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Philipp Blechinger

Barriers and solutions to implementing renewable energies on Caribbean islands in respect of technical, economic, political, and social conditions

Barriers and solutions to implementing renewable energies on Caribbean islands in respect of technical, economic, political, and social conditions

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Zusammenfassung

Die Stromversorgung auf karibischen Inseln wird derzeit zu 99 % durch fossile Brennstoffe bereitgestellt. Dies führt zu sehr hohen Kosten und CO_2-Emissionen. Eine günstige und nachhaltige Lösung kann die Nutzung regenerativer Technologien wie Solar-, Wind-, Wasser-, und Geothermiekraftwerke sein. Deren Implementierung geht allerdings, trotz ausreichender natürlicher Ressourcen, nur sehr langsam voran. Dieser Widerspruch stellt die Motivation für die Hauptforschungsfragen dieser Dissertation dar: (1) Wie hoch ist das technisch-wirtschaftliche Potenzial von erneuerbaren Energien auf karibischen Inseln und (2) welche Hemmnisse und Lösungen existieren zur Nutzung dieses Potenzials?

Um die erste Frage zu beantworten wurde ein Simulationsmodell entwickelt, welches sowohl erneuerbare als auch Dieselkraftwerke und Batteriespeicher abbildet. Mit diesem Tool können bestehende Inselenergiesysteme simuliert und erneuerbare und Speicherkapazitäten optimiert werden. Per GIS-Analyse wurden die karibischen Inseln mit mehr als 1.000 Einwohnern ausgewählt und für jede dieser 62 Inseln wurden die erneuerbaren Ressourcen, die Lastkurve und weitere Inputdaten wie zum Beispiel Technologiekosten bestimmt. Hieraus wurde das technisch-wirtschaftliche Potenzial für die Hybridisierung jedes Inselenergiesystems errechnet, welches für 60 der 62 Inseln hoch bis sehr hoch ist. Im kostenoptimalen Fall kann der Anteil erneuerbarer Energien von 1 % auf 45 % gesteigert werden bei gleichzeitiger Senkung der Stromgestehungskosten um 27 % von 0,30 USD/kWh auf 0,22 USD/kWh und der CO_2-Emissionen um 22 Mio. Tonnen pro Jahr. Investitionen in Höhe von 35 Mrd. USD sind notwendig um die folgenden optimierten erneuerbaren Kapazitäten auf den untersuchten Inseln zu erreichen: 760 MW Wasser-, 8.880 MW Solar-, 6.300 MW Wind- und 530 MW Geothermiekraftwerke plus 3.120 MWh Batteriespeicher.

Zur Beantwortung der zweiten Frage wurden empirische Analysen genutzt. In einem ersten Schritt wurden durch Literaturanalysen und qualitative Experteninterviews 31 bedeutende Hemmnisse für den Ausbau erneuerbarer Energien auf karibischen Inseln identifiziert, die in einer quantitativen Expertenbefragung nach ihrer Wichtigkeit eingestuft wurden. In dem daraus entstandenen Ranking zeigt sich, dass sich drei bestimmende Themen-Cluster ergeben. Das erste sind regulatorische und politische Rahmenbedingungen, wie zum Beispiel *fehlende regulatorische Rahmenbedingungen und Gesetze für Investoren* und *Lücken zwischen politischen Zielen und Umsetzung*. Das zweite sind Kosten und Finanzierungsmöglichkeiten, in welchem *hohe Investitionskosten* als wichtigste Barriere genannt werden und das dritte ist die Marktmacht der konventionellen Energieversorger. Als Lösungen für diese Hemmnisse werden Maßnahmen für Energieversorger, unabhängige Erzeuger und Privatpersonen vorgeschlagen. Die wichtigsten sind Verbesserungen der Regularien und des Marktzugangs, Investionsanreize wie zum Beispiel eine "Renewable Fuel Surcharge" und Finanzierungsinstrumente lokaler und internationaler Banken.

Mit den erarbeiteten Handlungsempfehlungen kann der volkswirtschaftlich und ökologisch sinnvolle Ausbau der Stromversorgung aus erneuerbaren Energien auf karibischen Inseln beschleunigt werden um die aufgezeigten Potenziale zu nutzen.

Abstract

Ninety-nine percent of the electricity supply on Caribbean islands is currently provided by fossil fuel based power plants which is very expensive and produces CO_2 emissions. The use of renewable energy technologies such as PV, wind, hydro, and geothermal power plants can be a cost-effective and sustainable solution to these problems. Implementing renewable energies has been rather slow despite sufficient natural resources. This has guided the two main research questions of this PhD thesis: (1) What is the techno-economic potential for renewable energies on Caribbean islands and (2) which barriers and solutions exist in the utilization of this potential?

An answer to the first research question was found using a technical analysis based on a self-developed island energy supply model. This model includes diesel and renewable power plants as well as battery storage systems and their respective power flows and costs. It is possible with the help of this tool to simulate the existing energy supply systems, the current status quo, and to optimize the renewable and battery capacities according to techno-economic factors. For this thesis Caribbean islands with more than 1,000 inhabitants were chosen by GIS analysis. The simulation of all 62 islands required assessing the renewable resources, specific load profiles, and other important input parameters. According to the simulations and optimizations 60 of the 62 islands demonstrate high to very high techno-economic potential for implementing renewable energies. The optimal renewable energy share is 45 % as opposed to the current 1 %, which would result in a decrease in levelized costs of electricity from 0.30 to 0.22 USD/kWh and the added benefit of a 22 million tons per year decrease in CO_2 emissions. Initial investments of 35 billion USD are required to reach the following optimized renewable capacities on the islands analyzed: 760 MW hydro, 8,800 MW PV, 6,300 MW wind, and 530 MW geothermal power plants plus 3,120 MWh of battery storage.

Empirical analyses were conducted to answer the second research question. The first step to determine significant barriers to implementing renewable energies on Caribbean islands involved literature analyses and qualitative expert interviews. This was followed by an extensive qualitative study to evaluate the importance of each barrier. The evaluation was performed with the help of questionnaires filled out by experts of renewable energies. According to the results the most important barriers are distributed among three main clusters. The first cluster is regulatory frameworks and policies, for example *lack of regulatory framework and legislation for private investors* and *gap between policy targets and implementation*. The second is costs and financing, of which *high initial investments* is the most important barrier. The last cluster is the clout of conventional power suppliers. Specific practical recommendations are outlined for overcoming these barriers that utilities, private investors, and private persons face. Most important are improvements to the regulatory frameworks and market access, incentives such as a "renewable fuel surcharge", and financing by local or international banks.

Following these recommendations will help to utilize the existing techno-economic potential for establishing highly cost-effective and sustainable energy supply systems on Caribbean islands.

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Chapter 1

Introduction

1.1 Motivation and research objective

Climate change and the finite nature of fossil resources are two of the main challenges for mankind in the 21st century [1, 2]. Climate change and global warming lead to a large number of weather extremes and catastrophes as well as harvest failures and rising sea levels causing enormous damages. In addition to that the shrinking availability of fossil energy resources causes environmental pollution by more dangerous exploitation methods and the overall price increases due to growing exploitation costs and risks [3]. Both challenges put economic pressure on the conventional power generation sector using coal, gas, and oil as fuels. The world's power generation in 2011 showed 9,000 TWh for coal, 5,000 TWh for gas, and 1,000 TWh for oil-fired power plants [4]. Currently, approximately one quarter of the global anthropogenic CO_2 emissions are emitted by these plants. In summary, the economic pressure on the conventional power generation sector is based on increasing fuel and exploitation costs and on political restrictions to reduce CO_2 emissions [5].

Renewable energy technologies can provide solutions for clean and stable in price energy supply [6]. Many different renewable resources exist such as solar, wind, hydro, geothermal, and bio energy [7]. All of them are CO_2 emission free in their operation and use no fossil fuels for power generation. Most of them are mature technologies, whose basic principles have been used since centuries such as wind and hydro power for milling. In addition, global trends show constantly decreasing costs for the implementation of these technologies which pushes their economic attractiveness as shown in the renewable energy technologies cost analysis series by IRENA [8–10]. The substitution of fossil based power generation by these resources is disputed among technological, economic, political, and social considerations and interests often described as barriers of implementation. According to the specific conditions these barriers differ from country to country and region to region as analyzed by Blechinger [11], which makes it difficult to derive global solutions.

Thus, the focus on the Caribbean region, more specific the Caribbean island states and countries, is set for this thesis to analyze these interactions and the implementation of renewable energy technologies more deeply. The reduced size of Caribbean closed island energy supply systems allows a detailed modeling of these systems without too many simplifications. The results can help to extrapolate valuable experiences to large scale systems [12, 13]. In general these islands are politically and economically stable countries which should possess the knowledge and economic capacity to transform the energy sector towards high share renewable energy systems. Additionally, it is worth investigating Caribbean countries and their relation to renewable energies as they already feel the ecological threats of climate change due to increased weather extremes such as floodings or hurricanes. As a consequence, a need exists to reduce CO_2 emissions from an environmental perspective. On the other hand the Caribbean power generation sector is mainly based on oil and diesel fired plants causing enormous fuel costs and locally and globally harmful emissions [14]. 22 GW of fossil based power plant capacities are operating on Caribbean island states which spend approximately four percent of their gross domestic product on imported fuels for power generation. The transition of the Caribbean power generation sector towards renewable energies would therefore release the economic pressure of burning imported fossil fuels and set a global example for potential low emission power generation by renewable energies [15].

Despite abundant renewable resources on Caribbean islands the beneficial implementation of renewable capacities for electricity supply is rather slow resulting from different barriers of implementation. In general, a lot of research work has been performed to understand the slow implementation of renewable power plants and four main categories of barriers are typically identified: technological, economic, political, and social barriers [16–18]. The studies by Ince [19], the ECLAC [20], and van den Akker [21] already provide a good overview on the barriers hindering the transformation of the power generation sector on Caribbean islands. For example missing role models, market distortions, and lacks of political capacities are mentioned as important barriers, but a proper ranking of barriers and a matching strategy to overcome them is lacking. In addition, the main question whether enough potential of renewable resources exist to compete with the conventional power generation technologies under the prevailing natural, technological, and economic conditions has not sufficiently been answered yet. This lack of knowledge in respect of the current techno-economic potential of renewable energies on Caribbean islands and of other additional barriers keep political, institutional, and economic decision makers from pushing renewable energies with the right measurements.

Thus, this thesis targets to identify the current status of implementation of renewable energies, in order to reveal the untapped techno-economic potential of renewable energies, and finally to evaluate barriers and to present solutions to implementing this potential. The approach follows six main research questions:

- What is the natural resource availability of renewable energies on Caribbean islands?
- How can technological solutions be applied to utilize these resources?
- To what extent can renewable energy technologies compete with the current conventional power generation system on Caribbean islands?
- Which barriers hinder the implementation of the existing techno-economic renewable energy potential?
- What are the most important barriers?
- What strategies have to be pursued to overcome these barriers?

The order of research questions allows a specification and interpretation of barriers. The main barrier to implementing renewable power plants would be the absence of sufficient natural renewable resources. Once the availability of renewable resources is analyzed the technological and economic feasibility can be tested by energy system modeling and simulations. Such energy system simulations allow realistic calculations of fossil and hybrid energy supply systems using optimization tools to derive the techno-economic potential. According to Painuly [16] "the techno-economic potential refers to the case when it is assumed that a technically feasible and economically viable technology is universally used in a competitive market and constraints such as consumer preferences, social and institutional barriers, financial barriers etc. to its usage do not exist". Assuming this techno-economic competitiveness of renewable energy power plants is proven compared to conventional power plants, additional barriers can be investigated which are not sufficiently considered in the simulations. The assessment of these barriers is based on empirical research to cover as many perspectives as possible. Finally, solutions to target the calculated potential and to overcome additional barriers can be pointed out. By these presented research steps the two main targets of this thesis can be reached: Firstly, the identification of the techno-economic potential of renewable energies on Caribbean islands and secondly the development of solutions to overcome barriers hindering its implementation.

1.2 Structure

This thesis is divided into seven main parts which are briefly described in this section. After the introduction an overview on the research object is given in Ch. 2. Within this chapter the Caribbean area and its specifics are presented followed by a demonstration of island energy supply systems. The specific characteristics and components - fossil based as well as renewable - are presented and discussed. In Ch. 3 the methodology of assessing the techno-economic renewable potential on Caribbean islands is displayed. Simulation tools to optimize island energy supply systems are compared and the self-developed simulation tool is described. This tool is specifically designed to reflect all characteristics of island energy systems in a simplified way. It uses a generic algorithm to find the techno-economic optimized configuration of each investigated island.

The results of the analysis of renewable potential on Caribbean islands are revealed in Ch. 5. First the self-developed simulation tool is tested and validated along two showcase islands. After the successful validation of this tool it is used to simulate the status quo of electricity supply on Caribbean islands which serves as baseline for further optimizations. The optimizations of the Caribbean island energy supply systems reveal the techno-economic potential. Results are shown for each island individually including parameters such as potential for additional renewable capacities, cost and fuel reductions, and overall renewable share. For certain cases sensitivity analyses are conducted and presented followed by a brief discussion of the results of the renewable potential.

Afterwards the additional barriers are specified in Ch. 6. First the empirical methodology is introduced followed by an overview on the main barriers. These barriers are evaluated with the help of a questionnaire which is presented afterwards. Results of the evaluation are shown in a ranking of the most important barriers. Based on this ranking the measurements to overcome these barriers are derived and written down in this chapter. At the end of this thesis all main findings are briefly concluded and summarized in the conclusion in Ch. 7 extended by recommendations for future research.

Chapter 2

Research object

This chapter provides an overview on the research object of this thesis: island states and autonomous and semi-autonomous states of the Caribbean. Information is given on geographic, demographic, political, and economic conditions. This is followed by an analysis of the Caribbean power generation sector and a description of island energy supply in general.

2.1 Overview Caribbean

In this thesis Caribbean islands were chosen as research object in order to analyze barriers of implementing renewable energies. As a restriction islands related to countries on the continent (e.g. Venezuelan islands) are excluded. This leads to a total research sample of 27 countries which are listed in Tab. 2.1. The high variety of island countries on a relatively small area makes this region especially attractive for this research as it provides many different case study islands for energy supply systems. The Caribbean area and the islands selected for this research are illustrated in Fig. 2.1.

The Caribbean region is defined by the Caribbean Sea. All islands within are labeled as Caribbean islands [22]. In the South its boundary is the South American continent. The Western border is defined by the Central American countries and the Gulf of Mexico, which is also part of the Northern border. This border is complemented by the U.S. state Florida and the North Atlantic Ocean which is the Eastern border as well.

The islands are mostly of volcanic origin and relatively mountainous, while only few of the islands are flat and based on coral atolls as for example Barbados. The

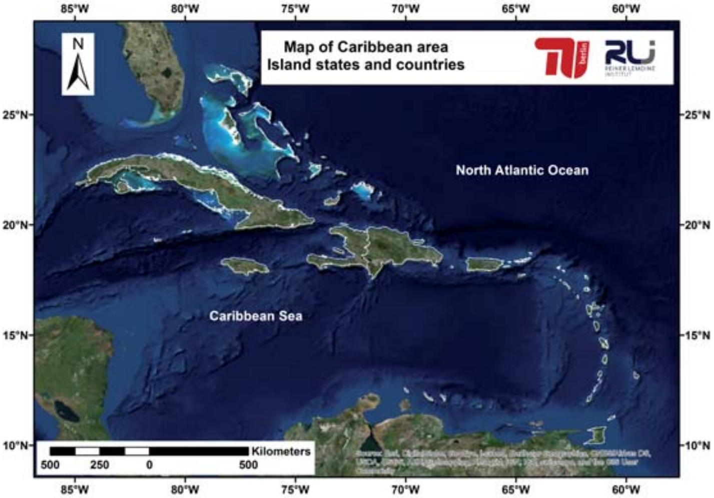


Figure 2.1: *Map of the Caribbean area - Islands related to island states and to autonomous and semi-autonomous island states are framed in white [22]*

climate is tropical and sub-tropical with average temperatures ranging from 24 to 29 degrees Celsius. Only two seasons exist in this region, a wet season from May to October and a dry season from November to April. Average annual precipitation values range from 60 cm/m^2 in the dry belt of Aruba, Bonaire, and Curacao over 150 cm/m^2 on Eastern Caribbean islands up to 500 cm/m^2 on large islands as Cuba or Hispaniola [23]. Due to the proximity to the equator sunshine hours are almost equally distributed over the year. The Eastern Caribbean islands are within the trade wind zone leading to constant high wind speeds over the year, which are more fluctuating on the other Caribbean islands. Weather extremes such as hurricanes can appear during the wet season and can cause extensive destruction such as hurricane "Ivan" in 2004 [24]. Based on the climate conditions rain forest is the typical vegetation cover, however the forest is often highly degraded due to its conversion to farmland [25,26].

The total population of the analyzed countries adds up to 41 million inhabitants with Cuba, Dominican Republic, and Haiti representing the biggest countries. Beside these three large countries many medium or small sized countries exist in the Caribbean. Especially in the Eastern Caribbean most countries have less than 100,000 inhabitants but constitute an independent entity such as for example Grenada, Saint Vincent and the Grenadines, and Dominica as it is shown in Tab. 2.1 [27]. For this region the annual population growth rate has varied between zero and one percent during the last decade and it is expected that this rise will continue in the future. A positive exception is Haiti with 2.31 percent per year and a negative exception is Puerto Rico with minus 0.92 percent per year [28].

Politically the Caribbean islands represent relatively stable states except Haiti, which is also the poorest and least developed country in the region. This is underlined by the human development index which classifies Haiti as a country of low human development (rank 161 out of 187), compared to Barbados for example which is classified as country of very high human development (rank 38) [29]. Most of them have democratically elected governments. The only exception is Cuba having a one-party communist system. Dominica is the only country that has never been ruled by another nation. All the others were colonized by Great Britain, the Netherlands, France, Spain, or the United States of America. Between 1950 and 1970 many gained independence while others remained fully (e.g. Martinique and Guadeloupe with France) or semi-dependent (e.g. Curacao with the Netherlands). The strongest interstate organization in the Caribbean area is the Caribbean Community (CARICOM). 12 of the sample countries are members of it: Antigua and

Barbuda, the Bahamas, Barbados, Dominica, Grenada, Haiti, Jamaica, Montserrat, Saint Lucia, St. Kitts and Nevis, St. Vincent and the Grenadines, and Trinidad and Tobago [30].

The main economic sectors on Caribbean islands are tourism, agriculture, light manufacturing and off-shore banking. Puerto Rico and Trinidad and Tobago have a positive trade balance while all the other islands strongly depend upon imports especially for fossil fuels from Venezuela or the United States. This is because oil and natural gas as fossil resources can only be found in some parts of the Caribbean area with Trinidad and Tobago having the biggest explorations. Main exports are based on agricultural goods [28]. The gross domestic product including informal economies is on average 9,700 USD/cap. On the top range countries such as Cayman Islands (47,000 USD/cap) and the Bahamas (32,000 USD/cap) which economies are mainly driven by the banking sector. The lowest economic activity is found on the small country Montserrat with only 650 USD/cap followed by Haiti, which still suffers under the effects of the devastating earthquake of 2010, with 1,400 USD/cap (cf. Tab. 2.1).

Looking at the energy supply infrastructure of the analyzed Caribbean countries underlines the low development of renewable energies. All countries have significant fossil power plant capacities, mainly diesel and heavy fuel oil fired. Only countries with hydro power resources possess notable shares of installed renewable energy capacities higher than 10 %. Guadeloupe has the only geothermal power plant and Aruba, Jamaica, the Dominican Republic, and Puerto Rico have the highest number of installed wind turbines. The overall operating power generation capacities of the Caribbean countries add up to 23 GW [14]. The electrification rate reaches almost 100 % on many of the islands, only Haiti with 36 % is significantly low-electrified. Other large islands such as Cuba, Dominican Republic, and Jamaica have electrification rates of around 90 % [29].

The overview on Caribbean countries is summarized in Tab. 2.1. The special characteristics of electricity supply on islands and the related technologies are explained in the next section.

Table 2.1: List of Caribbean countries including country ISO code [31], population [27], economic activity [32], power plant capacities in MW, and share of renewable energy capacities [14]

Country	**ISO code**	**Population**	**Econom. activity** [USD/cap]	**Power plants** [MW]	**RE-share** (Capac.)
Antigua and Barbuda	ATG	80,322	20,430	99	0 %
Aruba	ABW	104,642	27,026	232	13%
Bahamas	BHS	284,550	31,569	639	0 %
Barbados	BRB	273,513	21,140	262	0 %
Caribbean Netherlands	BES	12,483	22,511	18	2 %
British Virgin Islands	VGB	24,664	11,636	52	0 %
Cayman Islands	CYM	49,882	46,730	170	0 %
Cuba	CUB	11,503,135	11,165	5,358	1 %
Curacao	CUW	147,278	18,435	428	3 %
Dominica	DMA	67,629	5,763	26	28 %
Dominican Republic	DOM	9,973,154	7,020	3,876	16 %
Grenada	GRD	95,973	8,127	52	0 %
Guadeloupe	GLP	434,388	no data	614	8 %
Haiti	HTI	9,630,625	1,356	350	16 %
Jamaica	JAM	2,929,921	8,716	1,250	6 %
Martinique	MTQ	425,296	no data	501	1 %
Montserrat	MSR	4,753	652	10	2 %
Puerto Rico	PRI	3,589,226	25,787	6,082	3 %
Saint-Bartelemy	BLM	7,550	no data	21	0 %
Saint-Martin	MAF	33,430	no data	58	0 %
Saint Kitts and Nevis	KNA	45,823	10,759	55	4 %
Saint Lucia	LCA	143,632	14,419	77	0 %
Saint Vincent and the Grenadines	VCT	88,337	5,434	46	13 %
Sint Maarten	SXM	25,746	10,599	100	0 %
Trinidad and Tobago	TTO	1,213,758	24,416	1,739	0 %
Turks and Caicos Islands	TCA	32,400	4,228	63	0 %
Virgin Islands U.S.	VIR	103,648	19,364	683	0 %

2.2 Island energy supply

Island energy supply systems display typical characteristics which differ from centralized large scale systems. Due to relatively low loads and high population density large scale baseload power plants or high voltage transmission capacities are often not required for island energy supply [33]. While large centralized electricity systems typically consist of base, medium, and peak load power plants island energy systems are based on flexible medium and peak load power plants [34]. Low and fluctuating loads require these highly flexible plants, sufficient back-up capacities, and system stability services [35]. Nevertheless the system quality is often low regarding frequency and voltage control [36].

The countries chosen for this research show the typical characteristics of island energy supply systems. No baseload power plants such as coal or nuclear power plants with relatively low power generation costs are found in these countries. The load power is provided by gas and oil fired plants with high flexibility but also high fuel costs. Thus, the islands' energy supply depends on diesel or heavy fuel oil power plants using imported fuels. In addition, high voltage transmission lines are missing on Caribbean islands except for large countries such as Cuba and the Dominican Republic. It can be concluded that the targeted islands for this work are characterized by classic island energy supply systems according to the previously named papers [33, 34]. In the following sub-sections the power generation technologies for energy supply on islands are explained in a more detailed way.

2.2.1 Fossil power plants

The most common fossil power plant for island energy supply is diesel or oil [14, 34]. Such plants usually consist of several generation units and each unit has a combustion engine and a generator feeding its electricity to the central feeder of the plant. The nominal power of these units ranges from hundred kilowatts to several megawatts. An exemplary power station with 3 MW can be seen in Fig. 2.2.

The energy conversion within these plants is based on the combustion of liquid fossil fuels to drive an engine. The rotational energy is transformed to electrical energy by generators. The efficiency η_{fossil} of this process is described in Eq. 2.1.

Figure 2.2: *Picture of diesel power plant on the island Bequia, St. Vincent and the Grenadines, own photo source*

$$\eta_{\mathrm{fossil}} = \frac{\mathrm{E_{el}}}{\mathrm{E_{th}}} \tag{2.1}$$

$$\mathrm{E_{th}} = \mathrm{V_{fuel}} \cdot \mathrm{HV_{fuel}} \tag{2.2}$$

The thermal energy ($\mathrm{E_{th}}$) is injected through diesel or heavy fuel oil according to volume ($\mathrm{V_{fuel}}$) and higher heating value ($\mathrm{HV_{fuel}}$) as shown in Eq. 2.2. Heating values of these fuels are about 9.8 kWh/liter and 10.8 kWh/liter respectively [37]. They are normally burned in four stroke engines with 6 to 16 cylinders [38]. Most efficiency losses within the circular process are based on excess heat which cannot be used for power generation purposes and escapes through exhaust gases. Heat recovery systems for large scale diesel plants reduce these efficiency losses. In addition, exhaust gases represent not only heat losses but also environmental pollution due to nitric and sulphur oxides. Within the combustion engine a torque is induced driving the generator. This synchronous generator transforms the torque into electrical energy ($\mathrm{E_{el}}$) at 50 or 60 Hz. To maintain the right frequency, governors are installed which automatically or manually control the speed and load of the generator set. The full process of power generation in diesel or oil fired plants is described in Fig. 2.3.

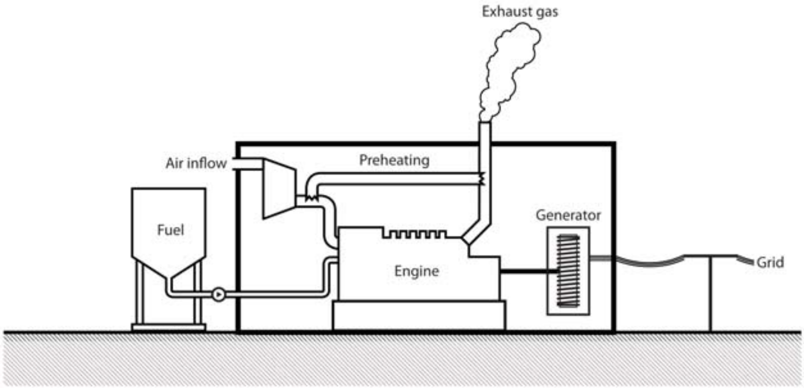


Figure 2.3: *Schematic of a diesel power plant [39]*

As aforementioned these plants are highly flexible within their operation. They can change their loads between 30 percent part load to full load within one minute. Once they are heated up they can even start from zero to full load within this time frame. This makes them especially attractive for island energy supply systems with very volatile loads. In addition the high energy density and simple transport infrastructure of diesel and oil has lead to a a high dissemination of these plants on Caribbean islands.

Beside fossil fuels these power plants can also be operated with renewable fuels such as biomass or biofuels. The general principle of power generation remains the same only the input fuel changes. In addition some technical adjustment of diesel plants might be necessary to avoid maintenance issues [40]. For this work biomass is excluded in the simulation and therefore no further technical descriptions are provided (cf. Subsec. 4.2.5).

2.2.2 Renewable energy technologies

Opposite to the fossil plants renewable energy technologies have not yet found such a high occurrence on Caribbean islands (cf. Tab. 2.1). Nevertheless these technologies are explained for a better understanding of the following simulations and the potential analyses of the islands energy supply. In general the application of these technologies for islands does not differ much compared to large scale on-grid applications. Photovoltaic plants are easy to scale down and for wind turbines smaller types are applied on islands than on continents. Hydro and geothermal power plants are as well suitable for small islands but they cause higher specific costs. In summary, it can be stated that the basic principles of renewable energy technologies remain the same for island energy supply and large scale systems. Technical peculiarities occur especially regarding system stability and storage systems which are presented in Subsec. 2.2.3.

Photovoltaic plants

Photovoltaic power plants are considered for power generation based on solar irradiation. Concentrated solar power is neglected for this research work as it has not yet been used in the Caribbean and it seems not competitive compared to photovoltaic plants [41]. Photovoltaics can be classified into three groups: mono-, polycristalline, and thin-film modules. All of them use the photovoltaic effect to convert solar radiation into electricity. An example of crystalline modules in the Caribbean can be seen in Fig. 2.4.

Figure 2.4: *Picture of a small photovoltaic plant on the island Mustique, St. Vincent and the Grenadines, own photo source*

When solar irradiation reaches the surface of a photovotaic cell electrons in the valence band absorb energy and are promoted to the conduction band. To use this electromotive force a p-n junction is created in photovoltaic cells by different layers directing the free electrons. Applying an electrical load closes the circuit and electrical energy with direct current can be used. This working principle is illustrated in Fig. 2.5.

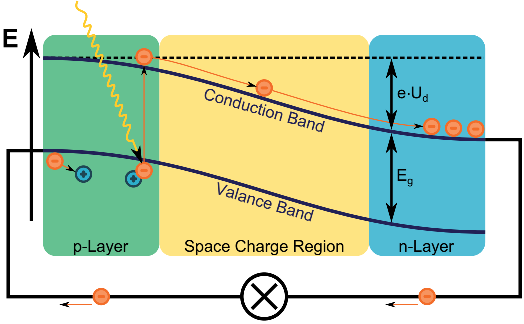


Figure 2.5: *Principle of a photovoltaic cell [7]*

Connecting cells in a row creates photovoltaic modules which typically have a size of 1.3 to 1.7 m^2 and the power ranges from 180 to 230 watts for mono- and polycrystallines. For the simulation silicium based crystalline modules were chosen because of having the highest share in the global market. They reach module efficiencies from 16 to 20 percent and overall power plant performance ratios from 80 to 90 percent [42].

Wind power plants

Wind turbines are applied to generate electricity from the kinetic energy of wind. The use of wind energy has long been established in human history beginning with windmills for grinding and water pumping. In modern times power generation by wind turbines has evolved as one of the major renewable energy technologies. The most common principle is using a three-blade horizontal axis turbine, but for special purposes also two-blade turbines and vertical axis are applied [43]. Two-blade turbines are for example installed on Nevis (cf. 2.6).

The kinetic energy of wind E_{wind} is determined by the mass m of the air and the velocity v as seen in Eq. 2.3.

Figure 2.6: *Picture of Vergnet wind turbines on Nevis, St. Kitts and Nevis, own photo source*

$$E_{wind} = \frac{1}{2} \cdot m \cdot v^2 \tag{2.3}$$

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \tag{2.4}$$

To derive the power P_{wind} the energy is differentiated according to the time. For constant velocities the mass flow is defined by air density ρ, area A, and velocity v. This power described in Eq. 2.4 is used by wind turbines to drive generators with the angular velocity ω. Physical limitations set the maximum efficiency of wind turbines to 59.3 percent at the ideal ratio of velocity v_2 and velocity v_1 set to one to three (cf. Fig. 2.7) [44].

Typically, large scale wind turbines reach a full conversion efficiency of 45 percent including losses in the generator and cabling [45]. Manufacturers provide power curves of the specific turbines to define the electric output for a certain wind velocity at hub height (cf. Fig. 4.5).

