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Renewable Technologies for Generation Systems in Islands and their Application to Cozumel Island, Mexico.

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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 shows 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 scenario). With this scenario, the government will achieve its targets in renewable energy and in the reduction of the emissions of CO₂. This will allow reaching a sustainable electricity sector.

Keywords: Cozumel Island, energy planning, hybrid system, renewable energy, renewable technology, sustainable energy.

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1. Introduction

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 [1].

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 [2]. 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.

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's potential, develop energy efficiency and enforce the SIDS program for a sustainable development [3]. Development is not possible without energy, and a sustainable development is not possible without a sustainable energy [4]. 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. Without proper management and protection of the environment and without investing in greening the sector, ecosystems and thousands of magnificent species will suffer, [5] among other impacts, especially on islands.

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 or small Island States. These micro-grids, combined with the Information and Communication Technologies (ICT), have activated the distributed renewable energy economy [1].

In this paper a review of several proposals for the application of Renewable Energy Technologies (RETs) on islands and the integration into their electrical grids is presented. Part two 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. Part three presents a study case: the integration of some RETs into the electric grid in Cozumel Island, illustrating the feasibility of the application of these technologies compared with the actual fossil fuel energy technology. Results of the study case indicate that, even without electricity storage (the possible cost/price reductions or pros and cons of integrating the electricity storage to this proposal, will be part of a future research), Mexico's government can meet its targets in the electric sector within a feasible financial proposal. Part four shows a brief description of the barriers and uncertainties found in the study case. Part five shows the conclusions of this work.

2. Renewable energy sources in Islands

RE's 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 [6]. 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 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 km² [7]. The 11% of the global population lives on islands. Approximately 2,000 islands have a between 1,000 and 100,000 inhabitants [8]. 77 islands from 45 countries are analysed 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.

There are extensive combinations in the application of RETs on islands within the literature reviewed (Figure 1). RETs included (not limited): 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 (H₂) 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. 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.

Figure 1. Combination of RET, RES and SGT, and their application on islands.

2.1. 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 [9]. For the islands in [9] [10] [11] [12], 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 [13].

2.2. Hydro

Hydropower 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 [14]. For example, the Caribbean area [12] 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% [15]. 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 [16].

2.3. 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 [17]. Papua New Guinea accounts with 6 MWe installed [15], Greece has 5.4 MWe [18] and Pantelleria, Italia, has an install capacity of 2.5 MWe (46% of Island consumption) [19].

2.4. Biomass

Every matter from biological source, except those stored in geological formations like fossil fuels, is known as biomass [20]. 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 [14]. 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 sugarcane bagasse, providing the 4.5% of the Island energy [21]. In the Island of Crete, there is a 166 kW biogas plant combined with another RETs. In Cape the biomass is used for heating [9]. 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 unviable [22]. 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 [23].

2.4.1. 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 [14]. 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 [18]. 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 [22]. 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 [24].

2.4.2. Biogas

Generally biogas is a biofuel in a gas state obtained from biomass, through a biological way by anaerobic digestion or fermentation of its organic matter [25]. In some cases, biogas is part of hybrid systems, indicated in section 2.8. In Samsø, Denmark, biogas from MWS is enough to supply the 100% of the primary energy needed on the Island [26]. In Canada, in Prince Edward Island, biogas is used for electricity generation with an operation cost of US\$ 0.02 per kWh. Production is 116,565 kWh per year, with a 14.4 kW equipment capacity [27].

2.5. 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 [28]. The main application of this technology is described below. Generally it is used in combination with another RETs (section 2.8, hybrid systems).

2.5.1. 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 [29]. 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 [30]. The rest of PV systems used on islands can be found in section 2.8.

2.5.2. Thermal

In the Caribbean, the Solar Water Heating (SWH) technology is used mainly for water heating and in the air conditioning of buildings [15]. There are 3.7 m² of solar thermal panel per capita installed in Ærø Island, Denmark, covering 26,800 m² in three districts, serving 2,070 households [9]. 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 m² 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 [26]. In the Aran Islands, Ireland, the solar thermal energy replaced the fossil fuel for heating [31]. The Penghu Island, Taiwan, had a total of 1,000 houses and an area of 6,400 m² 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 [32]. In 2009, 102,666 SWH systems (300 L equivalent) operated in Reunion Island, France. The total area of solar collectors installed reached 410,664 m² to produce 154 GWh. Household SWH systems could save 1,167.7 GWh of electricity per year. For commercial and institutional buildings 22,796 m² have been installed, saving 13.7 GWh [33]. In Pulau Ubin Island, the thermal equipment used together with the 25 kW Solar Stirling Dish (SSD) equipment gave as result that the second scenario will be the most viable long term [34].

