the LCOE for each system are compared in Figure 7.15. 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. As a future projection, the results by complementary methodologies, such as cost minimization methodology or multi-criteria methodology, would 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 [231, 232].

### 7.3.6 Emission Factor Reduction Results

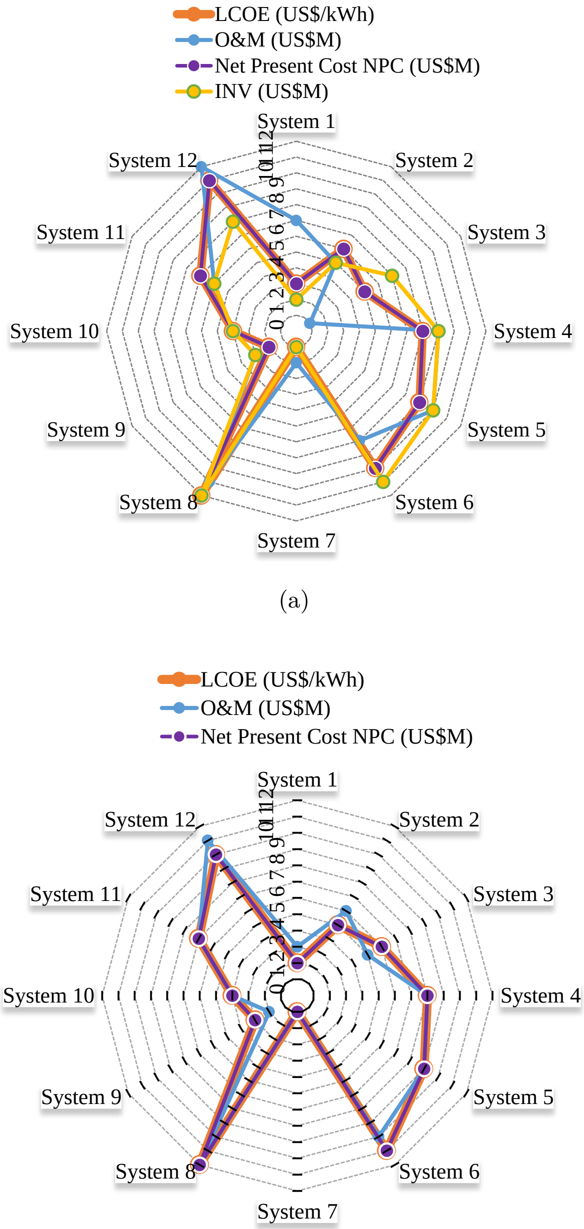
The results of the $CO_2$ factor emission reduction for each MWh produced through electricity generation are indicated in Figure 7.16 in the Base Scenario for 2050, as an example. In Table 7.3, point 7 specifies the minimum factor of this emission to achieve the goals in this matter. The amount of $CO_2$ emissions in the 2000 for an electricity generation of 165,638 MWh on Cozumel Island was 100,095 $tCO_2$eq [22]. The emission factor in that year was 0.6043 $tCO_2$eq/MWh. In 2014, this emission factor dropped to 0.454 (−24.87% respect to 2000) [233]. In 2018, 2020, 2024, 2030, 2035 and 2050, the minimum emission factor was used, as indicated in point 7 of Table 7.3.



(a)

(b)

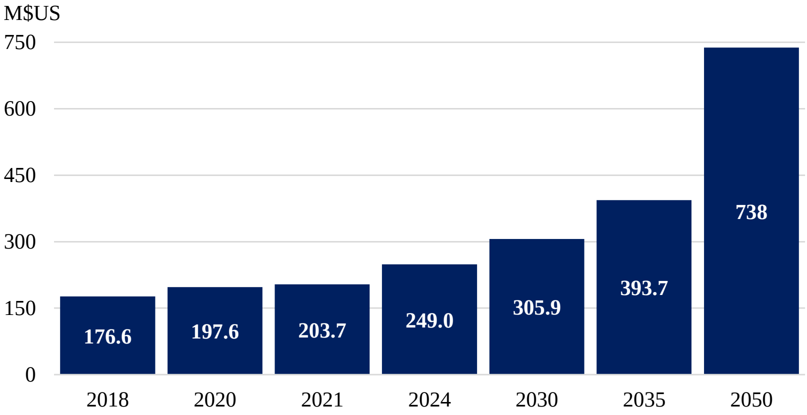
Figure 7.9: Technical evaluation results by system, from best (1) to worst (12) in 25-year lifetime on Cozumel Island for 2050 in the Base Scenario. (**a**) Renewable Electricity generated and RE fraction; (**b**) RE capacity installed and on-shore surface area used.



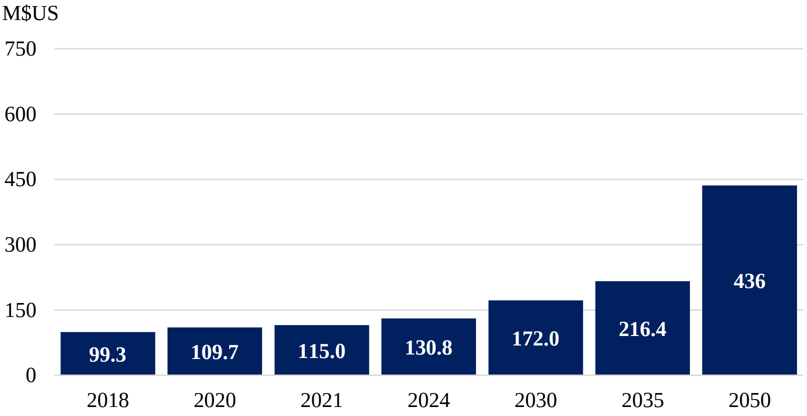
(a)

(b)

Figure 7.10: 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.

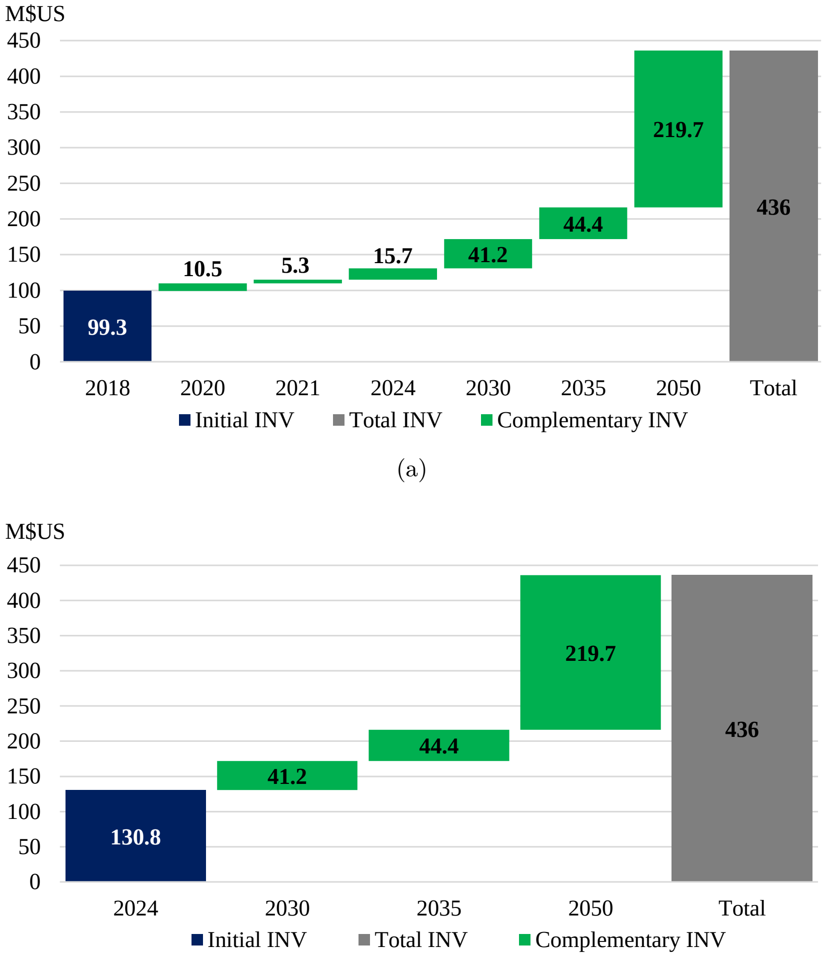


(a)



(b)

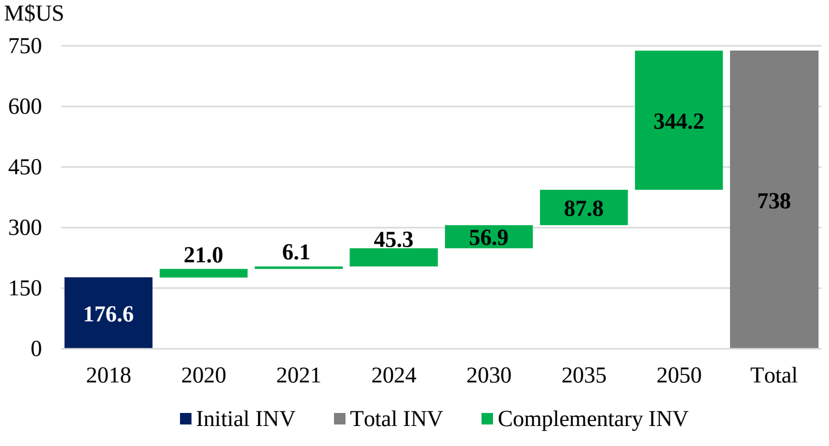
Figure 7.11: The results are the investments needed depending on when the project starts. These amounts are calculated on the basis of the money invested in 2016 in US$M. (**a**) Investments for System 2 in the Base Scenario; (**b**) Investments for System 7 in the Base Scenario.



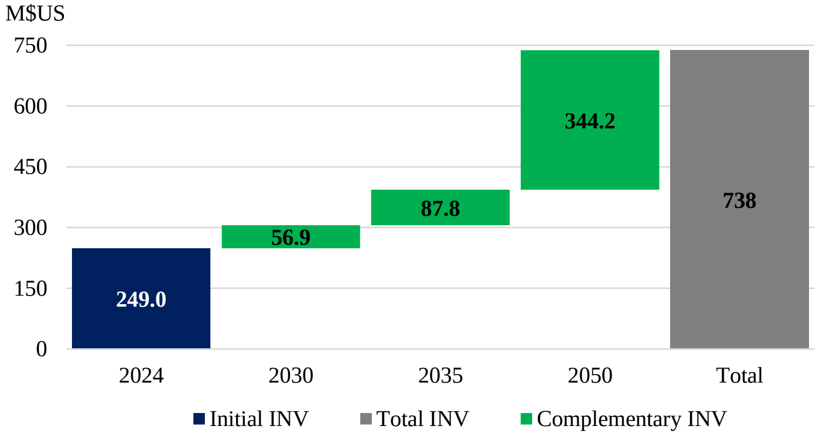
(a)

(b)

Figure 7.12: 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 7.13: 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.

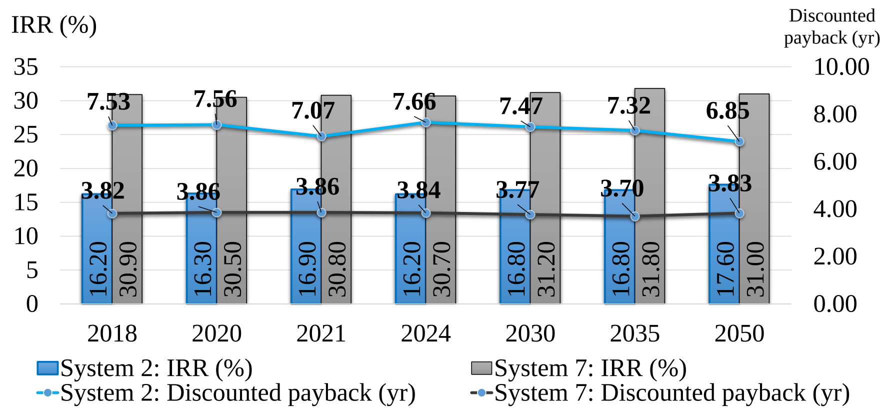


Figure 7.14: Comparison of economic results in Internal Return Rate (IRR) and Payback time between System 2 and System 7 in the Base Scenario.

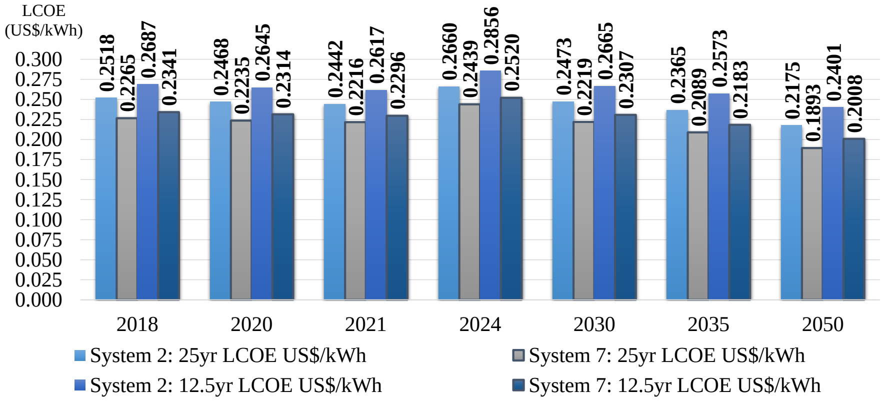


Figure 7.15: Economic results comparison in Levelized Cost Of Energy (LCOE) for 25-year and 12.5-year lifetime between System 2 and System 7 in the Base Scenario.