Hydropower plants

Another renewable energy source is the potential or kinetic energy of water flows. Hydropower is the oldest renewable technology for electric power generation and has been used since the 1880s [46]. The vast majority uses potential energy with the

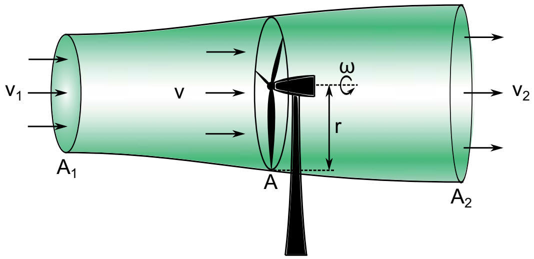


Figure 2.7: *Undisturbed flow profile of a wind turbine [7]*

help of dams to store the water and pipe systems to overcome the height difference. For this thesis it is therefore focused on the potential energy for hydropower. Run-of river plants without reservoirs or only small dams exist as well with the restriction that they cannot control the water and regulate therefore the mass flow over time. This means that time shifting of the renewable resource is impossible for these plants. The power generation is therefore directly dependent upon the temporary availability of the hydro resources. In the Caribbean, hydro power plants are the most common renewable technology [14]. One example can be found on St. Vincent as shown in Fig. 2.8.

Figure 2.8: *Picture of small hydro plant on St. Vincent, St. Vincent and the Grenadines, own photo source*

Equation 2.5 reveals that the potential energy of water resources for hydro plants is determined by the mass m, the gravitational constant ($g = 9.81\ m/s^2$) and the height difference $\triangle h$.

$$E_{water} = m \cdot g \cdot \triangle h \tag{2.5}$$

$$P_{water} = \triangle Q \cdot \rho \cdot g \cdot \triangle h \tag{2.6}$$

Similar to the wind energy it can be differentiated according to the time to derive the power (cf. Eq. 2.6). The mass flow of water is given by the volumetric discharge $\triangle Q$ and the density ρ. By the construction of walls in rivers water is dammed up to increase the height difference. To derive this difference the upper level h_1 of the upstream and the upper level h_2 of the downstream are compared as it is illustrated in Fig. 2.9.

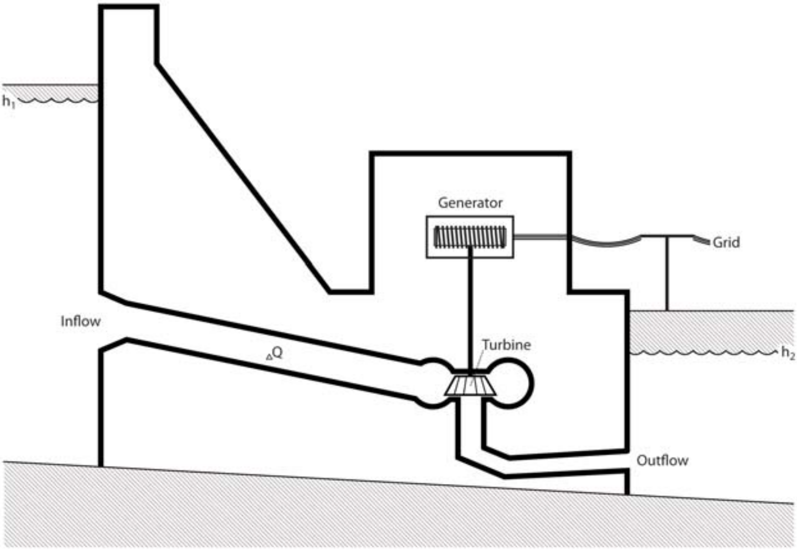


Figure 2.9: *Schematic of a hydro power plant [7]*

A distinction is made between three main types of turbines. Kaplan turbines are applied for large mass flows and low height differences, while Francis and Pelton turbines have advantages for higher height differences. Francis turbines can even be used for pumping in pump hydro storage plants. All turbine types reach efficiencies up to 90 %, but Kaplan turbines have a weak part-load behavior. The overall efficiency of hydro power plants is around 80 % [7].

Geothermal plants

As fourth renewable energy technology geothermal plants are presented. For geothermal power generation the earth's heat source, which means the internal thermal energy flows fed by radioactive decay, is used. Compared to the other renewable energies such as solar, wind, and biomass, geothermal energy is the only form of energy supplied by the planet earth and not by the sun [7]. Within conventional power plants the heat is used to drive steam turbines. This is often combined with heat supply for residential or industrial purposes which is not applied in the warm Caribbean region [47]. Figure 2.10 shows the only operating geothermal power plant in the Caribbean which is located on Guadeloupe.

Figure 2.10: *Picture of geothermal plant on Guadeloupe, photo source [48]*

The value of geothermal energy E_{geo} is determined by the mass m of the hot water, its specific heat capacity c and the temperature difference $\triangle T$ between the hot water and the re-injected water (cf. Eq. 2.7).

$$E_{geo} = m \cdot c \cdot \triangle T \tag{2.7}$$

$$P_{geo} = \triangle Q \cdot c \cdot \rho \cdot \triangle T \tag{2.8}$$

To determine the geothermal power P_{geo} not only the temperature difference but also the mass flow $\triangle Q$ of the collected water is essential as depicted in Eq. 2.8. As aforementioned hot groundwater is the source for power generation and has to be transported to ground level via pumps. In regions without sufficient groundwater sources water is injected into dry caverns to access the heat source. After the collection the hot water is converted into electrical energy within thermal power plants. This can be done via single flash, double flash, or binary plants. The difference of single and double flash plants is that the first uses only one separator while the second uses two. The principle of a single flash power plant can be seen in Fig. 2.11.

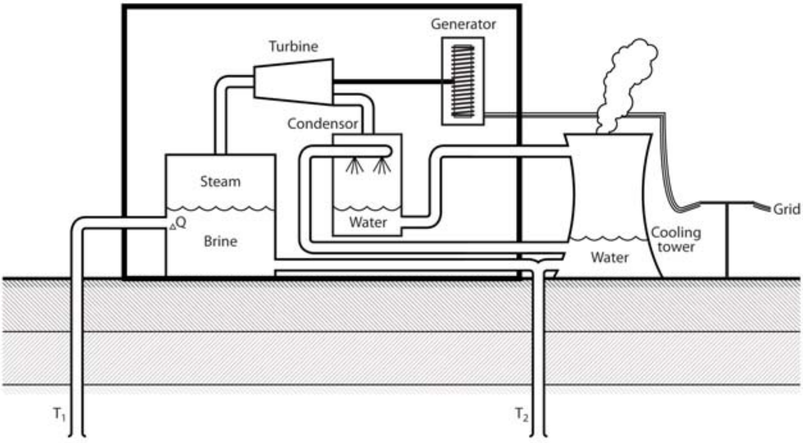


Figure 2.11: *Schematic of a single flash geothermal power plant [7]*

Binary plants use heat exchangers to transfer the heat from the groundwater to another fluid, typically with a lower boiling point than water. This is only necessary for low temperature differences. In areas such as the Caribbean single or double flash power plants are typically applied [49]. Similar to other steam plants the overall efficiency of this process is restricted by Carnot's theorem. As the temperature differences are relatively low in geothermal plants compared to fossil fired steam plants they reach overall efficiencies of only 8 to 15 percent [50].

2.2.3 Storage technologies and system stability

Due to low loads in island energy supply systems the introduction of fluctuating renewable energies can quickly lead to excess energy or system stability issues. For this reason system stability and storage technologies are described in this subsection, even though they are not yet necessary for simple on-grid renewable systems with low renewable penetration.

Energy storage technologies

In times of high renewable electricity supply, excess energy needs to be stored for availability during supply shortfalls. A large variety of storage technologies exist for this target. Figure 2.12 highlights the most important storage technologies and their range of application in respect of storage time and size.

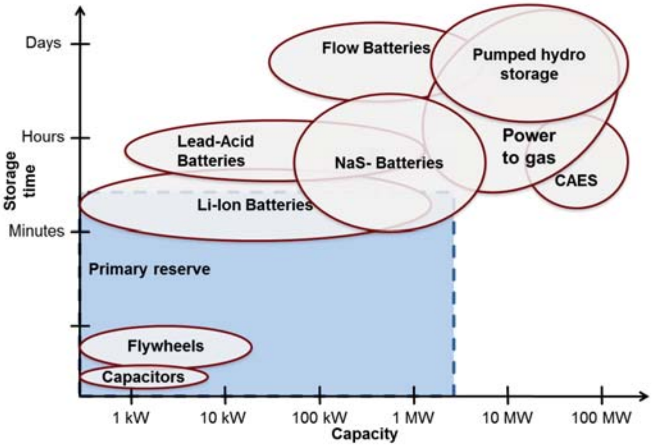


Figure 2.12: *Overview on energy storage technologies [51–55]*

Pumped hydro storage, power-to-gas systems, and compressed air energy storage (CAES) are not considered for the analyzed Caribbean islands. Geological and economic arguments restrict the current application of these technologies on these islands. Exceptions could be the larger islands of Cuba or the Dominican Republic, but these are not further investigated in this research work [35,55].

Flywheels and capacitor banks are mainly used for frequency stabilization and to compensate reactive power. They operate in very fast load changes to maintain the frequency within energy supply systems. They are not part of this research work as their real value can only be assessed in detailed grid studies with high time resolution [56].

As third category battery storage systems are presented. Batteries have the advantage that they do not rely on any topological constraints and are easy to scale. Thus, they cover a broad range of storage time and capacity. Nevertheless flow batteries are excluded as they are currently not competitive for island energy supply systems. Lead-acid batteries are not considered either due to environmental reasons. They are currently the most applied technology worldwide, but especially on islands the resulting toxic waste of used lead-acid batteries poses a serious environmental threat [35]. In conclusion the most appropriate storage technologies for islands are lithium ion (Li-Ion) and sodium sulfur (NaS) batteries. Both can be applied for high power storage as well as for long time storage [57]. For further analysis the sodium sulfur battery is chosen due to its higher range of capacities and lower C-rate, which is defined as the ratio of storage power and capacity. This makes sodium sulfur batteries more attractive for storing excess energy in island energy systems with a high share of renewable energy.

Within the sodium sulfur battery chemical processes allow to store or to supply energy. The high temperature process is based on free sodium ions Na^+ which move through ceramics towards the positive sulfur S electrode for discharging (cf. Eq. 2.9 and 2.10). For charging the process is reversed.

$$2\ \mathrm{Na} \rightleftharpoons 2\ \mathrm{Na}^+ + 2\ \mathrm{e}^- \tag{2.9}$$

$$2\ \mathrm{Na}^+ + \mathrm{x}\ \mathrm{S} + 2\ \mathrm{e}^- \rightleftharpoons \mathrm{NaS_x} \tag{2.10}$$

An electrical load is set between cathode and anode to use the created current. Figure 2.13 illustrates this discharging process.

Sodium sulfur batteries are high-temperature batteries. This means to keep the electrolytes liquid temperatures from 290 to 360 °C are applied. To reduce heat losses the battery cells are protected by vacuum layers. The battery has almost no self-discharge but energy is needed to keep the working temperatures stable. Round-cycle efficiency of these batteries is around 85 percent [59].

System stability

In electricity supply systems it is not only crucial to supply the demand by generating enough power. It is also important to keep the frequency, voltage, and system

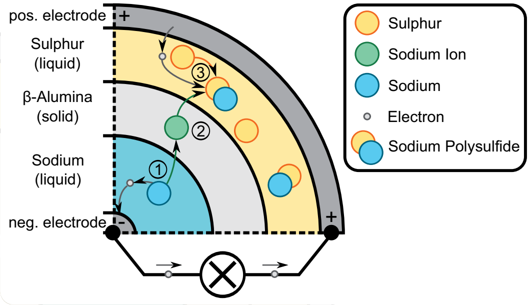


Figure 2.13: *Schematic of discharging process of sodium sulfur battery [58]*

stability within certain limits. The different levels of stability control are illustrated in Fig. 2.14.

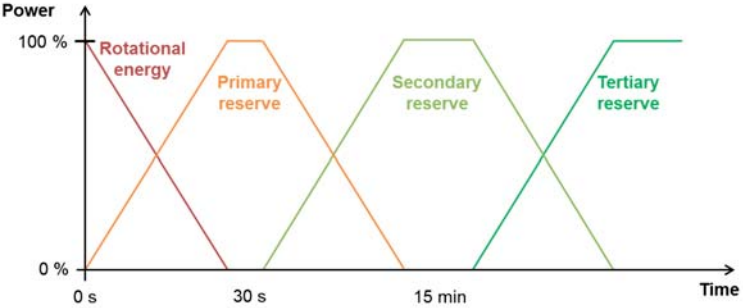


Figure 2.14: *Stability control functions within power generation systems [60]*

These stability functions can be performed by additional technologies and by specific operational modes of the existing components of island energy supply systems. These existing components can either be fossil power plants, controllable renewable plants, and / or batteries. Additional components for frequency control are shown in Fig. 2.12. As aforementioned these flywheels and capacitors are excluded for this work and rotational energy as control mode is not investigated. Thus, the operational modes of existing power plants or batteries are taken as system stability providers.

A common principle to provide this service is to set a certain spinning reserve covering the primary and secondary reserve for energy systems. According to Kirschen and Rebours [61] spinning reserve is defined as "the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power." This means it can either be provided by the idle capacities of already connected fossil plants and geothermal plants or by charged fast responding batteries with smart inverters [62, 63]. The purpose of this spinning reserve is to react on spontaneous supply shortfalls that fast that any fluctuations can be sufficiently covered by increased power generation. Thus, the system remains stable and the frequency does not drop below a fixed threshold.

For this thesis the spinning reserve is the determining factor for the system stability and is reflected in the energy system simulation. Rotating energy is not analyzed and tertiary control is neglected under the assumption that the existing fossil based energy supply systems have enough back-up capacities to cover outages of power generating units.

Chapter 3

Methodological approach - renewable potential

The methodology to analyze the techno-economic potential is an energy supply system model simulating different power generation system configurations to minimize the levelized cost of electricity (LCOE). Within this chapter the theoretical background and the model structure are explained.

3.1 Theoretical background

A self-developed energy system simulation tool is used for the assessment of the techno-economic renewable potential on Caribbean islands. For this research work it is not sufficient to look at the theoretical potential of single renewable power generation technologies, but the entire energy supply system needs to be analyzed in a very detailed way. This means that the interaction of the different technologies and resources combined with specific cost parameters for each island needs to be considered to derive the techno-economic potential.

Obviously, it is not feasible to analyze the potential directly within the real energy supply systems, therefore a virtual reproduction of these systems - a simulation model - is necessary. Simulations are defined as "the imitation of the operation of a real-world process or system over time" [64]. To run simulations a simulation model is crucial defining the main parameters and variables of the system as for example developed in the theses of Bognar [65] and Strauch [59]. The requirements of the model for island energy supply simulations are described in the following.

The timely resolution of the simulation should be at least in hourly time steps and one reference year should be simulated [66]. This allows to reflect seasonal differences as well as short time fluctuations in the load and in the renewable energy supply. The energy flows of a hybrid system including diesel, photovoltaic, wind, hydro, and geothermal power plants and batteries have to be considered. In addition the technological constraints of the aforementioned technologies should be flexibly adaptable. As a result the simulation reveals the technical and economic performance of the island energy supply system. An option to optimize the configuration to reduce the overall costs is also a prerequisite.

3.1.1 Simulation tools

Various simulation tools exist to calculate energy supply systems [67]. The most commonly used dimensioning tools for research and practical applications are listed in Tab. 3.1. Within this table they are compared along the previously described requirements to sufficiently simulate the techno-economic potential.

Table 3.1: *Overview about simulation tools for island energy supply systems*

	HOMER	**Hybrid2**	**PVDesignPro**
Developed by	National Renewable Energy Labroratory, USA	University of Massachusetts, USA	Maui Solar Energy Software Corporation, USA
Power generation options	Diesel, PV, Wind, Hydro, Biomass	Diesel, PV, Wind	Diesel, PV, Wind
Storage options	Batteries, hydrogen, flywheel	Batteries	Batteries
Time steps	hourly	hourly	hourly
Open programming code	no	no	no
Source	[68]	[69]	[70]

Table 3.1 reveals that all presented tools run at least in hourly time steps. This criterion is sufficiently fulfilled as well as the available storage options. In every tool, batteries are available for the system simulation. In opposite to the storage technologies constraints exist according to the power generation options. Hybrid2 and PVDesignPro lack the option to include hydro and geothermal power plants, while HOMER only misses the latter option. For all tools the programming code is not

accessible. This means that the missing technologies cannot be added. In general, HOMER would meet the requirements best and can be considered as most suitable for simulating island energy supply systems (cf. [65, 71, 72]). An example of other researchers successfully applying HOMER can be found in [73–75]. Subsequently, HOMER is chosen as reference simulation tool for this research work. The lack of an open accessible programming code restricts HOMER significantly. Not only the missing geothermal plant, but also the inability of simulating automatically a high amount of island energy supply systems underline the need to develop a specialized tool.

The tool is written in Matlab (cf. [76]) which allows a high flexibility combined with available toolboxes enabling fast calculations and optimization processes. According to the aforementioned requirements the tool simulates an energy system in hourly time steps for one reference year regarding the fossil and renewable resources and technical, economic, and load data. The considered power generation options are diesel, photovoltaic, wind, hydro, and geothermal power plants which are combined with batteries. Perfect competition is assumed, this means the most effective system is simulated without giving special tariffs to single power plants for the entire island leading to single-objective optimization [77]. In addition only one node is simulated, thus no optimization within the electricity grid is needed. This is based on the small size of the island systems, which allows to neglect the analysis of the islands' transmission grid. In the following subsection the optimization approach chosen for the described tool is presented.

3.1.2 Optimization approach

An optimization algorithm is applied to identify the most cost-effective configuration varying the parameters: photovoltaic, wind, hydro, and geothermal power plant and battery sizes. As the search space increases exponentially with each additional variable parameter a sophisticated optimization algorithm is needed. Such algorithms are often applied for solving complex problems in renewable energy system simulations [78]. The target of these algorithms is simply spoken to find the best solution. This means to solve an optimization problem described by a certain function and to identify its minimum or maximum (cf. Eq. 3.1 and 3.2).

$$\mathrm{f(x)} \rightarrow \min(\mathrm{or}\max), \qquad \mathrm{f}: \mathbb{R}^{\mathrm{n}} \rightarrow \mathbb{R} \tag{3.1}$$

$$\mathrm{x} \in \mathrm{M}, \qquad \mathrm{M} \subset \mathbb{R}^{\mathrm{n}} \tag{3.2}$$

For this work the optimization problems are differentiated along four criteria following the approach of Huyskens [72] based on the work of Marthaler [79].

- *Linearity*
  It is distinguished between linear and non-linear problems. The developed simulation model creates a non-linear problem due to technological constraints of the considered power generation and storage systems.
- *Objective/s*
  Normally the objective of the optimization is to minimize or maximize the output of one function. This is described as a single-objective solution. Another more complex possibility is the optimization of different objective functions at once as seen in Eq. 3.3.

  $$\min(\mathrm{or}\max)\{\mathrm{f}_1(\mathrm{x}), \mathrm{f}_2(\mathrm{x}), \ldots, \mathrm{f}_\mathrm{m}(\mathrm{x})\} \tag{3.3}$$

  Weighting of their outputs or a pareto-based algorithm can be used to find one optimal solution [80, 81]. As aforementioned the formulated problem in the developed simulation tool is single-objective.
- *Constraints*
  Limitations within the solution set are considered as constraints. Problems can be constrained or un-constrained. Constraints normally consist of an equality-function Eq. 3.4, an inequality-function Eq. 3.5 and lower lb or upper ub boundaries (cf. Eq. 3.6).

  $$\mathrm{h(x)} = 0 \tag{3.4}$$

  $$\mathrm{g(x)} \leq 0 \tag{3.5}$$

  $$\mathrm{lb} \leq \mathrm{x} \leq \mathrm{ub} \tag{3.6}$$

  The formulated problem for the developed simulation tool is constrained due to upper and lower boundaries in the solution set. These boundaries help to increase the velocity of finding the best solution.

- *Discretization*
  Input values and outputs can consist of discrete or continuous values. Discrete approaches reduce the solution set and therefore increase the optimization speed. Anyhow, for this research continuous input and output values are chosen to allow higher accuracy of the results.

In conclusion, the optimization problem is non-linear, single-objective, constrained, and continuous. A large variety of optimization solver exist to support an efficient approach finding the optimal solution. Nevertheless it is not guaranteed that the optimal solution is found at the end of the process. Local minima or maxima might be indicated as overall best solution [82]. To reduce discrepancies two general search strategies can be applied. The first is a trajectory approach using an iterative way. Algorithms assigned to the trajectory approach are found in [83–85]. The second approach is using population-based evolutionary algorithms. Inspired by natural evolution, solution options are evolving from one generation to the next as it is applied in [86]. For the existing optimization problem of this research work the genetic algorithm is chosen as the most appropriate solution. It handles non-linear and constrained optimizations and was successfully applied in similar simulations [72, 87]. In the following paragraphs the genetic algorithm is described.

Darwin's theory, often described as "the survival of the fittest", builds the basic concept of the genetic algorithm [88]. Within this algorithm a population is created based on many generations and individuals. In every generation the most optimal ("fittest") individuals are taken for further reproduction. The individuals are defined by the variable input parameters of a certain function and the fitness is measured according to the output of this function and to the optimization target. The entire optimization process runs along three steps.

The first step is the creation of the starter population, consisting of a certain amount of non-duplicate individuals. Several techniques exist to form a well-distributed first population (e.g. grow-, full-, or ramped half-and-half-method). Second, the individuals are ranked according to their individual performance. As a third step the evolution takes place via two basic operations. Reproduction is used for the individuals within the best ten percent of the generation which means they are just passed onto the next generation. For the remaining ninety percent new individuals are formed as cross-over pairs. Examples for these events are given in Fig. 3.1 and a detailed explanation can be found in [89].

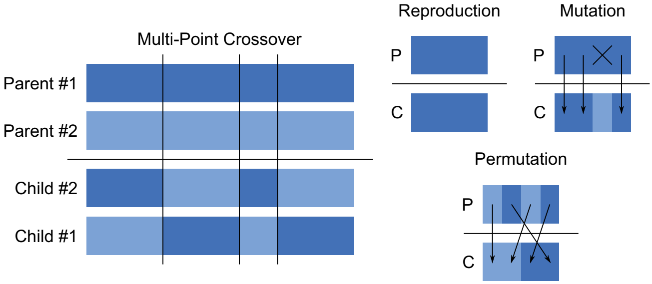


Figure 3.1: *Cross-over reproduction options applied in the genetic algorithm*

According to the settings of the algorithm the steps number two and three are repeated until the termination criterion is fulfilled. The final solution is the best performing individual of the last evolved generation. Even though this algorithm is highly sophisticated there is no guarantee to find the global optimum. Anyhow, it is very well applicable for the defined optimization problem and allows accurate results in a reasonable calculation time. Thus, a genetic algorithm is used to find the best solution for optimizing island energy supply systems. The structure of the related simulation model is explained in the following section.

3.2 Island energy supply model

As mentioned before many simulation tools for island energy supply systems exist, but none of them meets all criteria for this research work. Consequently, an own model was developed in Matlab inspired by the main functions of HOMER [68]. Within this section the structure of the model, its components, the dispatch strategy, and the financial calculations including the optimization function are described.

3.2.1 Model structure

The model is a one-node model to simulate and optimize island energy supply systems. This means the energy supply via one node is modeled only. In Fig. 3.2 the basic structure and energy flows of the model are shown.

On the upper part of Fig. 3.2 the power generation systems are illustrated. The fossil, system consisting of one fossil fuel fired plant, is a fixed part of the model and is

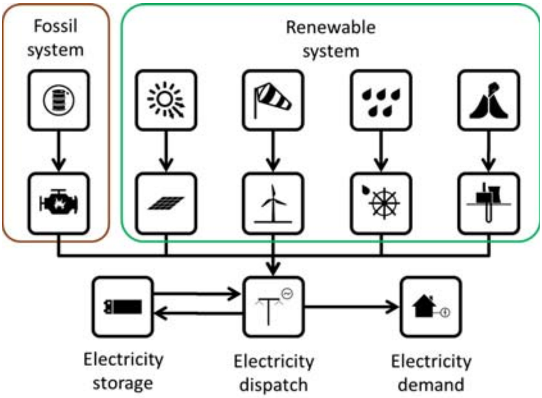


Figure 3.2: *Structure of simulation model*

able to supply the full demand for every hour of the reference year. The introduction of renewable energy technologies leads to a hybridization of the existing diesel power system. Thus, the configuration of the renewable system is flexible. Based on costs and resource availability the optimum size of each renewable technology - PV, wind, hydro, and geothermal power plants - can be determined. The conversion of renewable resources into electrical power is described in section 4.2 for this simulation model.

The fossil and the renewable power generation accumulates in one node and it serves one load demand. According to the fluctuating and non controllable renewable power generation the battery is either charging or discharging and the amount of required fossil power is determined by the dispatch strategy. Within the dispatch strategy stability criteria such as spinning reserve are reflected as well (cf. Subsec. 3.2.3).

The final outputs of the simulation model are the sizes of the renewable technologies and batteries and the related levelized costs of electricity (LCOE) of the island energy supply system. LCOE are based on fuel costs, initial costs, operation and maintenance costs, and capital costs. This is more precisely explained in Subsec. 3.2.4. LCOE are recommended as comparative value for different energy supply options within the same system boundaries [90].

3.2.2 Components

Fossil power plant

For the energy system simulation one generic fossil fuel based power plant is assumed. Even though several to many single diesel or heavy fuel oil generator sets form the power generation of each island, they are aggregated to one abstract plant for the simulation. This simplification is required as the characteristics of the existing plants are often not known and the simulation of each of these plants is too time-consuming.

The generic fossil plant is defined by one efficiency value (cf. 4.7). This efficiency value η_{fossil} determines the amount of consumed diesel $V_{\text{fossil-thermal}}(t)$ per time step t in thermal kilowatthours as seen in Eq. 3.7.

$$V_{\text{fossil–thermal}}(t) = \frac{P_{\text{fossil}}(t)}{\eta_{\text{fossil}}} \tag{3.7}$$

By that the total amount of used fossil fuels can be accumulated according to the requested fossil power $P_{\text{fossil}}(t)$ of each time step. The supplied fossil power has the upper boundary defined by the installed capacity ($P_{\text{fossil-installed}}$: cf. 4.7) and the lower boundary defined by the minimal loading of the plant $P_{\text{fossil-min}}$ as written in Eq. 3.8.

$$P_{\text{fossil–min}} \leq P_{\text{fossil}}(t) \leq P_{\text{fossil–installed}} \tag{3.8}$$

For each generic plant the minimal loading is set to 20 percent of the peak load of the reference year. This reflects the set up of normal diesel or heavy fuel oil plants with several generating units where each of them has a minimal loading of 50 percent. The parameter is essential to operate these plants within their technical limits to avoid additional maintenance effort due to low operation levels.

Renewable power plants

The renewable power plants are not as flexible as the fossil plants. Equation 3.9 shows that their current power $P_{\text{renewable}}(t)$ depends upon resource availability and size of each renewable plant (e.g. S_{PV}) in kilowatt. The calculation method and results of the electrical feedin (e.g. $\text{feedin}_{\text{PV}}$) in kilowatthours per kilowatt of each renewable technology is explained in Sec. 4.2.

$$
\begin{aligned}
\mathrm{P_{renewable}(t)} &= \mathrm{P_{PV}(t) + P_{wind}(t) + P_{hydro}(t) + P_{geo}(t)} && (3.9)\\
\mathrm{P_{PV}(t)} &= \mathrm{S_{PV} \cdot feedin_{PV}(t)} && (3.10)\\
\mathrm{P_{wind}(t)} &= \mathrm{S_{wind} \cdot feedin_{wind}(t)} && (3.11)\\
\mathrm{P_{hydro}(t)} &= \mathrm{S_{hydro} \cdot feedin_{hydro}(t)} && (3.12)\\
\mathrm{P_{geo}(t)} &= \mathrm{S_{geo} \cdot feedin_{geo}(t)} && (3.13)
\end{aligned}
$$

The predetermined renewable power of each time step can only be controlled in a negative way. This means in times of renewable overproduction the power can be cut, but in times of not sufficient supply according to the resource data the fossil plant and / or the battery system have to cover the negative residual load. This is further explained within the dispatch strategy in Subsec. 3.2.3.

Battery storage system

As described in Subsec. 2.2.3 a sodium sulfur battery is considered as electricity storage technology for this research work. Within the simulation model the basic behavior of this battery is reflected by the following parameters listed in Tab. 3.2.

Table 3.2: *Technical parameters of sodium sulfur battery model and chosen values for island energy supply system simulation [91]*

Parameter	**Unit**	**Value**
C-rate	kW/kWh	1/6
Maximum depth of discharge	%	80
Charging efficiency	%	90
Discharging efficiency	%	90
Initial state of charge	%	100

The nominal capacity $\mathrm{C_{nominal}}$ of the battery is determined by its size $\mathrm{S_{battery}}$ which can be changed within the optimization process. Based on this nominal capacity the usable capacity $\mathrm{C_{usable}}$ is derived according to the maximum depth of discharge $\mathrm{DOD_{max}}$ as written in Eq. 3.14.

$$\mathrm{C_{usable} = S_{battery} \cdot C_{nominal} \cdot DOD_{max}} \tag{3.14}$$

The maximum charging and discharging power $P_{\text{max-charge/discharge}}$ is determined by the size, the nominal capacity, and the C-rate (cf. Eq. 3.15). As C-rate the maximal ratio between storage power and capacity of the battery is taken.

$$P_{\text{max–charge/discharge}} = S_{\text{battery}} \cdot C_{\text{nominal}} \cdot \textit{C-rate} \tag{3.15}$$

This power $P_{\text{charge/discharge}}$ represents the maximum output of the battery inverter or converter of real systems. In case of charging or discharging the battery the related efficiencies η have to be applied. Equations 3.17 and 3.16 illustrate both cases.

$$P_{\text{charge}}(t) = \min\{P_{\text{max–charge}}, \frac{(1 - SOC(t-1)) \cdot S_{\text{battery}} \cdot C_{\text{nominal}}}{\eta_{\text{charge}}}\} \tag{3.16}$$

$$\begin{aligned} P_{\text{discharge}}(t) =& \min\{P_{\text{max–discharge}}, \\ & (SOC(t-1) - DOD_{\text{max}}) \cdot S_{\text{battery}} \cdot C_{\text{nominal}} \cdot \eta_{\text{discharge}}\} \end{aligned} \tag{3.17}$$

The available discharging and charging power for each time depends upon the state of charge SOC of the battery system of the previous time step (t-1). This is important to set the maximum discharging and charging constraints according to the current charging status to avoid overcharging or too deep discharging of the battery.