2.6. 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 [6]. The most used of this RESs is in combination with another RETs in the literature reviewed, as the following sub-sections show.

2.6.1. Tidal combined with wave and solar

In Peng Chau Island a tidal energy generation was proposed, according with [22]. In wave energy generation capacity 200 buoys of 40 kW each were 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.

2.6.2. 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 [35]. Wave energy in Aran Islands has a potential of 192 GWh/y with 22 MW installed [31]. 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 [36].

2.6.3. 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 [33].

2.7. 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 [29].

2.7.1. 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 [37]. The International Renewable Energy Agency (IRENA) [38] 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. [39] 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.

2.7.2. Flywheel, Electrical Vehicles (EV's) 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 [16]. In Aran Islands [31] EV was included for storage and control energy.

2.7.3. Electrolyser, H₂ and Fuel Cell and RETs

Generally when a H₂ production from an electrolyser 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 H₂ is produced by RE sources. A pilot plant in Porto Santo Island, Azores, has a 75 kW electrolyser unit, 300 kWh of H₂ storage, 25 kW FC and 1.1 MW of wind farm [9]. Figure 2, refers to Porto Santo, 100% renewable with 25 MW of wind turbines and nearly 20 MWp of solar PV installed. An electrolyser unit of 11 MW doubles the peak and a FC covers the peak of 5.5 MW [40]. 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 H₂. Malta has a fossil fuel, RE and hydrogen storage scenario for the transportation sector. This H₂ 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 H₂ 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 electrolyser unit, three H₂ storage tanks of 1,000 m³ of capacity and five H₂ thermal generators for a total of 250 kW [38]. The use of a hybrid system like Solid Oxide Fuel Cell (SOFC)/H₂/Trigeneration proposed [34] for Palau Ubin Island in Singapore, with a SOFC (200-350 kW) fed with H₂ from an electrolyser 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 H₂ storage [41]. In Saint Vicente, Cape, the obtaining of a RE integration was simulated with H₂ 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 [42].

Figure 2. The H2RES model version 2.8 used for Porto Santo, Mljet, Terceira, Malta and Ramea Islands [40] (adapted).

2.8. 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 3). 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.

Figure 3. Energy power flow diagram based in a RE integration on an hybrid system [8] (adapted).

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 [39]. 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 [9]. In the Caribbean, an hybrid system was proposed (Figure 4) taking into account the diesel Price in 0.6 €/l with an annual increase of 3%, a machine efficiency 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 [43].

Figure 4. Basic scheme of an hybrid system for the Caribbean zone [43] (adapted).

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 [44]. 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 5) [45]. 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 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 [24]. Rhodes Island, Greece [46], considered WP-PSSs (wind powered pumped storage systems) including diesel contribution. Pulau Ubin Island, Singapore, integrated micro turbines (MT) for a trigeneration system, single effect absorption chiller (Abs), Biomass cogeneration plant (BCP), PV, SSD, SOFC, Mechanical Chiller (MC), Auxiliary boiler (aux), using a TRNSYS 17 simulation tool (Transient System Simulation Program) [34].

Figure 5. Results of the modelling of a power supply system in Hainan Island, China [45] (adapted).

Greece has a combination of a pump storage system of 3.8 MW and 2.4 MW of wind [9]. 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 [41]. 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 [23]. In El Hierro, Spain, there is a 500,000 m³ upper water storage and a 150,000 m³ lower water storage in combination with Wind/Pump/Turbine for a total of 210 MWh with 2 pipes (Figure 6), 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 [47].

Figure 6. Hybrid system in El Hierro Island, Canary Islands, Spain [47] (adapted).

In Penghu Island, Taiwan, [32], a new methodology was developed to accomplish the government energy politics. In Salina Island, Italy, [48] 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 [39]. 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 bio-diesel, 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 [49]. Jarry et al. [39] 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 [42], 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 m³ per capita, executed with 6 inverse osmosis machines. This system has a 7,800 m³/day production fed by 8 wind turbines of 850 kW each with the construction of a 30,000 m³ desalinated water storage. There is also an analysis to storage 50,000 m³ 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 7). 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 m³/h and 230,000 m³ of storage. A desalinate equipment with a capacity of 2,000 m³/day and 5 kWh/m³ 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 [50]. Whereas in Pantelleria Island, Italy, [19] 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 m³/y (27% of the electricity required).