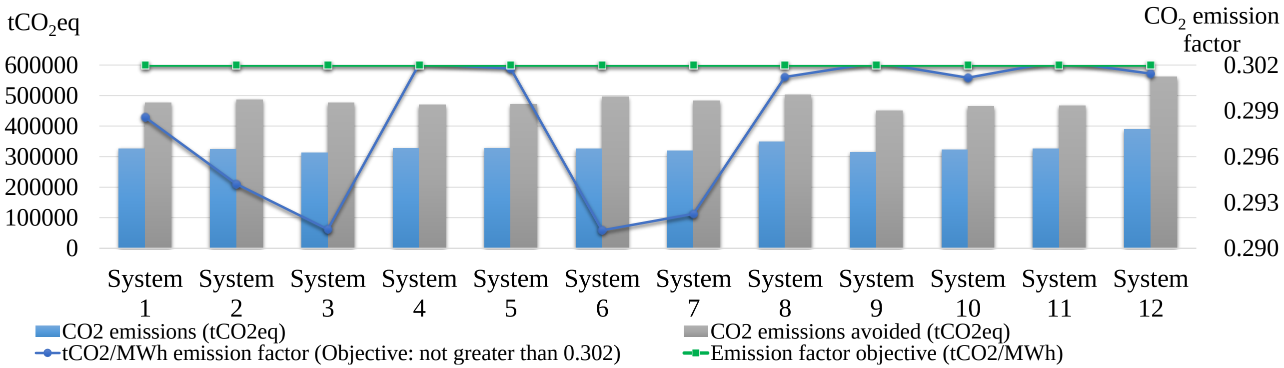


Figure 7.16: Results in $CO_2$ emissions emitted and avoided by each system and emission factor vs. their objectives on Cozumel Island for 2050 in the Base Scenario.

# 8 Optimization of Hybrid Power System Including Energy Storage

The sensitivity analysis is included on the basis of the use of two-dimensional linear interpolation through a probabilistic logic strategy using the complete enumeration method. Through this process, the software HOMER$^{©}$ simulation model [84] 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. Other studies that have used this software or a similar one to integrate the renewable electricity generation on the electric grids were reviewed [89] [93] [118] [234] [235] [236] [237] [238]. The optimum system or the best system configuration is the one that satisfies the specified constraints at the lowest total NPC. This simulation model uses the multi-year analysis. This model is based on a time-domain simulation run at the energy-flow level with discrete time-steps of 1 hour. It determines the NPV for a chosen configuration over a specified project lifetime [85]. More information about the model formulation is available at [30] [31]. Table 8.1 shows the technology used in the simulations that have done, including the four different battery technology: Ion-Lithium, Lead-Acid, Vanadium Redox Flow and Zinc-Bromine Redox Flow.

| Battery System type | PV Array | SE11520 2MW On | Enercon E115 3MW Off | 2018, 2024, 2035 and 2050 | | | 2024, 2035 and 2050 | Converter | Inflation Rate (%) | Cost Reduction | Efficiency Improved | Scenarios | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Unit1 | Unit2 | Unit4 | Unit5 | | | | | Low | Base | High |
| Ion-Lithium | √ | √ | √ | √ | √ | √ | √ | √ | 2.0 | | | √ | √ | √ |
| Ion-Lithium | √ | √ | √ | √ | √ | √ | √ | √ | 2.5 | √ | √ | √ | √ | √ |
| Lead-Acid | √ | √ | √ | √ | √ | √ | √ | √ | 2.0 | | | √ | √ | √ |
| Lead-Acid | √ | √ | √ | √ | √ | √ | √ | √ | 2.5 | √ | √ | √ | √ | √ |
| Vanadium Redox Flow | √ | √ | √ | √ | √ | √ | √ | √ | 2.0 | | | √ | √ | √ |
| Vanadium Redox Flow | √ | √ | √ | √ | √ | √ | √ | √ | 2.5 | √ | √ | √ | √ | √ |
| Zinc-Bromine Redox Flow | √ | √ | √ | √ | √ | √ | √ | √ | 2.0 | | | √ | √ | √ |
| Zinc-Bromine Redox Flow | √ | √ | √ | √ | √ | √ | √ | √ | 2.5 | √ | √ | √ | √ | √ |

Table 8.1: Technologies to consider in the simulations including the sensitivity constraints and the four different battery types

## 8.1 Hybrid system analysis and results

Results from the renewable energy system in combination with four different battery technologies show the number of batteries changes according to the type used. This is to maintain the backup time of 0.5 h and a REF penetration of 41.1% in the year 2018 and in the Base Scenario. These results came from 121 number of combinations of the hybrid system with the four different battery technologies, as shown in Fig. 8.1. In this graph, the red line is the backup time and the grey line is the batt-ratio. The green columns represent the REF penetration on the grid. In systems from 1 to 7 the battery bank is not considered. The four different batteries type are presented, as can be seen in this figure, but only the Lead- Acid, the Vanadium, and the Zinc-Bromine battery need a batt-ratio of 0.2 in order to have 0.5 h of backup time at least. For the Ion-Lithium battery, requires a batt-ratio of 0.3 for a $\geq$ 0.5 h of backup time. For the batt-ratio the follow formulae is used: Batt-ratio = Battery Capacity Installed / [$\sum$ (Diesel Capacity Installed + PV Capacity Installed + Wind Capacity Installed)].

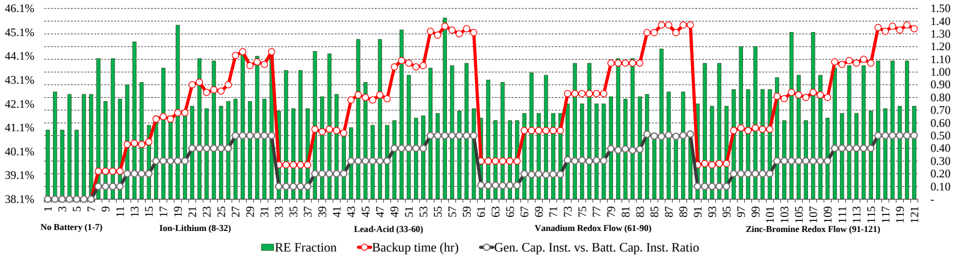


Figure 8.1: Results for the 121 hybrid power system in combination with the four batteries type in the Base Scenario by 2018 for Cozumel Island.

The selected systems, in which all the constrains are fulfilled in REF and backup time, are shown in Fig. 8.2 for each battery type in the same year and scenario. The green line is the backup time, the black line is the REF factor, the brown line is batt-ratio and the columns are the sum of the hybrid power generation capacity of its components, including the converter capacity. As in this graph appears all the systems that fulfil the constrains of all battery technologies, the economic analysis will determine the resultant system for each battery category. In Fig. 8.3 the hybrid system selected

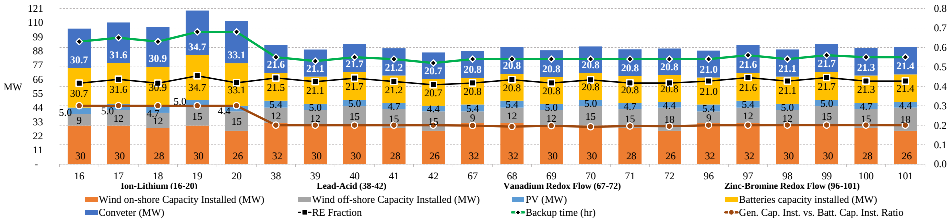


Figure 8.2: Results for the hybrid power system in combination with the four batteries type that fulfil the constrains in the Base Scenario by 2018 for Cozumel Island.

for each battery category is shown. In this graph, the same description and colours that in Fig. 8.2 is used to describe the results in each battery category. Fig. 8.4 and Fig. 8.5 shown the economic results by 2018 in the Base Scenario, which validate the hybrid systems selected in the last two figures. First, Fig. 8.4 shows that the system with the Zinc-Bromine battery bank has the highest IRR, the minimum ICC and the minimum time is taken for the Retention Guarantee Fund (RGF) to be equal to ICC. These economic results do not lessen the minimum IRR of 13.5% [61] [16]. Secondly, Fig. 8.5 shows the maximum NPV, the minimum LCOE, and the minimum NPC. The economic comparative is elaborated with an inflation rate of 2.0%, which does not include the cost reductions and the efficiency increase through the years as the worst case. The best case is made with a 2.5% of inflation rate, including the cost reductions and the efficiency increase through the years. The system selected by its best economic results is the system that includes the Zinc-Bromine battery bank. Fig. 8.6 shows the economic results by 2050 in the Base Scenario. The 2% indicator means that the cost reductions and the inflation rate are not been applied. Therefore, the 2.5% indicator means that the cost reductions and the inflation rate are been applied.

Fig. 8.7 shows the results in the ICC applying the cost reductions and the inflation rate increase. These results are for the Base Scenario by 2018

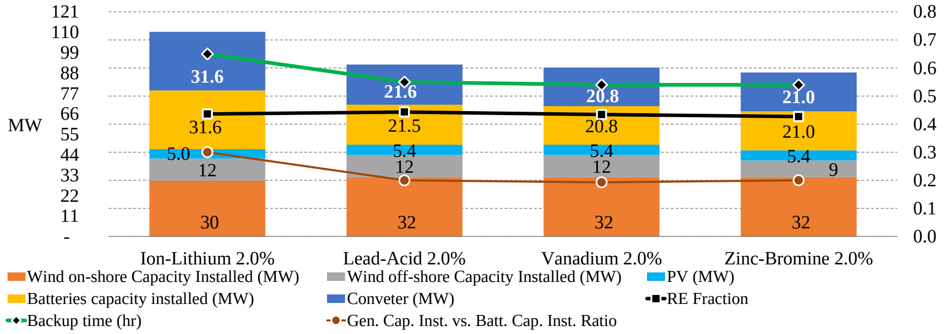


Figure 8.3: Results for the hybrid power system selected in combination with the four batteries type that fulfil the constrains in the Base Scenario by 2018 for Cozumel Island.

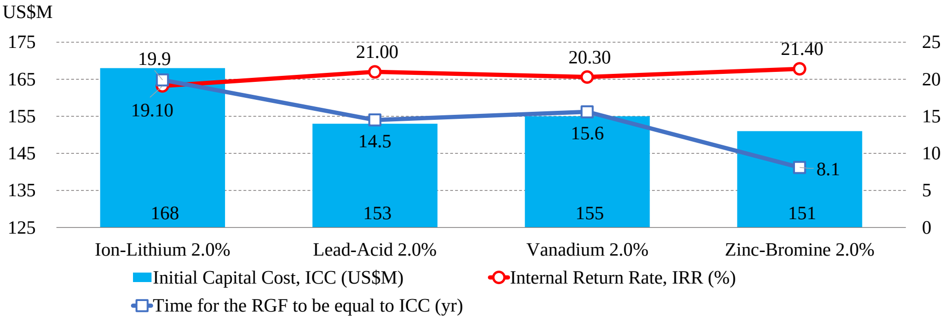
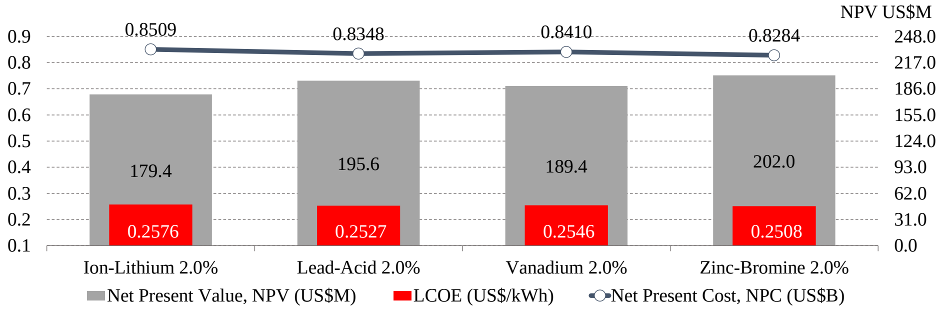
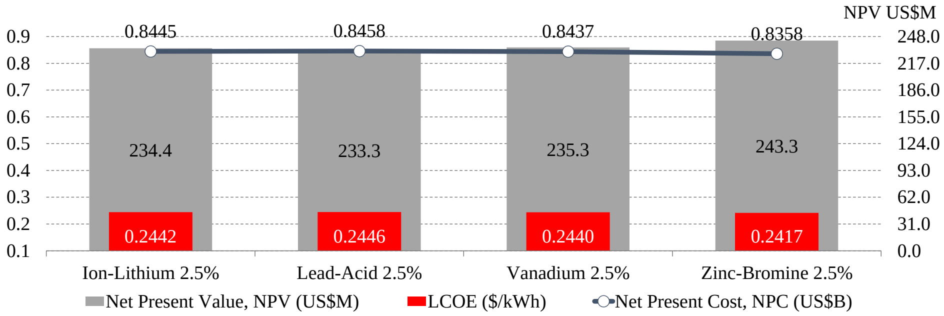


Figure 8.4: Economic results for the hybrid power system selected with the batteries type in the Base Scenario by 2018 for Cozumel Island.

(a) and by 2050 (b). In this figure, and according to the Energy Technology Reference Indicator projections for 2010-2050 [239], the reduction in the cost of the equipment it will be applied until 2050.