How the state of charge changes during the simulation and the application of self-discharging are presented in the following Subesc. 3.2.3. The initial state of charge SOC(t=0) expresses the battery status at the first time step of the simulation.

3.2.3 Dispatch strategy

For each time step of the island energy supply system simulation a certain dispatch strategy is applied. This strategy is illustrated in Fig. 3.3.

At the beginning of every time step t the residual load P_{residual} is determined according to Eq. 3.18 and Eq. 3.9 for the renewable power.

$$P_{\text{residual}}(t) = P_{\text{renewable}}(t) - P_{\text{load}}(t) \tag{3.18}$$

The first decision point of the dispatch strategy is set according to the residual load. If the renewable power is equal to or exceeds the current load demand the residual

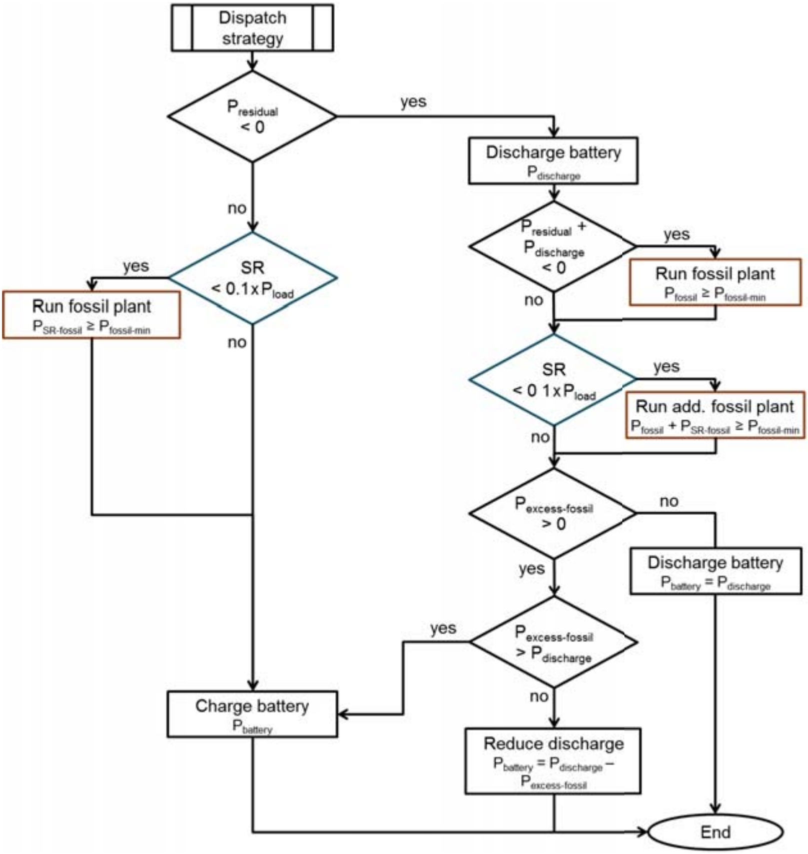


Figure 3.3: *Dispatch strategy of island energy supply system*

load is less or equal zero. This means that the load can fully be served by renewable energies (left side of Fig. 3.3).

In addition to meeting the demand it is also necessary to fulfill the stability criteria within each time step. The stability criterion is expressed by the spinning reserve SR. The spinning reserve can be provided by fossil plants, geothermal plants, and battery capacities (cf. Eq. 3.19) and has to be higher than 10 percent of the current load.

$$\begin{aligned} \mathrm{SR}(t) = & \mathrm{P}_{\text{fossil}}(t) + \mathrm{P}_{\text{geo}}(t) + \min\{\mathrm{P}_{\text{max-discharge}}, \\ & (\mathrm{SOC}(t) - (1 - \mathrm{DOD}_{\text{max}})) \cdot \mathrm{S}_{\text{battery}} \cdot \mathrm{C}_{\text{nominal}} \cdot \eta_{\text{discharge}}\} \end{aligned} \tag{3.19}$$

If the current spinning reserve SR(t) is not higher than 10 percent of the current load ($0.1 \cdot \mathrm{P}_{\text{load}}(t)$), for example due to a low charging level of the battery, additional fossil power $\mathrm{P}_{\text{SR-fossil}}$ is needed. This additional power is just needed for stability reasons and produces excess energy. At the end of the process excess energy of renewable capacities and - if applicable - of additional fossil capacities is used to charge the battery. The final power flow from the grid into the battery $\mathrm{P}_{\text{battery}}$ is determined by the charging capacity of the battery and the excess energy as illustrated in Eq. 3.20.

$$\mathrm{P}_{\text{battery}}(t) = \min\{\frac{\mathrm{P}_{\text{charge}}(t)}{\eta_{\text{charge}}}, (\mathrm{P}_{\text{residual}}(t) + \mathrm{P}_{\text{SR-fossil}}(t))\} \tag{3.20}$$

With this step the dispatch for non negative residual power has finished. Battery inflow and additional fossil power are used for further calculations as it is described in Eq. 3.24 and Subsec. 3.2.4. Before that, the dispatch strategy for negative residual power (right side of Fig. 3.3) is explained in the following.

The first step after the evaluation of the residual power is to check the available battery discharge power (cf. Eq. 3.17). If the residual power combined with the battery discharge power ($\mathrm{P}_{\text{residual}}(t) + \mathrm{P}_{\text{discharge}}(t)$) is still negative it is necessary to run fossil plants to cover the load keeping in mind the constraints of Eq. 3.8. The stability criterion is determined according to Eq. 3.19 once the load demand is met by renewable power, battery discharge, and / or fossil power.

In the case that the available spinning reserve exceeds ten percent of the current load all requirements are fulfilled. In the other case additional fossil capacities operate to provide the necessary spinning reserve. Afterwards it is tested if fossil excess power exists due to minimal loading of the fossil plant or due to additional spinning reserve requirements. If this is valid, the battery discharge can be reduced by the amount of fossil excess energy $P_{\text{excess-fossil}}$ which is determined in Eq. 3.21.

$$P_{\text{excess–fossil}}(t) = P_{\text{residual}}(t) + P_{\text{discharge}}(t) + P_{\text{fossil}}(t) + P_{\text{SR–fossil}}(t) \tag{3.21}$$

The final power flow from the grid into the battery is shown in Eq. 3.22 for the case that the fossil excess power is so high that the battery can even be charged.

$$P_{\text{battery}}(t) = \min\{\frac{P_{\text{charge}}(t)}{\eta_{\text{charge}}}, (P_{\text{residual}}(t) + P_{\text{fossil}} + P_{\text{SR–fossil}})\} \tag{3.22}$$

In the more likely case that the battery is discharged the following Eq. 3.23 is applied with the option of discharge reduction. Here $P_{\text{battery}}(t)$ stands for the power flow from the battery into the grid which can be used to serve the demand.

$$P_{\text{battery}}(t) = \min\{P_{\text{discharge}}(t), \frac{|P_{\text{residual}}(t)| - P_{\text{fossil}} - P_{\text{SR–fossil}}}{\eta_{\text{discharge}}}\} \tag{3.23}$$

Finally, the dispatch process is finished for all potential cases. This process is simulated for all 8,760 hourly time steps of the reference year. For each time step the related changes in the battery's state of charge $P_{\text{battery-in/out}}$ are determined, based on the power flows $P_{\text{battery}}(t)$ from and into the grid and the charging and discharging efficiencies. This is summarized in Eq. 3.24, 3.25, and 3.26.

$$\begin{align}
SOC(t) &= SOC(t-1) + \frac{P_{\text{battery–in/out}}}{S_{\text{battery}} \cdot C_{\text{battery}}} \tag{3.24}\\
P_{\text{battery–in}} &= P_{\text{battery}} \cdot \eta_{\text{charge}} \tag{3.25}\\
P_{\text{battery–out}} &= -\frac{P_{\text{battery}}}{\eta_{\text{discharge}}} \tag{3.26}\\
t(0) &= \text{initial state of charge}
\end{align}$$

The battery's state of charge is passed to each following time step until the end of the reference year. Generated kilowatthours of fossil electricity E_{fossil} are calculated for every time step and summed up for the full year as shown in Eq. 3.27.

$$\mathrm{E_{fossil}} = \sum_{t=1}^{8760} \mathrm{P_{fossil}(t) + P_{SR-fossil}(t)} \tag{3.27}$$

$$\mathrm{V_{fossil-thermal}} = \frac{\mathrm{E_{fossil}}}{\eta_{\mathrm{fossil}}} \tag{3.28}$$

Equation 3.28 illustrates that the total fossil fuel consumption is derived from the fossil electricity generation. Both values are passed to the financial model to calculate the total costs of the island energy supply system.

3.2.4 Financial modeling

After the description of the technical components and the dispatch of the electricity flows the financial part of the simulation model is explained. The financial model consists of three main parts: capital expenditures, operation and maintenance expenditures, and fuel costs. These costs are calculated for one reference year and divided by the annual load demand $\mathrm{E_{load}}$ to derive the LCOE as shown in Eq. 3.29 based on [90].

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX_{total} + OPEX_{total} + Fuel_{costs}}}{\mathrm{E_{load}}} \tag{3.29}$$

$$\mathrm{E_{load}} = \sum_{t=1}^{8760} \mathrm{P_{load}(t)} \tag{3.30}$$

The LCOE methodology can be applied as long as no non-linear changes of the input parameters occur over the project lifetime which is excluded for this research [90]. In the following the single cost categories are explained for the calculation of the LCOE.

Capital expenditures

The capital expenditures are determined by the initial costs IC and lifetime n of each technology. For the final calculation the costs are broken down to one reference year. Thus the initial costs are annualized with the related weighted average costs of capital WACC for each island. In summary, Eq. 3.31 shows the calculation of annualized capital expenditures CAPEX which consists of Eq. 3.32, 3.33, 3.34, 3.35, 3.36, and 3.37.

$$\begin{aligned}\mathrm{CAPEX_{total}} = {} & \mathrm{CAPEX_{fossil}} + \mathrm{CAPEX_{PV}} + \mathrm{CAPEX_{wind}} + \mathrm{CAPEX_{hydro}} \\ & + \mathrm{CAPEX_{geo}} + \mathrm{CAPEX_{battery}}\end{aligned} \tag{3.31}$$

$$\mathrm{CAPEX_{fossil}} = \mathrm{IC_{fossil}} \cdot \mathrm{S_{fossil}} \cdot \frac{(1+\mathrm{WACC})^{\mathrm{n_{fossil}}} \cdot \mathrm{WACC}}{(1+\mathrm{WACC})^{\mathrm{n_{fossil}}} - 1} \tag{3.32}$$

$$\mathrm{CAPEX_{PV}} = \mathrm{IC_{PV}} \cdot \mathrm{S_{PV}} \cdot \frac{(1+\mathrm{WACC})^{\mathrm{n_{PV}}} \cdot \mathrm{WACC}}{(1+\mathrm{WACC})^{\mathrm{n_{PV}}} - 1} \tag{3.33}$$

$$\mathrm{CAPEX_{wind}} = \mathrm{IC_{wind}} \cdot \mathrm{S_{wind}} \cdot \frac{(1+\mathrm{WACC})^{\mathrm{n_{wind}}} \cdot \mathrm{WACC}}{(1+\mathrm{WACC})^{\mathrm{n_{wind}}} - 1} \tag{3.34}$$

$$\mathrm{CAPEX_{hydro}} = \mathrm{IC_{hydro}} \cdot \mathrm{S_{hydro}} \cdot \frac{(1+\mathrm{WACC})^{\mathrm{n_{hydro}}} \cdot \mathrm{WACC}}{(1+\mathrm{WACC})^{\mathrm{n_{hydro}}} - 1} \tag{3.35}$$

$$\mathrm{CAPEX_{geo}} = \mathrm{IC_{geo}} \cdot \mathrm{S_{geo}} \cdot \frac{(1+\mathrm{WACC})^{\mathrm{n_{geo}}} \cdot \mathrm{WACC}}{(1+\mathrm{WACC})^{\mathrm{n_{geo}}} - 1} \tag{3.36}$$

$$\mathrm{CAPEX_{battery}} = \mathrm{IC_{battery}} \cdot \mathrm{S_{battery}} \cdot \frac{(1+\mathrm{WACC})^{\mathrm{n_{battery}}} \cdot \mathrm{WACC}}{(1+\mathrm{WACC})^{\mathrm{n_{battery}}} - 1} \tag{3.37}$$

Within these equations the specific investment costs IC are multiplied with the size S of the installed technology and the annuity factor. This is performed to distribute the investment costs equally according to the lifetime of the technologies and to account for interest payments means capital costs. The resulting equivalent annual costs are used in the final calculation of the LCOE in Eq. 3.29.

Operation and maintenance expenditures

In addition to the capital expenditures the yearly operation and maintenance expenditures are taken into account for financial modeling. They can be split into variable and fixed costs per year.

The only variable costs occur by the generated kilowatthours of fossil plants. As the maintenance effort of these plants significantly correlates with the operating hours a variable term is used as described in Eq. 3.38.

$$\mathrm{OPEX_{fossil}} = \mathrm{Cost_{OPEX-fossil-var}} \cdot \mathrm{E_{fossil}} \tag{3.38}$$

The annual operation and maintenance costs caused by the fossil plant $\mathrm{OPEX_{fossil}}$ are determined by the costs per kilowatthour $\mathrm{Cost_{OPEX\text{-}fossil\text{-}var}}$ and the generated electricity $\mathrm{E_{fossil}}$ calculated in Eq. 3.27. This means these expenditures are influenced by the outcome of the technical simulation - the energy dispatch.

For renewable technologies and batteries a fixed operation and maintenance cost value is assigned based on the size of installed capacity and the specific costs. Equations 3.39, 3.40, 3.41, 3.42, and 3.43 show this relationship of the yearly operation and maintenance costs.

$$\mathrm{OPEX_{PV}} = \mathrm{Cost_{OPEX-PV-fix}} \cdot \mathrm{S_{PV}} \tag{3.39}$$

$$\mathrm{OPEX_{wind}} = \mathrm{Cost_{OPEX-wind-fix}} \cdot \mathrm{S_{wind}} \tag{3.40}$$

$$\mathrm{OPEX_{hydro}} = \mathrm{Cost_{OPEX-hydro-fix}} \cdot \mathrm{S_{hydro}} \tag{3.41}$$

$$\mathrm{OPEX_{geo}} = \mathrm{Cost_{OPEX-geo-fix}} \cdot \mathrm{S_{geo}} \tag{3.42}$$

$$\mathrm{OPEX_{battery}} = \mathrm{Cost_{OPEX-battery-fix}} \cdot \mathrm{S_{battery}} \tag{3.43}$$

To derive the final costs all variable and fixed operation and maintenance expenditures of the reference year are summed up (cf. Eq. 3.44).

$$\begin{aligned}\mathrm{OPEX_{total}} = {} & \mathrm{OPEX_{fossil}} + \mathrm{OPEX_{PV}} + \mathrm{OPEX_{wind}} + \mathrm{OPEX_{hydro}} \\ & + \mathrm{OPEX_{geo}} + \mathrm{OPEX_{battery}}\end{aligned} \tag{3.44}$$

Fuel expenditures

As third annual cost parameter the fuel expenditures $\mathrm{Fuel_{costs}}$ of the island energy supply system are calculated. They depend upon the amount of fossil fuel consumed $\mathrm{V_{fossil\text{-}thermal}}$ in the reference year and the related costs of fossil fuel of each island $\mathrm{Costs_{fuel\text{-}island}}$ as written in Eq. 3.45.

$$\mathrm{Fuel_{costs}} = \mathrm{V_{fossil-thermal}} \cdot \mathrm{Costs_{fuel-island}} \tag{3.45}$$

By that all relevant equations and connections of the island energy supply system model are described. A useful and fast operating tool was developed considering all these equations to analyze the techno-economic potential of renewable energies on the Caribbean islands. Doing this, the input parameter and time series for each island have to be defined. This is conducted in the following Ch. 4.

Chapter 4

Input - renewable potential

This chapter describes the island sample and input parameter for the simulation of the techno-economic potential. First, the island sample is defined followed by a detailed resource assessment for solar, wind, hydro, geothermal and bio energy. It is concluded by an overview on the financial assumptions.

4.1 Island sample

Prior to the application of the simulation model the island sample has to be defined. For this analysis all countries as described in Tab. 2.1 are taken into account. These 27 countries are investigated with the help of geo-information system - GIS - tools to derive the island sample. The first sample includes all inhabited islands of each country with additional information on size of the island, location of the center of the island, and number of inhabitants.

To define the area of analysis the database of global administrative areas (GADM) is used [92]. All Caribbean countries of Tab. 2.1 are selected in this database to cover the research object entirely. Afterwards an extraction of countries of the global GADM file is performed. As the countries consist of multipart polygons in the GADM file they have to be dissolved into separate polygons to derive single islands of each country. Of each island's polygon the centroid is calculated to get the coordinates of the center. In addition the area of each island is computed. This is done by re-projecting the island shapefile from world geodetic system 1984 (WGS84) [93], which is in degree, to UTM 20N [94] to change the unit from degree to metric units. In addition, this re-projection allows an equal-area projection for the Caribbean region instead of a more generic global projection as WGS84. At this first step 564 islands are identified with a minimum size of one km^2.

These islands are combined with a population dataset which represents an average ambient population over 24 hours [27]. This means also touristic activities are reflected in this dataset. Due to the pixel size of one by one km of the population data, the vectorized island shapes are extended with a buffer of 707 m (half diameter of the pixel) to include all pixel centers for the population counting. This methodology is illustrated in Figure 4.1.

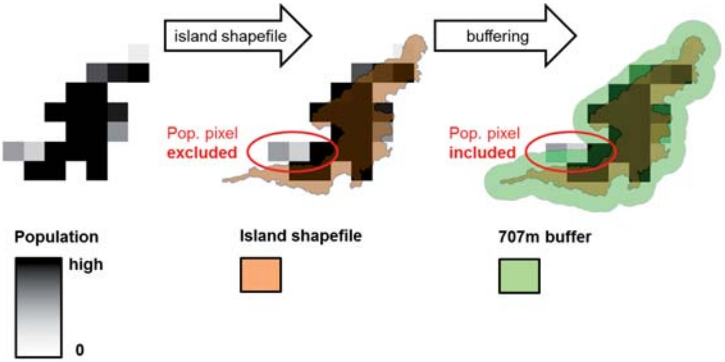


Figure 4.1: *Methodological approach of including all population pixel for one single island along the example of Bequia, St. Vincent and the Grenadines*

By this combination 193 populated islands are detected of which 62 have 1,000 inhabitants and above. These 62 islands are the final sample to simulate the regional techno-economic potential for renewable energies on Caribbean islands and are listed in Tab. 4.1.

Table 4.1: *Island sample - all target islands. Abbreviations stand for island ID (ID), and population (Pop.)*

ID	**Island name**	**Country**	**Area**	**Pop.**	**Pop. per area**
			km^2	# (sum)	# / km^2
ATG01	Antigua	Antigua and Barbuda	280	78,749	281.2
ATG02	Barbuda	Antigua and Barbuda	144	1,573	10.9
ABW01	Aruba	Aruba	184	104,642	567.5
BHS01	New Providence	Bahamas	229	204,168	891.4
BHS02	Grand Bahama	Bahamas	1,124	45,347	40.3
BHS03	Great Abaco	Bahamas	1,276	10,509	8.2
BHS04	Eleuthera	Bahamas	477	6,541	13.7
BHS05	Andros	Bahamas	3,986	5,338	1.3
BHS06	Great Exuma	Bahamas	248	3,190	12.9
BHS07	Long Island	Bahamas	480	2,954	6.1
BHS08	Great Harbour Cay	Bahamas	27	1,504	55.3
BHS09	Paradise Island	Bahamas	4	1,430	343.8
BHS10	Cat Island	Bahamas	374	1,207	3.2
BHS11	South Andros	Bahamas	886	1,195	1.3
BHS12	North Bimini	Bahamas	21	1,167	55.3
BRB01	Barbados	Barbados	436	273,513	627.6
BES01	Bonaire	Caribbean Netherlands	281	11,078	39.5
BES02	Saba	Caribbean Netherlands	14	1,405	98.0
VGB01	Tortola	British Virgin Islands	65	20,794	319.1
VGB02	Virgin Gorda	British Virgin Islands	24	3,870	161.9
CYM01	Grand Cayman	Cayman Islands	222	47,980	216.2
CYM02	Cayman Brac	Cayman Islands	45	1,902	42.0
CUB01	Cuba	Cuba	114,506	11,413,451	99.7
CUB02	Isla de Pinos	Cuba	2,458	89,684	36.5
CUW01	Curacao	Curacao	440	147,278	334.4
DMA01	Dominica	Dominica	754	67,629	89.7
DOM01	Hispaniola East	Dominican Republic	48,662	9,973,154	204.9
GRD01	Grenada	Grenada	317	89,852	283.9
GRD02	Carriacou	Grenada	32	6,121	188.7
GLP01	Basse/Grande-Terre	Guadeloupe	1,450	418,530	288.6
GLP02	Marie-Galante	Guadeloupe	160	11,959	74.8
GLP03	Terre-de-Haut	Guadeloupe	5	1,956	358.9
GLP04	La Désirade	Guadeloupe	21	1,943	91.5
HTI01	Hispaniola West	Haiti	26,764	9,499,815	355.0
HTI02	Île de la Gonave	Haiti	705	78,580	111.4
HTI03	Tortuga	Haiti	187	33,954	181.4
HTI04	Île à Vache	Haiti	47	14,427	303.9
HTI05	Grande Cayemite	Haiti	52	3,849	73.9
JAM01	Jamaica	Jamaica	11,630	2,929,921	251.9

ID	**Island name**	**Country**	**Area**	**Pop.**	**Pop. per area**
			km^2	# (sum)	# / km^2
MTQ01	Martinique	Martinique	1,115	425,296	381.4
MSR01	Montserrat	Montserrat	101	4,753	47.3
PRI01	Puerto Rico	Puerto Rico	8,751	3,577,940	408.8
PRI02	Isla De Vieques	Puerto Rico	137	9,548	69.8
PRI03	Isla De Culebra	Puerto Rico	29	1,738	60.9
BLM01	St. Bartelemy	Saint-Bartelemy	22	7,550	344.9
MAF01	St. Martin North	Saint-Martin	54	33,430	617.5
KNA01	St. Kitts	Saint Kitts and Nevis	172	35,669	207.8
KNA02	Nevis	Saint Kitts and Nevis	95	10,154	106.6
LCA01	St. Lucia	Saint Lucia	614	143,632	233.8
VCT01	St. Vincent	Saint Vincent and the Gr.	349	81,193	232.9
VCT02	Bequia	Saint Vincent and the Gr.	17	5,526	319.2
VCT03	Union Island	Saint Vincent and the Gr.	9	1,618	190.4
SXM01	St.-Martin South	Sint Maarten	38	25,746	679.0
TTO01	Trinidad	Trinidad and Tobago	4,836	1,168,108	241.5
TTO02	Tobago	Trinidad and Tobago	309	45,650	147.9
TCA01	Providencales	Turks and Caicos Islands	128	18,999	148.7
TCA02	Grand Turk	Turks and Caicos Islands	19	6,887	358.5
TCA03	North Caicos	Turks and Caicos Islands	217	4,901	22.5
TCA04	South Caicos	Turks and Caicos Islands	23	1,613	69.6
VIR01	St. Croix	Virgin Islands U.S.	220	53,791	244.8
VIR02	St. Thomas	Virgin Islands U.S.	76	47,218	619.5
VIR03	St. John	Virgin Islands U.S.	2,639	50.7	1715.49

Table 4.1 reveals that most countries consist of one main major island and none or few additional small island as for example for Aruba, Barbados, Cuba. Exceptions are the Bahamas, Turks and Caicos Islands, and U.S. Virgin Islands with a more diverse island landscape. These findings are underlined in the visualization of the sample islands in Figure 4.2

The three biggest islands are found in Cuba (CUB01) with 11,413,451 inhabitants, the Dominican Republic (DOM01) with 9,973,154 inhabitants, and Haiti (HTI01) with 9,499,815 inhabitants. Overall, the results of the GIS calculation are very robust compared to census data published in the CIA factbook [28].

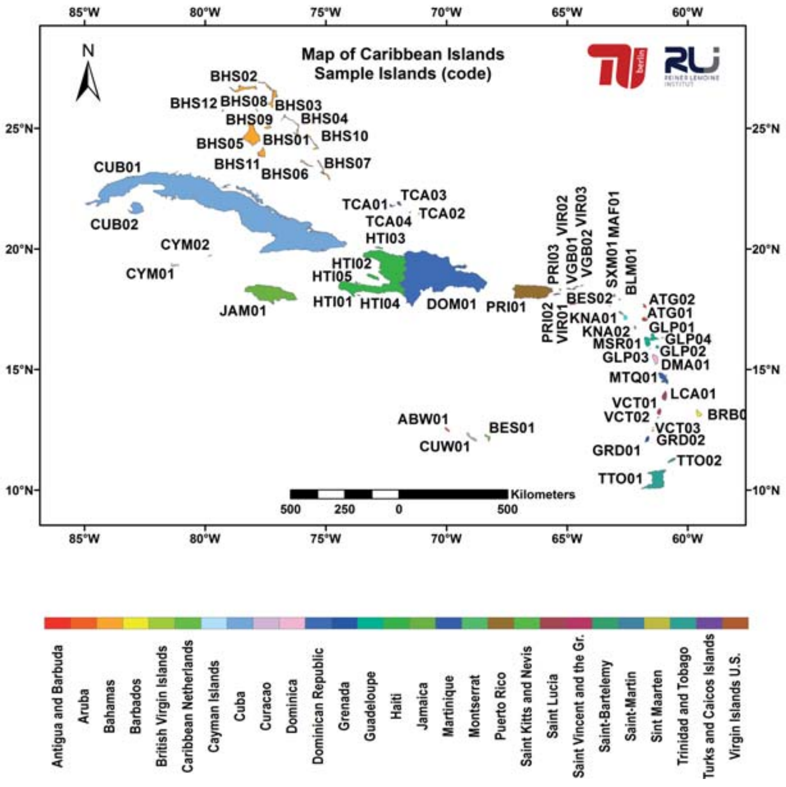


Figure 4.2: *Map of 62 sample islands and related countries (for island ID please compare with Table 4.1)*

4.2 Resource data

For the energy system model it is not only necessary to know the annual theoretical potential of different renewable technologies but also the time related distribution in hourly steps during the reference year. These time series are crucial for a detailed energy system simulation. Thus this section targets to show the way and results of deriving the electrical potential of different resources from existing resource data. For solar, wind and hydro power the potential is shown in resource maps and time series are calculated based on the physical constraints of each technology as shown in Subsec. 2.2.2. The geothermal and biomass potential are only explained theoretically.

4.2.1 Solar

The baseline to derive each islands solar potential is the local global horizontal irradiation (GHI). GHI values in hourly timesteps enable the generation of a synthetic PV production time line for the analyzed locations. The conversion follows the technological constraints for PV plants and efficiency assumptions as described in Subsec. 2.2.2.

GHI data are obtained from a NASA data set covering the years of 1984 to 2005 on a global scale in a 0.45° by 0.45° resolution and six hour time steps [95]. It is validated by the German Aerospace Agency (DLR) and rendered to hourly values using a clear sky approach [96]. For the simulation and optimization the year 2000 is chosen to compare the data with the hydro data which are only available until the year 2000. To eliminate outliers the hourly values of the year 2000 are scaled according to the average from 2000 to 2005. The resulting annual sums of solar irradiation for the Caribbean area are shown in Fig. 4.3.

As it can be seen in Fig. 4.3 the irradiation ranges from 1,700 to 2,300 kWh/(m^2*year) which are very high values compared to regions such as Germany (850 to 1,200 kWh/(m^2*year)) [95]. The smaller Eastern islands show a higher potential of solar as less cloud coverage can be observed compared to the large islands of Cuba and Hispaniola with high mountains. Within the simulation only one PV plant per island is assumed. For small islands the irradiation pixel which is reached by the centroid is taken as input parameter. For larger islands, that are covered by several irradiation pixels, the average solar irradiation of the island's area is used. The derived GHI values are further processed to get PV power generation profiles for each island.

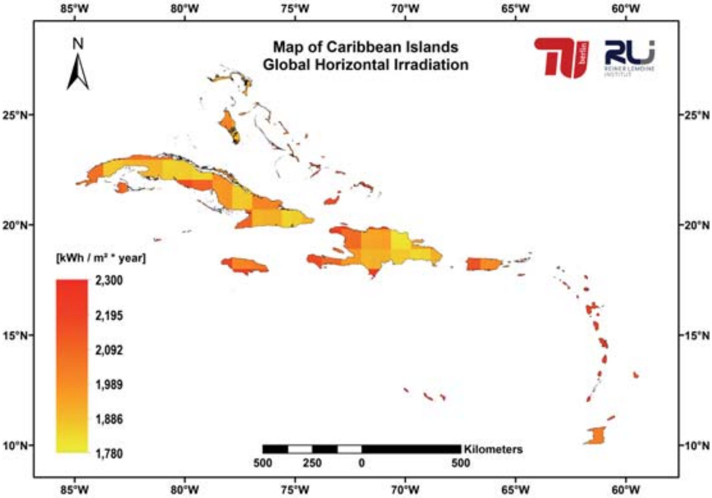


*__Figure 4.3:__ Annual sum of solar irradiation within the Caribbean area averaged for the years 2000 to 2005 in [kWh/(m^2 *year)]*

The conversion of resource data to electrical output is described in a model by Huld et al. [97]. In this paper a method to estimate the geographical variation of the performance of PV modules based on crystalline silicon (c-Si) cells is described and applied. The focus is set on the effects of climate parameters on the efficiency of the PV modules, in particular by solar irradiation and temperature. This temperature based efficiency is combined with other parameters such as degradation and internal efficiency losses by cabling and inverters to reflect a turn-key PV plant. Excluding temperature effects the performance ratio η_{system} is assumed to be around 80 percent [98].

An optimized angle for the PV plant has finally to be determined, which is based on a paper of Breyer and Schmid [99]. It shows that the optimized tilt angle is similar to the degree of latitude in regions close to the equator. Due to these findings the angle is chosen similar to the degree of latitude for the Caribbean islands.