Figure 7. Wind potential taken and rejected in S. Vicente for the BAU scenario [42] (adapted).

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 [9]. In the Pacific area, 31% of electricity is produced through hydro [15]. Metlakaka, Alaska, has 4.9 MW of hydroelectric system capacity, combined with diesel generator (3.3 MW) and battery storage (1 MW) since 1997 [38]. Biogas from biomass and waste were taken for CHP, in Reunion Island, France, where it reached 1.95 TWh/y of cogenerated energy and 1.28 TWh/y of electricity for a total of 3.11 TWh/y of the energy obtained [33]. 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 [26]. Pulau Ubin Island, China, proposed a Combined Cooling Heating and Power (CCHP) or trigeneration, with micro turbines (MT), single effect absorption chiller (Abs) for cold and heat management, a biomass cogeneration plant (BCP), SSD and a SOFC system [34].

2.9. 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 interisland network for bulk transmission, enabling networks to share centralized renewable power generation by the interconnection between countries and/or Islands States [51]. USA [10] considered 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. The Greek Islands analysed (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 €/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 with PV [18].

2.10. 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 [29]. 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 US\$ 0.074 in 2010 to US\$ 0.051 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: $COE = TAC / E_u$, where TAC (Total Annualized Cost) and E_u (Energy, useful) [45]. 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 US\$ 1.008 kWh to US\$ 0.686 kWh [37]. 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 1. 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.

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

Table 1. COE analysis [12] [24] [37] [38] [45] [52] [53].

2.11. 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 socio-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 unfeasible [19] [22] [24] [48], 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 siting were agreed in consensus by environmental specialist, land owners and government delegates, in an illustrative form.

3. Study case: Cozumel Island, México

After reviewing RETs in Part 2, it can be concluded that not all RETs should be considered on islands, because of geographic characteristics, natural protected areas, sensitive environment, like coral reefs, cultural and historic properties, 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.

This study case is about the RETs application on Cozumel Island, an island in the Mexican Caribbean, within of the Riviera Maya, Mexico, on the occidental Caribbean Sea (Figure 8). Cozumel's coral reef is part of the second world's largest coral reef and it is aimed to attempt tourism. The Island has a 647km² surface, a population of 79,535 inhabitants [54], a density of 123 inhabitants per km². The electrical system in this exercise will be simulated "off-grid", as in case of a hurricane 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 CO₂ global emissions. So if this activity does not grow in a sustainable way, it could generate a serious environmental damage [5].

Figure 8. Cozumel Island localization.

3.1. 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 [55]. This measure is supported by UNWTO and aims to maximize the environmental profits, minimizing the environmental damages [56]. 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 [57]. 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 [58].

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 [59]. 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 3.

3.2. Renewable energy policy in 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) [60]. Because of the lack of specific objectives in Cozumel Island, Mexico's national objectives in renewable energy will be taken (Table 3) 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 [54] [57] [58] [59] [61]. Even so, we believe these data considerations do not modify the validity of the results obtained.

3.3. Cozumel Island electrical system characteristics

	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 2. Cozumel Island's electrical main features [54] [61] [62].

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 2. Figure 9 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 [62]. In figure 9, 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 [63].

Figure 9. Cozumel Island's maximum power demand [62].

Table 2 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. These values combined with the values of figure 9 helped in developing the power demand seasonal profile and the data obtained in [54] [62] [64] [65]. With these data, the hourly power demand seasonal profile was elaborated and used in the simulations of Cozumel Island's electric grid (Figures 10 and 11).

Figure 10. Cozumel Island's Power Demand Seasonal Profile in 2013 [62] [64] [54] [66].

Figure 11. Grid-off simulation without RE sources, also without communication and control systems [54] [62] [67].

3.4. Simulation of the Cozumel electrical grid

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 [67] and running the Newton Raphson algorithm, by using the Matlab® program [68] to verify the results of this flow load. Using 2013 data from Table 2 and Figure 9 (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 3 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 [66] and RETScreen® programs [69] 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 [68] 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 [70]. 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 160W 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 [71]. 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 [72]. 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 [73]. M. Reyesudin 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 [74].

3.5. Fulfilment the objectives

As it was indicated at the beginning of point 3.1, the Mexican Government needs to achieve 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) called SCENARIOS, and they have been gathered in 3 work lines (Table 3): work line 1) decrease the greenhouse gases emissions (CO₂); 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 3 indicates the main objectives in RE for Mexico’s electric system.