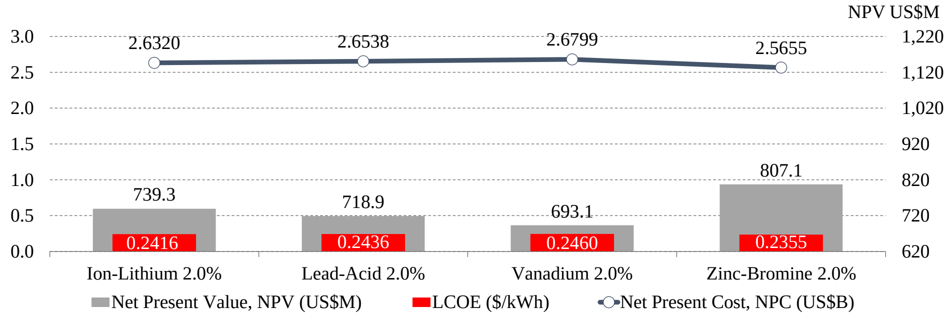


(a) Economic results with 2.0% of inflation rate

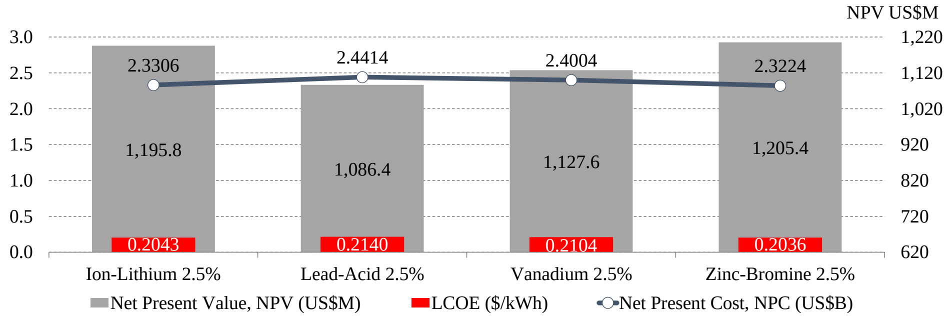


(b) Economic results with 2.5% of inflation rate

Figure 8.5: Economic results without (a) and with (b) the sensitivity variables for the hybrid power system selected with the batteries type in the Base Scenario by 2018 for Cozumel Island.

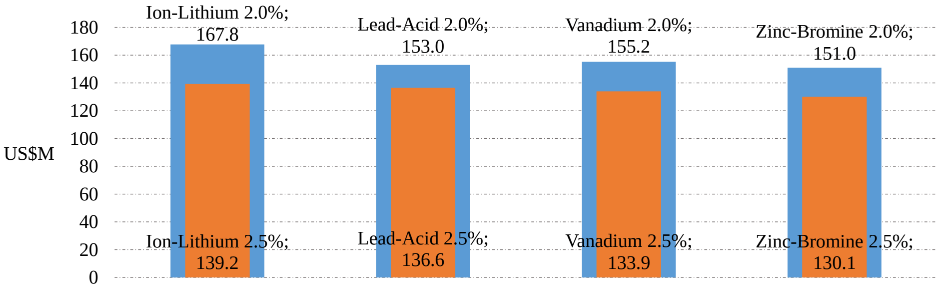


(a) Economic results with 2.0% of inflation rate

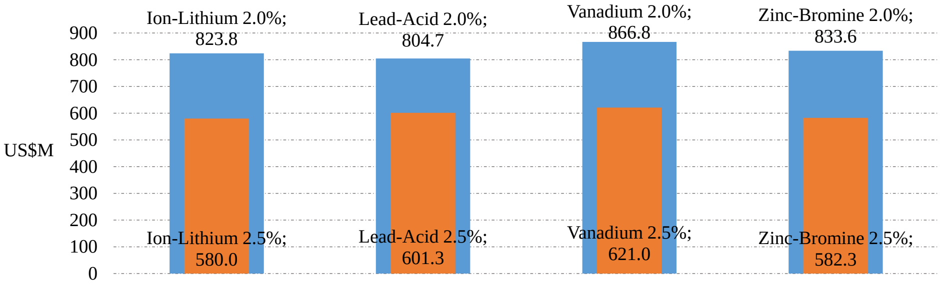


(b) Economic results with 2.5% of inflation rate

Figure 8.6: Economic results without (a) and with (b) the sensitivity variables for the hybrid power system selected with the batteries type in the Base Scenario by 2050 for Cozumel Island.



(a) ICC results by 2018 with 2% and 2.5% indicators applied.



(b) ICC results by 2050 with 2% and 2.5% indicators applied.

Figure 8.7: ICC results with and without cost reductions, and inflation rate increasing for the hybrid power system selected with the batteries type in the Base Scenario by 2018 (a) and by 2050 (b) for Cozumel Island.

## 8.2 Power Flow and Short Circuit Analysis

### 8.2.1 A reliable assessment of the static and dynamic grid safe response in a fossil fuel and in a 100% renewable electric system

In the previous results, the 100% of the renewable generation supplying the electric load was given during 188 hours by 2018. By 2024 this 100% of renewable energy supplying the electric load was given during 209 hours. By 2035 this 100% of renewable energy supplying the electric load was given during 509 hours. By 2050 this 100% of renewable energy supplying the electric load was given during 1,258 hours. The following steady-state analysis and the dynamic analysis are done under a 100% of renewable energy supplying the electric load. In the following sections, the steady-state analysis is done for two options: ***1) An electric grid with only fossil fuel power generation in the three scenarios (Low, Base and High) and through the key years selected (2018, 2024, 2035, 2050)***, and; ***2) An electric grid with a hybrid power generation in the same scenarios and years***.

## 8.3 Steady-state analysis and results

In a non-faulted or steady-state (free of short-circuit) conditions, the load flow calculations to analyze the power system are used. In this steady-state, all the variables and parameters on the grid are assumed as constants during the period of time analyzed. This reflects the system response in a specific time with the specific variables and parameters given [176]. To do this, the Newton Rapshon method can be used in a numerical iterative way. The basic formulas for the derivative power flow equations based on the admittance of the network can solve by means of this method [240] [241]. First at all, with the grid data in 2018 the power flow analysis is carried out, and once the grid is stable, reliable, and with a safe response, the simulations analysis for the year of 2024 will be done. If the grid does not respond within the allowed parameters, then the reinforcements or modifications will be done until the system response will be stable. This new grid will be the initial one to run the 2035 steady-state analysis and so on until 2050. For the Base Scenario and in the year 2018 the grid has been modified and reinforced after the hourly power flow analysis. The voltage results in the busbars are shown in Table 8.2. The loading results from the hourly power flow analysis for the same scenario and year are shown in Table 8.3. In these results tables, for the fossil fuel generation option and for the 100% renewable generation option, the results are compared. With the same power demand to supply, it can see that the voltages values in the busbars are improved when the distributed renewable generation is placed and integrated (see Fig. 7.3 for the renewable technology sites), which is shown in Table 8.2 and Table 8.3. These results in voltage and loading are within the MGC parameters for a continuous system operation [201].

The grid code is the interconnection rules and controls for the RETs or any generation sources at the moment they are integrated into the electric system, keeping the reliability and stability of the electrical grid. To make this possible, this grid code has the minimum or maximum control and protection parameters. The grid code depends on the country in which the RETs are going to be interconnected. For instance, Fig. 8.8 shows the different system response boundaries in case of a fault in the electric system. This failure produces a voltage dips in the system and is indicated for Mexico, Ecuador, UK, and Continental Europe. These graphs are the limits of the system response.

In the power flow, the hourly power demand for each load of the Cozumel Island are analyzed through a DIgSILENT Programming Language (DPL) command script function [176]. This function allows the hourly power system simulations during the year and its power flow response (Quasy-dynamic simulations). As January 17th at 19:00 h by 2018 is the time that the 100% of the electric load is supplied by the renewable generation, it has chosen ± 1 day in the operation analysis results signals to show.

Fig. 8.9 shows the fossil fuel units operation comparing a fossil fuel generation grid (continuous lines) vs. renewable energy generation grid (dotted lines). As it can be seen, the present of the intermittent and

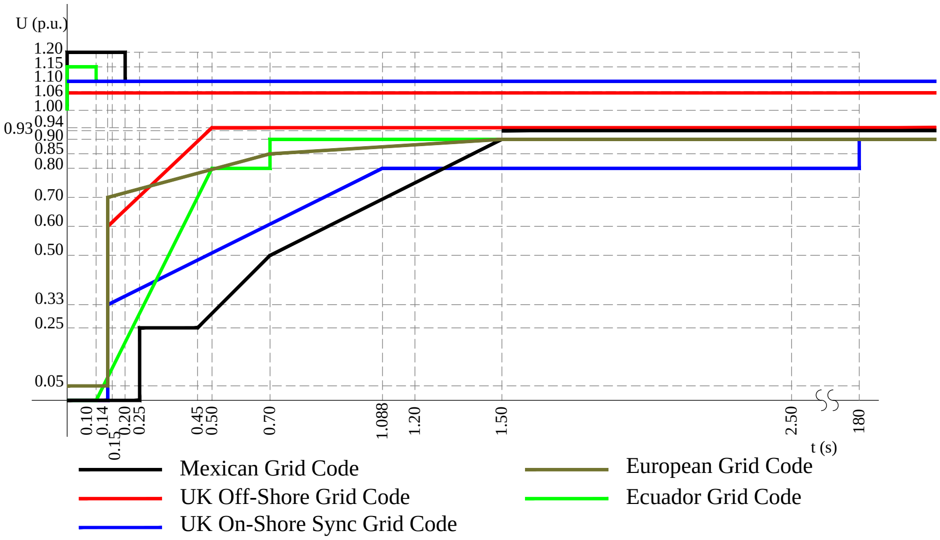


Figure 8.8: Different system response boundaries in the grid codes for Mexico, Ecuador, UK and Continental Europe in a presence of a fault that produces a voltage dips in the system.

variable energy production of the renewable technologies on the grid modify substantially the fossil fuel operation of the generation units in the virtual date from January 16th at 00:00 h to January 19th at 00:00 h by 2018. In case of a fossil fuel generation grid (continuous lines), the fossil fuel unit operation follow the load profile in the grid. Meanwhile, in the renewable energy generation grid (dotted lines), the fossil fuel unit operation does not follow the load profile in the grid. The 100% of the electric load is supplied by the renewable electricity during some hours of the day (Fig. 8.9 January 17th-18th). In Fig. 8.10 the renewable electricity production by PV and Wind (On-Shore and Off-Shore) is shown. Table 8.2 shows the busbars voltage values improvement, due to the renewable energy integration on the Island's electric grid. Moreover, Fig. 8.12 shows this busbar voltages improvement, as can be seen in Fig. 8.12a, which indicates that the voltage values in a fossil fuel generation grid follow the load profile. Meanwhile, Fig. 8.12b shows that the voltages values do not follow the load profile in the grid. Despite having voltage variations, these voltage values present an

**Fossil Fuel Generation Grid**

| **Branch, Substation or Site** | **Voltage Max. (p.u.)** | **Time Point Max** | **Voltage Min. (p.u.)** | **Time Point Min** |
|---|---|---|---|---|
| Cedral | 0.983 | 2018.01.13 04:00:00 | 0.931 | 2018.09.02 22:00:00 |
| Chankanaab 34.5 kV | 1.002 | 2018.01.03 04:00:00 | 0.993 | 2018.09.17 22:00:00 |
| Chankanaab U1 13.8kV | 1.000 | 2018.03.01 10:00:00 | 1.000 | 2018.04.05 05:00:00 |
| Chankanaab U2 13.8kV | 1.000 | 2018.03.0110:00:00 | 1.000 | 2018.04.03 05:00:00 |
| Chankanaab U4 13.8kV | 1.000 | 2018.01.01 00:00:00 | 1.000 | 2018.01.01 00:00:00 |
| Mega 13.8kV | 0.994 | 2018.01.05 04:00:00 | 0.963 | 2018.09.24 22:00:00 |
| Mega 34.5kV | 1.001 | 2018.01.03 04:00:00 | 0.988 | 2018.09.17 22:00:00 |
| Office 13.8kV | 0.995 | 2018.01.26 04:00:00 | 0.964 | 2018.09.14 22:00:00 |
| Office 34.5 kV | 1.002 | 2018.01.03 04:00:00 | 0.989 | 2018.09.17 22:00:00 |
| **100% Renewable Generation Grid** | | | | |
| Cedral | 1.013 | 2018.01.11 04:00:00 | 0.946 | 2018.09.04 22:00:00 |
| Chankanaab 34.5 kV | 1.002 | 2018.02.06 03:00:00 | 0.995 | 2018.09.10 22:00:00 |
| Chankanaab U1 13.8kV | 1.000 | 2018.01.31 01:00:00 | 1.000 | 2018.04.09 12:00:00 |
| Chankanaab U2 13.8kV | 1.000 | 2018.01.31 01:00:00 | 1.000 | 2018.07.07 14:00:00 |
| Chankanaab U4 13.8kV | 1.000 | 2018.01.01 00:00:00 | 1.000 | 2018.01.01 00:00:00 |
| Mega 13.8kV | 0.995 | 2018.01.15 04:00:00 | 0.967 | 2018.09.2122:00:00 |
| Mega 34.5kV | 1.002 | 2018.01.15 04:00:00 | 0.992 | 2018.09.21 22:00:00 |
| Office 13.8kV | 0.996 | 2018.01.15 04:00:00 | 0.967 | 2018.09.10 22:00:00 |
| Office 34.5 kV | 1.003 | 2018.01.15 04:00:00 | 0.992 | 2018.09.10 22:00:00 |

Table 8.2: Voltage results of the hourly power flow analysis in a fossil fuel generation grid (upper part), and in a 100% renewable generation grid (lower part) in the Base Scenario by 2018 in Cozumel, Island.

improvement.

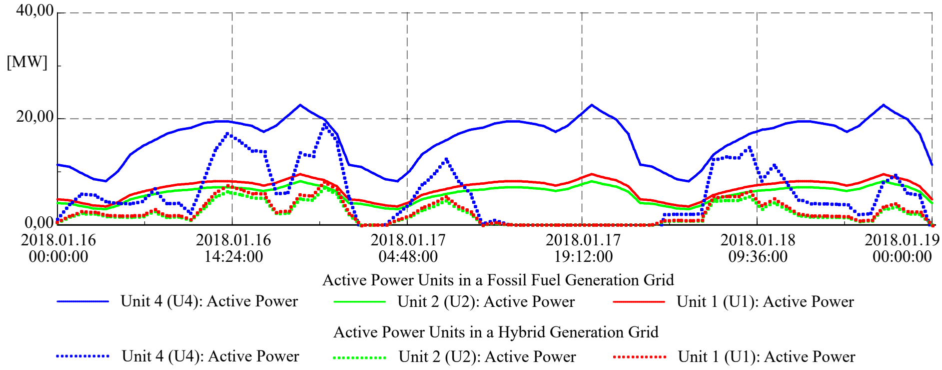


Figure 8.9: Active power in a fossil fuel generation grid (continuous lines), and active power in a 100% renewable generation grid (dotted lines) in the Base Scenario by 2018 for Cozumel Island. Virtual date: January 16th to 19th of 2018.