In summary the following steps are computed to derive the PV yield. The GHI is adapted to the tilted surface of optimized angle. This adapted GHI, further called irradiation I on modules, is fed into Eq. 4.1 to derive the electric output of the PV modules $\mathrm{P}_{\mathrm{modules}}$.

$$\mathrm{P}_{\mathrm{modules}} = \mathrm{I} \cdot \eta_{\mathrm{T}} \tag{4.1}$$

The electric output is also influenced by the temperature efficiency η_{T}.

$$\begin{aligned}\eta_{\mathrm{T}} = (1 + 0.0012 \cdot (\mathrm{T}_{\mathrm{module}} - 25^{\circ})) \cdot (1 + 0.033 \cdot \log(\mathrm{I}) \\ -0.0092 \cdot \log(\mathrm{I})^2 - 0.0046 \cdot (\mathrm{T}_{\mathrm{module}} - 25^{\circ}))\end{aligned} \tag{4.2}$$

As seen in Eq. 4.2 the temperature efficiency η_{T} is derived from the module temperature $\mathrm{T}_{\mathrm{module}}$ and irradiation I.

$$\mathrm{T}_{\mathrm{module}} = \frac{\mathrm{I}}{\mathrm{I}_{\mathrm{NOCT}}} \cdot (\mathrm{NOCT} - 20^{\circ}) + \mathrm{T}_{\mathrm{extern}} \tag{4.3}$$

The module temperature $\mathrm{T}_{\mathrm{module}}$ increases or decreases with the current irradiation I compared to the irradiation under a normal operating cell temperature (NOCT, $\mathrm{I}_{\mathrm{NOCT}}$=800 W/m^2) and the ambient temperature $\mathrm{T}_{\mathrm{extern}}$ [100, 101]. As ambient temperature only daily values are taken as applied by Montes et al. [102].

The calculated output of the PV modules $\mathrm{P}_{\mathrm{modules}}$ is combined with the overall performance ratio to derive the PV plants output $\mathrm{feedin}_{\mathrm{PV}}$ as described in Eq. 4.4.

$$\mathrm{feedin}_{\mathrm{PV}} = \mathrm{P}_{\mathrm{modules}} \cdot \eta_{\mathrm{system}} \tag{4.4}$$

With all the aforementioned Eq 4.1, 4.2, 4.3, and 4.4 based on Quaschning [7] the PV yield time series $\mathrm{feedin}_{\mathrm{PV}}$ for each sample island can be derived. This represents the PV plants output of one year in hourly time steps.

4.2.2 Wind

Similar to the PV yield in Subsec. 4.2.1 the potential wind power generation of one wind power plant for each island is derived. As main input data the wind speeds at 50 m height are found in a NASA data set [95]. The data set has the same spatial resolution, 0.45° by 0.45° as the GHI data and hourly time series from the year 1985 until 2005 are available. On a rough comparison these data are validated by a more detailed study of Chadee and Clarke [103]. As these detailed data are not accessible for this thesis the hourly time series from NASA [95] are used. To eliminate extreme years with exceptional high or low wind speeds an average wind speed from 2000 to 2005 is derived and illustrated in Fig. 4.4.

For larger islands with more than one data point for wind speeds the following assumption is made. It is anticipated that for wind farms special locations with high wind speeds are preferred. Thus the average value of the mean and the maximum wind speed of the islands is used instead of the overall mean wind speed. Applying these averaged values the time series of the year 2000 is scaled accordingly for each island. This keeps the hourly wind profile comparable to the other renewable resources such as solar and hydro and adjusts the yearly wind power generation to a 6 year average.

The derived hourly wind speed values are converted into electric output of wind turbines. Two different wind turbines are chosen based on existing projects in the Caribbean. The first turbine is a smaller wind turbine from Vergnet (GEV MP275 - 275 kW [104]) which are installed in a 1.1 MW park on Nevis [105]. This turbine is especially advantageous for smaller Caribbean islands due to the easy erection and maintenance concept. No heavy equipment is needed to install this turbine as it has a self-erecting concept. In case of hurricanes it can easily be lowered to the ground and therefore survives hurricanes up to category 5 on the Saffir-Simpson hurricane

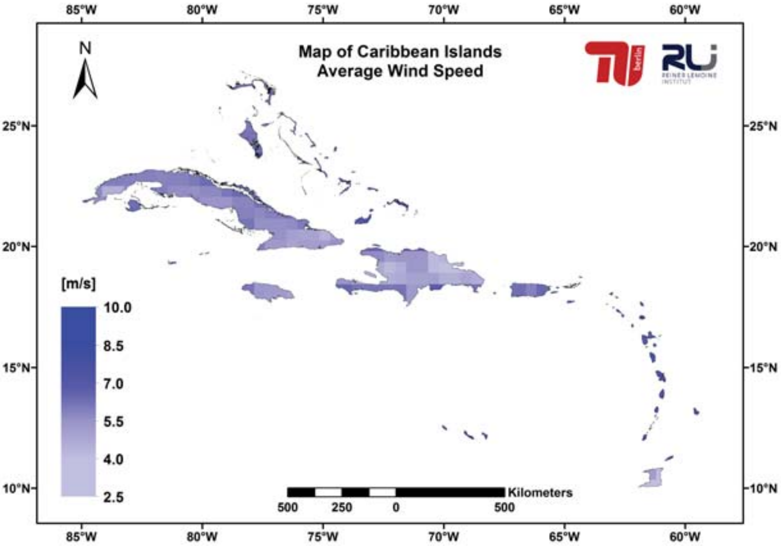


Figure 4.4: Average wind speeds within the Caribbean area for the years 2000 to 2005 in [m/s]

wind scale [106]. Based on these features the GEV MP275 turbine is selected for all smaller islands below 50,000 inhabitants.

The other turbine type is installed in one of the first large wind farms in the Caribbean - in Wigton, Jamaica [105, 107]. This farm is comprised by 14 Vestas V80-2000 (2,000 kW) turbines [108]. The turbine is classified for IEC-1 strong-wind locations which fits very good to the Caribbean islands with very high prevailing wind speeds. The technical specifications of the chosen wind turbines are listed in Table 4.2.

Table 4.2: *Technical overview on GEV MP275 (Vergnet) and V80-2000 (Vestas) wind turbine*

Category	**GEV MP275 (Vergnet)**	**V80-2000 (Vestas)**
Rated capacity	275 kW	2,000 kW
Regulation	Pitch	Pitch
Number of blades	Two	Three
Hub height	55 m	80 m
Cut in wind-speed	3.5 m/s	4 m/s
Cut out wind-speed	25 m/s	25 m/s
Lowering system	Yes	No

To convert the wind speed values into electric output two steps are necessary. First, the wind speeds available in 50 m height have to be transformed to the wind speeds at hub height of the wind turbine. Second, these adjusted wind speeds are combined with the power curve of each wind turbine to derive the power output on hourly basis for one wind park at each analyzed island. The power curve is defined by the respective manufacturers and indicates the expected power output of the wind turbine at certain wind speeds.

The adaption of the wind speeds according to the height is based on Eq. 4.5.

$$\mathrm{v_2(h_2) = v_1(h_1) \cdot \frac{\ln(\frac{h_2}{z_0})}{\ln(\frac{h_1}{z_0})}} \tag{4.5}$$

The wind speed $\mathrm{v_1}$ from the global data set on the height $\mathrm{h_1}$ is transformed to the wind speed $\mathrm{v_2}$ on the hub height $\mathrm{h_2}$. A crucial factor is the roughness length $\mathrm{z_0}$. The longer the roughness length the higher is the influence of the height difference. The roughness length is determined by the topography, surface, vegetation, and urban development of the location. For the Caribbean it is expected that the turbines are erected in coastal zones close to the sea, therefore a roughness length z_0 of 0.03 m is chosen [109].

After applying Eq. 4.5 the resulting wind speed v_2 is combined with the power curves illustrated in Fig. 4.5.

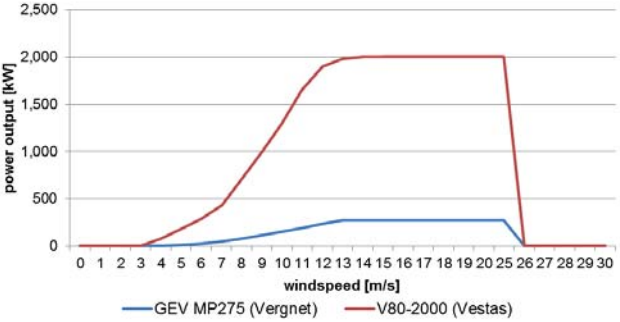


Figure 4.5: *Power curves of GEV MP275 (Vergnet) and V80-2000 (Vestas) for wind speeds from 0 to 30 m/s (values obtained from [104, 108])*

By applying the power curves (cf. Fig. 4.5) the electric output of potential wind turbines on each sample island is derived. This output $feedin_{wind}$ is given for one year in hourly time steps for each island.

4.2.3 Hydro

Within this subsection the derivation of the hydropower potential for Caribbean islands is explained. Assessing the hydropower potential of a certain region requires sophisticated water flow modeling. As it is far beyond the scope of this work to set up an own water flow model a collaboration with the waterGAP research group of the University of Kassel were established. More details on the water flow model waterGAP can be found in the literature [110–113].

The target within this thesis is to determine hydropower potential of different areas based on local discharge (runoff) and height values. Local discharge values are based on the results of waterGAP. This is combined with existing hydropower plants to examine the developed hydropower potential. In theory five different potentials are distinguished (cf. [114]):

- *Gross hydropower potential*: Annual energy that is potentially available if all natural runoff at all locations were to be harnessed down to the sea level (or to the border line of a country) without any energy losses.
- *Technical hydropower potential*: Has been or can be developed under current technologies. This is done by multiplying efficiency by the gross hydropower potential.
- *Economic hydropower potential*: Has been or can be developed cost competitive compared to current energy sources. To derive this potential costs of hydropower and other energy sources need to be compared.
- *Exploitable hydropower potential*: Environmental or other restrictions are taken into account. This means for example excluding protected areas and reducing usable discharge due to environmental reasons.
- *Developed hydropower potential*: Actual potential of existing hydro power plants. By that only discharge values for existing hydropower plants are taken into account.

This research work focuses on the gross and developed hydropower potential only. For the power simulations only the developed one is considered as it is too difficult to assess the amount of untapped exploitable potential due to missing data about environmental or other restrictions. However, to derive the developed potential, the gross has to be determined. The gross hydropower potential GHP is defined by Eq. 4.6.

$$\mathrm{GHP} = \eta \cdot \rho \cdot \mathrm{g} \cdot \mathrm{Q} \cdot \triangle \mathrm{h} \tag{4.6}$$

Efficiency η is assumed to be 100 percent for all plants to develop the global GHP. Density of water (ρ = 1,000 kg · m^3) and gravitational acceleration constant (g = 9.81 m / s^2) are known on a global scale, but the discharge flow Q and height differences $\triangle$h need to be assessed for each specific location. As aforementioned the discharge values are taken from the waterGAP model and are based on precipitation, evaporation, water use, soil, and vegetation. Daily values are provided for the years 1961 to 2000 in cell sizes of a 5 by 5 arc minutes grid for the Caribbean area. For the simulation the daily values of 40 years are averaged and used to level the daily values of the year 2000 as input parameter for further calculations.

In order to validate the waterGAP input data a global potential analysis is performed and results are compared to similar reports. Doing this the hydropower potential of each cell worldwide is calculated down to sea level. This means the height difference $\triangle$h is the mean height level of each cell minus sea level (equals to zero). To reduce the calculation effort the cell size is much greater than for the detailed study in the Caribbean (0.5° by 0.5°). Table 4.3 shows the results of this calculation and other global studies.

Table 4.3: *Theoretical world gross hydropower potential*

Source	**Potential**
Own calculation	41,326 TWh/year
Hydropower and Dams Atlas [115]	40,500 TWh/year
2000 Eurowasser Article [116]	45,000 TWh/year
2005 Eurowasser Article [117]	52,500 TWh/year

As seen in Tab. 4.3, the overall gross hydropower potential of the world calculated in this thesis adds up to 41,326 TWh/year. This theoretically calculated value is almost similar to the value of 40,500 TWh/year given in [115]. Lehner et al published two global values, 45,000 TWh/year and 52,500 TWh/year [116, 117]. The changes in these values are not explained within the literature. Anyhow, the results are still within 20 % accuracy which is acceptable for a theoretical global overview and the methodology and input data can be used for further research.

To derive the specific local potential the next downstream cell of the data grid is taken as reference instead of the sea level (cf. [116]). For each cell two height values are needed, the mean height and the minimum height. By that the internal and external hydropower potential of each cell can be calculated. The internal potential is based on $\triangle h_{int}$ as the difference between mean height h_{mean} and minimum height h_{min} of the cell (cf. Eq. 4.8) which is multiplied by the internal discharge Q_{int} only (cf. Eq. 4.7).

$$\mathrm{Pot}_{int} = \triangle h_{int} \cdot \eta \cdot \rho \cdot g \cdot Q_{int} \tag{4.7}$$

$$\triangle h_{int} = h_{mean} - h_{min} \tag{4.8}$$

In contrast to the internal potential Pot_{int} the external potential Pot_{ect} can consist of zero to maximum eight single values depending on the number of upstream cells n. Summing up all single external potentials leads to the overall external potential of one cell as it is shown in Eq. 4.9.

$$\mathrm{Pot_{ext}} = \sum_{i=1}^{n} \triangle \mathrm{h_{ext_i}} \cdot \eta \cdot \rho \cdot \mathrm{g} \cdot \mathrm{Q_{ext_i}} \tag{4.9}$$

$$\triangle \mathrm{h_{ext_i}} = \mathrm{h_{min_i}} - \mathrm{h_{min}} \tag{4.10}$$

$$\mathrm{Q_{ext_i}} = \mathrm{Q_{int_i}} + \mathrm{Q_{ext_{ii}}} \tag{4.11}$$

The difference between the minimum height $\mathrm{h_{min_i}}$ of each upstream cell i and the minimum height $\mathrm{h_{min}}$ of the lower analyzed cell results in $\triangle$ $\mathrm{h_{ext_i}}$ as illustrated in Eq. 4.10. This value is multiplied by the discharge of cell i into the lower cell which is the sum of the internal $\mathrm{Q_{int_i}}$ and external $\mathrm{Q_{ext_{ii}}}$ discharge of cell i (cf. Eq. 4.11). Finally as shown in Eq. 4.12 the sum of internal $\mathrm{Pot_{int}}$ and external $\mathrm{Pot_{ext}}$ potential leads to the overall potential $\mathrm{Pot_{overall}}$ of each cell which can be harvested maximally.

$$\mathrm{Pot_{overall}} = \mathrm{Pot_{int}} + \mathrm{Pot_{ext}} \tag{4.12}$$

To know the connection of the different cells a flow direction model is applied. For a better understanding of the relation between the single cells and the accumulation of discharge values an example is drawn in Fig. 4.6.

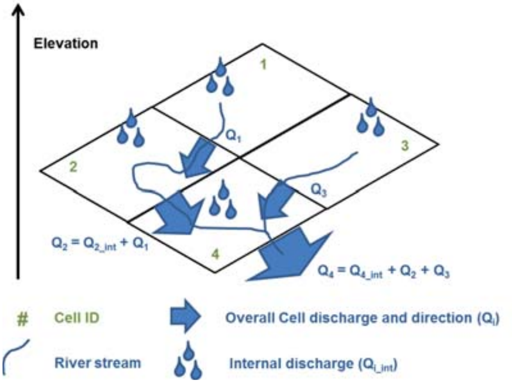


Figure 4.6: *Sketch of discharge accumulation*

Based on the aforementioned input data of the waterGAP model the gross hydropower potential is derived for the Caribbean. According to the resolution of approximately 9 km by 9 km for the Caribbean island area 4,352 cells are identified on land. Due to their connection to the South American shape file within the waterGAP model Aruba, Bonaire, Curacao, and Trinidad and Tobago are excluded in this detailed analysis. For each available cell the flow direction of the discharge is known. Based on this information the upper cells for each cell are determined. Afterwards the internal, external, and overall potential for each cell is calculated along Eq. 4.7, 4.9, and 4.12. The following Fig. 4.7 illustrates the gross overall hydropower potential for the analyzed cells in the Caribbean area.

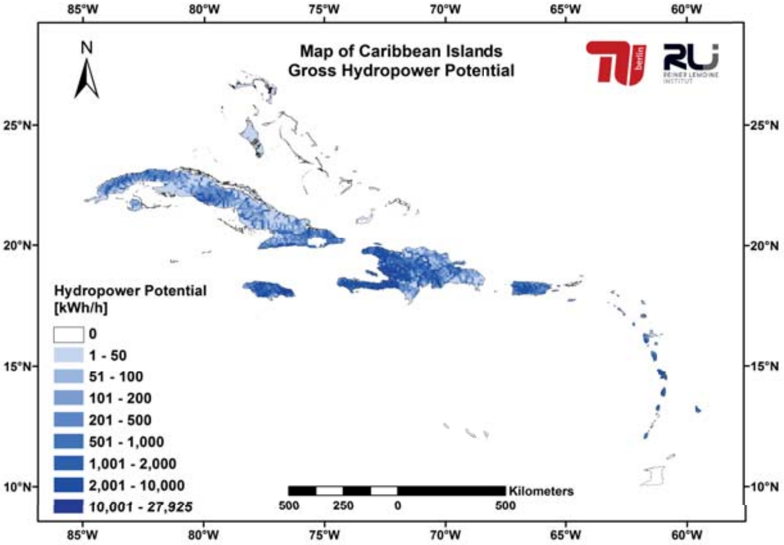


Figure 4.7: *Average theoretical gross hydropower potentials within the Caribbean area for the years 1961 to 2000 in [kWh/h]*

It can be seen that islands with large landmass and high mountains bear the highest potential. The mountains increase on one hand the precipitation and therefore the discharge as they force clouds to rise and to release the rain. On the other hand they increase the energy potential due to bigger height differences in mountainous areas. Consequently, the largest theoretical hydro power potential can be found on the main island of Cuba, Haiti, Dominican Republic, Jamaica, and Puerto Rico. The Bahamas with very flat islands hold almost no hydro power potential.

The second analyzed potential is the developed potential which can only be assessed for existing power plants. For that it is necessary to locate all existing operating hydropower plants on the investigated Caribbean islands. These islands are Cuba, Dominican Republic, Dominica, Guadeloupe, Haiti, Jamaica, Puerto Rico, and Saint Vincent and the Grenadines according to [14].

To derive the developed potential all known hydropower plants have to be geo-referenced. They are identified according to their name and listed location in the database [14] and cross-checked on Google Maps. Multiple units in one location are combined to one power plant. The resulting power plant locations are indicated in Fig. 4.8.

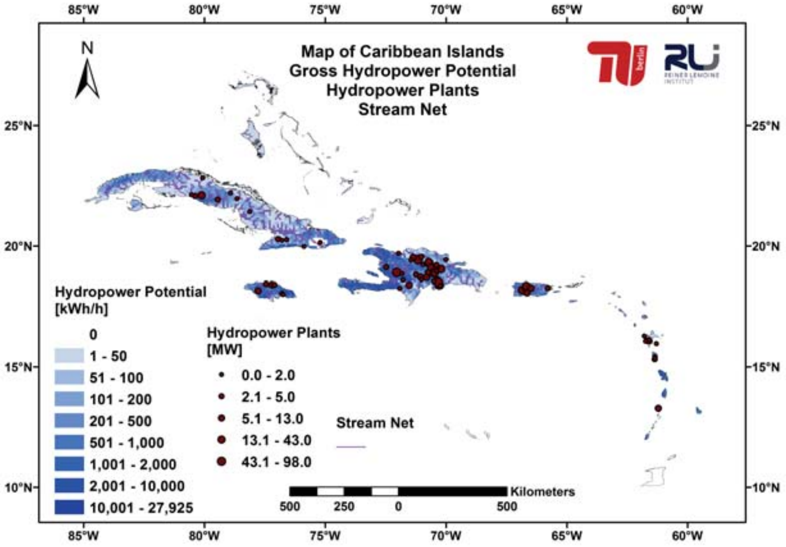


Figure 4.8: *Average theoretical gross hydropower potential within the Caribbean area for the years 1961 to 2000 in [kWh/h] combined with hydropower plant locations and stream net of discharge flows*

As it can be seen in Fig. 4.8 and Tab. 4.4 68 hydropower plant locations are identified. These are supplied by the calculated theoretical hydropower potential of the cell of the location and of all accumulated cells which feed into this cell and are not part of a different hydropower plant. To illustrate this method the stream net of the discharge flows is plotted in Fig. 4.8. Following the stream net up the river from

Table 4.4: *Overview on plant locations (plants), installed hydropower plant capacities [14], calculated hydropower generation, and reference values by IEA World Energy Outlook [118] on Caribbean islands*

Country	**Plants**	**Total capacity**	**Calculated hydropower generation**	**Reference values IEA**
(Island ID)	#	[MW]	[GWh/year]	[GWh/year]
Cuba (CUB01)	13	60.4	114	97
Dominica (DMA01)	3	6.7	19	-
Dominican Republic (DOM01)	27	544.3	1,084	1,435
Guadeloupe (GLP01)	6	8.8	18	-
Haiti (HTI01)	5	55.3	429	177
Jamaica (JAM01)	6	23.8	82	152
Puerto Rico (PRI01)	6	95.4	237	-
St Vincent and the Grenadines (VCT01)	2	6.5	18	-

one power plant location all hydropower potential is summed up for this plant until another plant is found on this stream. This leads to a total accumulated potential energy input for each hydropower location for each hour of the chosen reference year. To adjust this theoretical potential to the usable potential an efficiency factor needs to be determined.

Three reference plants are chosen: Jiguey and Valdesia from the Dominican Republic and the total production capacity of St Vincent [119–121]. For the year 2000 the full load hours of the theoretical values are compared with the real values from the listed sources. By that a conversion factor of 0.8 is derived to adjust the theoretical potential. Equations 4.7 and 4.9 are taken and the efficiency η is changed from 1 to 0.8. With this new equation the production values for all 68 locations are scaled down. The resulting time series are taken as electrical output for the hydropower locations with the constraint that the maximum production of each location cannot be higher than the installed capacity.

These production values are summed up and visualized in Tab. 4.4. The comparison with the 2010 values of the IEA world energy outlook [118] underlines the validity of the derived hourly production values which can be fed into the energy system model. The significant deviation for Haiti is based on the bad conditions of the local power plants since the earthquake in 2010. To account for this huge exemption the hydropower feedin for Haiti is adjusted according to the IEA values. For the Dominican Republic and Jamaica it is assumed that the deviation is based on differences in the precipitation for the considered years so the calculated values can be taken as input for further simulations. By that the hydropower generation time series ($\mathrm{feedin}_{\mathrm{hydro}}$) are finalized and validated. Similar to the PV and wind power yield they can be fed into the simulation tool as kWh/kW. For the developed potential the hydropower capacity for the simulation is determined by the real installed capacity and then multiplied with the time series.

4.2.4 Geothermal

As next renewable resource for power generation geothermal energy and its potential in the Caribbean area is explained in this subsection. In opposite to PV, wind, and hydropower resources no calculations are performed to derive the geothermal potential as it would require local geophysical studies which are not available for this work. Nevertheless the calculation steps of deriving geothermal energy potential are explained and the known potential for Caribbean islands is shown by literature analysis.

As explained in Subsec. 2.2.2 the earth's heat source is powering geothermal plants. Normally, the heat energy in depths down to 4,000 m is not sufficient to generate economically viable electrical power, but in some regions the heat source is much more attractive as it requires less deep drilling to access it or it is even accessible on the surface. This is reflected in the geothermal gradient, which varies from region to region. It averages at 1° C/ 33 m in most regions, but can be several times higher in high-grade geothermal regions [122]. This can be observed in volcanic regions and on the border of continental plates. In the Caribbean area geothermal potential can especially be found along the border of the Caribbean and North Atlantic continental plates. This boundary line is illustrated in Fig. 4.9.

For the island belt along the boundary line several studies were made to assess the geothermal potential. Departments of the University of West Indies and private consultancies have conducted theoretical analyses and drillings to evaluate the potential [47, 122–126]. For the simulation the upper limit for geothermal power generation is determined by the theoretical potential of these studies as shown in Fig. 4.10 and Tab. 4.5.

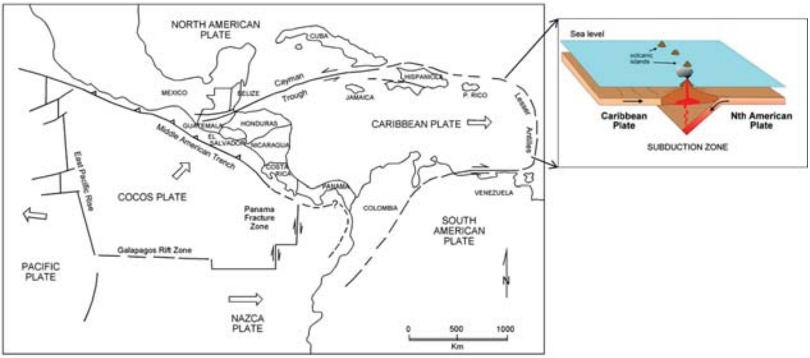


Figure 4.9: Map of continental plates within the Caribbean area [47, 122]

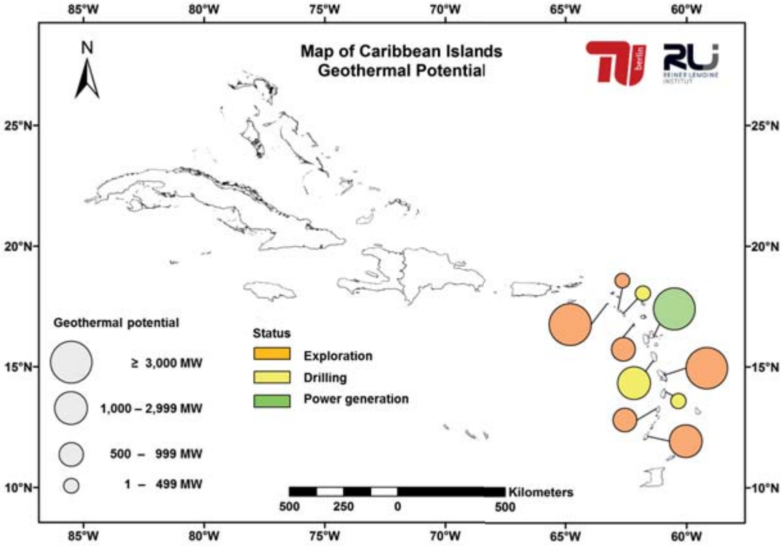


Figure 4.10: Geothermal power potential on Caribbean islands

Table 4.5: Overview on geothermal power potential in the Caribbean area according to [124]

Island (Island ID)	**Geothermal potential** MW	**Status of exploitation**
Saba (BES02)	3,000	Exploration
Dominica (DMA01)	1,390	Drilling
Grenada (GRD01)	1,100	Exploration
Guadeloupe (GLP01)	3,500	Power generation
Martinique (MTQ01)	3,500	Drilling
Montserrat (MSR01)	940	Drilling
Saint Kitts (KNA01)	30	Exploration
Nevis (KNA02)	20	Drilling
Saint Lucia (LCA01)	180	Drilling
Saint Vincent (VCT01)	890	Exploration

On most of the shown islands exploration or drilling have been conducted and on Guadeloupe one geothermal power plant is already operating. Regardless of the status of exploitation as indicated in Fig. 4.10 and Tab. 4.5 the full geothermal potential is used for the energy system simulation of each island. As this potential has no seasonal or daily variations it is assumed as a constant resource. This means for each assumed installed geothermal power capacity the capacity is fully available for each hour of the simulation. Thus each of the islands listed in Table 4.5 holds a constant resource of one kilowatthour electrical output per hour per installed kilowatt geothermal capacity. The only constraint is the upper limit of the theoretical potential.

4.2.5 Biomass

Biomass and biofuels are also seen as renewable resources. Even though they can play a significant role in the paradigm shift of the power generation system they are not considered for the simulations within this work. Two reasons for this exclusion exist: Firstly, biofuel resources are not bound to a particular location or island as all before presented resources solar, wind, hydro, and geothermal energy. Biomass can serve as fuel for conventional combustion and gas power plants and can be transported as well as fossil fuels. Thus the specific local potential for each analyzed island has not to be investigated. Secondly, no sufficient data base exists to estimate at least the technical biomass potential (cf. [127]) for power generation on Caribbean islands within a reasonable time frame. In conclusion, this resource is neglected within the simulations, but still has a great potential to substitute fossil fuels and to support the shift of power generation systems towards 100 percent renewable energies.

Nevertheless, the potential of biomass for energy supply is discussed within this sub-section for Caribbean islands which have a long history of agriculture and farming. Especially sugar cane production has been essential for the economy of these islands but it significantly declined at the beginning of the 21st century [128]. A re-opening of these agricultural facilities bears an enormous potential to produce energy crops [129]. According to the World Bank "the Caribbean region does have biomass resources, however, no projects are in the pipeline and definitive estimates of power generation potential are not available" [130]. Contrary to this statement Jamaica seems to be the driving force of biomass exploitation for power generation with capacities of 41 MW in 2011 [131]. In summary, it can be stated that biomass as fuel for power plants has a great potential for power generation on Caribbean islands due to the high agricultural yields. In addition it can be stored as fuel and power plants can generate flexible power on demand. Thus, it should be considered as substitute for fossil fuels in future energy supply scenarios for Caribbean islands.

With this subsection the overview on resource data for assessing the renewable potential is completed. Overall, very promising natural renewable resources for power generation are found. The timely resolution of hourly steps allows a detailed simulation for one reference year. To conduct this detailed load profiles are necessary which are presented in the next Sec. 4.3.

4.3 Load profiles

Within this section the load profiles for each analyzed island are presented. If real load data are available they are used for the simulation of the related island. For all other islands synthetic profiles are derived. One standard load profile for all low consuming and one for all high consuming islands (energy consumption higher than 100,000 MWh/year) is developed. They are scaled along the countries electricity production from the literature and the islands local gross domestic product.

As a first step the electricity production, which equals to the load demand in this thesis, for every island is derived. Main sources for these data are the CIA factbook [28], a report for the World Bank [132], and data from local utilities. The first two sources provide data on a country level only. To distribute the country's power generation on all single islands the local gross domestic product is used. This approach reflects not only the population of each island but also their economic activity. As the economic activity is strongly linked to the energy consumption it is more precise to use this correlation than the population data only [133]. The data on economic activity are taken from [32] and accumulated for each island similar to the approach used for the population explained in Sec. 4.1. Results for the electricity production of each island are presented in Tab. 4.6.

To distribute the total electricity production on 8,760 hours of a reference year two typical load profiles are applied. For islands with low electricity consumption the load profile of two Grenadine islands is taken: Bequia and Union Island [134]. For these islands no significant difference between week and weekend days can be seen, on all days an evening peak is dominating the daily profile (cf. Fig. 4.11).

Islands with high consumption are reflected by the islands of Aruba, Barbados, Dominica, and Saint Vincent [134–137]. These islands all show similar load profiles with peaks during noon on weekdays and peaks in the evening during weekends as seen in Fig. 4.11. This represents the electricity demand for commercial and industrial purposes. To compensate the different years of the real load profiles all annual load data are shifted that they start with the first Monday in January. Thus, week and weekend days can be identified for all four islands.