Work lines	SCENARIOS				
	2018	2020	2024	2035	2050
Line 1: decrease of fossil fuel percentage 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.	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.
	34.6% of electricity generation capacity with clean and renewable energy.				
Line 3: decrease of greenhouse emission (CO₂).		30% decrease of greenhouse emission respect to 2000.			50% decrease of greenhouse emission respect to 2000.

Table 3. Summary of the achievement of the objectives in three working lines. Five different scenarios for electricity generation with RE, fossil fuels participation and decrease of greenhouse emissions in Mexico [57] [58] [59] [64] [75] [76] [77] [78] [79] [80].

3.6. Implementation of RETs and RESs in Cozumel Island

Considering the targets in Table 3 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 [65]. 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 edited by the Secretary of Energy [81] indicates a national increase 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 [62], it can be determined the goals in Table 3 will be achieved if the data in Table 4 (specific objectives for Cozumel Island) is accomplished. Table 4 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 4.

Scenarios:	2018	2020	2024	2035	2050
<i>Electricity to be consumed in Cozumel (GWh):</i>	312	341	408	668	1305
<i>Maximum power demand (MW):</i>	53	57	69	112	220
Fulfilment objectives:					
<i>Max. fossil fuel electricity generation (MW):</i>			45	67	110
<i>RE electricity to be generated (GWh):</i>	78	120	143	267	653
<i>RE generation capacity to be installed (MW):</i>	24	24	24	45	110
<i>Pollutant emissions (CO₂) compared to 2000:</i>		-30%			-50%

Table 4. Objectives to be fulfilled in CO₂ emissions, power capacity, electricity generation and RE required for Cozumel Island. Using a growing factor of 6.19% in electricity consumption and a 4.57% increase factor in power demand [62] [65].

The results obtained by HOMER® [66] and RETScreen® programs [69] show details about generation capacity, electricity generated, COE, technology cost and return period. These results cover the data Table 4 indicates. All the outcomes in these five scenarios are shown in Table 5. The cost of the kWh paid by the government used in the financial part was the CTCP (Marginal Cost) for the year of 2013. The costs of the renewable technologies were considered with the same year prices [62] [82] [83]. If it uses the 2014 CTCP prices, the results indicated in Table 5 will reduce considerably, because in 2013 the average of CTCP price was 112.27 \$US/MWh, and dropped to 75.84 \$US/MWh in 2014. So far this year, the CTCP price was 45.60 \$US/MWh (Jan-Mar 2015). Knowing the cost varies according to the specific area of generation and to the oil price, these prices will change during the year. The electricity generation that supplies electricity to the Cozumel node comes from the Southwest Division and the Peninsular Division, where the base of the electricity generation depends mainly on hydroelectric power systems.

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 [62] [84] [85]. The RETScreen® program was used to calculate the amount of electricity 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 10) 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 COE 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 [62]. Table 5 indicates the COE 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.

	<i>Power demand (MW)</i>	<i>Capacity installed (MW)</i>	<i>Energy generated (GWh)</i>	<i>Total project cost (M\$US)</i>	<i>COE (\$US/kWh)</i>	<i>Return period (Years)</i>	<i>Capital repayment time (Years)</i>	<i>Cost-benefit relation</i>
2018 Scenario								
<i>Wind</i>	30.0	30.0	57.3					
<i>Photovoltaic</i>	2.6	2.6	22.6	255.7	0.37	3.6	2.5	3.3
<i>Diesel</i>	27.8	63.0	234.7					
2020 Scenario								
<i>Wind</i>	30.0	30.0	57.3					
<i>Photovoltaic</i>	17.4	17.4	152.1	284.6	0.32	2.6	1.3	6.4
<i>Diesel</i>	28.3	67.0	134.7					
2024 Scenario								
<i>Wind</i>	30.0	30.0	57.3					
<i>Photovoltaic</i>	25.1	25.1	220.3	315.6	0.32	2.2	1.1	8.0
<i>Diesel</i>	34.3	79.0	134.1					

2035 Scenario								
Wind	30.0	30.0	57.3					
Photovoltaic	54.9	54.9	480.7	438.0	0.33	1.6	0.7	11.9
Diesel	57.5	130.0	134.9					
2050 Scenario								
Wind	60.0	60.0	114.7					
Photovoltaic	125.3	125.3	1,085.5	941.9	0.24	1.6	0.7	12.1
Diesel	108.9	260.0	115.5					

Table 5. Project cost, amount of RE to install, COE and electricity generation results [62] [65] [66] [69] [83].