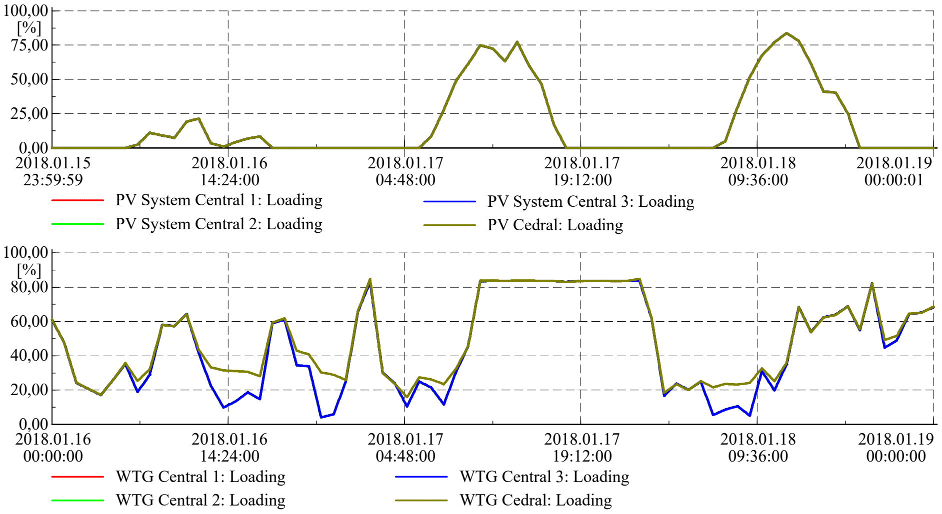


Figure 8.10: Renewable production loading in a 100% renewable generation grid. The upper figure indicates the photovoltaic production and the lower figure indicates the wind turbine generators (WTG) production. Base Scenario by 2018 for Cozumel Island. Virtual date: January 16th to 19th of 2018.

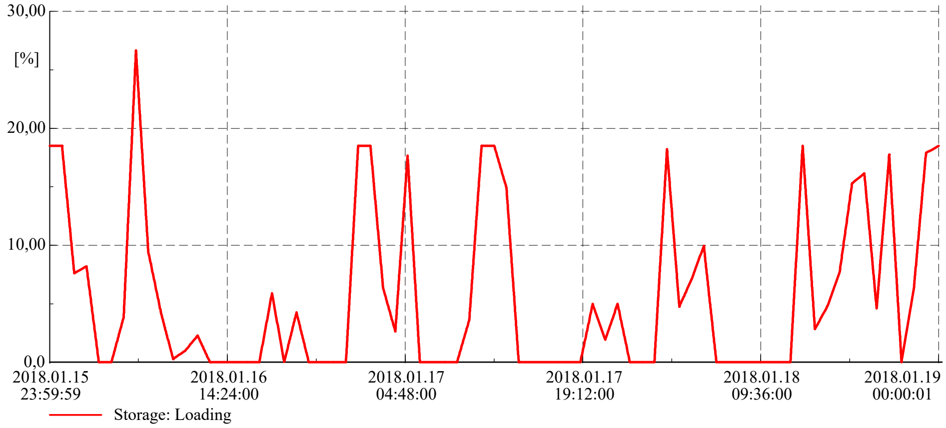
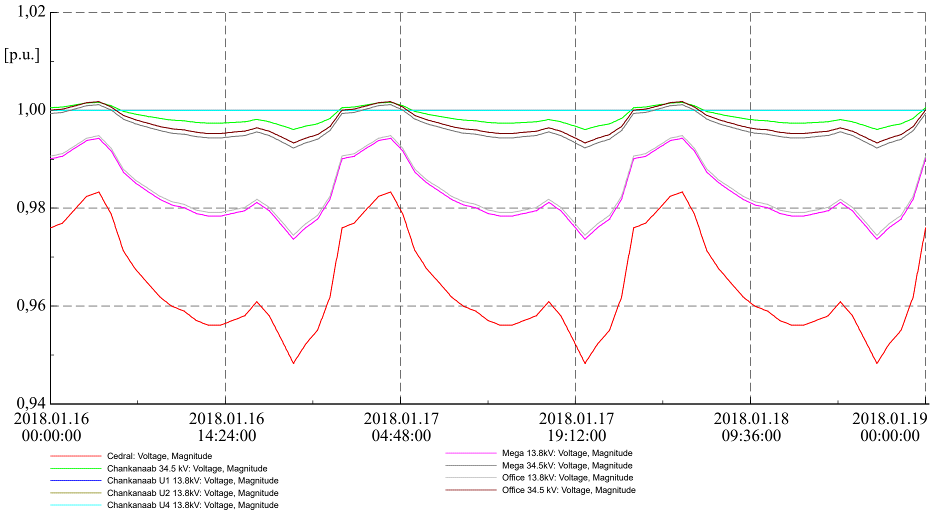


Figure 8.11: Flow battery bank (Zinc-Bromine) loading in a 100% renewable generation grid in the Base Scenario by 2018 for Cozumel Island. Virtual date: January 16th to 19th of 2018.

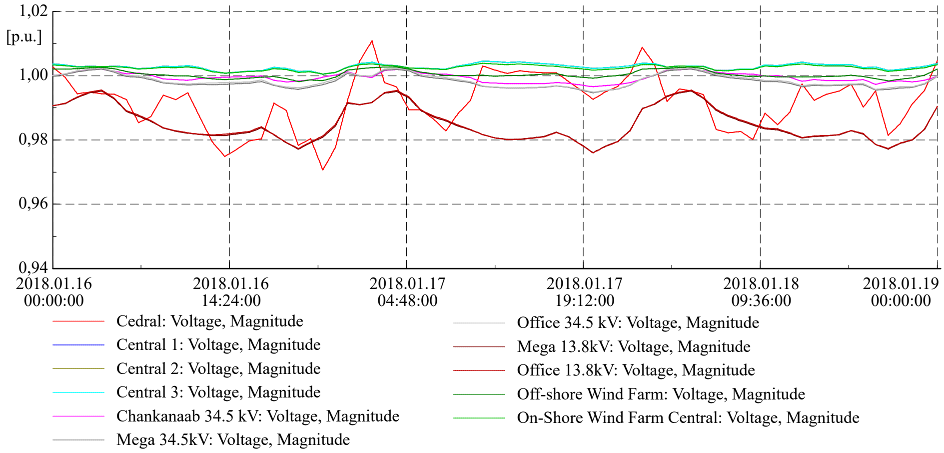
## 8.4 Dynamic analysis and results

After small or large disturbance effects, the power systems must stay operating in a stable manner, and the system has to be able to return to the original steady-state without subsequent failures. Thereby, the stability analysis is made to ensure the voltage and frequency stability [178]. The transient stability is the power system ability of remain in synchrony in presence of small or large disturbances [242]. The numerical analysis techniques are used to solve these non-linear equations. Commonly the non-linear differential algebraic equations are used. Fig. 8.13 is a simple chart flow of what has been done in this stage, a dynamic state analysis to ensure that the grid response is within the MGC parameters and so returns to the previous steady state [36].

The power system response when an electric load is lost and when Unit 2 is disconnected in a fossil fuel generation grid is shown in Fig. 8.14. The maximum frequency values for the Chankanaab busbar in 34.5 kV, the active power unit variation, and the maximum voltage in the units busbars are indicated in this figure. According to the MGC, the values for this frequency response must be 1.005 p.u. as the upper limit and 0.995 p.u. as the lower



(a) Busbar voltages in a fossil fuel generation grid.



(b) Busbar voltages in a 100% renewable generation grid.

Figure 8.12: Busbar voltages in a fossil fuel generation grid (a), and in a 100% renewable generation grid (b) in the Base Scenario by 2018 for Cozumel Island. Virtual date: January 16th to 19th of 2018.

limit. Meanwhile, the values in voltage must be between 1.05 p.u. as the upper limit and 0.93 p.u. as the lower limit in medium tension ($\leq$ 34.5 kV) in a continuous operation (frequency and voltage limits are indicated with

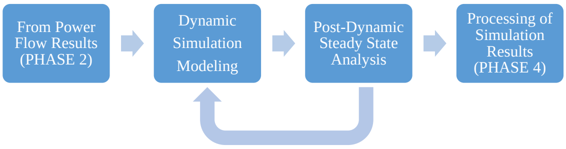


Figure 8.13: Phase 3 chart flow ([36] adapted)

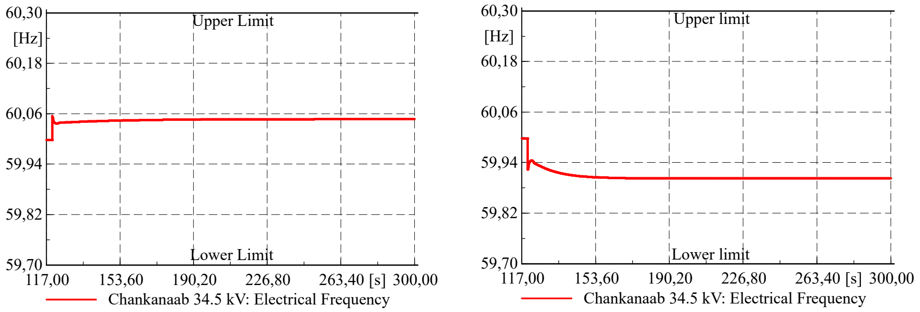
their upper and lower limits). These limit values are for an isolated electric system and the results are in the virtual date of September 11th at 22:00 h by 2018, when the system reports a maximum power demand in a fossil fuel generation grid.

Unlike Fig. 8.14, which shows the fossil fuel generation grid operating when a load loss occurs, or when Unit 2 is disconnected, Fig. 8.15 shows the system response when the wind production is lost in a 100% renewable energy generation grid. In Fig. 8.15 the maximum frequency values for the Chankanaab busbar in 34.5 kV, the active power units' variation, and the maximum voltage in the units busbars are indicated. The values for the frequency response and for the busbar voltage must be maintained within those previously indicated in a continuous operation. These limit values are for an isolated electric system, and the results are in the virtual date of January 17th at 19:00 h by 2018, when the system reports a 100% of renewable production supplying the electric load. As can be seen in Fig. 8.15a, the frequency response signal goes beyond the isolated system lower limit during 0.89s. After this time the value returns to a continuous frequency value. Also, in Fig. 8.15c the voltage response signal goes beyond the isolated system upper limit during 0.80s. After this time the voltage value returns to a continuous voltage value. As MGC requires, the power system response is within the parameters for a continuous operation of the electric grid, for both options, isolated and interconnected system in a 100% renewable energy generation grid. The resultant power flow chart for the Cozumel Island's electric grid when the renewable electricity generation supplying the 100% of the power demand is shown in Fig. 8.16. In this figure, the electric grid resultant values are indicated in the specific virtual date of January 17th at 19:00 h by 2018. The turbogas diesel machines are settled to supply the reactive power needed in the grid.

**Fossil Fuel Generation Grid**

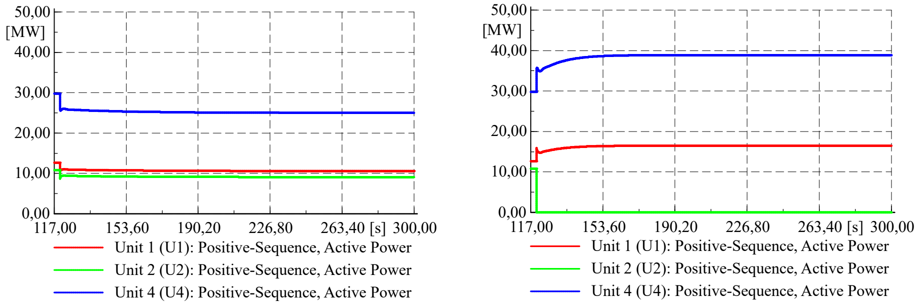
| Branch, Substation or Site | Max. Loading [%] | Time Point Max | Min. Loading [%] | Time Point Min |
|---|---|---|---|---|
| Cedral- Chankanaab | 31.4 | 2018.09.26 22:00:00 | 8.3 | 2018.01.18 04:00:00 |
| Chankanaab- Mega | 18.7 | 2018.09.10 22:00:00 | 4.9 | 2018.01.28 04:00:00 |
| Office- Chankanaab | 28.7 | 2018.09.16 22:00:00 | 8.1 | 2018.01.08 04:00:00 |
| Office-Mega | 6.8 | 2018.09.27 22:00:00 | 3.1 | 2018.01.27 04:00:00 |
| Tie Transfer U1-U2 | 0.0 | 2018.03.20 10:00:00 | 0.0 | 2018.06.28 11:00:00 |
| Tie Transfer U2-U4 | 0.0 | 2018.01.01 00:00:00 | 0.0 | 2018.01.01 02:00:00 |
| Tranformer U1 | 25.3 | 2018.09.19 22:00:00 | 6.3 | 2018.01.31 04:00:00 |
| Tranformer U2 | 11.3 | 2018.09.14 22:00:00 | 2.7 | 2018.03.24 03:00:00 |
| Tranformer U4 | 64.7 | 2018.09.06 22:00:00 | 17.9 | 2018.01.23 04:00:00 |
| Transf. Mega | 48.2 | 2018.09.10 22:00:00 | 13.2 | 2018.01.05 04:00:00 |
| Transf. Office | 48.7 | 2018.09.16 22:00:00 | 13.4 | 2018.01.2604:00:00 |
| Unit 1 (U1) | 82.7 | 2018.09.11 22:00:00 | 19.1 | 2018.01.08 04:00:00 |
| Unit 2 (U2) | 71.8 | 2018.09.14 22:00:00 | 17.6 | 2018.01.12 04:00:00 |
| Unit 4 (U4) | 67.263 | 2018.09.06 22:00:00 | 18.236 | 2018.01.06 04:00:00 |
| **Hybrid Generation Grid** | | | | |
| Cedral- Chankanaab | 27.7 | 2018.09.04 22:00:00 | 2.84 | 2018.01.31 04:00:00 |
| Chankanaab- Mega | 17.6 | 2018.09.04 22:00:00 | 0.94 | 2018.10.05 05:00:00 |
| Office- Chankanaab | 27.8 | 2018.09.04 22:00:00 | 1.22 | 2018.11.18 02:00:00 |
| Office-Mega | 9.9 | 2018.01.11 04:00:00 | 2.00 | 2018.01.02 04:00:00 |
| Tie Transfer U1- U2 | 0.0 | 2018.01.31 01:00:00 | 0.02 | 2018.07.18 10:00:00 |
| Tie Transfer U2- U4 | 0.0 | 2018.01.01 00:00:00 | 0.02 | 2018.01.01 00:00:00 |
| Tranformer U1 | 36.7 | 2018.04.26 22:00:00 | 0.43 | 2018.12.19 03:00:00 |
| Tranformer U2 | 23.7 | 2018.03.15 21:00:00 | 0.34 | 2018.01.03 10:00:00 |
| Tranformer U4 | 86.2 | 2018.01.11 04:00:00 | 0.35 | 2018.04.16 01:00:00 |
| Transf. Mega | 48.0 | 2018.09.21 22:00:00 | 13.21 | 2018.01.15 04:00:00 |
| Transf. Office | 48.6 | 2018.09.10 22:00:00 | 13.36 | 2018.01.24 04:00:00 |
| Unit 1 (U1) | 71.5 | 2018.09.04 22:00:00 | 4.04 | 2018.02.06 03:00:00 |
| Unit 2 (U2) | 67.4 | 2018.09.04 22:00:00 | 4.93 | 2018.01.14 04:00:00 |
| Unit 4 (U4) | 65.6 | 2018.09.04 22:00:00 | 2.59 | 2018.01.17 03:00:00 |