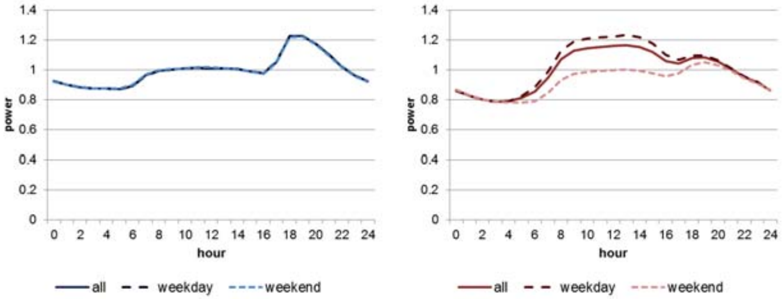


Figure 4.11: *Daily loads for low (left graph) and high (right graph) electricity consumption on Caribbean islands - power scaled to one*

Looking at Fig. 4.12 differences are revealed between the annual load curves of the derived standard load profiles for low and high consumption islands. The profile for high consumption has less variations and peak loads are lower compared to the average load. The summer months show a slightly higher consumption than the winter months on high consumption islands. In opposite to that low consumption islands have a higher load level during winter months. During winter is the peak tourist season, influencing these islands significantly which can also be recognized along the peaks around Easter and Pentecost.

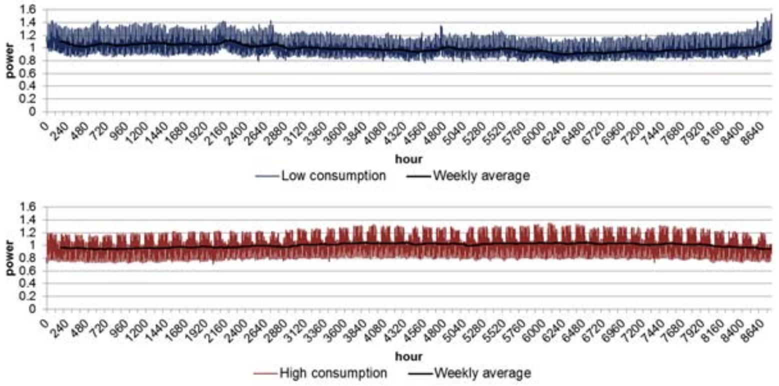


Figure 4.12: *Annual load curve for low (upper graph) and high (bottom graph) electricity consumption on Caribbean islands - power scaled to one*

As aforementioned the presented load profiles are scaled according to the electricity consumption for each island. To choose between low and high consuming islands a threshold value of 100,000 MWh per year is chosen. This makes Dominica the first high consuming island. Dominica shows already the typical profile of a high consumption island with peaks during midday at week days and during the evening on weekend days. Applying the profiles to each island results in an individual annual load profile in hourly steps for each of them. The overall electricity production and the peak load of each island are listed in Tab. 4.6.

By that all time series - resources and loads - for each sample island are presented and available for the simulation. The question about the natural resource availability of renewable energies on Caribbean islands is therefore answered within this chapter. Most of the analyzed islands have abundant wind and solar resources supplemented by hydro and/or geothermal resources. Table 4.6 summarizes the resource data and demand for each island.

Table 4.6: *Results of resource and load assessment for each sample island*

ID	**Solar irradiation**	**Wind-speed**	**Hydro**	**Geo-thermal**	**Peak load**	**Electricity consumption**
#	[kWh/(m^2*y)]	[m/s]	[GWh/y]	[MW]	[MW]	[MWh/y]
ATG01	2,192	7.42			47.3	307,841
ATG02	2,300	7.49			1.8	10,159
ABW01	2,174	9.62			127.5	947,186
BHS01	2,067	6.62			158.8	1,032,866
BHS02	2,067	6.43			92.7	603,200
BHS03	1,901	6.41			8.4	47,925
BHS04	2,044	6.45			11.8	67,576
BHS05	1,988	6.19			6.5	37,397
BHS06	1,988	6.20			7.8	44,481
BHS07	1,988	6.14			6.9	39,291
BHS08	1,934	6.40			0.7	3,820
BHS09	1,864	5.84			4.6	26,588
BHS10	1,946	6.06			3.3	18,999
BHS11	1,930	6.17			2.3	13,025
BHS12	1,932	6.31			0.8	4,721
BRB01	2,257	7.94			163.0	1,053,700
BES01	2,177	8.78			15.6	89,162
BES02	2,131	7.38		3,000	0.9	4,869
VGB01	2,130	7.11			7.7	43,820
VGB02	2,130	7.12			1.1	6,210
CYM01	2,129	6.98			87.4	568,792
CYM02	2,129	6.77			4.4	25,214
CUB01	2,083	6.27	114		2,718.0	17,682,059
CUB02	1,847	6.06			18.1	117,941
CUW01	2,216	9.05			274.4	1,785,000
DMA01	2,209	7.55	19	1,390	17.2	101,667
DOM01	1,907	5.64	1,084		2,012.1	13,090,000
GRD01	2,183	7.94		1,100	29.2	190,074
GRD02	2,183	7.98			1.9	11,039
GLP01	2,182	7.20	18	3,500	254.7	1,657,163
GLP02	2,232	7.25			8.3	47,351
GLP03	2,182	7.36			1.4	7,745
GLP04	2,084	7.17			1.3	7,693
HTI01	2,084	6.09	429		110.9	721,197
HTI02	1,964	5.36			0.5	2,913
HTI03	2,098	4.72			0.2	1,243
HTI04	2,051	5.80			0.0	242
HTI05	2,190	6.51			0.1	452
JAM01	2,081	5.69	82		608.3	3,957,000
MTQ01	2,221	7.56		3,500	249.0	1,620,000

ID	**Solar irradiation**	**Wind-speed**	**Hydro**	**Geo-thermal**	**Peak load**	**Electricity consumption**
#	[kWh/(m^2*y)]	[m/s]	[GWh/y]	[MW]	[MW]	[MWh/y]
MSR01	2,176	7.36		940	4.2	24,000
PRI01	2,034	6.60	237		3,068.0	19,959,090
PRI02	2,034	6.69			8.4	48,071
PRI03	2,068	6.24			2.3	12,896
BLM01	2,176	7.38			5.2	29,894
MAF01	2,179	7.37			42.5	276,406
KNA01	2,177	7.43		30	25.5	166,000
KNA02	2,177	7.42		20	11.7	67,000
LCA01	2,214	7.60		180	54.7	356,000
VCT01	2,182	7.96	18	890	20.9	126,120
VCT02	2,204	7.79			1.5	7,609
VCT03	2,210	7.72			0.5	2,774
SXM01	2,183	7.37			46.8	304,300
TTO01	2,028	5.11			1,184.1	7,703,466
TTO02	2,144	6.86			45.3	294,560
TCA01	2,172	7.48			23.0	149,616
TCA02	2,172	7.44			4.5	26,010
TCA03	2,161	7.21			3.1	17,846
TCA04	2,158	7.23			1.3	7,557
VIR01	2,160	7.16			76.6	498,073
VIR02	2,131	7.10			40.4	262,737
VIR03	2,039	7.04			5.8	33,204

4.4 Economic input data

After presenting the resource and load data this section gives an overview of the economic input data for the different technologies. The values are distinguished for small or large islands (population less or higher than 50,000) and low or high consumption islands (electricity consumption lower or higher than 100,000 MWh/year).

The fossil plants represent the current conventional energy supply on the analyzed islands and their specifics can be found in Tab. 4.7. The installed capacities are assumed to be two times the peak load for islands with low consumption profiles and 1.5 times the peak load for islands with high consumption profiles as indicated in Tab. 4.6. Initial costs (IC) for diesel plants are set at 550 USD/kW for medium speed diesel on low consumption islands and at 500 USD/kW for islands with high consumption profiles using low speed diesel. Even though these plants are already installed the replacement of old capacities over the project lifetime and the current depreciation are reflected in the initial costs. Operation and maintenance expenditures (OPEX) in USD per kWh electrical output are given with 0.06 USD/kWh for small high speed diesel plants and 0.04 USD/kWh for large low speed diesel plants [38, 138]. The lifetime for fossil plants on both types of islands is assumed to be 30 years and the efficiency on low consumption islands is 36 % and on high consumption islands the efficiency is 40 % [40, 139]. In the specification sheets of power generating units efficiencies with a five percentage points higher efficiency are found compared with the previously mentioned ones. The reduction of the efficiencies for the simulation is made due to part load operation and high ambient temperatures in the Caribbean.

Table 4.7: *Economic input parameter for simulation - Fossil plant*

Parameter	**Unit**	**Low consumption**	**High consumption**
Capacity	kW	2 * peak load	1.5 * peak load
IC	USD/kW	550	500
OPEX	USD/kWh	0.06	0.04
Lifetime	y	30	30
Efficiency	%	36	40
Fuel costs	USD/kW$_{\text{th}}$	cf. Tab. 4.8	cf. Tab. 4.8

As final input parameter for fossil plants, the fuel costs for the power plant are determined. They are individually chosen for each country based on the fuel surcharge of the country. Fuel costs on side islands are raised by 15 percent compared to the related main island due to transport costs and lack of economies of scale. Tab. 4.8 shows the fuel costs and sources for each country.

For islands with fuel surcharge the values are taken from a CARILEC survey [140] or updated by other sources as indicated in Tab. 4.8. To derive the price per thermal kilowatthour the fuel surcharge is multiplied with the average efficiency of the fossil power plants on the island according to Tab. 4.8. For islands without fuel surcharge either costs of the neighbouring islands are taken or fuel prices are taken into account, which is further explained in Tab. 4.8. Fuel prices for Cuba and Dominican Republic are built of three quarter of heavy fuel oil (HFO) costs (600 USD/ton [142]) and one quarter of diesel costs (1.3 and 1.35 USD/liter [143]) according to the share of HFO and diesel power plants derived from a power plants data base [14]. For Haiti only

Table 4.8: *Fuel costs for all countries in USD per thermal kWh and commercial bank rates*

Country	**Costs** [USD/kWh$_{\text{th}}$]	**Comment/ Source**	**Bank rate**
Antigua and Barbuda	0.100	[140]	9.40 %
Aruba	0.088	[141]	10.50 %
Bahamas	0.072	[140]	4.75 %
Barbados	0.088	[140]	8.50 %
Caribbean Netherlands	0.076	[140]	2.30 %
British Virgin Islands	0.061	[140]	4.40 %
Cayman Islands	0.094	[140]	4.40 %
Cuba	0.068	HFO and diesel [142, 143]	9.60 %
Curacao	0.084	[140]	2.30 %
Dominica	0.068	[140]	9.10 %
Dominican Republic	0.069	HFO and diesel [142, 143]	13.60 %
Grenada	0.092	[140]	9.40 %
Guadeloupe	0.084	Dominica and Antigua	3.10 %
Haiti	0.095	Diesel [143]	9.20 %
Jamaica	0.092	[140]	17 %
Martinique	0.078	Dominica and St. Lucia	3.10 %
Montserrat	0.126	[144]	8.30 %
Puerto Rico	0.092	Jamaica	3.30 %
Saint-Bartelemy	0.076	[140]	3.10 %
Saint-Martin	0.072	Sint Maarten	3.10 %
Saint Kitts and Nevis	0.065	[140]	8.90 %
Saint Lucia	0.088	Including adjustment [145]	9.30 %
Saint Vincent and the Grenadines	0.080	[140]	9.40 %
Sint Maarten	0.072	[140]	2.30 %
Trinidad and Tobago	0.008	Natural gas [146]	7.50 %
Turks and Caicos Islands	0.083	[140]	4.40 %
Virgin Islands U.S.	0.124	[140]	3.30 %

diesel plants are assumed with costs of 1.03 USD/liter [143]. Trinidad and Tobago is an exception with very low fossil costs due to the usage of own natural gas resources with very low exploration costs in power plants with gas turbines [146].

After presenting the input parameters for fossil plants the ones for renewable energies are shown. These parameters are distinguished for small and large islands according to the population threshold of 50,000. The economic values for the renewable energies focus on initial costs, OPEX, and lifetime. For turn-key photovoltaic systems, which include modules, mounting structure, and balance of system components, the initial costs are 2,000 USD/kW$_\mathrm{p}$ for small and 1,800 USD/kW$_\mathrm{p}$ for large islands. These values are based on personal communications with VINLEC [147]. OPEX are assumed to be 2 percent of initial costs per year and kilowattpeak installed and the lifetime is 20 years [8]. The economic values of the wind turbines are taken from existing implemented projects. For both, Vergnet and Vestas turbines, the turn-key installation costs are 2,500 USD/kW and lifetimes for Vergnet are 20 and for Vestas 25 years [148,149]. OPEX are based on standard values and result in 5 percent of the initial costs [9, 150]. Hydropower plants are all already in place but still initial costs are assigned as they are depreciated over a long lifetime of 50 years. These costs add up to 4,000 USD/kW and 3,000 USD/kW depending on the size of the island. OPEX per year are 120 and 90 USD/kW (3 % of IC) respectively [10]. As last renewable technology geothermal plants are presented. They reflect one exception as they have a fixed and a variable value for the initial costs. The fixed value is introduced due to the high initial costs for drilling to exploit the geothermal resources. For each geothermal project a fixed value for boreholes of 2 million USD is applied [151]. The variable investment costs are 3,800 USD/kW for double flash power plants such as it is installed in Guadeloupe. Operation and maintenance expenditures add up to 200 USD per year and kilowatt installed [152, 153].

As storage technology a sodium sulfur battery with a fixed c-rate of 1 kW / 6 kWh is chosen. The cost for battery storage include inverters and all components for a fully working storage system and are given per kilowatthour. Initial costs add up to 550 USD/kWh and OPEX are 10 USD/kWh/year [154]. The lifetime is assumed to be 14 years [91].

As final economic input parameter the weighted average costs of capital (WACC) are essential for the simulation. For all projects an equity ratio of 30 to 70 is taken and a fixed equity rate of return of 15 percent. Interest rates for loans are adjusted according to the commercial bank prime lending rate of each country [28] which are listed in Tab. 4.8. The lending rate is not available for Cuba, therefore an average value of all countries, which are not connected to any other countries such as the United States or an European country, is assumed for Cuba. Finally, all presented values for all countries are summarized in Tab. 4.8 and in Tab. 4.9. Using these values the techno-economic potential of renewable energies on Caribbean islands can be calculated as presented in the next chapter.

Table 4.9: *Economic input parameter for simulation - Renewables, battery, and other*

Technology	**Parameter**	**Unit**	**Small Island**	**Large Island**
PV plant	IC	USD/kW	2,000	1,800
	OPEX	USD/kW/y	40	36
	lifetime	y	20	20
Wind turbine	IC	USD/kW	2,500	2,500
	OPEX	USD/kW/y	125	125
	lifetime	y	20	25
Hydropower plant	IC	USD/kW	4,000	3,000
	OPEX	USD/kW/y	120	90
	lifetime	y	50	50
Geothermal plant	IC	USD/kW	3,800	3,800
	OPEX	USD/kW/y	200	200
	lifetime	y	30	30
	Boreholes	USD	2,000,000	2,000,000
Battery	IC	USD/kWh	550	550
	OPEX	USD/kWh/y	10	10
	lifetime	y	14	14
Other	WACC	%	cf. Tab. 4.8	cf. Tab. 4.8

Chapter 5

Results of techno-economic optimization - renewable potential

This chapter is separated into four sections to present the techno-economic potential of renewable energies for Caribbean island energy supply systems. Firstly, two showcases demonstrate the functionality and validity of the self-developed simulation tool. Secondly, the overall potential for all 62 target islands is derived. This is followed by a sensitivity analysis of certain input parameters for special islands and concluded by a brief discussion of the results.

5.1 Detailed analyses

As a first step of applying the developed simulation tool detailed analyses for two case study islands are conducted. One small island, Bequia (VCT02), with approximately 5,500 inhabitants is chosen to test a hybrid renewable system consisting of a fossil plant, PV, wind power plants, and batteries. The results of this analysis are compared with the results of other simulation tools. In addition, one larger island - Saint Vincent (VCT01) - with approximately 80,000 inhabitants is selected to show the inclusion of hydro and geothermal power into the aforementioned tool and the validation of the new model components.

5.1.1 Tool comparison

The first detailed analysis serves to compare the self-developed simulation model Matlab (1 h) with the commercially available tool HOMER Energy (cf. Subs. 3.1.1) and one advanced self-developed tool with higher time related resolution named Matlab (1 min). Besides the higher timely resolution the 1 min-model considers a more sophisticated fossil plant dispatch taking into account several generators [72, 155]. The target of this subsection is to understand the differences in the results of different models and to test the applicability of the developed 1 h matlab simulation tool.

The example island Bequia is part of the Grenadine islands and shows a population of around 5,500. It is listed as island VCT02 in Tab. 4.1 and illustrated in Fig. 4.2. The economy is mainly based on tourism which leads to a load profile with an evening peak typical for small islands as shown in Fig. 4.11. The overall electricity consumption per year is 7,609 MWh and the peak load is 1.5 MW. This load is currently supplied by diesel generator sets with an average fuel conversion efficiency of 36 percent.

Within this research part the hybridization of the current diesel system with PV, wind power, and batteries is simulated. The following simulation steps are performed within this section for model comparison: The fossil-only system is simulated for each model and compared with real consumption and cost data of 2013 (indicated as "reality check" in Fig. 5.1). This is followed by a techno-economic optimization of the hybrid system by the 1 h matlab tool once without and once with batteries. In a final step the optimized configurations of these optimizations are simulated in the other two tools in order to analyze possible differences. This is indicated by arrows in Fig. 5.1.

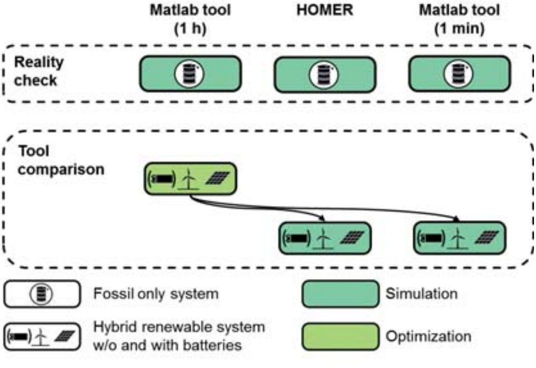


Figure 5.1: *Simulation and optimization steps for tool comparison*

As simulation input parameters photovoltaic and wind power feedin data derived in Subs. 4.2.1 and 4.2.2 are used. They are complemented by the economic input data in Tab. 4.7 and 4.9 for small islands and by the aforementioned load profile.

Reality check - fossil system

During a field trip in April 2014 the current supply system of Bequia was investigated and data were collected to validate the results of fossil-only system simulations. In Tab. 5.1 the results for fossil-only systems are shown for the real system for the year 2013 and simulations with Matlab (1 h) model, HOMER, and Matlab (1 min) model.

Table 5.1: *Tool comparison and reality check for fossil-only system on Bequia*

	Reality	**Matlab (1 h)**	**HOMER**	**Matlab (1 min)**
Fossil fuel consumption [l]	2,157,000	2,147,000	2,147,000	2,157,000
LCOE [USD/kWh]	-	0.341	0.341	0.353
LCOE [USD/kWh] (excl. CAPEX)	0.317	0.316	0.316	0.317

The comparison in Tab. 5.1 shows that the output of 1 h Matlab model and HOMER deviates from the real values but just below 0.5 percent, even though only one generic fossil plant is applied for these two simulation tools. As the 1 min Matlab model is able to simulate three diesel gensets and reflects quick changes in the load in a minutely resolution its results are even closer to the real system with a deviation below 0.1 percent. The LCOE full cost comparison including capital expenditures cannot be performed due to missing values for the real system. The capital expenditures within the 1 min simulation are the highest due to the highest assumed diesel capacities which are necessary to simulate three different gensets. Overall it can be stated that the simulation of fossil-only systems is validated for the island energy supply system of Bequia for all three simulation tools. The Matlab (1 h) model performs sufficiently, therefore it can be used to simulate the status quo of the Caribbean island energy supply systems. In the next step the configurations of renewable hybrid systems are techno-economically optimized.

Tool validation - hybrid system

Looking at Fig. 5.1 reveals that the next procedures are optimizations of hybrid systems without and with batteries. These optimizations are performed with the 1 h Matlab tool and the results are checked by simulations with HOMER and 1 min Matlab tool. The optimization without batteries shows a system configuration with 360 kW PV capacity and 4 wind turbines (1,100 kW). Initial costs of 5,152,000 USD occur for this hybrid island energy supply system (cf. Tab. 5.2).

Table 5.2: *Optimization and simulation results for hybrid system without batteries on Bequia*

	Matlab (1 h)	**HOMER**	**Matlab (1 min)**
PV size	360 kW		
Wind size	1,100 kW - 4 turbines		
Initial costs	5,152,000 USD		
Fossil fuel consumption [l]	1,190,000	1,173,000	1,492,000
LCOE [USD/kWh]	0.278	0.278	0.322
RE-share	45 %	45 %	33 %

The Matlab 1 h tool shows a fuel consumption of 1.19 million liters per year which leads to a renewable share of 45 percent. According to the stability criteria only the fossil plant can provide spinning reserve within this tool and has to supply at least 10 percent of the current load for each time step. HOMER does not directly allow this constraint as the renewable plants provide spinning reserve in HOMER's simulation as well. This leads to slightly lower fuel consumption as the fossil plant supplies less than 10 percent of the load or is even switched off in times of sufficient renewable power generation covering the load plus the spinning reserve. Without batteries or other stability systems this can be considered as unstable operational mode and is therefore a weakness of simulations with HOMER. A trial optimization of the system via HOMER has resulted in a system configuration with a renewable share of 70 percent which can be considered as very unstable system without batteries. Anyhow, as the presented system configuration - optimized by 1 h Matlab tool - shows only short periods of more than 90 percent renewable penetration the results of 1 h Matlab and HOMER are quite similar. The same LCOE indicate the correctness of the applied financial equations.

The 1 min Matlab tool considers spinning reserve just by fossil plants similar to the 1 h Matlab tool. The energy supply system is therefore always in a stable operational mode. The simulated system performs not as well as in the 1 h tool which leads to higher fossil fuel consumption and costs and lower renewable share (34 %). This is due to the fact that the considered fossil power plants are optimized for the fossil-only scenario. They do not show enough flexibility for the hybrid system and often run in part load with lower efficiencies. Thus, these plants should be replaced by more suitable sized plants. The generic plant of the 1 h model fits better with the hybrid system. The higher time resolution underlines the inflexibility as the fossil plants have to react quickly on the fluctuating renewable power supply without the support of batteries.

In conclusion, the 1 min model reflects best the case of implementing renewable plants into an existing fossil fueled system while the 1 h model shows a fully optimized system configuration assuming replacement of existing fossil plants. HOMER can consider both options but has its weaknesses according to stability considerations.

For a final tool comparison batteries are introduced into the energy supply system. Again, an optimization is performed by the 1 h matlab tool followed by simulations with the other tools. The optimization indicates a hybrid system configuration with 624 kW PV and 1,650 kW wind power extended by 862 kWh battery capacitiesas listed in Tab. 5.3.

Table 5.3: *Optimization and simulation results for hybrid system with batteries on Bequia*

	Matlab (1 h)	**HOMER**	**Matlab (1 min)**
PV size		624 kW	
Wind size		1650 kW - 6 turbines	
Battery size		862 kWh - 144 kW	
Initial costs		7,529,000 USD	
Fossil fuel consumption [liter]	647,000	651,000	686,000
LCOE [USD/kWh]	0.250	0.252	0.262
RE-share	70 %	70 %	70 %

Matlab (1 h) and HOMER show only deviations within one percent range in the results. As the battery can provide spinning reserve in the Matlab tool the fossil plant can be switched off. Thus the 1 h Matlab tool and HOMER show almost exactly the same results. The little deviation is based on a bias in the PV generation between both tools which influences the charging/discharging times of the battery. Simulating a one minute time resolution with three different fossil plants leads again to higher fossil fuel consumption and higher costs, but only by five percent. The renewable share is even equal. This is based on the effect of the battery allowing to switch off the fossil plant and to smooth the fluctuations in the renewable energy supply. For hybrid island energy supply systems with such high renewable shares and including batteries the 1 h Matlab tool performs almost as well as the 1 min and similar to HOMER.

Finally, it can be summarized that the optimized results of the 1 h Matlab model are very robust compared to the other applied simulation tools. The standard tool HOMER provides similar simulated results for the example island. The higher detailed time resolution of the 1 min Matlab model and the more detailed diesel power generation plants show potentially more realistic fossil fuel consumption results for hybrid systems. However, the results of the 1 h model, under the constraints of considering just one fossil plant, are still acceptable especially under the assumption that the existing fossil plants are replaced by more suitable ones on the hybridized islands. For further analyses the 1 h model has shown to be able to simulate and optimize fossil-only and hybrid systems properly. Due to constraints in simulation time - it takes 60 times more time to simulate in minutely time steps - and uncertainty about local diesel power plant conditions the 1 min Matlab model is no longer used for the following simulations.

5.1.2 Introduction of hydro and geothermal power

After the optimization for photovoltaic-wind-battery-fossil hybrid systems which was tested previously, the integration of hydro and geothermal power plants within the simulation tool is shown along the example of St. Vincent (cf. island VCT01 in Tab. 4.1 and Fig. 4.2). The load of this island has the profile of large islands with midday peaks during the day on weekdays as shown in Fig. 4.11. It peaks at 21 MW and the annual electricity consumption sums up to 126 GWh. St. Vincent has an existing hydro power infrastructure of 6.5 MW installed run-off river power plants and an estimated potential for geothermal energy of 890 MW, which is more than 20 times of the current peak load [124]. It is therefore perfectly suitable to show the integration of hydro and geothermal power into the simulation tool.

The following steps are performed to show the impact of certain technologies and to validate the results: First, a fossil-only system is simulated, followed by the integration of the existing hydro plants to reflect the current status quo of power generation on St Vincent. Subsequently the existing system is optimized in the model by extending it with geothermal power plants.

The configurations of all three scenarios are revealed in Tab. 5.4. In the fossil-only scenario no renewable capacities are considered and for the status quo scenario the existing hydro power capacities of 6.5 MW are introduced. For all simulations the economic input parameters are assigned based on the assumptions in Sec. 4.4. Even though the existing system is simulated, initial costs are considered reflecting depreciation, refurbishment, and potential new installations.

Table 5.4: *Fossil-only, status quo, and geothermal scenario of energy supply system on St. Vincent*

	Fossil-only	**Fossil-only + existing hydro (Status quo)**	**Status quo + geothermal**
Existing hydro size	-	6.5 MW	6.5 MW
Geothermal size	-	-	13.5 MW
Initial costs [USD]	15,800,000	35,200,000	89,047,000
Fossil fuel consumption [liter]	32,050,000	27,333,000	4,469,000
LCOE [USD/kWh]	0.254	0.241	0.152
RE-share	0 %	15 %	86 %

The results of the fossil-only system in Tab. 5.4 allow a comparison with the fuel surcharge. Subtracting capital and operational expenditures from the overall LCOE leads to power generation costs of 0.20 USD/kWh based on fuel costs only. This reflects exactly the current fuel surcharge of St. Vincent (cf. [140]). Thus the efficiency and cost values for the fossil system are valid. Introducing the existing hydro power plants leads to cost reduction of 0.02 USD/kWh which shows the economic viability of this implementation. The renewable share of 15 percent saves approximately. 4.7 million liters of fossil fuel every year. Comparing the simulated power generation output with real production values shows very similar amounts. The simulated hydro power plant generates 18 GWh per year which results in 2,770 full load hours. According to a study by Knopp [156] the „dry season operation allows four to five hours of full load [...]. The rain season with nearly double precipitations allows about eight to twelve hours of full load". Real full load hours add up to 2,875 when combining five operating hours per day for half a year with ten operating hours for the other half. This validates the successful integration of hydropower into the simulation tool.

For the introduction of geothermal power plants into the simulation tool the status quo is taken as baseline as shown in Tab. 5.4. The introduction of a cost-optimized geothermal plant of 13.5 MW (70 percent of peak load) reduces the LCOE significantly and pushes the renewable share up to 86 percent. The initial costs for the suggested geothermal plant add up to 65 million USD which are in the range of estimated costs of 50 million USD for a 10 MW plant on St. Vincent [157]. For geothermal plants the power generation costs are given between 0.09 to 0.14 USD/kWh in the literature [153], therefore 0.14 USD/kWh power generation costs for the island energy supply system dominated by geothermal power seem to be realistic.

In conclusion the comparison of the simulated hydro and geothermal plant with the real existing hydro plant and studies about geothermal plants reveals the ability of the developed 1 h Matlab tool to reflect these technologies. This tool therefore allows the simulation of the techno-economic potential of renewable energies on Caribbean islands including photovoltaic, wind, hydro, and geothermal plants and battery storage. This potential is derived in the next section.

5.2 Derived Caribbean potential

Within this section the main output of simulation and optimization for Caribbean island energy supply systems is presented. At first the status quo for fossil and existing renewable power plants is simulated and shown for each island. Secondly, the techno-economic optimized hybrid system configurations are presented.

5.2.1 Simulation of the status quo

Fossil based power plants and existing renewable plants are considered for the status quo. For renewable plants the exception that just plants which can easily be located on certain islands are used is made. This is true for all hydropower capacities, the geothermal plant on the main island of Guadeloupe (GLP01), and large scale wind parks. These wind parks are identified for Aruba (ABW01), Cuba (CUB01), the Dominican Republic (DOM01), Jamaica (JAM01), Nevis (KNA02), and Puerto Rico (PRI01) [158]. PV plants could not be georeferenced on single islands, therefore they are excluded for the status quo. Input parameters are chosen as described in Ch. 4. Table 4.6 lists detailed resource and load data for the simulations. They are performed for each island individually and the results are shown in Tab. 5.5.