Note: Conditions for financial and energetic calculation of Table 5 include:

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 [84].
4. The technology cost was taken from CFE [62], Energy Regulatory Commission (CRE, for its Spanish acronym) [82] and IEA [83].
5. This exercise was based as an off-grid system.
6. Emission factor was obtained from Programa GEI Mexico [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 [62]. 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.

3.7. CO₂ emission

One of the government aims is to reduce the amount of CO₂ emissions by electricity generation for future years compared with the year 2000. The value in the year 2000 for CO₂ emissions by electricity generation of 165,638 MWh in Cozumel Island [65] were 100,095 tCO₂eq. This result was reached using an emission factor of 0.6043 tCO₂eq/MWh for the 2000 year. In 2013 this emission factor dropped to 0.4999 (-17.28% compared to 2000) [86]. For the years 2018, 2020, 2024, 2035 and 2050 a 0.525 emission factor was used [86]. The emission reduction due to the integration of RETs is indicated in Table 6. 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 CO₂ through the electricity generated only with diesel generators based on a current emission factor.

Year	Electricity generated with diesel (GWh)	Total pollutant emissions of CO ₂ (kton)	Pollutant emissions compared to year 2000	Emission decrease of CO ₂ by RE integration (kton)	New pollutant emissions of CO ₂ (kton)	New pollutant emissions compared to yr 2000
2000	166	100	0.00%			
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	1305	685	585%	636	48.94	-51%

Table 6. Reducing CO₂ emissions compared to year 2000 (ktCO₂eq.) through the RETs integration in Cozumel Island [62] [65] [86].

4. 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.

4.1. 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.

4.2. 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.

4.3. 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.

5. 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 shows how feasible is RE integration into the electric grid, in both economic and environmental terms in Cozumel Island. The decrease of COE 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.

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6. References.

- [1] for the 21st Century RREP. Renewables 2014, Global Status Report 2014.
- [2] Carpio MM. PRINCIPALES CONCLUSIONES DEL WORLD ENERGY OUTLOOK 2014 2015.
- [3] for All (SE4A) SE. Sustainable Energy for All (SE4A). 2011.
- [4] for Sustainable Energy for All (UN) HLG. Sustainable Energy for All: a World Action Program 2012.
- [5] Efficiency R. Harnessing the Power of One Billion Tourists for a Sustainable Future Resource Efficiency , Conservation , and New Technologies the Focus of New International Partnership on Sustainable Tourism 2014;33:74–6.
- [6] Estrada C, Samperio JI. Energías Alternas : Propuesta de Investigación y Desarrollo 2010:152.
- [7] Blechinger P, Howe E, Cader C, Plessmann G, Hlusiak M, Seguin R, et al. Energy Storage Systems for Renewable Islands Systems - An Enormous Global Market Potential. Proc 7th IRES 2012:1–7.
- [8] Blechinger P. Mini-Grids for Off-Grid Energy Supply – Global Potential for Rural Electrification and Islands 2013.
- [9] Chen F, Duic N, Manuel Alves L, da Graça Carvalho M. Renewislands-Renewable energy solutions for islands. Renew Sustain Energy Rev 2007;11:1888–902. doi:10.1016/j.rser.2005.12.009.
- [10] Corbus D. Inter-island Power Transmission Energy Workshop Overview • Hawaii Study • Submarine Power Transmission • Caribbean Study 2011.