Table 8.3: Loading results of the hourly power flow analysis in a fossil fuel generation grid (upper part), and in a 100% renewable generation grid (lower part) in the Base Scenario by 2018 in Cozumel, Island.



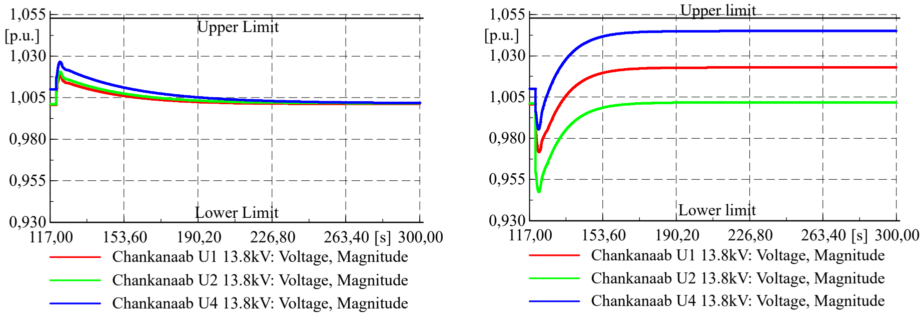
(a) Frequency response signal when an electric load is lost.

(b) Frequency response signal when the Unit 2 is disconnected.



(c) Active power generation response signal when an electric load is lost.

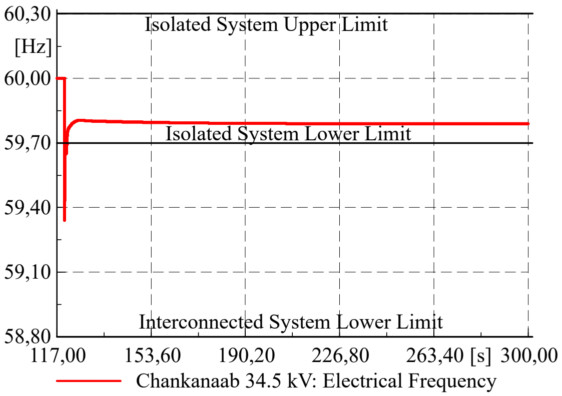
(d) Active power generation response signal when the Unit 2 is disconnected.



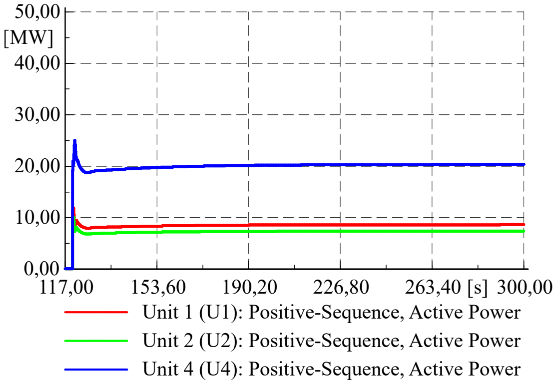
(e) Units busbar voltage response signal when an electric load is lost.

(f) Units busbar voltage response signal when the Unit 2 is disconnected.

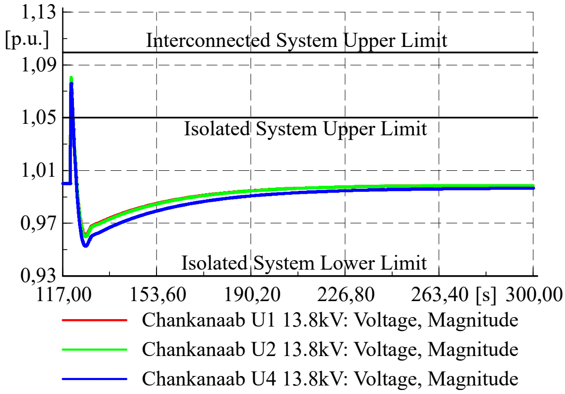
Figure 8.14: System response when an electric load is lost in the virtual date: September 11th at 22:00 hr by 2018. (Figures 8.14a, 8.14c and 8.14e). System response when the Unit 2 is disconnected in the virtual date: September 11th at 22:00 hr by 2018. (Figures 8.14b, 8.14d and 8.14f). Running on the basis of a fossil fuel generation grid, in a Base Scenario for Cozumel Island.



(a) Frequency response.



(b) Active power generation response.



(c) Units busbar voltage response.

Figure 8.15: System response in a renewable production loss in a 100% renewable generation grid in the Base Scenario in the virtual date: January 17th at 19:00 hr by 2018 for Cozumel Island.

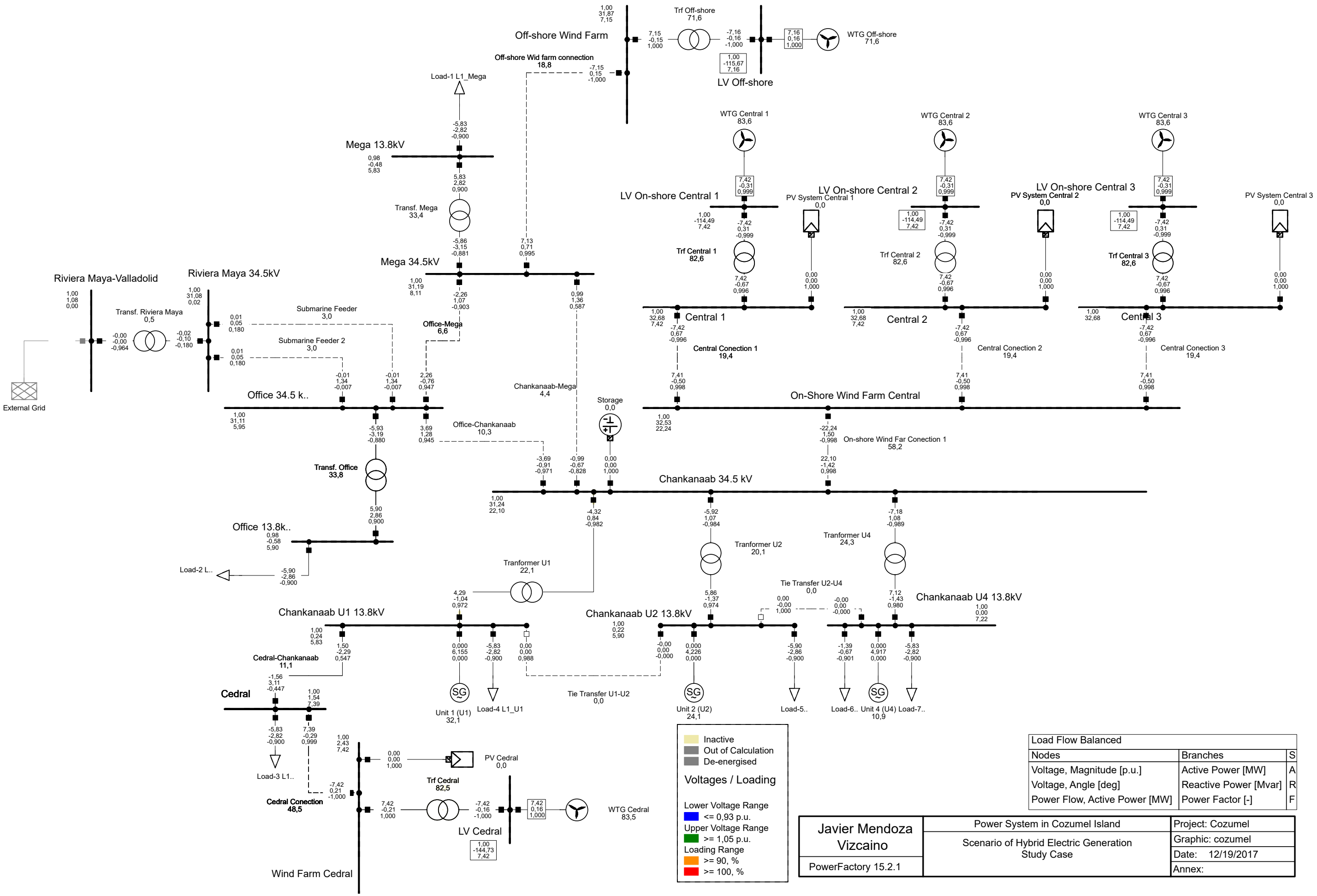
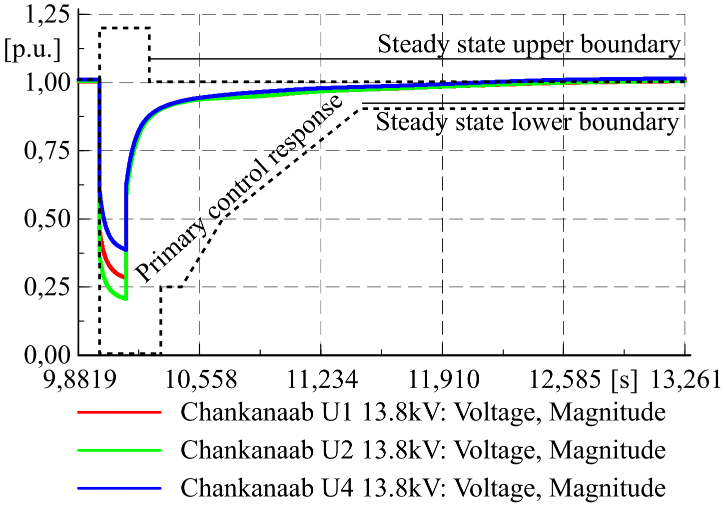
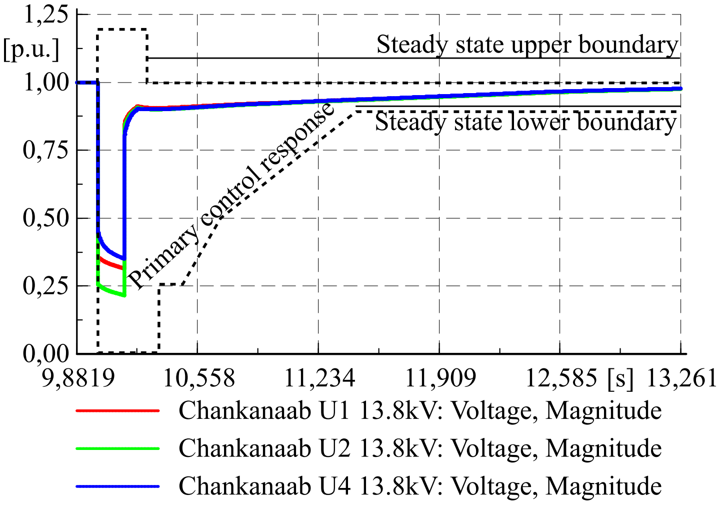


Figure 8.16: Chart of the electric system response in a 100% renewable generation grid in the Base Scenario by 2018 for Cozumel Island, in the virtual date of January 17th at 19:00 hr.

A three phases failure is simulated and localized in the Chankanaab 34.5 kV busbar. The system response is shown in Fig. 8.17. This figure also indicates the steady-state boundaries. This failure is simulated 10 s after the analysis was started, and it was cleared it after 0.150 ms, according to the MGC parameters. As it can be seen in this figure the voltage value returns within the time and limits allowed (area within the dotted lines). The continuous lines in the figure indicate the unlimited time allowed for the electric system in a steady-state operation. This simulation is made in the Base Scenario by 2018 and with the fossil fuel generation running (Fig. 8.17a). The power system response in the same scenario and year is analyzed when a 100% of renewable energy is supplying the power demand (Fig. 8.17b). The date of the dynamic simulation analysis for a fossil fuel generation grid (Fig. 8.17a) is September 11th at 22:00 h, at this time the system is running at 100% of maximum power demand. The date of the dynamic simulation analysis in a 100% renewable generation grid (Fig. 8.17b) is January 17th at 19:00 h. At this time the system is supplying the 100% of the electricity on renewable power. In the same virtual date for the two options analyzed, Fig. 8.18 shows the frequency response resultant. This dynamic analysis is made in the Base Scenario by 2018 and with the fossil fuel generation running (Fig. 8.18a), also the frequency response in the same scenario and year, is analyzed when a 100% of renewable energy are supplying the power demand (Fig. 8.18b). In these figures, the frequency signal returns to a steady-state within the continuous values according to the MGC. Is important to indicate that these failure simulations were done in all scenarios and key years, and the results are very similar.