Table 5.5: *Results of simulation of status quo for all target islands. Categories are: island ID (ID), size of fossil plant (Fossil plant), size of renewable plant (RE plant), hydropower (hyd.), wind power (wind), and geothermal power (geo), initial costs (IC), fossil fuel consumption (Fuel), CO_2 emissions (CO_2), levelized costs of electricity (LCOE), and share of renewable energies (RE-share)*

ID	**Fossil plant**	**RE plant**	**IC**	**Fuel**	**CO_2**	**LCOE**	**RE-share**
	[MW]	[MW]	[mil. USD]	[TSD liter/year]	[tons/ year]	[USD/ kWh]	[%]
ATG01	71	-	35.5	78,212	206,478	0.303	0.0
ATG02	4	-	2.0	2,868	7,571	0.402	0.0
ABW01	191	30 wind	170.6	188,574	497,835	0.239	18.6
BHS01	238	-	119.1	262,415	692,776	0.230	0.0
BHS02	139	-	69.5	153,252	404,586	0.257	0.0
BHS03	17	-	9.2	13,529	35,716	0.307	0.0
BHS04	24	-	13.0	19,076	50,362	0.307	0.0
BHS05	13	-	7.2	10,557	27,871	0.307	0.0
BHS06	16	-	8.6	12,557	33,150	0.307	0.0
BHS07	14	-	7.6	11,092	29,282	0.307	0.0
BHS08	1	-	0.7	1,078	2,847	0.307	0.0
BHS09	9	-	5.1	7,506	19,815	0.307	0.0
BHS10	7	-	3.7	5,363	14,159	0.307	0.0
BHS11	5	-	2.5	3,677	9,707	0.307	0.0
BHS12	2	-	0.9	1,333	3,519	0.307	0.0
BRB01	245	-	122.3	267,709	706,753	0.260	0.0
BES01	31	-	17.2	25,170	66,449	0.285	0.0
BES02	2	-	0.9	1,374	3,628	0.317	0.0
VGB01	15	-	8.4	12,370	32,657	0.246	0.0
VGB02	2	-	1.2	1,753	4,628	0.271	0.0
CYM01	131	-	65.6	144,510	381,507	0.285	0.0
CYM02	9	-	4.9	7,118	18,791	0.377	0.0
CUB01	4,077	16 hyd. 12 wind	2117.7	4,477,040	11,819,385	0.223	0.3
CUB02	27	-	13.6	29,965	79,107	0.249	0.0
CUW01	412	-	205.8	453,506	1,197,256	0.258	0.0
DMA01	26	7 hyd.	33.0	21,136	55,798	0.214	18.2
DOM01	3,018	544 hyd. 34 wind	3227.0	3,032,797	8,006,585	0.233	8.8
GRD01	44	-	21.9	48,291	127,488	0.283	0.0
GRD02	4	-	2.1	3,116	8,227	0.376	0.0
GLP01	382	9 hyd. 16 geo	280.2	380,871	1,005,499	0.242	9.5
GLP02	17	-	9.1	13,367	35,289	0.343	0.0
GLP03	3	-	1.5	2,186	5,772	0.343	0.0
GLP04	3	-	1.5	2,172	5,733	0.343	0.0

ID	**Fossil plant**	**RE plant**	**IC**	**Fuel**	**CO_2**	**LCOE**	**RE-share**
	[MW]	[MW]	[mil. USD]	[TSD liter/year]	[tons/year]	[USD/kWh]	[%]
HTI01	166	55 hyd.	249.0	138,227	364,920	0.255	24.6
HTI02	1	-	0.6	822	2,171	0.385	0.0
HTI03	0	-	0.2	351	926	0.385	0.0
HTI04	0	-	0.0	68	181	0.385	0.0
HTI05	0	-	0.1	128	337	0.385	0.0
JAM01	912	24 hyd. 42 wind	632.6	968,023	2,555,581	0.288	3.7
MTQ01	374	-	186.8	411,585	1,086,585	0.244	0.0
MSR01	8	-	4.6	6,775	17,886	0.431	0.0
PRI01	4,602	95 hyd. 78 wind	2782.2	4,962,408	13,100,757	0.276	2.1
PRI02	17	-	9.2	13,570	35,825	0.369	0.0
PRI03	5	-	2.5	3,640	9,611	0.369	0.0
BLM01	10	-	5.8	8,439	22,279	0.286	0.0
MAF01	64	-	31.9	70,225	185,394	0.229	0.0
KNA01	38	-	19.1	42,175	111,341	0.215	0.0
KNA02	23	2 wind	5.5	17,327	45,742	0.259	8.4
LCA01	82	-	41.0	90,447	238,780	0.273	0.0
VCT01	31	7 hyd.	35.2	27,333	72,160	0.241	14.7
VCT02	3	-	1.7	2,148	5,670	0.341	0.0
VCT03	1	-	0.6	784	2,069	0.340	0.0
SXM01	70	-	35.1	77,312	204,104	0.228	0.0
TTO01	1,776	-	888.1	1,957,181	5,166,959	0.072	0.0
TTO02	68	-	34.0	74,837	197,571	0.075	0.0
TCA01	34	-	17.2	38,012	100,352	0.257	0.0
TCA02	9	-	5.0	7,343	19,384	0.342	0.0
TCA03	6	-	3.4	5,038	13,300	0.342	0.0
TCA04	3	-	1.5	2,133	5,632	0.342	0.0
VIR01	115	-	57.4	126,543	334,073	0.359	0.0
VIR02	61	-	30.3	66,752	176,226	0.406	0.0
VIR03	12	-	6.4	9,373	24,745	0.471	0.0
Sum	**17,689**	**971 RE**	**11,676**	**18,824,542**	**49,696,790**	**0.300**	**ø 1.1**

The results of the simulation of status quo are based on the experience made during the tool validation and reality check in Subsec. 5.1.1. Thus, the applied simulation tool is adjusted to reflect Caribbean energy supply systems. The assumed fossil and renewable power plant capacities add up to 18 GW which is an underestimation compared to the 23 GW in Tab. 2.1. However, this underestimation has no influence on the energy system simulation as all stability criteria meet with the considered power generation capacities. On the contrary it reveals that in reality overcapacities of fossil plants exist which could be taken out of operation. The highest capacities are found on Puerto Rico (PRI01) and Cuba (CUB01) with more than four gigawatts and on the Dominican Republic (DOM01) with more than three gigawatts, while the lowest capacities under one megawatt exist on the smaller Haitian islands (IDs HTI02 to HTI05). This range underlines the diversity of the Caribbean islands energy supply systems which could lead to different applications of renewable energies. The average fossil plant capacity is 285 MW and the related efficiencies just differ between 36 and 40 percent depending upon the energy consumption of each island.

Renewable capacities are detected on 11 islands only with the by far highest capacities on the Dominican Republic (DOM 01) (cf. Tab. 4.4). Still, the renewable share on this island is only 9 percent of the consumed electricity. The highest share of renewable energy - by hydropower only - is reached on the main island of Haiti (HTI01) with 25 percent due to the combination of large hydropower capacities and low overall electricity consumption. It is followed by two middle-sized islands Dominica (DMA01), showing a share of 18 percent, and Saint Vincent (VCT01) with 15 percent. Aruba (ABW01) has the highest share of renewable energy by wind power with 19 percent and Nevis (KNA02) the second highest with 8 percent. The geothermal power plant on Guadeloupe (GLP01) contributes to ten percent of this island's energy supply. Beside these exceptions the great majority of islands shows a renewable share of zero percent in the simulated status quo.

The combined initial costs of all simulated islands for the fossil and renewable capacities add up to 11.6 billion USD. Most of this capital has already been invested, but interest payments and depreciation continuously influence the power generation costs. The highest initial costs are paid in the Dominican Republic (DOM01) due to the biggest hydropower capacities which are very capital-intensive compared to the fossil fuel plants. Assuming a lifetime of 30 years for fossil and hydropower plants, 370 million USD have to be invested into these plants on average each year for all islands together. In addition, operation and maintenance expenditures of 3 billion USD have to be paid each year. This is on average 50 million USD per island with the great majority spent on operation and maintenance expenditures for the fossil fuel plants.

The overall sum of fossil fuel consumption for power generation is 19 billion liters of diesel equivalent per year. This leads to about 50 million tons of CO_2 emissions by burning fuel in power plants. This value represents 0.2 percent of the global CO_2

emissions which is only a small share. Anyhow, looking at the carbon intensity per consumed kilowatthour the simulated islands emit 0.7 $\mathrm{kg_{CO_2}}$/kWh which is quite high in global comparison. For Latin America the average value is 0.2 $\mathrm{kg_{CO_2}}$/kWh and for the European Union it is 0.4 $\mathrm{kg_{CO_2}}$/kWh. In conclusion, even though the overall contribution of Caribbean islands to the worldwide CO_2 emissions is rather low the specific carbon intensity reveals significant reduction potential [159].

The CO_2 emissions of each island are directly related to the fossil fuel consumption, therefore only the fossil fuel consumption is described in a more detailed way. Again, Puerto Rico (PRI01), Cuba (CUB01), and the Dominican Republic (DOM01) lead the list of the fuel consumption similar to the power plant capacities. They use 5.0, 4.5, and 3.0 billion liters followed by Trinidad (TTO01) with 2 billion liters. On average 300 million liters of fossil fuel are burned on each island for power generation per year. 11 islands use between 100 and 1,000 million liters, 22 islands use between ten and 100 million liters and 20 islands use between one and ten million liters of fossil fuel annually. Only five islands consume less than one million liters of fuel for power generation, four small Haitian and one small Grenadian island. The ranking of the consumption of each island is illustrated in Fig. 5.2 complimented by the indication of the respective LCOE.

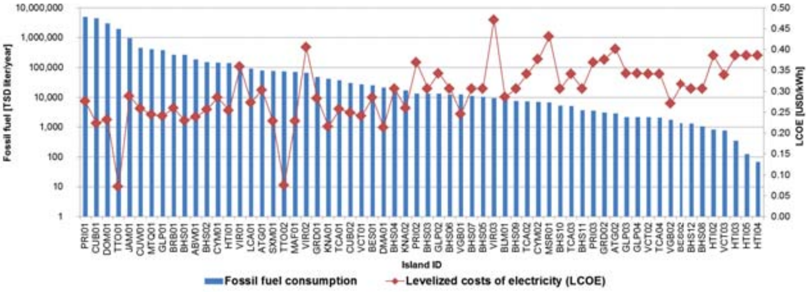


Figure 5.2: *Ranking of all islands according to annual fossil fuel consumption extended by specific LCOE*

The fossil fuel consumption is displayed on a logarithmic scale to show the full bandwidth for all islands. As aforementioned this range reaches from less than one million to more than five billion liters per year. The LCOE show a range of 0.07 to 0.47 USD/kWh. The lowest LCOE are calculated for Trinidad (TTO01) and Tobago (TTO02) with 0.072 USD/kWh and 0.075 USD/kWh respectively. These low LCOE are based on the significantly low fossil fuel prices on these islands. Beside these two outliers a general trend can be observed looking at Fig. 5.2: The higher the fuel consumption the lower the LCOE and vice versa. This phenomenon is based on two reasons: Firstly, highly consuming islands have power plants with higher efficiencies and less overcapacities which reduces the LCOE. Secondly, on smaller islands, higher fuel prices are detected due to assigned transport costs and diseconomies of scale. Consequently, the overall highest LCOE are found on the Virgin Islands (VIR02 and VIR03) and Montserrat (MSR01) based on very high local fossil fuel prices due to expensive transport costs and missing subsidies. Another positive effect on the LCOE is the implementation of renewable power plants. All islands with renewable capacities have lower LCOE than the average of 0.30 USD/kWh which is especially driven by hydropower. This underlines the attractiveness of using hydropower on Caribbean islands, even though the current average share of renewable energies adds up to 1.1 percent only.

In summary, all target islands rely strongly upon expensive and high polluting fossil power plants in the status quo as only few renewable plants are installed. The total fossil fuel consumption of approximately 19 billion liters per year leads to 50 million tons of CO_2 emissions per year for power generation on Caribbean islands. The annual fuel expenditures of 13.4 billion USD represent a high burden on the islands' economies and send the average LCOE up to 0.30 USD/kWh which is far higher than LCOE in large scale centralized power supply systems. This expensive status quo builds the baseline for the techno-economic optimization of the island energy supply systems by renewable energies and batteries. The results of these optimizations are presented in the following subsection.

5.2.2 Techno economic potential for renewable energies

The derived renewable potential for island energy supply systems is based on the explained economic input parameters, feedin time series of renewable energies, and load data of Ch. 4. For each island the developed simulation and optimization algorithm is applied to demonstrate the techno-economic renewable potential. On each of them at least PV and wind power plants and batteries are allowed to upgrade the status quo. Geothermal plants can be considered on all listed islands of Tab. 4.5. The renewable capacities are optimized to minimize the LCOE of the related island energy supply system. As results these optimized and capacities and the related renewable energy share are presented followed by the economic performance of the optimized system for each island compared to the status quo.

Renewable energy capacities and share of optimized energy supply systems

The overall results of the optimized capacities and the renewable energy share of these systems are presented in Tab. 5.6 for each island. The capacities are sorted along the different renewable energy technologies and batteries.

Summing up all renewable capacities in Tab. 5.6 reveals the enormous techno-economic potential on Caribbean islands. The total potential PV capacities add up to almost nine gigawatts and the wind power capacities add up to more than six gigawatts. For islands with geothermal potential it is suggested to install 530 MW geothermal capacities and all islands together would need three gigawatt-hours of battery capacities to operate the hybrid energy supply systems. The average share of renewable energy in the total consumed energy is 62 percent ranging from 0 to 99 percent.

The highest capacities - not shares - of renewable energies are found on Puerto Rico (PRI01), Cuba (CUB01), and Dominican Republic (DOM01). For the first it is suggested to install 3.3 GW of PV power and 4.1 GW of wind power to supply a peak load of 3 GW. To store excess energy and for stability reasons a battery capacitiy of 1.8 GWh is proposed for this island energy supply system. For island CUB01, 2.3 GW of PV and 0.7 GW of wind power lead to the techno-economic optimized supply system while for island DOM01 only new potential PV capacities of 1.6 GW are detected to extend the existing 544 MW of hydropower and 34 MW of wind power. After the top three islands with the highest renewable capacities, 12 islands follow in the ranking with potential renewable capacities of more than 100 MW. Between ten and 100 MW of potential renewable energy capacities, 20 islands are identified, followed by 25 islands with a renewable potential ranging from ten to 0.1 MW. At the bottom of this ranking two islands without any techno-economic potential for renewable energies are listed.

Table 5.6: *Techno-economic optimized renewable and battery capacities on Caribbean islands. Categories are: island ID (ID), size of hydropower plant (Hydropower), size of photovoltaic plant (PV), size of wind plant (Wind), size of geothermal plant (Geo), size of battery capacitiy (Battery), and share of renewable energies (RE-share)*

ID	**Hydro-power**	**PV**	**Wind**	**Geo**	**Battery**	**RE-share**
	[MW]	[MW]	[MW]	[MW]	[MWh]	%
ATG01	-	40.8	52.0	-	27.9	72
ATG02	-	1.4	2.2	-	1.2	69
ABW01	-	-	154.0	-	76.5	84
BHS01	-	183.1	120.0	-	94.3	59
BHS02	-	126.2	38.5	-	55.0	46
BHS03	-	9.0	6.1	-	4.2	50
BHS04	-	12.3	8.0	-	6.4	51
BHS05	-	7.1	4.1	-	3.4	48
BHS06	-	8.6	4.4	-	4.0	46
BHS07	-	7.3	2.8	-	3.5	41
BHS08	-	0.7	0.6	-	0.4	52
BHS09	-	5.7	0.3	-	2.3	34
BHS10	-	3.7	1.4	-	1.6	41
BHS11	-	2.4	1.4	-	1.1	46
BHS12	-	0.9	0.6	-	0.5	49
BRB01	-	89.5	186.0	-	97.2	75
BES01	-	4.6	21.2	-	8.8	81
BES02	-	0.0	-	0.6	0.5	99
VGB01	-	6.4	6.3	-	3.6	55
VGB02	-	0.9	1.1	-	0.6	60
CYM01	-	111.6	72.6	-	54.5	56
CYM02	-	4.7	4.4	-	3.5	59
CUB01	16.4	2,296.0	712.0	-	-	32
CUB02	-	15.5	8.0	-	-	35
CUW01	-	46.5	338.0	-	161.8	85
DMA01	6.7	0.0	-	10.8	10.1	95
DOM01	544.3	1,553.8	34.0	-	-	27
GRD01	-	2.3	-	23.5	16.8	99
GRD02	-	1.0	2.8	-	1.2	76
GLP01	8.8	27.6	-	204.4	147.3	99
GLP02	-	7.1	11.6	-	5.9	71
GLP03	-	1.1	1.9	-	1.0	73
GLP04	-	1.1	1.9	-	1.0	70
HTI01	55.3	115.6	60.0	-	65.7	69
HTI02	-	0.7	-	-	0.3	36
HTI03	-	0.3	-	-	0.1	35
HTI04	-	0.1	-	-	0.0	35

ID	Hydro-power [MW]	PV [MW]	Wind [MW]	Geo [MW]	Battery [MWh]	RE-share %
HTI05	-	0.1	-	-	0.0	35
JAM01	23.8	554.8	42.0	-	-	26
MTQ01	-	26.5	-	202.6	144.5	99
MSR01	-	-	-	3.0	2.5	99
PRI01	95.4	3,310.1	4,108.0	-	1,861.5	69
PRI02	-	8.6	11.3	-	7.0	64
PRI03	-	2.7	2.5	-	2.4	57
BLM01	-	4.1	5.8	-	2.8	65
MAF01	-	45.4	40.4	-	24.9	62
KNA01	-	2.0	-	20.2	14.5	98
KNA02	-	-	2.2	7.6	6.1	98
LCA01	-	4.7	-	43.8	31.5	99
VCT01	6.5	-	-	13.5	12.3	94
VCT02	-	0.6	1.7	-	0.9	70
VCT03	-	0.3	0.6	-	0.3	67
SXM01	-	49.8	47.0	-	27.4	63
TTO01	-	-	-	-	-	0
TTO02	-	-	-	-	-	0
TCA01	-	26.3	20.4	-	13.6	62
TCA02	-	4.0	5.2	-	3.0	68
TCA03	-	2.9	3.3	-	2.0	65
TCA04	-	1.2	1.4	-	0.9	65
VIR01	-	81.8	106.0	-	49.2	77
VIR02	-	54.0	60.2	-	40.7	73
VIR03	-	6.6	8.3	-	7.3	73
Sum	**757.2**	**8,882.0**	**6,324.0**	**530.0**	**3,117.7**	**ø 62**

The sum of renewable capacities is quite strongly related to the peak load (cf. Tab. 4.6) with a few exceptions. The biggest negative exceptions are Trinidad (TTO01) and Tobago (TTO02) with zero renewable capacities and the biggest positive exception is found on the Virgin Islands (VIR01, VIR02, and VIR03) with renewable capacities higher than 2.5 times the peak load. These exceptions are mainly based on very low or very high fossil fuel prices. After presenting the capacities a more detailed view on the single island energy supply systems is taken in respect of renewable share and distribution of renewable capacities.

In Fig. 5.3 the target islands are ranked according to the renewable share of the techno-economic optimized systems which is indicated by the green line with values

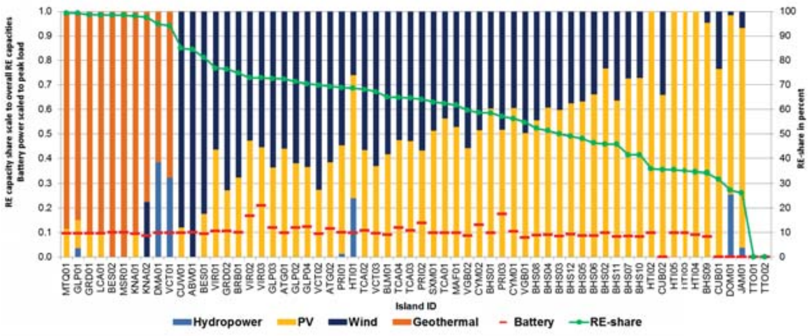


Figure 5.3: *Renewable energy and battery capacities and renwable share for all optimized island energy supply systems - islands ranked according to renewable share*

on the right axis. On the left axis the renewable capacities scaled to the total renewable capacities of each island are plotted. Battery power capacities are scaled to the peak load and illustrated as well. Hydropower capacities are shown in light blue, PV power capacities in orange, wind power capacities in dark blue, and geothermal capacities in brown. The battery capacities are not added up on the renewable capacities and just illustrated with a red dash.

It becomes obvious that islands with geothermal power capacities have the highest renewable share of all techno-economic optimized island energy supply systems. Due to the assumption of 8,760 full load hours geothermal plants represent a very attractive energy supply option which can even provide spinning reserve. On all ten islands bearing geothermal potential the geothermal power plants claim the highest share of renewable capacities pushing the renewable share up to 99 percent. On some islands they are supported by other renewable capacities and for all geothermal islands battery power capacities of approximately 10 percent of the peak load are suggested. These battery capacities help to cut off peak loads and store excess energy in times of low loads. In addition it is more economical to provide the spinning reserve (10 percent of the peak load) in times of high loads by batteries instead of installing overcapacities of expensive geothermal plants. In summary, it can be stated that the successful exploitation and use of geothermal resources lead to very high share renewable energy supply systems with little support of PV power and no wind turbines. As the exploitation of geothermal resources contains high risks due to the uncertainty of the resource availability in the underground higher interest rates might be applied for this technology. The influence of different risk rates is tested in Subsec. 5.3.3.

For islands without geothermal potential the average distribution of renewable capacities is almost equal between PV and wind power. This is mostly supplemented by battery power capacities of ten percent of the peak load for stability reasons. Islands with relatively high wind resources reach the highest share of renewable energies compared to other hybrid systems considering PV, wind, hydropower, fossil plants, and batteries. This is especially true for Aruba (ABW 01) where only wind and battery capacities are potentially installed reaching a renewable energy share of 84 percent. An existing wind farm on Aruba has more than 5,000 full load hours which underlines that the simulation results with approximately 6,000 full load hours and resulting high renewable shares seem realistic [160]. The neighboring islands of Aruba (ABW 01) - Curacao (CUW01) and Bonaire (BES01) - have similar excellent wind energy resources and reach similar renewable shares with nearly using wind power plants only.

With decreasing wind resources the ratio between potentially installed PV and wind power shifts towards higher PV capacities. While the solar resources differ only around ten percent compared to the average value for all target islands the wind resources differ from plus 240 to minus 70 percent (cf. Subsec. 4.2.1 and 4.2.2). Thus, the share of PV and wind power capacities is more strongly influenced by the changes in the wind resources. In Fig. 5.6 it can be observed that the renewable share decreases with reduced wind power capacities on the target islands. On small Haitian islands (HTI02 - HTI05) no techno-economic wind power potential can be found at all. Their optimized energy supply systems consist of PV, batteries, and fossil plants only. These systems reach renewable shares of around 35 percent. Lower shares of renewable energies are derived for the three large islands of Cuba (CUB01), the Dominican Republic (DOM01), and Jamaica (JAM01). For all of them the installation of batteries is not recommended under the assumed input parameter as the large fossil plants seem more economical than storing renewable energies and even for providing spinning reserve. Thus, only low renewable shares between 27 and 32 percent are accomplished. For JAM01 and DOM01 it is only suggested to install additional PV capacities as the wind resources are less favorable. In reality, some wind farms are already in places on these islands and operate profitably. This might be based on the rough wind speed data grid which is smoothing local spots of high wind speeds.

In summary, it can be stated that the optimizations reveal a huge potential of installing additional renewable capacities for Caribbean energy supply systems. Currently, only two out of 62 islands show no potential under the used input parameters. Geothermal power seems to outperform PV and wind plants while they are often complementarily used on many islands. Battery capacities are mainly used for stability reasons which is indicated by the scaled value of installed power of ten percent of the peak load. On some islands the battery capacities are significantly higher (e.g. Virgin Islands VIR02 and VIR03) which is mainly driven by the high fossil fuel costs. Different applications for different types of battery storage technologies are further analyzed in Subsec. 5.3.1 for Caribbean islands. The economic results of the techno-economic optimization and the comparison with the status is given in the next paragraphs.

Performance of optimized energy supply systems and comparison to the status quo

The high renewable capacities and renewable share of the techno-economic optimized island energy supply systems indicate that renewable technologies are competitive compared to fossil fuel plants on almost all of the investigated islands. The additional investments for these hybrid systems and their fuel consumption, CO_2 emissions, and LCOE are shown in Tab. 5.7. In addition, for the latter three categories the changes compared to the status quo are revealed.

To untap the techno-economic potential of renewable energies 35 billion USD investment costs have to be spent which is three times as much as for the status quo. This investment would save 8.3 billion liters of fossil fuel per year, which is a total reduction of 44 percent. The average reduction per island is 62 percent which is due to higher relative reductions on smaller islands without high influence on the total number. The same relative distribution is true for CO_2 emissions and their overall reduction would be 28 million tons per year (cf. Tab. 5.7).

Table 5.7: *Performance of techno-economic optimized island energy supply systems on Caribbean islands. Categories are: island ID (ID), additional investment costs (Add. IC), fossil fuel consumption (Fuel), CO_2 emissions (CO_2), change in fuel consumption and CO_2 emissions (change (Fuel + CO_2)), levelized costs of electricity (LCOE), and change of levelized costs of electricity (change (LCOE))*

ID	**Add. IC**	**Fuel**	**CO_2**	**Change**	**Opt. LCOE**	**Change**
	[mil. USD]	[TSD liter/year]	[tons/ year]	(Fuel + CO_2)	[USD/kWh]	(LCOE)
ATG01	218.7	21,591	56,999	-72 %	0.208	-31 %
ATG02	8.9	879	2,321	-69 %	0.284	-29 %
ABW01	352.1	36,076	95,241	-81 %	0.135	-43 %
BHS01	681.4	108,633	286,792	-59 %	0.188	-18 %
BHS02	379.0	82,883	218,810	-46 %	0.225	-13 %
BHS03	35.4	6,762	17,851	-50 %	0.261	-15 %
BHS04	48.1	9,277	24,490	-51 %	0.253	-18 %
BHS05	26.4	5,476	14,457	-48 %	0.261	-15 %
9BHS06	30.4	6,733	17,776	-46 %	0.263	-14 %
BHS07	23.5	6,490	17,134	-41 %	0.264	-14 %
BHS08	2.9	514	1,356	-52 %	0.259	-15 %
BHS09	13.4	4,937	13,033	-34 %	0.270	-12 %
BHS10	11.7	3,140	8,289	-41 %	0.267	-13 %
BHS11	8.9	1,993	5,260	-46 %	0.265	-14 %
BHS12	3.5	678	1,791	-49 %	0.262	-15 %
BRB01	679.5	67,301	177,676	-75 %	0.177	-32 %
BES01	66.9	4,735	12,500	-81 %	0.165	-42 %
BES02	4.6	21	54	-99 %	0.115	-64 %
VGB01	30.6	5,600	14,785	-55 %	0.215	-13 %
VGB02	4.8	708	1,868	-60 %	0.225	-17 %
CYM01	434.8	63,173	166,777	-56 %	0.231	-19 %
CYM02	22.3	2,940	7,761	-59 %	0.284	-25 %
CUB01	5882.8	3,067,324	8,097,734	-31 %	0.209	-6 %
CUB02	48.0	19,335	51,044	-35 %	0.230	-8 %
CUW01	1017.7	67,711	178,756	-85 %	0.118	-54 %
DMA01	48.5	1,335	3,526	-94 %	0.131	-39 %
DOM01	2796.8	2,410,628	6,364,058	-21 %	0.230	-1 %
GRD01	104.7	641	1,693	-99 %	0.108	-62 %
GRD02	9.6	733	1,934	-76 %	0.252	-33 %
GLP01	846.7	2,912	7,689	-99 %	0.083	-66 %
GLP02	46.3	3,831	10,113	-71 %	0.238	-31 %
GLP03	7.5	599	1,582	-73 %	0.234	-32 %
GLP04	7.6	641	1,693	-70 %	0.242	-29 %
HTI01	394.2	57,378	151,477	-58 %	0.217	-15 %
HTI02	1.4	528	1,394	-36 %	0.324	-16 %

ID	**Add. IC**	**Fuel**	**CO_2**	**Change**	**Opt. LCOE**	**Change**
	[mil. USD]	[TSD liter/year]	[tons/ year]	(Fuel + CO_2)	[USD/kWh]	(LCOE)
HTI03	0.6	228	602	-35 %	0.333	-14 %
HTI04	0.1	45	118	-35 %	0.333	-14 %
HTI05	0.2	82	218	-35 %	0.328	-15 %
JAM01	998.6	730,509	1,928,543	-25 %	0.273	-5 %
MTQ01	899.1	2,645	6,982	-99 %	0.082	-66 %
MSR01	14.6	101	267	-99 %	0.121	-72 %
PRI01	17057.0	1,574,939	4,157,839	-68 %	0.204	-26 %
PRI02	49.2	4,867	12,850	-64 %	0.277	-25 %
PRI03	12.8	1,559	4,115	-57 %	0.295	-20 %
BLM01	24.3	2,950	7,789	-65 %	0.216	-25 %
MAF01	205.6	26,868	70,932	-62 %	0.188	-18 %
KNA01	90.9	779	2,057	-98 %	0.106	-51 %
KNA02	34.1	436	1,151	-97 %	0.103	-60 %
LCA01	194.3	1,218	3,215	-99 %	0.107	-61 %
VCT01	60.1	1,871	4,940	-93 %	0.129	-46 %
VCT02	5.8	647	1,707	-70 %	0.250	-27 %
VCT03	2.2	256	677	-67 %	0.258	-24 %
SXM01	232.1	28,627	75,575	-63 %	0.185	-19 %
TTO01	0.0	1,957,181	5,166,959	0 %	0.072	0 %
TTO02	0.0	74,837	197,571	0 %	0.075	0 %
TCA01	110.9	14,266	37,662	-62 %	0.202	-22 %
TCA02	22.7	2,335	6,166	-68 %	0.240	-30 %
TCA03	15.2	1,782	4,705	-65 %	0.247	-28 %
TCA04	6.4	748	1,976	-65 %	0.246	-28 %
VIR01	439.3	29,237	77,185	-77 %	0.202	-44 %
VIR02	280.9	18,052	47,657	-73 %	0.256	-37 %
VIR03	37.9	2,536	6,695	-73 %	0.288	-39 %
Sum	**35,095**	**10,553,737**	**27,861,866**	**ø-62 %**	ø **0.215**	**ø -27 %**

The economic savings by reduced fossil fuel consumption would add up to 6.8 billion USD in total for each year. Compared to the additional investment costs of 35 billion USD listed in Tab. 5.7, these savings enable low amortization times (cf. Fig. 5.6). Thus, the CO_2 reduction would even be profitable and negative CO_2 avoidance costs occur which is further discussed by Breyer et al. [161]. On average, the LCOE would be decreased by 27 percent down to 0.215 USD/kWh. The specific results are illustrated in Fig. 5.4.

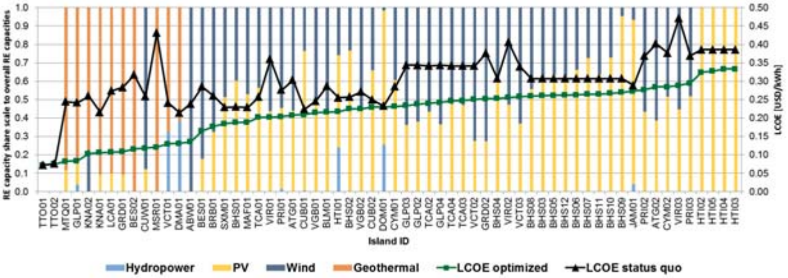


Figure 5.4: *Renewable energy capacities and levelized costs of electricity (LCOE) for all optimized island energy supply systems and for status quo - islands ranked according to minimal optimized LCOE*

At the first glance a correlation between the LCOE of the status quo and of the optimized systems can be observed. The higher the current LCOE the higher are the optimized LCOE and the other way around. This is mainly based on the fossil fuel costs which drive the costs in the status quo as well as in optimized systems where still on average 38 percent of the electricity is supplied by fossil fuel plants. This relation is only decoupled for very high share renewable systems as on islands with geothermal resources and plants. For example Montserrat (MSR01) has one of the highest LCOE in the status quo but by installing geothermal plants and batteries the renewable share would reach 99 percent and the optimized LCOE are the eleventh lowest with 0.121 USD/kWh. On the other hand the island Saint Kitts (KNA 01) has one of the lowest LCOE in the status quo but reaches only 1.5 UScent lower LCOE than Montserrat as both have such high renewable shares.