- [11] Bahadoorsingh S, Ramdathsingh R, Sharma C, Member S. Integrating Wind Energy in a Caribbean Island : A Case Study of Anguilla 2012:1–8.
- [12] Shirley R, Kammen D. Renewable energy sector development in the Caribbean: Current trends and lessons from history. *Energy Policy* 2013;57:244–52. doi:10.1016/j.enpol.2013.01.049.
- [13] Island B, Farm W. Environmental Report / Construction and Operations Plan 2012.
- [14] Ghosh TK, Prelas M a. *Energy Resources and Systems volume 2: Renewable Resources*. 2009. doi:10.1007/978-94-007-1402-1.
- [15] Mitra I. A renewable island life. Electricity from renewables on small islands. *Refocus* 2006;7:38–41. doi:10.1016/S1471-0846(06)70658-8.
- [16] Pina A, Ioakimidis CS, Ferrão P. Introduction of electric vehicles in an island as a driver to increase renewable energy penetration. 2008 IEEE Int Conf Sustain Energy Technol ICSET 2008 2008:1108–13. doi:10.1109/ICSET.2008.4747172.
- [17] Orecchibi F, Naso V. *Green Energy and Technology*. London, UK: Springer-Verlag; 2012. doi:10.1007/978-0-85729-244-5.
- [18] Xydis G. Comparison study between a Renewable Energy Supply System and a supergrid for achieving 100% from renewable energy sources in Islands. *Int J Electr Power Energy Syst* 2013;46:198–210. doi:10.1016/j.ijepes.2012.10.046.
- [19] Riva Sanseverino E, Riva Sanseverino R, Favuzza S, Vaccaro V. Near zero energy islands in the Mediterranean: Supporting policies and local obstacles. *Energy Policy* 2014;66:592–602. doi:10.1016/j.enpol.2013.11.007.
- [20] Idae. *Energía de la biomasa*. 2007.
- [21] Corbus D, Kuss M, Piwko D, Hinkle G, Matsuura M, McNeff M, et al. All Options on the Table. *IEEE Power Energy Mag* 2013;65–74.
- [22] Baği B. Towards a Zero Energy Island. *Renew Energy* 2009;34:784–9. doi:10.1016/j.renene.2008.04.027.
- [23] Ciapessoni E, Cirio D, Gatti a, Pitto a. Renewable power integration in Sicily : frequency stability issues and possible countermeasures Power system model 2013.
- [24] Liu HY, Wu S De. An assessment on the planning and construction of an island renewable energy system - A case study of Kinmen Island. *Renew Energy* 2010;35:2723–31. doi:10.1016/j.renene.2010.04.021.
- [25] Ramirez de la Piscina P, Chimenos Ribera JM. Biogas, biodiesel i bioetanol 2012.
- [26] Colmenar-Santos A, Monzón-Alejandro O, Borge-Diez D, Castro-Gil M. The impact of different grid regulatory scenarios on the development of renewable energy on islands: A comparative study and improvement proposals. *Renew Energy* 2013;60:302–12. doi:10.1016/j.renene.2013.05.032.
- [27] Houston C, Gyamfi S, Whale J. Evaluation of energy efficiency and renewable energy generation opportunities for small scale dairy farms: A case study in Prince Edward Island, Canada. *Renew Energy* 2014;67:20–9. doi:10.1016/j.renene.2013.11.040.
- [28] Abdreu Batallé J. *Solar Energy Conversion* 2012:1–17.
- [29] Michaelides EE (Stathis). *Green Energy and Technology (Alternative Energy Sources)*. Heidelberg: Springer-Verlag Heidelberg; 2012. doi:1.1007/978-3-642-20951-2.
- [30] Aghaei M, Hanum Y, Imamzai M, Piy P, Amin N, Arabia S. Design of a Co ost-Efficient Solar Ener rgy Based Electrical Power r Generation System fo or a Remote Island - Pulau u Perhentian Besar in Malaysia M 2013:203–8. doi:10.1109/PEOCO.2013.6564543.
- [31] Denny E, Keane A. A smart integrated network for an offshore Island. *Proc IEEE* 2013;101:942–55. doi:10.1109/JPROC.2012.2226131.
- [32] Trappey AJC, Trappey C V., Lin GYP, Chang YS. The analysis of renewable energy policies for the Taiwan Penghu island administrative region. *Renew Sustain Energy Rev* 2012;16:958–65. doi:10.1016/j.rser.2011.09.016.