(a) Voltage response signal in a presence of a three phases fault.



(b) Voltage response signal in a presence of a three phases fault.

Figure 8.17: Voltage response signal in a fossil fuel generation grid (8.17a) in the virtual date: September 11th at 22:00 hr by2018. Voltage response signal in a 100% renewable generation grid (8.17b) in the virtual date: January 17th at 19:00 hr by 2018. Both in the Base Scenario for Cozumel Island.

## 8.5 Techno-economic analysis for the hybrid power system and the electric grid

The NPC is the present value of all the costs of installing and operating the project over its lifetime minus the present value of all the revenues that it earns over the project lifetime. This is the results of the ratio of the annualized cost of the project and the capital recovery factor. The annualized cost of a project is the cost that, if it were to occur equally in every year of the project lifetime, would give the same net present cost as the actual cash flow sequence associated with that project. For this two concepts, the less cost result, the more attractive for the investments will be. The capital recovery factor is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The real discount rate is used to convert between one-time costs and annualized costs. The real discount rate is used to calculate discount factors and to calculate annualized costs from net present costs. The LCOE is considered as the average cost per kWh of useful electrical energy produced by the system. For this concept, also applies that the less cost result, the more attractive for the investments will be. To calculate the LCOE, the annualized cost of producing electricity is divided by the total electric load served. The RGF has the objective of guarantee the ICC, without the detriment of the IRR of the project. The RGF time is the result of the annual sum of the NPV annualized affected by the Retention Guarantee Rate (RGR). This yearly sum must be done until the RGF is equal to the ICC [179]. With this analysis, the money to be spent in case of a natural affectation to the renewable energy site will be done without impairment of the IRR.

The costs of the technologies used were obtained through the Energy Technology Reference Indicator projections for 2010-2050 [239] and the Materials Roadmap Enabling Low Carbon Energy Technologies of the European Commission [243]. Also, the technology costs indicated by Georgianne Huff et. al [222] have been considered as reference for this proposal. All the costs were changed to $US 2016 constant and nominal money, taking into account the Consumer Price Index (CPI) [244] and the exchange rate published by the European Central Bank [245] from €to US$.

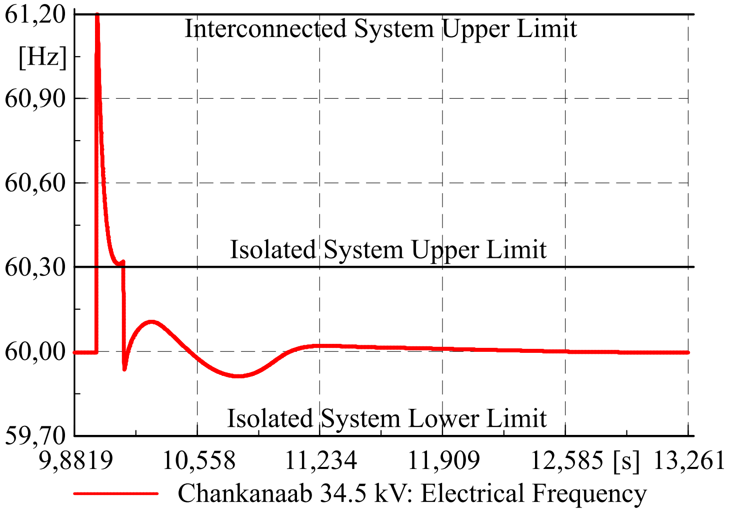
As results of the economic analysis done in section 8.1, figures Fig. 8.4, Fig. 8.5, Fig. 8.6 and Fig. 8.7 represent the ICC, the IRR, the RGF, the time for the RGF, the NPV, the NPC, the LCOE and how the ICC results change with the sensitivities applied. This analysis is made comparing the fossil fuel generation technology vs. the renewable generation technologies, including the storage bank. Each analysis is made for the three scenarios created in the four key years. An over-investment needs to be done in order to modify and reinforce the electric grid through the years, according to the growing perspectives outlined in Table 7.1 and Fig. 7.1. These over-investments are the result of the grid modification done in STEP 7 in PHASE 2 section 3.2.2, and in STEP 10 in Phase 3 section 3.2.3. As can be seen in Table 8.4, the fossil fuel generation grid changes and their cost appear in the middle part of this table. These over-investments are the result of the only fossil fuel operation through the years. Also, the hybrid generation grid changes and their cost appear in the right section of this table. These over-investments are the consecutive investments to be done on the electric grid depending on the way chosen to supply the electric demand chosen: only fossil fuel or hybrid system. The amount indicated for these changes is the quantity needed to have a reliable, strong and safe power system. As it can be seen in the lower part of Table 8.4, the total investments by 2050 are almost the same for each option. Therefore, integrate or not, the renewable electricity generation technologies will practically result in the same amount of money.

The total ICC for each year in the Base Scenario is indicated in Fig. 8.19a, where also the NPV and the RGF are showed. In this figure, the total cost of the project is indicated in two terms. The first, includes the power system cost obtained in the subsection 8.1 and the grid modifications done, as indicated in Table 8.4. The second term, is without considering the modification costs indicated in Table 8.4 and only considering the power system cost obtained in the subsection 8.1. Fig. 8.19b shows the IRR, the retention guarantee fund rate (RGFR) and the time to take the RFG to be equal with the ICC. These values include, in the first term, the power

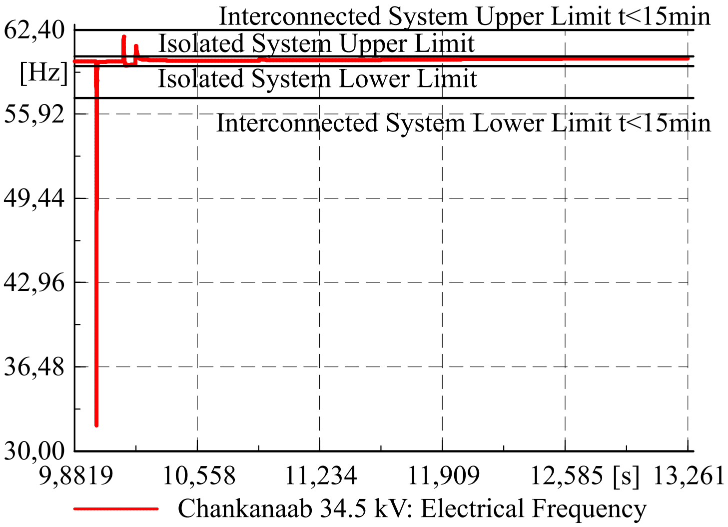
| ***Grid investments through key years for each Scenario*** | | | |
|---|---|---|---|
| ***Year*** | ***Scenarios*** | ***Fossil Generation*** | ***Hybrid Generation*** |
| ***2018*** | Low | 703,171 | 20,922,001 |
| | Base | 8,770,145 | 19,687,787 |
| | High | 8,844,343 | 20,996,199 |
| ***2024*** | Low | 10,141,164 | 5,012,695 |
| | Base | 14,284,204 | 16,659,519 |
| | High | 10,249,647 | 12,782,832 |
| ***2035*** | Low | 27,182,972 | 34,142,158 |
| | Base | 27,549,120 | 26,679,273 |
| | High | 35,478,544 | 32,972,858 |
| ***2050*** | Low | 38,580,382 | 49,140,151 |
| | Base | 61,339,979 | 82,122,748 |
| | High | 122,294,918 | 113,774,477 |
| ***Total grid investments for each Scenario*** | | | |
| ***2018-2050*** | Low | 76,607,689 | 109,217,005 |
| | Base | 111,943,449 | 145,149,327 |
| | High | 176,867,452 | 180,526,366 |

Table 8.4: 2018-2050 Over-investments summary for each Scenario in Cozumel Island.

system cost obtained in subsection 8.1 and the grid modification done, as is indicated in Table 8.4. The second term does not consider the modification costs indicated in Table 8.4, it only considers the power system cost obtained in the subsection 8.1. In Fig. 8.19 the ICC, including the grid cost, will be obviously bigger than the ICC without it. Even so, the NPV, including the grid cost, is lower than the NPV without it. Normally, if the project would cost more, the value at the end of its lifetime should be smaller, but in this case, by 2050, the results show that is the opposite. Simultaneously, the IRR has the same results, because the new diesel turbines will be installed that year.

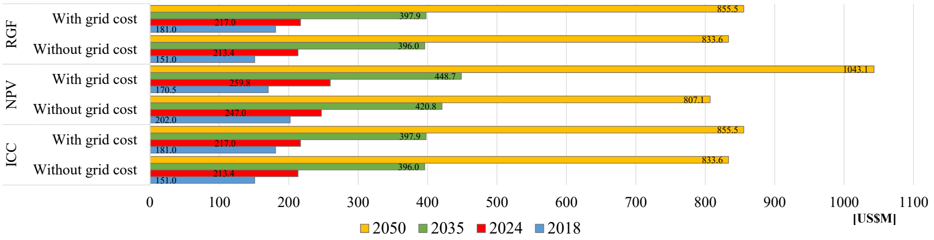


(a) Frequency response signal in a fossil fuel generation grid.

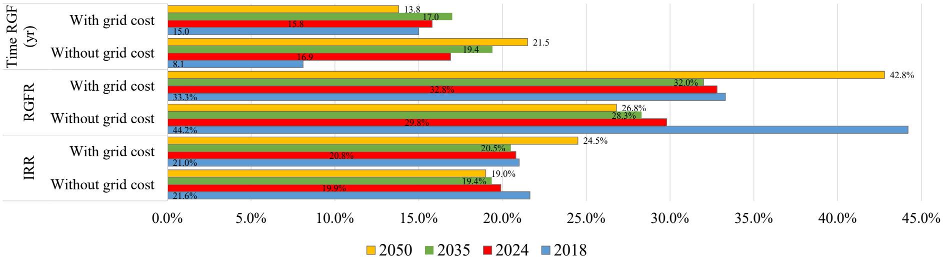


(b) Frequency response signal in a 100% renewable generation.

Figure 8.18: Frequency response signal in presence of a three phases fault in the Chankanaab busbar in 34.5 kV, in a fossil fuel generation grid 8.18a (Virtual date: September 11th at 22:00 hr by 2018), and in a 100% renewable generation grid 8.18b (Virtual date: January 17th at 19:00 hr by 2018) in the Base Scenario by 2018 for Cozumel Island.



(a) ICC, NPV, and RGF results including and not including the grid cost in the ICC.



(b) IRR, RGFR, and time RGF results including and not including the grid cost in the ICC.

Figure 8.19: Economic results of include or not the grid modifications cost, in this case, without the sensitivities variables incorporated to the ICC in the Base Scenario by 2050 for Cozumel Island.

# 9 100% Renewable Energy Generation, a Pre-Analysis

## 9.1 100% renewable energy supplying the electric load, a pre-analysis result

In an attempt to visualize what combination of PV/Wind/Battery would be conformed to supply the 100% of the electric load for all the year in Cozumel Island, in the Base Scenario by 2050 this pre-analysis is elaborated. The initial input data is maintained equal to Chapter 8, as well as the equipment cost for the renewable technology and for the diesel turbo-gas machine. Other considerations are maintained, like the sensitivities variables, the constrains and the inflation rate. Four system configurations are been settled and a fifth is taken as comparative: 1) system with the sensitivity variables applied; 2) system without the sensitivity variables applied; 3) system with the sensitivity variables applied and including the 8 wind turbines of 3 MW Off-shore resultant in the previous sections by 2050; 4) system without the sensitivity variables applied and including the 8 wind turbines of 3 MW Off-shore resultant in the previous sections by 2050, and; 5) system with only diesel generation as comparative. Fig. 9.1, Fig. 9.2 and Fig. 9.3 show the results obtained. Fig. 9.1 indicates the system configurations to be install in four different combinations. As can be seen in this figure, the PV and Wind on-shore results are the same in the four configurations, this is because for each wind turbine will be installed 333.33 kW of PV. As the sensitivity variables includes only a PV efficiency improvement, there will be only a few production increasing. In two of them are including 8 off-shore turbines of 3 MW each by 2050. The number of batteries and the converter capacity have to be increased for these two configuration. This will increase directly the NPC and the ICC and it will reduce the LCOE resultant, as it is shown in Fig. 9.2. In this figure, the LCOE for only diesel remains lower compared with the configuration without the sensitivity variables applied but is higher than those that apply these sensitivity variables. This is the result of the cost reduction and the efficiency increase applied. Finally, Fig. 9.3 shows the technical results of each configuration compared with the use of only diesel. These four configurations keep all the time the 100% of the renewable energy supplying the electric load without diesel consumption. In this figure is clear that there is not an electricity excess production in the diesel comparative configuration. This happens because that the fossil fuel machines can follow the electric load profile. The electricity excess produced in the first four configurations is due to the need to combine the three renewable technologies operations in order to supply all the electric load according to the electric load profile.