Looking at the highest LCOE reduction again the islands with geothermal potential lead this list. A general trend is the relation between the attractiveness of the renewable resources and the level of LCOE reduction. The average LCOE reduction for all islands without geothermal potential is 21 percent. And the biggest relative reductions are found on islands like Curacao (CUW01), Aruba (ABW01), and Bonaire (BES01) with very high wind resources. Other influence parameters for the amount of LCOE reduction are the weighted average costs of capital and the local fuel prices on the analyzed islands. As an example the Virgin Islands with weighted average costs of capital (WACC) of only 3.3 percent and fuel prices of 0.14 USD/kWh$_{\text{thermal}}$ are taken. On these islands (VIR01, VIR02, and VIR03) LCOE reductions range around 40 percent even though their overall optimized LCOE is still comparatively high. In summary, the main influencing parameters on the LCOE reduction are resource availability, fuel prices, and WACC which are presented for each island in Fig. 5.5.

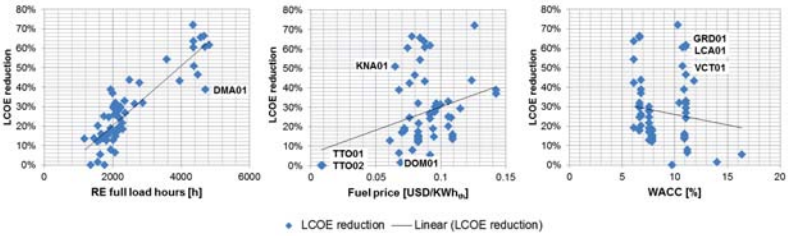


Figure 5.5: *Relation between relative levelelized costs of electricity reduction (LCOE reduction) and averaged full load hours of renewable energies (RE full load hours), fossil fuel price (fuel price), and weighted average costs of capital (WACC) for each island*

Figure 5.5 shows on the left side the relation between resource availability, expressed in average full load hours of available optimized resources (solar, wind, and geothermal energy) and the relative LCOE reduction in percent. A strong correlation between these parameters can be noticed, high full load hours lead to high LCOE reductions with only few outliers. One of them is Dominica (DMA01) with the second highest full load hours but only LCOE reductions of 39 percent. The correlation coefficient for full load hours and relative LCOE reduction is very high with 0.89.

The fuel price is plotted in the center of Fig. 5.5 as next analyzed parameter. It becomes clear that it correlates less than the resource availability with the LCOE reduction showing a correlation coefficient of 0.30. Still a general trend is detected: Higher fossil fuel costs lead to higher relative LCOE reductions which is also described in the discussion of Fig. 5.4 comparing the LCOE of the status quo and of the optimized system. Especially for islands with zero LCOE reduction based on the low fossil fuel costs this correlation is true (TTO01 and TTO02). Nevertheless the influence of fuel costs is further investigated in Subsec. 5.3.2. For others this trend is not proven as the Dominican Republic (DOM01) has fuel costs of 0.069 USD/kWh$_{\text{thermal}}$ leading to just one percent LCOE reduction while Saint Kitts (KNA01) reaches LCOE reductions of 51 percent with similar fuel costs of 0.065 USD/kWh$_{\text{thermal}}$.

Finally, the correlation between LCOE reduction and weighted average costs of capital (WACC) is illustrated on the right side of Fig. 5.5. There a negative correlation between LCOE reduction and WACC is revealed - the higher the WACC the lower the LCOE reduction - with a correlation coefficient of -0.13. This is based on the fact that renewable power plants have high upfront investment costs and their capital expenditures are quite sensitive according to the WACC. For example the aforementioned Virgin Islands show very high LCOE reductions having low WACC of 6.8 percent. Outliers exist for example on the Eastern Caribbean islands Grenada (GRD01), St. Lucia (LCA01), and St. Vincent (VCT01) where high WACC of 11.8 percent are assumed but still LCOE reductions of more than 45 percent are reached. Based on many outliers and the low correlation coefficient the influence of WACC on the LCOE can be seen as statistically the lowest among the three tested parameters.

In conclusion, all three identified parameters have an influence on the LCOE reduction by the optimized island energy supply system. The resource availability is the most important parameter followed by the fuel costs and the WACC. Apart from the relative cost reduction and its causes the overall cost reduction potential for the target islands is described in the next paragraphs.

As aforementioned overall additional investments of 35.1 billion USD would be required to implement the techno-economic optimized system configurations. Out of these 35.1 billion USD it is suggested to spend 16.1 billion USD for PV plants and another 15.3 billion USD for wind power plants. Geothermal installations would require 2.0 billion USD investments and battery capacities 1.7 billion USD. The distribution of the additional investments and the amortization times to recover these are illustrated in Fig. 5.6 for each island.

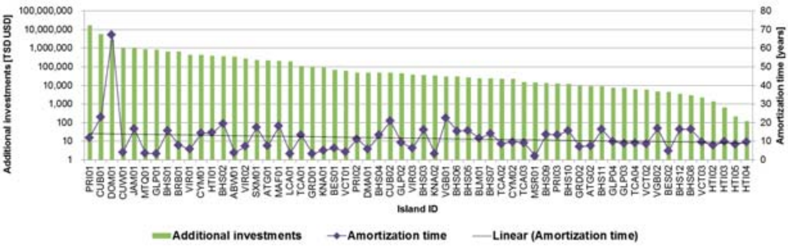


Figure 5.6: *Additional investment costs and amortization time for optimized island energy supply systems - excluding island TTO01 and TTO02*

Additional investment costs in thousand USD are shown on the left axis on a logarithmic scale. Puerto Rico (PRI01) alone holds with 17 billion USD almost half of the overall additional investment costs. For Cuba (CUB01) six billion USD, for the Dominican Republic (DOM01) 2.8 billion USD, and for Curacao (CUW01) and Jamaica (JAM01) about one billion USD are calculated as additional investments into the optimized system. In addition to these islands another 7 billion USD are revealed as supplementary investments for the following 39 islands in Fig. 5.6. These are complimented by the last 16 islands having additional investment costs of less than 10 million USD each.

The amortization times for these additional investments are illustrated on the right axis of Fig. 5.6. They are calculated by dividing the investment costs through the total annual savings of each optimized energy supply system. The average amortization time is around 12 years with the maximum of 67 years (DOM01) and the minimum of two years (MSR01). In total eleven islands have amortization times below five years which can be seen as financially very attractive. Another 22 islands are still attractive showing amortization times between five and ten years. 23 islands with lower attractiveness - range between ten and 20 years - are detected and four islands can be considered as unattractive as their amortization time for the full system is higher than 20 years. Nevertheless on these unattractive islands the amortization time for specific plants might be lower as the presented amortization time counts for the entire supply systems. This information is especially important for larger islands where investments into single power plants are possible.

In conclusion, the analyzed Caribbean islands bear a high potential for renewable based island energy supply systems. By investing 35 billion USD, more than 16 GW capacities of renewable power plants - 8.8 GW PV, 6.3 GW wind, and 0.5 GW geothermal - and 3.1 GWh of batteries can be installed to implement the optimized configurations. This results in a mean share of renewable energies of 62 percent and average LCOE of 0.215 USD/kWh. These systems reach an average LCOE reduction of eight UScent/kWh compared to the status quo and the average amortization time is 12 years. Eight billion liters of fossil fuel can be saved each year and the CO_2 emissions can be reduced by 22 million tons per year via implementing the optimized island energy supply systems. To give an idea about the spatial distribution of the techno-economic potential for renewable energies the sum of new potential renewable capacities and the LCOE reduction for each island are illustrated in Fig. 5.7.

In Fig. 5.7 the results of the optimization are summarized. The potential additional renewable capacities for the techno-economic optimized system configurations are indicated by the size of the bubble for each island. In addition the cost reduction by the optimized system is illustrated within each bubble along the color scheme from red (zero reduction) to dark green (very high reduction). The highest cost reduction

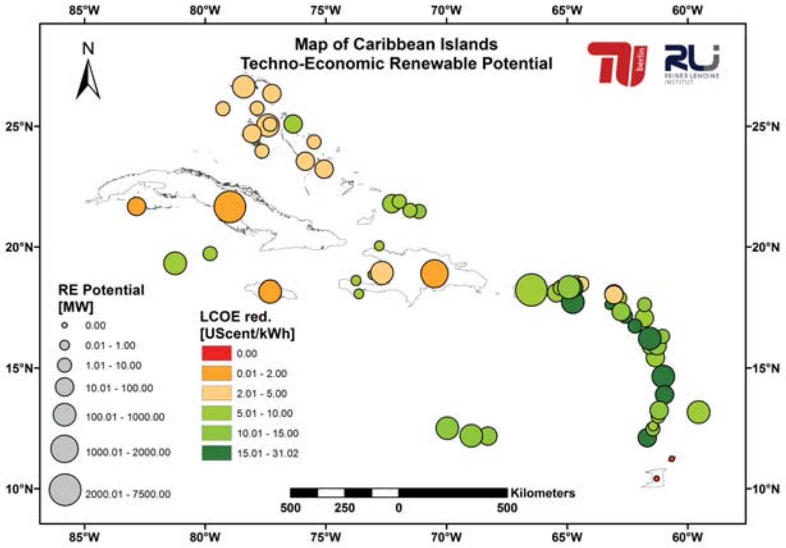


__Figure 5.7:__ Results of techno-economic optimization for Caribbean islands - potential additional capacities and cost reduction

potential is found on the Eastern Caribbean islands with more than 15 UScent/kWh on some of them. The ABC islands (Aruba, Bonaire, and Curucao) bear a high cost reduction potential as well. Lower potentials are detected on the large islands of Cuba, Hisponiala, and Jamaica, even though the highest capacities for new renewable installations are located on these large islands.

In summary, a vast potential for new renewable capacities on Caribbean islands exist. The cost reductions are the highest on smaller islands while the overall potential new capacities are the highest on larger islands. Only two out of 62 islands show no renewable potential under the assumed input parameters. As the optimization is only performed for one certain set of input parameters for each island the robustness of the results is tested in Sec. 5.3. Within this section several sensitivity analyses are conducted to show the influence of certain input parameters on the overall result.

5.3 Sensitivities for selected islands

During the analysis of the results of the techno-economic optimization several crucial parameters were identified which are worth for detailed investigations. Firstly, a battery technology comparison between lithium ion and sodium sulfur batteries is shown on one Bahamian island (BHS09) and one of the Virgin Islands (VIR03). Afterwards a fuel price sensitivity for Tobago (TTO02), one of the two islands without renewable energy potential, is performed. The dominance of geothermal plants over PV and wind power plants is tested for different risk rates for geothermal plants on the example of Grenada (GRD01). Finally, two 0 to 100 percent renewable energy scenarios are conducted for the same island with and without geothermal plants. The performed sensitivity analyses are special as not only one input parameter is changed but also some or all plant sizes are optimized.

5.3.1 Battery technology comparison

The results of the techno-economic optimization reveal that most times batteries are used for stability reasons - spinning reserve - primarily, and secondary for storing excess energy. The considered sodium sulfur battery technology can provide both, spinning reserve and high storage capacities, for example to shift solar energy into the night. Anyhow, for spinning reserve applications, special high power batteries exist with higher C-rates, which are cheaper in respect of the installed kilowatt power. Such a high power battery (lithium ion) with a C-rate of one is introduced to be compared with the sodium sulfur battery (C-rate 1/6). This comparison should indicate which technology fits best for which of the two optimized island energy supply systems of island BHS09 and VIR03. Island BHS09 has one of the lowest renewable energy shares so the battery is mainly used for spinning reserve, while island VIR03 possesses one of the highest renewable shares without geothermal power. So it is assumed that for this island high storage capacities are needed.

Beside the c-rate, the initial costs of each technology are different. 550 USD per installed kilowatthour are assumed for sodium sulfur and 1,200 USD per installed kilowatthour for lithium ion. These 1,200 USD are based on 700 USD per kilowatt power and 500 USD per kilowatthour capacity [154]. For sodium sulfur batteries one kilowatt power costs as well 700 USD and the capacity 433 USD per kilowatthour. The main difference in the system costs is therefore based on the different c-rates leading to specifically high storage power or capacity costs. All other input parameters remain similar as it is listed in Tab. 5.8.

Table 5.8: *Technical and economic parameters for comparison of sodium sulfur (NaS) and lithium ion (liIon) batteries*

Parameter	**Unit**	**NaS**	**LiIon**
C-rate	kW/kWh	1/6	1/1
Maximum depth of discharge	%	80	80
Charging efficiency	%	90	90
Discharging efficiency	%	90	90
Initial state of charge	%	100	100
Initial costs	USD/kWh	550	1,200
OPEX	USD/kWh/y	10	10
Lifetime	y	14	14

To understand the different performances of the island energy supply systems with the different battery technologies, for certain calculations are performed. For each of the two islands the battery capacity is optimized independently while the renewable capacities are fixed according to the previously optimized values. In Tab. 5.9 the results of these optimizations are listed.

With lithium ion batteries the LCOE are reduced slightly for both islands with a bit higher savings for island BHS09 with lower shares of renewable energies. For this island the system performance even remains the same which means the renewable

Table 5.9: *Results of battery technology comparison. Abbreviations stand for battery capacity (Bat cap) and battery power (Bat power)*

	Island BHS09		**Island VIR03**	
Battery Technoloy	LiIon	NaS	LiIon	NaS
PV [kW]	5,668	5,707	6,625	6,625
Wind [kW]	-	275	8,250	8,250
Bat cap [kWh]	512	2,338	1,319	7,328
Bat power [kW]	512	390	1,319	1,221
RE share [%]	34	34	69	73
LCOE [USD/kWh]	0.254	0.270	0.281	0.288

share is still 34 percent. The results underline the theory that high power batteries are the more economical choice for low share renewable systems providing efficiently spinning reserve. For island VIR03 with very high shares of renewable energies the introduction of a high power battery leads to a drop of the renewable share by four percent points as not enough excess energy can be stored. In conclusion, both battery technologies fit for renewable island energy supply systems with slight advantages for lithium ion batteries in low share renewable systems and for sodium sulfur in very high share cases.

5.3.2 Fossil fuel costs

The fuel price is one of the crucial input parameters for the techno-economic potential of renewable energies. For the islands Trinidad (TTO01) and Tobago (TTO02) no renewable potential could be identified due to very low fossil fuel costs. Along the example of Tobago different fossil fuel prices are taken as input parameters to identify certain thresholds for the optimized system configuration. To show the full range it is started with fuel costs of zero USD/kWh$_{\text{thermal}}$. A step wise increase takes place in 0.01 USD steps until 0.4 USD/kWh$_{\text{thermal}}$. The results for the installed capacities and renewable share are shown in Fig. 5.8.

Looking at Fig. 5.8 reveals four main configurations of the island energy supply system depending upon the fossil fuel price. Until a fossil fuel price of 0.05 USD/kWh$_{\text{thermal}}$ no renewable capacities are installed at all. This is also true for the current fossil fuel price on Tobago at approximately 0.01 USD/kWh$_{\text{thermal}}$. Within the range of 0.05 and 0.09 USD/kWh$_{\text{thermal}}$ only one renewable technology - PV - is implemented

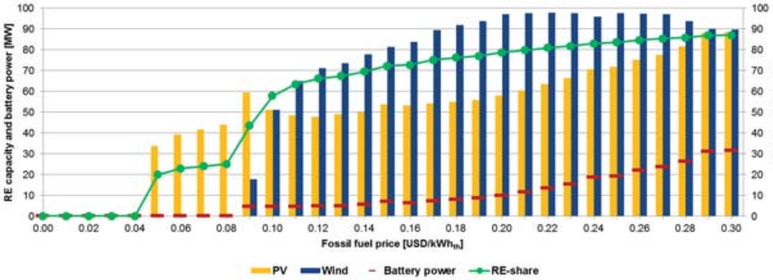


Figure 5.8: *Results of optimization of Tobago's energy supply system showing renewable capacities, battery power, and renewable share under different fossil fuel price levels*

without battery capacities. This concept represents the first step of hybridization of fossil based island energy systems and is often called "fuel saver" (cf. for example [162]) reaching a renewable shares of around 30 percent. The next type of configuration is a hybrid system of PV, wind, and fossil plants extended by batteries. For this analysis sodium sulfur batteries are considered only similar to the calculation of the overall renewable potential in Sec. 5.2. It is the most economical solution for Tobago up from fossil fuel prices of 0.09 USD/kWh$_{\text{thermal}}$. This limit is also the average fuel price on all analyzed Caribbean islands. By introducing wind and batteries all renewable and battery capacities increase with increasing fuel prices expanding the renewable share continuously from 30 to 80 percent. This is true up to fuel prices of 0.20 USD/kWh$_{\text{thermal}}$ and covers therefore the maximum fuel price on the Caribbean islands found on the Virgin Islands (VIR02 and VIR03) as well.

At fuel prices higher than 0.20 USD/kWh$_{\text{thermal}}$ the renewable share is slowly increasing as each burned fossil fuel unit is becoming more and more expensive (cf. Fig. 5.9). According to the resource availability it is also more economical to use more solar energy and higher battery capacities while reducing the share of wind energy. This is due to the fact that no long term storage technologies are considered within this simulation and therefore no wind energy can be economically shifted from months with high wind speeds to months with low wind speeds by sodium sulfur batteries. Contrary solar energy is available almost every day and just has to be stored for short time until it can be used during the evenings and nights. The potential of long term storage compared to batteries is for example discussed by Couchoud et al. [163] for compressed air energy storage. This topic is picked up in Subsec. 5.3.4 as well.

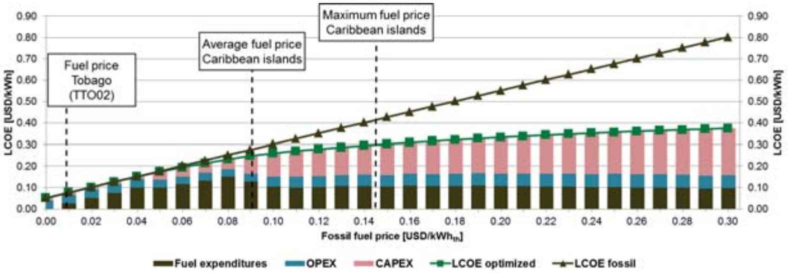


Figure 5.9: *Results of optimization of Tobago's energy supply system showing LCOE of fossil-only and optimized system under different fossil fuel price levels*

Another interesting aspect of the fossil fuel price sensitivity is to look at the economics and share of costs which are illustrated in Fig. 5.9. The LCOE for the optimized systems and for the fossil fuel only system are shown in green and brown lines for every fuel price level. Until 0.05 USD/kWh$_{\text{thermal}}$ the fossil only system presents the optimal case so no difference can be observed. With further increased fuel costs the gap between the fossil and optimized LCOE rises if more and more fossil fuel is substituted by renewable power generation to reach the techno-economic optimum. This is also expressed in the structure of the LCOE. For fossil only systems the LCOE are dominated by fuel expenditures and only small parts by operational expenditures (OPEX) and capital expenditures (CAPEX). This dramatically changes high shares of capital expenditures in optimized systems with high renewable capacities. This development is based on the cost structure of renewable power plants with high initial costs, low operational costs, and zero fossil fuel costs. These systems are less vulnerable to unforeseen fuel price fluctuations as well.

In summary the sensitivity analysis reveals for Tobago (TTO02) that renewable energy plants are not competitive under the current fossil fuel price level. If the average price level of the Caribbean target islands is taken as reference it would be economical to have renewable shares between 40 and 50 percent on this island. Another advantage of implementing renewable power plants is the more secure power generation cost level due to lower fossil fuel consumption. This reduces the dependency on fossil fuels with varying and hard to predict costs and could therefore stabilize the electricity tariff level of an island energy supply system.

5.3.3 Risk rate for geothermal plant

For geothermal projects often high risk premiums are paid due to the uncertainty of the resource. The final value of the underground resource can only be assessed after drilling of the borehole. This high exploration risk is often reflected in specific interest rates for geothermal projects. Thus the influence of changing interest rate on the economic viability of geothermal plants is examined along the example of Grenada (GRD01). This island has an indicated geothermal potential of 1,100 MW (cf. Tab. 4.5) and in the techno-economic optimized configuration it is suggested to install 23.5 MW geothermal capacities. This is complemented by just 2.3 MW of PV power and no wind power capacities at all. This is surprising as the solar and wind resources are abundant on this island with approximately 1,800 solar full load hours and 4,000 wind full load hours respectively. In this sensitivity analysis the capital costs for the geothermal plant ($\mathrm{WACC_{geo}}$) are changed from 10 to 30 percent in 2.5 percent point steps while for all other investments the capital costs remain the same at 11.08 percent as for the optimization in Sec. 5.2. The results of the sensitivity analysis are illustrated in Fig. 5.10 showing the renewable and battery capacities and the related LCOE and renewable energy share for each analyzed capital cost level.

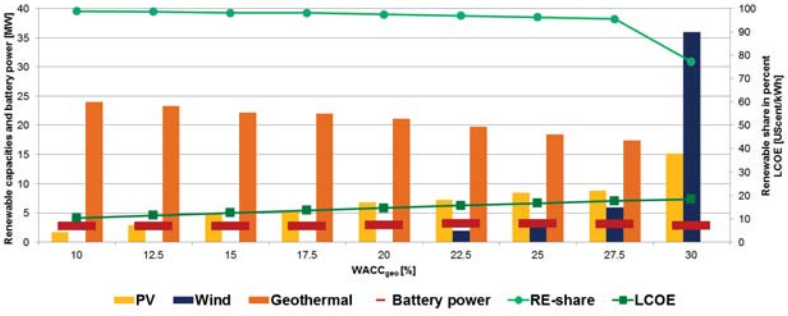


Figure 5.10: *Results of optimization of Grenada's energy supply system under different capital costs for geothermal plants*

From capital costs of 10 until 20 percent for the geothermal plant the results of the techno-economic optimization do not differ much as shown in Fig. 5.10. The PV capacity is increased by five MW and the geothermal capacity is decreased by three megawatts while the battery power remains almost constant. While the renewable energy share just drops by one percent point from 99 to 98 the LCOE increase from

0.10 to 0.14 USD/kWh. This is due to the increased capital costs for the highest investment sum, the geothermal plant. Anyhow the geothermal plant still represents the most competitive solution compared to the other renewable technologies. This competitive advantage is stepwise decreased while rising the capital costs from 20 percent to 30 percent. Wind power is introduced into the island energy supply system and substituting geothermal capacities. This continuous trade off is accelerated at a certain threshold. At capital costs of 30 percent geothermal plants are not competitive anymore at all and only PV, wind power, batteries, and the fossil plant are used for supplying electricity. For this solution the renewable share drops down to 77 percent and the LCOE are 0.18 USD/kWh. The higher LCOE have to be compared to the risk involved in applying geothermal power which is not only uncertain in terms of resource availability but also vulnerable to operation failures which would affect the full island as it depends mainly on one single geothermal plant. Thus the decision to choose the right risk rate for implementing geothermal plants is crucial in finding the optimal system configuration.

5.3.4 Zero to 100 percent renewable share scenarios

As final sensitivity the island energy supply system of Grenada (GRD01) is analyzed again. This time the renewable share of the system is predetermined and the techno-economic optimized solution for each related renewable share is calculated. As geothermal plants hold a special position this sensitivity is performed twice: Once with geothermal plants (scenario geo) and once without (scenario PV-wind). These sensitivities show potential pathways towards 100 percent renewable energy supply on Caribbean islands along the example of Grenada. In Fig. 5.11 the installed capacities for both scenarios are drawn and in Fig. 5.12 the related costs of energy supply.

Comparing the results of both scenarios the competitive advantage of geothermal plants on Grenada can be seen. The LCOE constantly decrease by the increased implementation of geothermal capacities while for the scenario PV-wind the LCOE reach the lowest point between 75 and 80 percent renewable share and increase dramatically afterwards. Comparing the lowest overall LCOE scenario geo reaches 0.11 USD/kWh and sceario PV-wind 0.18 USD/kWh. This advantage of geothermal plants might decrease by considering higher risk rates for these plants (cf. Fig. 5.10).

Using just PV, wind power, and battery energy storage a 100 percent renewable energy supply is very expensive to realize. LCOE go up to 0.49 USD/kWh sub-

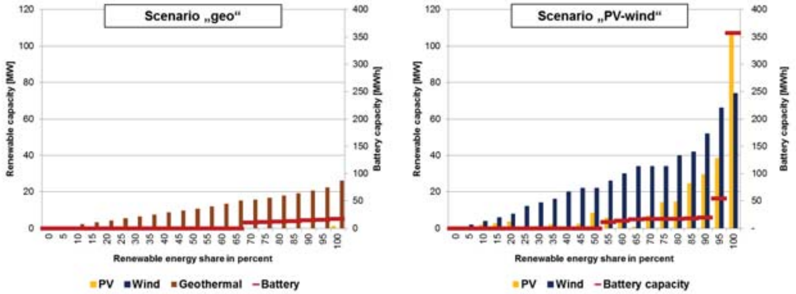


Figure 5.11: *Capacities of optimized island energy supply system of Grenada at different shares of renewable energies*

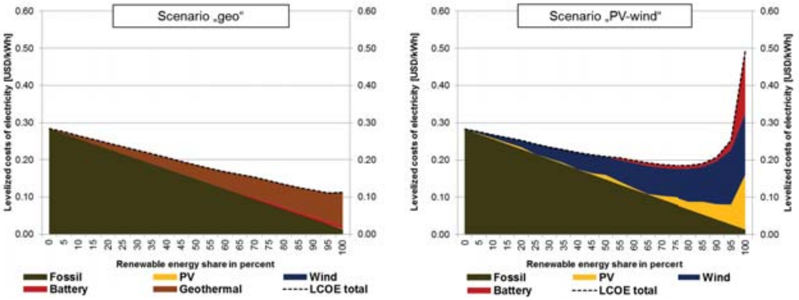


Figure 5.12: *LCOE of optimized island energy supply system of Grenada at different shares of renewable energies*

stituting each unit of fossil fuel by renewable energies. This is especially based on high storage capacity needs. If a more flexible long term storage system with more economical capacity costs could be applied the 100 percent renewable energy supply would be more cost competitive as discussed in the battery comparison (cf. Subsec. 5.3.1 and [163]).

In conclusion for renewable shares higher than 90 percent long term storage technologies such as compressed air energy storage or pumped hydro power (cf. Fig. 2.12) and / or the substitution of fossil fuels by bio fuels should be applied to keep the system competitive. This substitution would allow to run a flexible and dispatchable back-up power plant to fill the remaining few supply gaps during the year which are very expensive to cover with storage technologies. The pathway towards 100 percent renewable share is not a direct way as the preference between wind and solar power changes at certain shares of renewables and with higher battery storage capacities. To give suggestions for an implementation plan it is recommended to optimize the 100 percent case and allow a flexible way towards this configuration or to define certain intermediate steps without creating overcapacities (cf. [164]). A special view is directed on the battery capacities. Up from 50 percent renewable shares batteries are implemented to fulfill mainly stability services and to provide spinning reserve (cf. Subs. 5.3.1). Only at shares of 90 percent renewable energies and higher it becomes economical to install significantly higher storage capacities.

In opposite to scenario PV-wind the scenario geo shows a continuous decrease of LCOE by increasing the renewable share. The cost optimized system reaches almost 100 percent renewable share therefore such ambitious plans are easier to realize by using constant geothermal than fluctuating solar and wind resources. Anyhow, for supplying peak loads it is more economical to install battery capacities instead of covering everything by geothermal plant capacities. This is due to the high initial costs of geothermal plants and the absence of variable fuel costs. Up from 65 percent renewable energy share batteries are introduced in the island energy supply system. For this sensitivity geothermal plants are supplemented by small PV capacities only which would change at very high risk rates for geothermal plants (cf. Fig. 5.10).

In summary, it becomes obvious that geothermal plants are dominating the configuration of the power generation so it is an "either-or decision" to use geothermal power or PV and wind power to reach high shares of renewable energies. This dilemma has to be kept in mind for strategic energy supply planning on Caribbean islands. In the beginning a diversified approach could be chosen, but up from a certain threshold the technology choice hast to be clarified to avoid uneconomical competition between the single renewable energy plants.

By these two zero to 100 percent renewable share scenarios the sensitivity analyses are concluded. In general they underline the robustness and applicability of the results of techno-economic optimizations presented in Subsec. 5.2.2 for all target islands. For the final planning process several scenarios should be calculated to indicate the specific pathway, but the derived results point already in the right direction. Before focusing on additional barriers of implementation the calculated techno-economic potential of renewable energies on Caribbean islands is briefly discussed in the following section.

5.4 Discussion of results

As presented, the simulation and optimization of Caribbean island energy supply systems reveals an attractive potential for implementing renewable energies in various combinations. The comparison with simulated real status quo shows that new potential PV capacities of 8.9 GW, new wind power capacities of 6.1 GW, and new geothermal plants with more than 500 MW could be economically installed. The results of the optimization are discussed in the following.

Discussion

One of the more comprehensive overviews about renewable potential on Caribbean islands can be found in [165]. Within this report 13 Caribbean countries are presented with their specific renewable potential based on resource availability. For the Eastern Caribbean islands the results are similar to the presented ones showing excellent solar, wind, and geothermal potential. In addition, for the large islands the solar potential is indicated as high as in the IRENA report which is congruent to the techno-economic potential analysis. For wind energy some of IRENAS's indications are different to the results in the optimized scenarios but in general the tendency is similar. The biggest difference between the studies lays in the lack of an economic comparison in IRENA's report [165]. While in this report just the natural potential is shown, for this thesis the detailed comparison of resources, costs, and timely availability is performed. This can best be explained along the example of Trinidad and Tobago. IRENA reveals a high renewable potential in this country while the detailed study of this thesis shows no economic renewable potential at all owing to very low fossil fuel prices on these islands (TTO01 and TTO01).

Already in 2001 an overview on wind power potential for Caribbean islands has been conducted [166]. In this paper it is stated that "it is clear that wind, as a renewable energy resource, will become an important part of the energy mix of many Caribbean islands in the next decade". This is underlined by a study prepared for the Caribbean Renewable Energy Development Programme of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH [167]. In both studies the favorable wind conditions on Caribbean islands are discussed and in the latter even high wind power penetration systems are demonstrated. These ideas are also part of the simulation of this thesis by considering system stability technologies (cf. Subsec. 2.2.3). Thus, the calculated wind power potential seems realistic and should be continuously implemented.