- [33] Praene JP, David M, Sinama F, Morau D, Marc O. Renewable energy: Progressing towards a net zero energy island, the case of Reunion Island. *Renew Sustain Energy Rev* 2012;16:426–42. doi:10.1016/j.rser.2011.08.007.
- [34] Chua KJ, Yang WM, Er SS, Ho C a. Sustainable energy systems for a remote island community. *Appl Energy* 2014;113:1752–63. doi:10.1016/j.apenergy.2013.09.030.
- [35] Veigas M, Iglesias G. Potentials of a hybrid offshore farm for the island of Fuerteventura. *Energy Convers Manag* 2014;86:300–8. doi:10.1016/j.enconman.2014.05.032.
- [36] Schallenberg-Rodríguez J, Notario-del Pino J. Evaluation of on-shore wind techno-economical potential in regions and islands. *Appl Energy* 2014;124:117–29. doi:10.1016/j.apenergy.2014.02.050.
- [37] Anwari M, Rashid MIM, Muhyiddin HTM, Ali a. RM. An evaluation of hybrid wind/diesel energy potential in Pemanggil Island Malaysia. 2012 Int Conf Power Eng Renew Energy, ICPERE 2012 2012. doi:10.1109/ICPERE.2012.6287244.
- [38] Komor P, Glassmaire J. Electricity Storage and Renewables for Island Power 2012:48.
- [39] Jarry G, France CRE, Maire J, France EDFSEI, Strang KA, Barlier Y, et al. 22 nd International Conference on Electricity Distribution HOW TO DEVELOP ADDITIONAL RENEWABLE ENERGY IN ISLAND AREAS ? 22 nd International Conference on Electricity Distribution 2013:10–3.
- [40] Architecture FOME and N (University of Z. H2RES 2009. <http://h2res.fsb.hr> (accessed July 23, 2014).
- [41] Duić N, Krajačić G, da Graça Carvalho M. RenewIslands methodology for sustainable energy and resource planning for islands. *Renew Sustain Energy Rev* 2008;12:1032–62. doi:10.1016/j.rser.2006.10.015.
- [42] Segurado R, Krajačić G, Duić N, Alves L. Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde. *Appl Energy* 2011;88:466–72. doi:10.1016/j.apenergy.2010.07.005.
- [43] Blechinger P, Seguin R, Cader C, Bertheau P, Breyer C. Assessment of the global potential for renewable energy storage systems on small islands. *Energy Procedia* 2014;46:294–300. doi:10.1016/j.egypro.2014.01.185.
- [44] Mahmud N, Hassan A, Rahman MS. Modelling and cost analysis of hybrid energy system for St. Martin Island using HOMER. 2013 Int Conf Informatics, Electron Vision, ICIEV 2013 2013. doi:10.1109/ICIEV.2013.6572678.
- [45] Ye B, Tang J, Liji, Huang J, Lv X. Feasibility study of renewable energy powered Island-Hainan. *Proc - 2012 Int Conf Comput Distrib Control Intell Environ Monit CDCIEM* 2012 2012:330–3. doi:10.1109/CDCIEM.2012.85.
- [46] Katsaprakakis D Al, Christakis DG. Seawater pumped storage systems and offshore wind parks in islands with low onshore wind potential. A fundamental case study. *Energy* 2014;66:470–86. doi:10.1016/j.energy.2014.01.021.
- [47] Pezie M, Cedres VM. Unit commitment in fully renewable, hydro-wind energy systems. *Int Conf Eur Energy Mark EEM* 2013:1–8. doi:10.1109/EEM.2013.6607331.
- [48] Andaloro APF, Salomone R, Andaloro L, Briguglio N, Sparacia S. Alternative energy scenarios for small islands: A case study from Salina Island (Aeolian Islands, Southern Italy). *Renew Energy* 2012;47:135–46. doi:10.1016/j.renene.2012.04.021.
- [49] Roose L, Piwko R. *Catching Some Rays* 2013:33–44.
- [50] Patlitzianas KD, Christos K. Effective financing for provision of renewable electricity and water supply on islands. *Energy Sustain Dev* 2012;16:120–4. doi:10.1016/j.esd.2011.11.003.
- [51] Paolone PDPM. Editorial, Sustainable Energy, Grids and Networks Journal. *Sustain Energy, Grids Networks* 2015.
- [52] Centeno Brito M, Lobato K, Nunes P, Serra F. Sustainable energy systems in an imaginary island. *Renew Sustain Energy Rev* 2014;37:229–42.