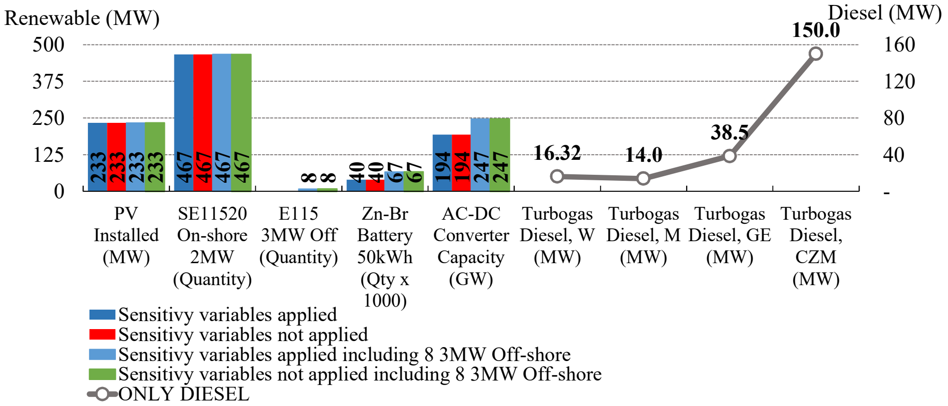


Figure 9.1: Equipment capacity installed in a 100% renewable generation grid in the Base Scenario by 2050 for Cozumel Island.

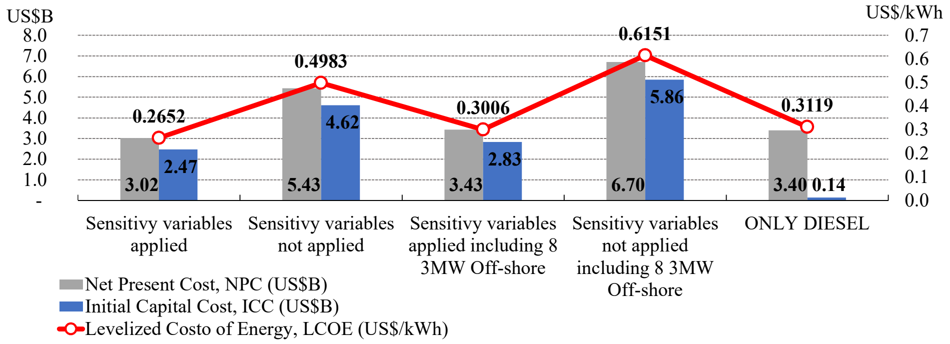


Figure 9.2: Economic results in a 100% renewable generation grid in the Base Scenario by 2050 for Cozumel Island.

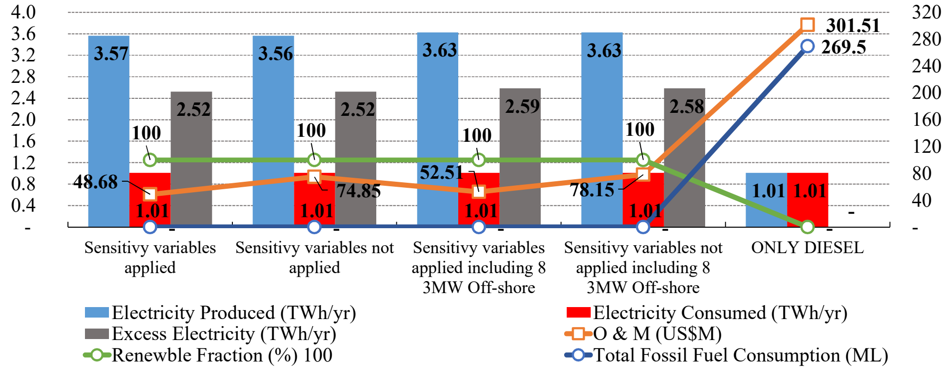


Figure 9.3: Technical results in a 100% renewable generation grid in the Base Scenario by 2050 for Cozumel Island.

# 10 Discussions and Results Summary

## 10.1 Discussions

### 10.1.1 Barriers and Uncertainties

The challenge in Mexico is finish setting the strategy for a clean, real and sustainable energy sector, in order to face the incoming years. This strategy needs the cooperation between government, community, research sector and investment enterprises, because the integration of RETs is vital, especially in Cozumel Island. Some barriers and uncertainties have been found and need to be overcome.

#### Barriers

- Regulate the access to the information of electrical grids in order to bring clear opportunities to companies, professionals and researchers to develop efficient proposals in the electric sector.

- Publish the appropriate local strategies in public policies, in order to establish a real engagement for the integration of the RE technologies in all sectors on the islands.

- Develop of specific rules to determine a steady economic framework to encourage and stimulate the investments for the RE, not only for big consumers and utilities, but also for small and medium consumers. Since the enforcement of the 2013 Mexican energy reform, that includes the electric sector, a good transformation for better future RE electric generation is taking place.

- Integrate the participation of local organizations, authorities and environmental specialists for the correct integration of RETs on the electric grid in Cozumel Island, reaching a sustainable energy development for the benefit of the community.

#### Uncertainties

There are many design options for sustainable electricity supply on islands. In consequence, there are a number of variables that cannot be controlled, representing an uncertainty for the energy planning of the island. A sensitive analysis would help in assessing the effects of uncertainty in non-control variables such as wind speed average and fuel prices among others. Through the use of statistical models that perform time-series simulations, grid operations can be obtained with an optimization degree that defines how these components will work together.

Government reports, programs and strategies could indicate uncertainty in the sector, such as fuel prices variations, power demand expected or electricity generated in a medium or long term of time. These reports can help evaluating the risk of investments in such technologies.

### 10.1.2 Access to Financing

Some inputs cannot be used with a minimum uncertainty. An example is the lack of credits for the use of RETs, for domestic users or small and medium consumers. Reaching these credits would lead to reduce the electricity consumption and the power demand as a variable in the simulations.

## 10.2 Results Summary

The methodology proposed is validated on a real electric grid on a Caribbean Island by means of its application as a case of study. Always fulfilling the renewable energy targets in the REF generated for the electric system. This system has a reliable, strong and safe operation response even in case of a disturbance presence considering the continuous operation constraints based on the MGC parameters. Likewise, the sensitivity input values considered and the system response results to obtain a final technical proposal was analyzed and solved. All these technical results were the basis for the economic analysis and obtain the lowest LCOE, ICC and NPC, as well as the biggest NPV of the project suggested. As there is a long-term planning evaluation, many things can change over time. This methodology can apply several time-variables and the results will have enough certainty once the changes or risks are uploaded on it, then the new results can be compared against the originals and modify policies or initials statements. The sensitivity analysis can be done with guaranties of a final and reliable outcomes. For instance, in a real case, the implementing of the renewable energy integration projects could take 7-15 years [61] [16], more or less. For this project, it will be selected 7 years for its implementation. This process must be done in the Energy Regulatory Commission (CRE, for its Spanish acronym) in Mexico. According to the CRE procedure time [246], if the project starts in 2017, it will be finished in 2024. In this year the investments should be applied and the project must be running. As the idea in this proposal is to have a modular system growing until 2050, and the Renewable Technology Equipment (RTE) lifetime average is 25 years, then all the RTE installed in 2024 will be substituted by new RTE in 2050. In 2035 the RTE installed in 2024 will still have a lifetime left to work, so that the new RTE quantity will be the difference of the total RTE considered to be installed in 2035 minus the existent RTE from the year 2024. In 2050 the RTE installed in 2024 will be replaced with new RTE, meanwhile, those that have been installed in 2035 will still be working and their replacement will be done after 10 years, approximately. The final investment in RTE to make by 2050 will be the difference of the total RTE considered being installed by 2050 minus the RTE installed in 2035. If something changes over time, the initial variables can be modified in order to adapt the modular growing of the system to the new parameters. Table 10.1 shows these investments over the key years, considering the RTE quantities as investments. In this table, the grey areas belong to the newly installed equipment that will need to be installed in each indicated key year

| | | PV (MW) | SE11520 2MW (Quantity) | E115 3MW (Quantity) | Battery (Quantity) | DC-AC Converter (MW) |
|---|---|---|---|---|---|---|
| 2024 | | 7.0 | 21 | 5 | 548 | 27.4 |
| 2035 | | 13.0 | 39 | 8 | 900 | 45.0 |
| 2050 | | 34.7 | 104 | 8 | 1943 | 97.2 |
| 2035 | Existent | 7.0 | 21 | 5 | 548 | 27.4 |
| | New | 6.0 | 18 | 3 | 352 | 17.6 |
| 2050 | Existent | 6.0 | 18 | 3 | 352 | 17.6 |
| | New | 28.7 | 86 | 5 | 1591 | 79.6 |

Table 10.1: New Renewable Technology Equipment (RTE) to install (grey areas) in each key year starting in 2024 in the Base Scenario for Cozumel Island.

From Fig. 9.3, it can be seen that there is a huge potential to interconnect electric vehicles taking advantage of the electricity excess production. With the right policies, Cozumel Island's Government can activate cleaner energy strategies for the public transport sector, changing fossil fuel vehicles to electric vehicles, for instance. Even the private transport sector could be benefited by this electricity excess production. This is one of the most interesting points to be developed in Cozumel Island, discussions held with government personnel have confirmed that the results seem to be very attractive to carry it out, for them. For future works, it can develop the analysis of how many gasoline vehicles can be substitute by electric vehicles and which control side demand will be the optimum, in order to utilize all the electricity excess production on the Island. The classification of global small islands gives the overview that in many of them the RES implementation can carry out with significant and positive results on it. Therefore, it supports the transfer of proven, well-working concepts and the direct adoption of these concepts by suitable islands. The work of Meschede et al. is applied in those islands that are very similar to Cozumel Island and the islands which have especially high potentials for the use of a specific renewable energy source can be easily recognized [184]. Despite this similar characteristics, this work is not similar, because in this document the integral analysis of the RE implementation in a existing fossil fuel generation grid is carried out. It includes: a) RETs integration and combination (PV/Wind/Battery); b)

Power flow analysis and quasy-dynamic simulations; c) Grid reinforcements and modifications proposed, applied and validated in a real current electric grid in a small island; d) a dynamic analysis to assess the strong and safe grid response in case of fault or system unbalance getting back to the original steady state operation, and; e) a complete financial analysis including the grid modifications and reinforcements costs did through time until 2050; all this without detriment of the renewable fraction of electricity integrated and fulfilling the Mexican Grid Code in its operation.

This work results match with results published by Gioutsos et al. in some aspects [247]. One of the most important of them is that with the results in the levelized cost of systems for electricity generation decrease considerably with increasing renewable energy penetrations, to an optimal point in the range of 40% to 80% penetration. Likewise, this work match with the RETs including in the simulations as Adefarati and Bansal show in their work, where present a comprehensive reliability assessment of the distribution system that satisfies the consumer load requirements with the penetration of wind turbine generator, electric storage system and photovoltaic [102]. In this proposal, like theirs, the results obtained from the case studies have demonstrated the effectiveness of using Wind/PV/Batt to enhance the reliability of the conventional distribution system. Same results presented by Sigrist et al. [96] gives a clear idea that the results showed by this document has enough certainty and validation to be applied by other small islands in every tropical region of the world.

Small Tropical Islands share a lot of common things between them, as can be: weather, fossil fuel generation of electricity, off-grid operation, tourism high dependence and sensitive environmental, among others. According to Blechinger et al. almost 1800 islands with approximately 20 million inhabitants currently supplied by 15 GW of diesel plants [11]. With the proper regulations can be accelerated the implementation of this enormous potential, so this document can be a good mechanism for it, once that includes a renewable energy integration analysis, a grid assessment and its response analysis in a steady and dynamic state, grid modifications through time and a financial analysis to obtain the appropriate resultant system to be installed on Cozumel Island.

# 11 Contributions and Conclussions

## 11.1 Contributions

### 11.1.1 Thesis Originality

The proposed solution from the results obtained proves its viability and was validated on Cozumel Island. These results support that the thesis accomplish its general and specific objectives settled on Chapter 1.

### 11.1.2 Initial Objectives Fulfilment

The initial objectives on this thesis were accomplished and corroborate them through this work. As is marked at Chapter 1:

*The general objective of this thesis proposal is help to fulfil the Mexican government goals in renewable energy sector and to reduce the fossil fuel consumption and its generation cost in the electricity production.* The methodologies to accomplish it were developed in Chapter 3, and were used and applied them on the forwards chapters.

*Specific objectives*

1. *Create a tool to allow an integration of renewable energy sources on islands, within of their national electrical system, with which also can be develop future scenarios in electric sector, through the implementation of the renewable energy technology.* This thesis can considerer as a real tool to do it, through Chapter 3 and Chapter 4 the necessary steps to develop this stage were developed.

2. *Study the holistic integration of the renewable energy, applying them to the power generation systems on islands, achieving reliability and*

*optimization for the hybrid system, also providing a reliable, secure, rational and flexible electric system. Reducing, at the same time, the fossil fuel consumption and its generation cost in the electricity production.* In Chapter 2, the renewable energy systems on islands are well defined and analized. For the proposed system on Cozumel Island, to accomplish this specific objective the optimization carried out was developed on Chapter 8 and Chapter 9.

3. *Determine the economic and fiscal incentives models to promote the develop of renewable energy systems, and to maintain an accessible cost of the electric tariff for population, industries and services, achieving with this, the reduction of electricity generation costs and the amount of the government budget that spends in fossil fuels consumption, through the subsidies.* The economical model was well defined through from Chapter 7 to Chapter 9. The cost in the electricity production have been decreased compared vs. the initial fossil fuel electricity generation cost, likewise, the Mexican government expenditure on this concept. The fiscal incentives model was not well defined, due to the innumerable quantity of departments and government offices that intervene on the subsidies applied to the fossil fuels used to the electricity production. This topic is out of reach of this thesis scope.

### 11.1.3 Methodologies Used

Two planning methodologies were developed and applied on this work:

*Three Steps Methodology*

1. Analysis of the existing energy system supplying the electricity to the island, likewise the renewable energy integration targets for short, medium and long term growing scenarios, integrating the renewable energy technologies to the current electric grid.

2. Renewable energy sources integration and production simulations run, injecting the energy to the fossil fuel generation grid on the island.