- doi:10.1016/j.rser.2014.05.008.
- [53] Blechinger P. Global PV market potential for small island energy systems 2015.
- [54] INEGI. INEGI 2010. http://www.inegi.org.mx/lib/olap/consulta/general_ver4/MDXQueryDatos.asp?#Regreso&c=27770 (accessed January 14, 2015).
- [55] Sectur. Programa de Turismo Sustentable en México. Planeación Estratégica Del Tur En México 2013.
- [56] Sectur. Lineamientos para el Aprovechamiento Sustentable de los Recursos Naturales y Culturales del País 2012.
- [57] Energía S De. Prospectiva del Sector Eléctrico 2013-2027. Mexico City, Mexico: 2013.
- [58] Energía S De. Prospectiva del Sector Eléctrico 2014-2028. Mexico City, Mexico: 2014.
- [59] Energía S De. Programa Especial para el Aprovechamiento de Energías Renovables (PEAER). México, D.F.: 2013.
- [60] Plan Municipal de Desarrollo 2013 – 2016 del Municipio de Cozumel. Cozumel, Q. Roo: 2013.
- [61] Quintana Roo State G. e-local Gobierno de Q. Roo 2015. <http://www.e-local.gob.mx/work/templates/enciclo/EMM23quintanaroo/municipios/23001a.html> (accessed January 14, 2015).
- [62] Electricity) CF de E (Federal C of. Economic Dispatch (Despacho económico) 2015. <http://app.cfe.gob.mx/Aplicaciones/OTROS/costostotales/SolicitudDeInformacion.aspx> (accessed January 13, 2015).
- [63] Secretaría de Turismo del Estado de Quintana Roo. Indicadores Turísticos QROO 2012. 2013.
- [64] Energía S De. Prospectiva de Energías Renovables (PER) 2014 - 2028.pdf. Mexico City, Mexico: 2014.
- [65] INEGI. BIINEGI 2015. <http://www3.inegi.org.mx/sistemas/descarga> (accessed February 9, 2015).
- [66] Energy LLC H. HOMER PRO 2015.
- [67] Gmb H Di. DIgSILENT Power Factory 2013.
- [68] MathWorks. MATLAB 2014.
- [69] Canada NR. RETScreen 1997.
- [70] Dornan M, Jotzo F. Renewable technologies and risk mitigation in small island developing states: Fiji's electricity sector. *Renew Sustain Energy Rev* 2015;48:35–48. doi:10.1016/j.rser.2015.03.059.
- [71] Shivarama Krishna K, Sathish Kumar K. A review on hybrid renewable energy systems. *Renew Sustain Energy Rev* 2015;52:907–16. doi:10.1016/j.rser.2015.07.187.
- [72] Khare V, Nema S, Baredar P. Solar-wind hybrid renewable energy system: A review. *Renew Sustain Energy Rev* 2016;58:23–33. doi:10.1016/j.rser.2015.12.223.
- [73] Khare R, Kumar Y. A novel hybrid MOL–TLBO optimized techno-economic-socio analysis of renewable energy mix in island mode. *Appl Soft Comput* 2016;43:187–98. doi:10.1016/j.asoc.2016.02.044.
- [74] Basir Khan MR, Jidin R, Pasupuleti J. Data from renewable energy assessments for resort islands in the South China Sea. *Data Br* 2016;6:117–20. doi:10.1016/j.dib.2015.11.043.
- [75] Secretaría de Energía (SENER). Prospectiva de Energías Renovables 2013-2027. Mexico City, Mexico: 2013.
- [76] Energía S De. Estrategia Nacional de Transición Energética y Aprovechamiento Sustentable de la Energía (ENTEASE) 2014. Mexico City, Mexico: 2014.
- [77] Energía S De. Programa Sectorial de Energía (PSE) 2013-2018. Mexico City, Mexico: 2013.
- [78] República P de la. Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética (LAFATERTE). *Congr La Union* 2013:1–16. www.dof.gob.mx (accessed January 20, 2015).
- [79] Sener. Estrategia Nacional de Energía 2013-2027 2013:73.
- [80] Semarnat. Estrategia Nacional de Cambio Climático 2013:60. doi:10.4206/agrosur.1974.v2n2-09.
- [81] Secretaría de Energía (SENER). Balance Nacional de Energía (BNE) 2014. Mexico City, Mexico: 2014.
- [82] Energía (CRE) CR de. TABLA DE PERMISOS DE GENERACIÓN E IMPORTACIÓN DE ENERGÍA ELÉCTRICA ADMINISTRADOS AL 31 DE MAYO DE 2014 2014. www.cre.gob.mx.
- [83] International Energy Agency. Technology roadmap - Wind energy 2013:58.
- [84] Gobernación S de. Indicadores. D Of La Fed 2014. http://www.dof.gob.mx/indicadores_detalle.php?cod_tipo_indicador=158&dfecha=01%2F01%2F2013&hfecha=31%2F12%2F2013# (accessed February 17, 2015).
- [85] Gobernación S de. Indicadores. D Of La Fed 2015. http://dof.gob.mx/indicadores_detalle.php?cod_tipo_indicador=158&dfecha=01%2F01%2F2014&hfecha=31%2F12%2F2014 (accessed February 17, 2015).
- [86] ecretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), Comisión de Estudios del Sector Privado para el Desarrollo Sustentable (CESPEDES), Consejo Coordinador Empresarial (CCE) I de RM (World RI-W y W. Factor de Emisión Eléctrico 2013 (Programa GEI México) 2013. <http://www.geimexico.org/factor.html> (accessed February 24, 2015).

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