3. Technical, economical and land use impacting analysis, selecting at the end the best system to be installed on the island.

*Four Steps Methodology*

1. From step three in three steps methodology, the sensitivity analysis is settled to carry out the hybrid energy system optimization and accomplish the national grid code parameters selected.
2. Simulating the growing perspectives in energy demanded for the hybrid system from step 1 in the three steps methodology, the steady state analysis is elaborated. This can determine the operation response and the growing scenarios through the period of time selected. These simulations are carried out for the fossil fuel generation grid and for the hybrid generation grid to compare the results.
3. The dynamic state analysis is elaborated in the same growing scenarios and through the period of time selected like the last step 3 of this methodology. The modification or reinforcements to the grid are included in these dynamic state analysis to have a system response according to the grid code selected.
4. The economical model of the hybrid system that fulfil the initials objectives is obtained. This model must comply the targets in the renewable energy integrated on the electric grid, the safe operation response and the flexibility to supply the electric demand for the growing scenarios through the period of time selected.

### 11.1.4 Thesis Impact

The three papers published from this work on international and peer review journals validate its originality. The impact of the published papers is growing, this made that this work offer a clear renewable energy integration mechanic on the fossil fuel generation grids. At the same time, the impact is reflected on an better understanding in how can be developed an optimization and improvement of the existing hybrid system operation and response.

This thesis shows the electric grid topology of the study case; the steady and dynamic analysis are present; uses and applies the dynamic models of controls for the generation machines existing on the grid; integrates the renewable energy technologies on the fossil fuel generation grid; includes and compare four different energy storage technologies; keeps the stability and the good operation response of the grid and the complete hybrid system, always within of the grid code parameters published by the site authorities; identifies the weakest section of the grid and propose the reinforcements or modifications to carry out on the distributed generation grid; determines the growing scenarios for short, medium and long term for the electricity consumption on the electric grid, and; performs the financial analysis for the hybrid system to determine its performance and economical viability.

## 11.2 Conclusions

PV and Wind power is the most used RETs on islands. Generally in combination with another RETs and SGTs, they achieve feasible and viable applications of these technologies. All results show that the integration of RE on islands (when viable), results in a fossil fuel consumption reduction, bringing them closer to a sustainable development in energetic sector.

The outcome obtained in this study case as the first approach, shows how feasible is RE integration into the electric grid, in both economic and environmental terms in Cozumel Island. The decrease of LCOE from an initial value of 0.37 $US/kWh to 0.24 $US/kWh in scenario 2050 shows that a RES integration into the grid is viable and the capital repayment time is very short.

The use of fiscal incentives will help to a fast integration of RES in Mexico. Some incentives were well defined until the secondary laws for the energetic reform in August 14th of 2014 were enforced (for example: 100% of the Income Tax can be considered immediately in the year of the RETs investment). However, these incentives remain until the new rates are announced. Clean Energy Certificates (CEL for its Spanish acronym) will be another financial mechanism to promote the insertion of RE in electrical grids.

On the second approach, 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 7.4 shows the quantity of the equipment selected to achieve this target. Meanwhile, Table 7.6 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 7.8 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 7.11). 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 7.5). Figure 7.15 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, and reducing the battery backup time to 1 hour, 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 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 7.14 in section 7.3.5). It is important to remark that these economic analyses were conducted without capital cost reductions through time. The main objective in this stage was to formulate an approach to the investment needed according to the increase in RE and the fulfilment of the targets indicated at Chapter 5. The reference 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 in 58.6% by 2050 in relation to the 2014 prices in the high CAPEX consideration [239]. This consideration is used as the worst case scenario with no cost reductions.

The decision to choose and 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 [199]. The three phases methodology used in stage of the 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. This three phases methodology is used as the first part of the final hybrid system selection carried out in Chapter 8.

Chapter 8 proposes an integral methodology to study a renewable power system integration and performs a grid assessment, in order to achieve the energy planning within the National legal framework, that includes the renewable energy targets to be fulfilled until 2050. Therefore, to do it in an optimal manner and to accomplish the renewable energy target, in this second approach was optimized and reduced the backup time of the battery system, and was compared four different battery technologies, simultaneously. This methodology is validated in the small Caribbean island of Cozumel, Mexico, and it focuses on the electric grid response (according to the MGC) where the renewable electricity generation is integrated into an real operating fossil fuel generation grid.

1. As the results show, the Zinc-Bromine battery bank included in the initial hybrid system selected is the best battery technology resultant.
2. From the four different battery bank technologies selected to compare the complete power system response and grid behaviour, the Zinc-Bromine redox flow battery showed the best results, both economically and technically for all scenarios and through the four key years until 2050. With the sensitivity variables (cost reduction and the increasing efficiency parameters) included in the analysis, these results were even better by 2050.
3. Combining this battery bank with the diesel turbo-gas machines, the wind turbines placed off-shore and on-shore and the PV array the economic results were the lowest LCOE, ICC and NPC and the biggest NPV from the system combination studied, as Table 11.1 shows:

| **Diesel Turbogas (MW)** | **Off-shore turbine (MW)** | **On-shore turbine (MW)** | **PV (MW)** | **DC-AC Converter (MW)** | **Battery (MWh)** | **Battery (Type)** | **LCOE ($US)** | **Renewable Fraction (%)** |
|---|---|---|---|---|---|---|---|---|
| 58.32 | 27 | 64 | 5.4 | 20.95 | 20.95 | Zc-Br | 0.2417 | 43% |
| 58.32 | 36 | 64 | 5.4 | 20.77 | 20.77 | Vanadium | 0.2440 | 43% |
| 58.32 | 36 | 60 | 5.0 | 31.60 | 31.60 | Ion-Lithium | 0.2442 | 44% |
| 58.32 | 36 | 64 | 5.4 | 21.54 | 21.54 | Lead-Acid | 0.2446 | 44% |

Table 11.1: Final LCOE in the Base Scenario by 2018

4. From the steady-state power flow analysis results, the voltage and loading values from using only the fossil fuel generation or from using

the hybrid power generation showed a huge difference. Despite the variations in the equipment operation respect to the load profile, the performance in the hybrid grid resultant was improved and the system response made visible that the system turned reliable, strong and safe.

5. In the voltage results with only fossil fuel generation the furthest bus-bar, called Cedral in 13.8 kV had a value of 0.983 p.u. as a maximum and 0.931 p.u. as a minimum (always within the MGC parameters for a continuous operation). With the hybrid generation, the voltage result for this bus-bar was 1.013 p.u. as a maximum and 0.946 p.u. as a minimum. These results were obtained once the electric grid was modified and reinforced (see Table 8.2 and Table 8.4), and they were performed in the Base Scenario by 2018.

6. The results from the dynamic analysis showed that the final power system is strong enough to have a response within the MGC parameters, once the modifications and reinforcements were done. In both, fossil fuel generation grid and hybrid power generation grid.

7. The dynamic analysis response of the power system accomplishes the primary control response to maintain a stable and continuous operation, according to the grid code mentioned.

8. Theoretically by 2035, 8 off-shore wind turbines of 3 MW of capacity each one in combination with 13 MW of PV, 39 on-shore 2 MW wind turbines, and 900 Zn-Br redox flow batteries of 50 kWh each must be installed. As by 2050, the best result shows that no off-shore wind turbine would be installed, a final combination has been proposed: 8 off-shore 3 MW wind turbines, 104 on-shore 2 MW wind turbines combined with 34.7 MW of PV total array, 1,943 Zn-Br redox flow batteries of 50 kWh each and 97.15 MW of DC-AC converter capacity. As by 2035, the off-shore connection must be included in the techno-economic analysis, this underground lines and protection equipment will be used for the 2050 off-shore wind farm to be installed.

9. For Cozumel Island's electric grid (without the power generation technologies), the results in the total investments in the High Scenario in 2050 are almost the same for each option (both, fossil fuel generation grid or hybrid generation grid). Integrate or not, the renewable electricity generation technologies will result in the same amount of money invested (see Table 8.4).

Finally, it can be achieve the 100% renewable electricity generation supply for the small islands, but it has to elevate the sustainability development value to do it. Chapter 9 shows this proposal, where it can activate the renewable and sustainable energy system if it can eliminate the political and economical analysis as the only way to affront this paradigm change.

From the pre-analysis elaborated in Chapter 9 to supply the 100% of the electric demand with renewable electricity on the island, results show that this can be done using the diesel machines only to keep the reliability on the grid, supplying the reactive power need it to maintain the system in balance. This can be changed substituting the diesel machines by Voltage Source Converters (VSC). This solution can be developed, taking into account the converter ability to control the distribution of power ensuring the network stability.

## 11.3 Future Research

The findings in this thesis can lead to some important future researches, they can inspire a better understanding of renewable energy integration development. Chapter 2 shows how the islands around the world deal with global warming issues effects. Many solutions in order to reduce the impact have been developed, but apparently, all the global efforts will be not enough to do it because there is a lack of awareness, for instance, the fact that the United States going out from the Paris Agreement justified by a supposed unfair economic treatment.

As it can be seen on the Chapters 6 and 7, where both, without and with energy storage, the electricity excess production resultant from the renewable technologies integration can be used to substitute the existing fossil fuel transport, public and private. The integration of the electric vehicles can be an important research line to develop in the short term. Other important research line that can take advantage of this electricity excess production can be the Hydrogen production by the electrolizer use, as energy storage solution, or exploit it in a methanization process. The optimization of these proposals is the key to improve the renewable energy systems operation. As can see in the techno-economic analysis results in Chapter 8, substituting or not the fossil fuel generation machines for RETs on Cozumel Island, result in almost the same quantity of money investment to modify and adapt the electric grid for the electricity consumption growth through the time. Thereby, the decision of change these old and discontinued fossil fuel technologies relays on a integral future research line to elaborate an attractive energy policies to make easier the politician's decision.

Chapter 9 shows that to supply the 100% of the electric demand with renewable electricity on the island it will need the supply of the reactive power to maintain the system in balance. In a future research line, this can be achieving by substituting the diesel machines by VSC. The actual research demonstrates the converter ability to control the distribution of power among the transmission system while ensuring the network stability. This research has been demonstrated by M. Raza [248] in an Off-shore wind farm interconnection study.

# Appendix A

# Author Publications

## A.1 Publication in Journals

As results of the thesis elaboration, three journal papers were elaborated and published. They are listed below:

### A.1.1 Paper 1 of 3

Paper published: “Renewable Technologies for Generation Systems in Islands and their Application to Cozumel Island, Mexico.”
https://doi.org/10.1016/j.rser.2016.06.014 Volume 64, October 2016, Pages 348-361, in the Renewable & Sustainable Energy Reviews Journal, with an impact factor of 6.798 according to Thomson Reuters Journal Citation Reports 2015.

#### Abstract

The electric generation systems on islands are based generally on fossil fuel. This fact and its supply make the electricity cost higher than in systems used in the continent. In this article, we present a review of the renewable energy generation systems on islands. To do it, we analysed 77 islands from 45 different countries. This work will allow us to know how the implementation of renewable energy sources could help these islands in developing a renewable and sustainable energy sector, including a reduction of electricity generation cost. This paper shows the results from a study case of the application of renewable energy technology in Cozumel Island, Mexico. This Island is

located in front of the Riviera Maya area. The analysis was made through long- term statistical models. A deterministic methodology was used to perform time-series simulations. The simulations show that in the year 2050 a feasible integration of a system based on wind/PV can be achieved on the Island, reducing the electricity price from 0.37 US/$kWhto0.24US$/kWh (2050 scenario). In this scenario, the government will achieve its targets in renewable energy and in the reduction of the emissions of $CO_2$. This will allow reaching a sustainable electricity sector.

### A.1.2 Paper 2 of 3

Paper published: “PV, Wind and Storage Integration on Small Islands for the Fulfilment of the 50-50 Renewable Electricity Generation Target” http://www.mdpi.com/2071-1050/9/6/905 in the Sustainability Journal 2017, 9(6), 905. With an impact factor of 1.789 according to Thomson Reuters Journal Citation Reports 2016.

#### 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.

### A.1.3 Paper 3 of 3

Paper published: "Integral Approach to Energy Planning and Electric Grid Assessment in a Renewable Energy Technology Integration for a 50/50 Target Applied to a Small Island"
https://doi.org/10.1016/j.apenergy.2018.09.109 in the Applied Energy Journal, with an impact factor of 7.900 according to Thomson Reuters Journal Citation Reports 2017.

#### Abstract

This paper presents an energy planning, a grid assessment, and an economic analysis, considering three growing scenarios (Low, Base and High) in the electricity consumption, to supply the energy demand for a hybrid power system (Photovoltaics/Wind/Diesel/Battery) on a small island by 2050. The main aim of this study is to present a methodology to optimize and reduce the backup time of the battery bank, included from the hybrid power generation system selected. Also, it will compare four different battery technologies, simultaneously, without changes in the renewable energy targets settled in 50% until 2050 and without changes in the safe continuous operation of the grid. The methodology includes a grid assessment analysis to obtain a reliable, strong and safe operation response based on the grid code parameters, even in case of disturbance.

In the proposed methodology the analysis is developed on the basis of

the use of two simulation model tools. The First simulation model tool determines the optimal values of variables that the system designer controls, such as the mix of components (Photovoltaics/Wind/Diesel/Battery) that make up the system and the size or quantity of each variable. This model uses the multiyear analysis based on a time-domain simulation run at the energy-flow level with discrete time-steps of 1 hour. The Second simulation model tool assumes all the variables and parameters on the grid as constants during the period of time analyzed. The power flow is analyzed through a programming language command script function and reflects the system response at a specific time with given specific variables and parameters. The final technical proposal and its financial analysis are obtained applying and validating this methodology on a small island, as well as, the selection of the system to be installed for the renewable electricity generation. The electric grid modifications and reinforcements through the years until 2050, according to the grid code and the renewable energy targets settled for the island's electric power system are included.

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