The natural solar potential on Caribbean islands is very high which is pointed out for example by Schwerin [168]. This is also confirmed by the results of the techno-economic potential analysis. Only if it is outperformed by other renewable technologies the PV potential is shrinking which is neglected in the existing overviews on solar power for electricity supply. Thus, this shows the added value by the integrated system approach of this thesis comparing all technologies at once and not only showing the generation costs of one single technology.

Also studies exist focusing on the implementation of large scale fossil plants and suggesting the substitution of oil plants by gas or coal fired power plants [131, 132]. In these studies the most economical long term solution is implementing fossil power plant capacities with lower fuel costs. Coal plants are indicated with power generation costs of 0.12 USD/kWh for Jamaica [131]. This is significantly lower than the optimized LCOE within this thesis for this island using PV, wind power, hydropower, and fossil fuels. Anyhow, the optimized system is strongly affected by high capital costs, therefore a reduced interest rate would make these renewable technologies competitive to coal plants. In a NEXANT report [132] power generation costs of different technologies are compared and it is mainly suggested to implement gas power plants with cheap gas out of inter-island pipelines. The interconnection of islands is briefly further discussed in the limitations. Renewable technologies are considered as competitive as well, especially geothermal power plants which LCOE range in the same heights as in this thesis - around 0.10 to 0.12 USD/kWh. Finally, comparing the results of the techno-economic optimization with the suggestions of the two shown studies, it shows the competitiveness of hybrid systems and the accuracy of the applied methodology by calculating full reference years.

In summary, the presented techno-economic renewable potential analysis provides new information about existing and untapped renewable potentials on the analyzed Caribbean islands. Fundamentally the results - especially about the available natural resources (cf. Ch. 4) - are in line with the presented studies about renewable energies on Caribbean islands [131, 165–168]. Anyhow, the more detailed techno-economic optimization allows to consider more influence factors such as resource availability, local fuel prices, local costs of capital, and the hourly load profiles. The differences in these factors and their interactions lead to a detailed distinction of the renewable energy potential for each island. On this basis the calculated potential represents real economic and ecological benefits under the assumed input parameters. Other influence parameters which hinder using these opportunities are picked up in the following paragraphs and chapters.

The pathway of implementing the revealed potential is a difficult decision for each island. As presented in the sensitivity analyses of Sec. 5.3 many options exist to reach the suggested techno-economic optimized renewable share. Especially if geothermal plants are part of the renewable strategy a comprehensive planning is crucial. These plants might displace previously installed PV or wind power capacities and increase the uncertainty for investors and operators selling the renewable power. Thus, implementing the geothermal potential often is an all in once solution which requires strong will to change the full island energy supply system. If these plans exist but are not realized they hinder the development of PV and wind power due to the aforementioned reason. This barrier for PV and wind energy is further discussed in the next part of the thesis. Even though the final system might not be as cost competitive as with geothermal energy these considerations lead to the idea of implementing just PV and wind power in small steps. This requires less planning effort and less investment capital at one time. In addition many smaller power plant capacities increase the security of supply instead of relying on one single geothermal or fossil plant.

The calculated potential for renewable energies on Caribbean islands reaches 15.5 GW and would save 8.3 billion liters of fossil fuel and 22 million tons of CO_2 each year. The average share of 62 percent renewable energies for all optimized islands is far higher than the status quo of two percent. This means huge untapped potentials of economically implementing renewable power capacities are detected by the applied simulation tool. However, these numbers are derived under certain assumptions and simplifications and might differ in reality.

Limitations

The limitations of the methodology which could distort the results for some islands are explained in the following. First of all within the model only one power plant per technology type is considered (cf. Fig. 3.2). By this simplification a few effects are excluded: for fossil plants the part load behaviour, different efficiencies, and different fuel types cannot be varied for several single plants but are aggregated in one generic plant for the entire island. For renewable plants only one resource time series can be applied which does not allow balancing effects which can occur if several - for example PV plants - are installed on different locations of larger islands. This would smooth the solar power generation and reduce the instant fluctuations by cloud coverage. For wind power plants the aggregation on one single plant for each island is especially disadvantageous on islands with a few very good wind spots which are not reflected in the broad resource data grid. Anyhow these limitations can be removed for single detailed island energy supply studies and do not affect the results too much.

Another aspect which is not reflected in the simulation model is the land availability for renewable plants. Especially wind farms need wide areas of open cleared land which is not always accessible on islands. Thus, an upper limit for implementing renewable capacities could exist on the analyzed islands but it is not considered in the optimization due to the lack of sufficient data. If the land availability would be known such upper limit could be easily implemented into the tool. This special issue of land availability is also discussed in the following analysis of barriers of implementation.

The negligence of the electricity grid is to mention as third main restriction. Two major aspects of grid studies are excluded for this work: On one hand the capacity of the existing island grid to cope with fluctuations of the potential renewable plants should be tested. All different scenarios such as for example short circuits, voltage and frequency drops, and instant load increases have to be checked for the suggested optimized system. These tasks are way beyond the scope of the developed simulation tool but commercial tools such as PowerFactory from DIgSILENT are recommended for such an analysis. Before implementing the renewable systems detailed studies have to be performed, even though the stability parameter in the one hour tool helps to set certain security constraints. On the other hand the connection of several island grids to one large scale supply system is not investigated in this thesis. A NEXANT report reveals many different supply strategies by various interconnection scenarios [132]. These interconnections are especially attractive if they can be combined with large scale power plants with low operation and fuel costs. This is for example true for geothermal plants which could supply neighboring islands via undersea transmission lines. This is calculated for four Eastern Caribbean islands by [169]. A slight cost reduction is reached in this study for one island without geothermal potential by connecting it to another island with geothermal plants. Not considering interconnection scenarios means that not the full cost reduction potential of renewable energies is detected in this study. However, the effects are rather low and the uncertainties for cost estimations for undersea transmission lines are quite high so it is acceptable to neglect this option. In further studies it can be taken up to analyze additional renewable energy potentials.

Despite the aforementioned limitations the results seem valid and robust comparing them to other studies. The detailed input parameters and accurate energy system modeling reveal quite realistic implementation potential for renewable energies on Caribbean islands. The full system perspective is always assuming perfect competition and the absence of market distortions. Ideal economies would therefore follow the suggestions and quickly implement the suggested renewable capacities. In contrast to the calculated 15.5 GW of additional renewable capacities, there are currently 1.1 GW installed of which 800 MW are hydropower plants. This enormous gap between the techno-economic potential and the real implemented capacities of renewable energies on Caribbean islands leads to the assumption that various barriers exist which are hindering the anticipated development. These barriers can be of technological, economic, political, and social nature and are therefore not all considered within the techno-economic model as it assumes perfect market conditions. In conclusion the pure calculation of the optimized energy supply does not help implementing the revealed renewable energy potential without considering further barriers and their solutions. In the following chapters these barriers are identified, analyzed, and evaluated for Caribbean islands to develop strategies to overcome these barriers.

Chapter 6

Empirical analysis - barriers of implementation

All first three research questions were sufficiently answered in the first part of this thesis. Abundant availability of resources to apply renewable energy technologies is shown in Ch. 4. The technological solutions are tested by island energy supply systems modeling which is presented in Ch. 3. Finally, the results of the analysis of the techno-economic potential reveal the attractiveness of renewable energies on Caribbean islands in Ch. 5. A theoretical potential to implementing renewable energies on Caribbean islands is proven from this. Resources and matching technologies are available and under the assumed circumstances they are competitive on almost all islands. Anyhow, the implementation of this potential is enormously lagging behind because of the existence of other important barriers which are not yet reflected in the modeling of the techno-economic potential. Within this chapter additional barriers are identified and evaluated to derive solutions to overcome them.

6.1 Theoretical background and approach

In general, a lot of studies have been conducted to analyze barriers to implementing renewable energies and to find solutions to overcome them (cf. review by Blechinger [11]). One of the most cited papers is from Painuly [16], setting a basic framework to analyze barriers to high renewable energy penetration. Within this paper general categories of barriers and methodologies to obtain them are suggested:

- *Literature surveys*: Scientific literature or reports can provide deep insights on barriers. Optimally, similar regional, political, or natural conditions exist in the studied regions to derive suggestions for the new research field.

- *Site visits*: On-site visits allow un-distorted views on the research object. By these visits barriers can directly be observed and evaluated if access to all local information is available. They can be combined with stakeholder interactions (cf. next item). Case studies are often located in the category of site-visits as well, even though they are sometimes based on literature review only.
- *Interaction with stakeholders*: By empirical research on stakeholders' perception of local barriers of implementation two aims can be achieved. Firstly, the identification of the barriers themselves is possible via structured interviews and / or questionnaires which does not necessarily require costly field trips. Secondly, in addition to the barriers the point of view of different stakeholder groups can lead to a deeper understanding of the special interests of these groups and more specific measures to overcome certain barriers can be derived.

Deployment and analysis of barriers within a general context is mainly performed by literature reviews. Hereby other papers, reports, or policies are investigated as it has been performed by Beck and Martinot [18], Verbruggen et al. [170], Timilsina et al. [171], and Negro et al. [172]. The global perspective often does not allow to apply site-visits or stakeholder interviews. One exception, focusing on case studies, is found in the work of Boyle [173], where case studies in ten different countries are compared to derive barriers. Usually, the specific methodologies of site visits or interaction with stakeholders are used for the investigation of certain regions, countries, or areas only. Studies which present barriers on country level with the help of case studies are performed for example for Greece [174] and Bangladesh [175]. One exemplary research in the United States [176] and one in the United Kingdom [177] use extensive empirical research by interrogating stakeholders. Two other papers can serve as example for combined methodologies of literature survey, site-visits, and stakeholder interviews: in Honkong [178] and in rural Tanzania and Mozambique [179]. All aforementioned papers have given valuable inspirations for this research work to apply scientific proven methodologies for the analysis of barriers.

Anyhow, for the Caribbean region only few scientific work is published. Some barriers are elaborated by Shirley and Kammen [149] while Ince [19] presents a very in-depth research about barriers for renewable energy industries in the Caribbean. In his work he points out the need for more quantitative studies to validate his results. Other reports of different institutions target barriers as well, but they are lacking a clear scientific methodology (e.g. [21, 168, 180]). In summary, barriers to implementing renewable energies on Caribbean islands have not yet been sufficiently analyzed. Thus, this thesis continues the work of many researchers by applying all three aforementioned methodologies, which means literature reviews, case studies, and stakeholder interviews.

Firstly, detailed literature reviews are conducted to derive an overview of barriers relevant for Caribbean islands. A literature synthesis matrix is applied to structure the barriers and identify the most important ones. This matrix helps in organizing and structuring results of literature review and in narrowing of the focus to extract only valuable information. For the basic structure main categories are derived to sort the barriers. These categories are relatively broad to avoid the impediment of the incorporation of new and different ideas from the specific literature. This literature is derived from scientific journals as well as from public available reports.

After the identification of barriers by literature review the regional focus is strengthened. This is conducted via semi-structured interviews of the main stakeholders of the Caribbean power sector. To reduce the amount of interviews only three special experts, so called "super-experts", are selected as representatives of the main stakeholder groups: utilities, governments, and the private and institutional sector. Utilities are represented by the executive director of the Caribbean Electric Utility Services Corporation (CARILEC [181]). Another association is chosen to speak for the governmental sector, the Caribbean Community (CARICOM [30]), which represents 12 of the analyzed countries of this thesis as mentioned in Sec. 2.1. As CARICOM expert the Programme Manager of the CARICOM Energy Desk is the best match to give insights on renewable energy development from the political perspective. One former member of the Caribbean Renewable Energy Development Program (CREDP [182]) is selected as a representative of the third group, the private and institutional sector. Experts of CREDP have over ten years of experience in supporting private and public sector investments in renewable energy deployment and in policy advice. Thus, a lot of knowledge according to barriers and solutions to implementing renewable energies is gained within this program initiative. The results of the semis-structured "super-expert" interviews lead to the final table of barriers to implementing renewable energies on Caribbean islands with a strong regional validation.

These barriers are evaluated in the next step by another empirical analysis. This time the field of experts is extended. Renewable energy experts from utilities, the governmental, private, and academic sector, additionally from non-governmental organizations and institutions are selected to fill out questionnaires to evaluate the importance of each of the previously identified barriers. All experts have professional experience in the Caribbean which deepens the regional context of the empirical analysis. A simple evaluation system is applied using a Likert-scale from zero to five. This scale allows to rank the barriers according to their average importance and to show the variance. By that the final ranking of barriers of implementation is completed. In addition, the selection of experts from different stakeholder groups allows a comparison of different perspectives on certain barriers.

After revealing the most important barriers, strategies to overcome these barriers can be derived. These solutions consider suggestions from the used literature as well as comments during the semi-structured interviews and within the questionnaires. The different perception of the barriers by the selected stakeholder groups additionally influences the proposed solutions. Finally, case studies are analyzed to validate the empirical results and to derive solutions to overcome the most crucial barriers. These solutions are summarized in a strategy roadmap to facilitate the implementation of renewable energies on Caribbean islands. The full process of identifying and evaluating barriers and developing solutions is illustrated in Fig. 6.1.

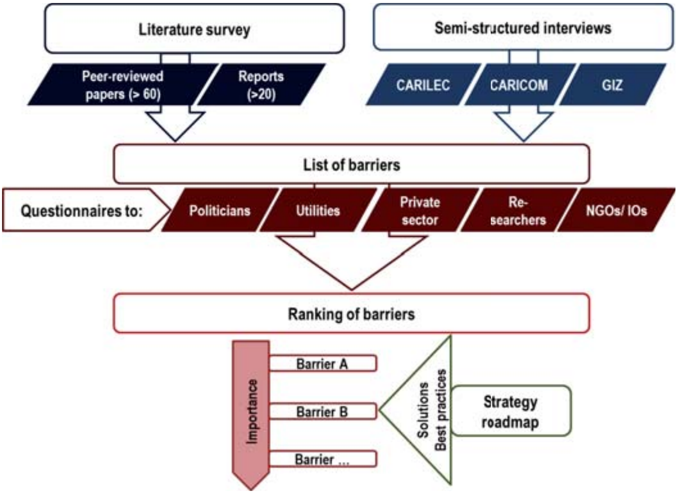


Figure 6.1: Empirical research approach to identify and evaluate barriers of implementation and to derive solutions

The final target of recommending a strategy roadmap to remove and overcome barriers of implementation is reached after the most important barriers are identified and ranked as shown in Fig. 6.1. The single research steps and their specific methodology and results are presented in the following sections. It is started with the literature review in Sec.6.2 followed by the regional validation of the identified barriers in Sec. 6.3. After the ranking and evaluation based on questionnaire results in Sec. 6.4 the final recommendations are given in Sec. 6.5.

6.2 Literature review of barriers

As aforementioned the empirical study starts with a literature review to derive the main important barriers to implementing renewable energies on Caribbean islands. To structure the various sources and to identify the most crucial barriers a literature synthesis matrix is developed as shown by Ingram et al. [183].

More than 60 peer-reviewed papers and 20 reports are identified for the first view on the barriers. Studies looking at the Caribbean Islands or comparable regions such as other small island developing states are taken for further analysis. These studies are deeply investigated along the different categories of the synthesis matrix. For clustering the barriers these categories are technical issues such as natural conditions, technological constraints, and infrastructure and economic hurdles which can be named as costs/prices, financial aspects, or market failures/distortions. In addition, political aspects such as regulatory frameworks and policies and institutional capacities are taken for clustering categories as well as social aspects (consumer behavior/education/societal attitudes, interactions/networks, cultural habits, and psychological/moral issues). For a better understanding the structure of barriers for the synthesis matrix is illustrated in Fig. 6.2.

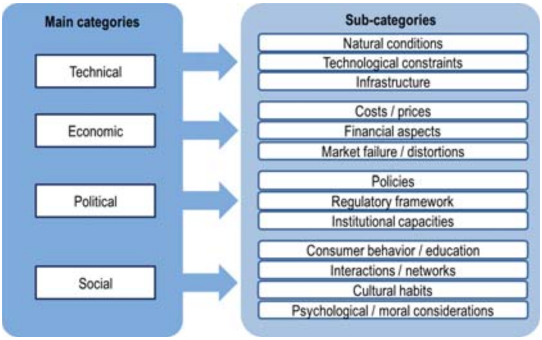


Figure 6.2: *Identified main and sub-categories of barriers as applied in the literature survey*

Additionally the papers are analyzed according to measures to overcome barriers referring to the paper's solutions. This is interesting for the later comparison as since solutions are derived in a final stage of this thesis. The respective methodology of ranking and identification of the barriers in each investigated paper is analyzed as well. It is important in order to compare other papers' methods for potential improvements in the presented empirical approach.Only papers whose findings could be applied to renewable energies in the Caribbean are deeply analyzed. Thus, this so called extrapolation status (e.g. development status, island, region) referring to the suitability of the individual paper to the topic is another category in the synthesis matrix. To allow further research on barriers, seminal papers referenced are written down in the synthesis matrix. In addition renewable energy experts are identified as potential interview partners and questionnaire participants for the following research steps. All categories presented in this paragraph have influenced the research and improved the methodologies and the sample of experts. Anyhow, the findings among these categories are not further explained in this thesis as it is focused on the main categories of barriers in the following. Along these four main categories the barriers are elaborated and summarized in bullet points after each sub-category.

Technical barriers

At first it is looked for technical barriers mentioned in the analyzed papers. Within the natural conditions which may hinder the implementation of renewable energies the restricted area of available land is one factor. This results in increased prices for land [184], in competition for land and water resources, especially for tourism and agriculture [19,185,186], and a lack of landmass between wind and solar sites to level out fluctuations in production capacity [19]. In addition, the resource availability is limited on certain islands due to seasonality of biomass in the Caribbean and to limitations of geothermal and hydropower potential [19, 171, 187]. Environmental externalities from renewable energies count also as barrier from natural conditions. These can be migratory bird disturbances and noise pollution from wind parks [188], toxic spills and deforestation from geothermal drilling as well as pollution of hydrological ecosystems from hydropower plants [20, 165]. Hurricanes, floodings, earthquakes, and other natural disasters and weather extremes count as natural barrier to implementing renewable technologies as well [189].

- Limited availability of land
- Limited natural resource availability

- Environmental externalities from renewable energies
- Natural disasters

In terms of technological constraints only three specific Caribbean barriers could be identified. One is based on efficiency restrictions for PV and wind power plants, which leads to high land use of PV plants [20]. For wind power the most efficient large scale turbines are often too big for small Caribbean islands due to low load demands or less developed infrastructure. Thus, turbines with lower efficiencies have to be used [171]. Secondly it is quite complex to implement high shares of renewable energies into island energy supply systems. This means sophisticated control strategies and technologies such as high power batteries or flywheels are needed to keep the supply system stable. This lack of grid stability structure and integration and transmission capacity hinders the quick implementation of renewable energies and even arbitrary caps could be set on maximum fluctuating renewable electricity production by both utilities and regulators [168, 187, 188]. Thirdly, the absence of local technology manufacturers imposes another technical barrier which means Caribbean islands and other small island developing states are often "takers of technology" only [34]. This is especially disadvantageous in case of maintenance issues and if spare parts are not locally available.

- Efficiency constraints
- Immaturity of island energy systems with a high renewable energy share
- Non-existence of local manufacturers

Two barriers are referenced in terms of the sub-category infrastructural conditions. The first is the availability of transport and installation equipment and infrastructure. For example missing appropriate port and road facilities hinder the transport of renewable technologies while missing cranes hinder the installation [188]. Another issue is the status of transmission and distribution grids along Caribbean islands. This can mean a lack of sufficient transmission lines from remote areas, low transmission voltages with high losses, and difficulties of achieving grid interconnection between single islands. All these weaknesses complicate the implementation of renewable energies due to insufficient grid capacities [19].

- Transport and installation equipment and infrastructure
- Transmission and distribution grid capacities

Economic barriers

Next, the literature is scanned for specific economic barriers. Very often high initial investment costs are mentioned as barrier in the sub-category costs or prices. Due to the nature of renewable plants very high initial costs occur while often only few operation costs and zero fuel costs have to be paid. Thus, in the long run viable electricity supply options by renewable energies are often not installed because of the high upfront investment which is seen as important barrier (cf. [18,20,171,182,187]). High transaction costs count as another cost driven barrier. On many small islands the transaction costs per installed kilowatt capacity are higher than in large scale systems. This increases the cost level of renewable technologies as well as the lack of experience in evaluating and operating renewable energy projects [16, 18, 19, 187, 190, 191]. Similar to that diseconomy of scale represents the third barrier which is based on costs and prices. Low absolute demand and size of power plants on smaller Caribbean islands do not allow the installation of large scale renewable plants and implementation projects. Thus, no scaling effects for transport, installation, and purchase costs can be applied which makes the renewable plants more expensive on these islands [16, 19, 34, 186].

- High initial investments
- High transaction costs
- Diseconomy of scale

The subsequent economic sub-category is financial aspects in which four different specific barriers are identified. In the Caribbean the lack of access to low cost capital or credits is one of these four barriers. This is based on high interest rates within the countries due to unstable currencies and economic conditions. In addition, most analyzed Caribbean countries have large foreign debts which leads to a shortage of low cost loans for investments as high risk rates have to be added [20, 182]. Not only capital from banks or public financing is expensive in the Caribbean but also private capital is lacking. This means insufficient investments and innovations come from the local private sector which is usually a driver for new technologies [16]. Another financial aspect are the uncertainties around project cash flows. Due to missing experience in renewable island energy supply systems, local financing institutions and project developers have difficulties to assess future cash flows of such projects taking into account technology risks and fluctuating fossil fuel prices [18, 19]. This is also reflected in the next barrier, the time frame of procurement contracts and power purchase agreements. Usually such contracts cover only a short term, but long payback periods of high share renewable energy projects require long-term financing which is then either not available or very expensive [16, 18, 19, 187].

- Lack of access to low cost capital or credits
- Lack of private capital
- Uncertainties around project cash flows for hybridization projects
- Short terms of procurement contracts and power purchase agreements

The third economic sub-category is based on a macro-economic view and considers market failures and distortions. One barrier under this sub-category is the utility monopoly of production, transmission, and distribution of electricity on most of the Caribbean islands. Often the local utility possesses a natural monopoly due to the character of electricity supply which does not economically allow a second supply system with power plant and grid capacities as competitor. This monopoly is a huge barrier to market entrance for renewable energy investors and if the monopolistic utility is reluctant versus renewable energy investments it is difficult to force it [19, 21, 192]. The following barrier, which is based on the small size of Caribbean islands, is the small market size for electricity supply and renewable energies. Similar to the aforementioned monopolies the small size of market acts as barrier to competition and investment opportunities [16, 19, 170, 192]. One less specific but still important barrier is the so called lock-in dilemma. The lock-in dilemma describes the institutional and technological bias of changing prevailing systems by inability to adopt innovation due to imperfect competition, lack of research and development culture, or loss of legitimacy by breaking informal and formal institutions. For the Caribbean power generation sector this dilemma means that the existing and established conventional power generation sector is not able and/or willing to shift towards renewable energies and it is hard to overcome this hurdle due to manifested power structures [16, 19, 173, 193]. The last identified economic barrier is the market distortion by fossil fuel subsidies and fuel surcharges. In some Caribbean countries governments either subsidy the fossil fuel prices or the electricity tariffs of fossil based energy supply which makes it harder for renewable power plants to compete with conventional sources. In addition, the system of fossil fuel surcharges which allows the direct passing of fuel costs for power generation to the end-customer sets disincentives of investing into renewable or fuel saving power generation capacities [180, 192].

- Utility monopoly of production, transmission, and distribution of electricity
- Small market sizes
- Lock-in dilemma
- Fossil fuel subsidies and fuel surcharge

Political barriers

The next main category which is focused on is political barriers. As first identified barrier within this category the gap between policy targets and real implementation is to mention. Most Caribbean states have renewable energy policy roadmaps, however, the commitment on paper contradicts reality at the moment. The goals are either too ambitious or their enforcement is too weak, which both do not support the implementation of renewable energies [20]. Another political barrier is the lack of prioritization of renewable energies through taxes, reduction of trade barriers, and subsidies [19].

- Gap between policy and implementation
- No prioritization of renewable energies

More specific than policies are regulatory frameworks which built the next political sub-category. The lack of such regulatory frameworks is one barrier in terms of incentives (e.g. guaranteed feed-in tariffs, allowance of self-consumption, or net metering) and secure investment frameworks for private investments [19, 20]. Another barrier is the missing legal framework for independent power producers and power purchase agreements. This means on a business to business level no guidelines or laws exist to coordinate such contracts which leads to high investment risks and transaction costs [18].

- Lack of regulatory framework
- Lack of legal framework for independent power producers and power purchase agreements

Besides the policies and regulatory frameworks the institutional capacities of the Caribbean governments and administrations are analyzed as well in the literature survey. From that two specific barriers are derived. The first is the lack of formal institutions on country and regional level. In many Caribbean countries specialized government departments are missing for renewable energies to disseminate information and foster investment. Often departments focusing on energy issues only do not exist as they are combined with infrastructure or agricultural responsibilities to multi-purpose ministries. On regional levels only one initiative has started to create an Eastern Caribbean Energy Regulator (ECERA) which could help to overcome the lack of specialization on governmental level but its implementation is rather slow [16, 19]. The second barrier is the lack of renewable energy experts within the aforementioned institutions. Due to the small island populations it is often difficult to find trained staff to support renewable energies from the governmental perspective [19, 186, 194].

- Lack of formal institutions
- Lack of renewable energy experts within institutions

Social barriers

As last category the social barriers are presented, beginning with those identified along the sub-categories consumer behavior / education. Firstly, a lack of social norms and awareness in respect of renewable energies is found as specific barrier. Thus, the acceptance for and education about the different renewable energy technologies and their economics is missing, which reduces the support from the local population [16,20,170,184,186,194]. Similar to that, a lack of educational institutions and human capital is identified as next barrier. Local trained staff for implementation and operation of renewable energy plants is not sufficiently available which is partly based on the absence of institutionalized learning and the lack of technology transfer centers. Missing local experts increase the project costs for renewable energy projects and hinder the innovation and project initiative from local companies which summarizes this specific barrier [192].

- Lack of social norms and awareness
- Lack of educational institutions and human capital

Two barriers are found based on the sub-category interactions and networks. The lack of supporting regional networks and initiatives is named as one barrier. Such missing networks would act as facilitator of innovation and adaptation of renewable energies which has been quite successful for example in Germany [195]. As aforementioned these initiatives for renewable energies are lacking on Caribbean islands and only networks among the fossil fuel based power supply exist which might even block the deployment of renewable technologies [19,20]. The other important driver, which is mostly missing on Caribbean islands, is the existence of local champions or entrepreneurs. This lack is the other barrier as such champions are important in markets with high uncertainties which is true for renewable based island energy supply in the Caribbean. They would reduce transaction costs and could provide information to investors supporting the implementation of renewable energies [19].

- Lack of renewable energy supporting regional network
- Lack of local or national champions or entrepreneurs

One cultural barrier is the dominance of energy over environmental policy. The real and perceived need for accelerated economic development outweighs ecological considerations of dwindling natural resources in most developing countries which is also true for Caribbean islands. Thus, the access to energy as driver for the local economy is of higher importance than implementing renewable energies due to environmental considerations [187].

- Dominance of energy over environmental policy

The last specific barrier is found within the sub-category psychological or moral considerations. In this case the barrier is the preference for the existing status quo - the electricity supply based on fossil fuels. This emerges from an historical bias which ranks the known existing technology superior to unknown future options. In addition, negative examples from the past increase the reluctance versus renewable projects. These examples may be based on very expensive projects which would be much more economical under the current price conditions or on technological failures of small pilot projects without proper maintenance [19, 187, 194].

- Preference for the status quo

Overall 32 specific barriers to implementing renewable energies on Caribbean islands are identified by the literature survey. They are distributed along the four categories of technical, economic, political, and social barriers and the most fall under the category economic barriers. A validation round with Caribbean renewable energy experts is performed in the next section to extract the final list of barriers. This is necessary as not all of the used literature is Caribbean specific and some of the papers and reports are not up to date.

6.3 Empirical validation of barriers

As mentioned in Sec. 6.1, three "super-experts" are chosen to validate the list of barriers derived from the literature survey. This validation is conducted via semi-structured interviews to allow qualitative research results. At first, the methodology is explained and the interviewees are presented which is followed by revealing the results of the interviews. Lastly, these results are merged with the list of barriers from the literature review to derive the final barriers for evaluation.

6.3.1 Qualitative approach and structure of interviews

The approach of semi-structured interviews is selected as validation method. Its purpose is to find common ground between inductive and deductive research, in this case what the barriers to renewable energies on Caribbean islands are [196]. Such semi-structured interviews are recommended and applied by many researchers for data gathering as shown in the next paragraph.

Useful insights into the research topics can be gained by open-ended and semi-structured questions that provide direct quotations. In addition, in-depth results of discursive or exploratory nature that deliver holistic understanding of participants' perspectives are collected [197–201]. The methodology is also described as picturing a complete process and gaining rich and deep data with the focus on the meaning or why participants hold their respective views [202–204]. All these advantages help to strengthen the local context in the empirical research and to improve the literature survey results by selecting the right "super-experts". The questions are looking for the experts' personal perspective on the topic, which consequently points out the nature of the Caribbean specific barriers and potential solutions [205, 206]. In conclusion, such semi-structured interviews match perfectly to improve the theoretical derived barriers from the literature.

For the management of the interviews guidelines are developed and their theoretical background is explained in the following. In general the interview technique is based on the conceptualization of the problem-centered interview by Witzel [196,207], but it is also characterized by the methods of expert interviews as shown by Meuser and Nagel [208]. Optimally, the interview guide should thematically organize the researcher's background knowledge for an analytic and comparative approach to the topic, but it has to be avoided to dominate the talk [207]. The previous data collection - literature review on barriers - serves as heuristic-analytical framework to generate ideas for the questions that are asked [196]. Finally, for this thesis an entire interview guide was developed which can be found in Appendix A.1.

The interview guide is divided into three main parts. First, the interviewed person should give a personal introduction and talk freely about renewable projects and challenges on Caribbean islands. This allows an understanding of the personal background and perspective of the "super-expert" and an undisturbed view on the main important barriers from his/her point of view. Afterwards more specific questions are asked according to the barriers to implementing renewable energy technologies. For the single sub-categories of barriers firstly general questions followed by more specific ones are asked. This order avoids a leading role of the interviewer (researcher) in this process [209]. At the end of the interview the "super-expert" is asked for any additional information which is not covered by the questions on barriers and a follow up is suggested. The presented interview guide is applied for three interviews. During these interviews the behavior of the interviewer should remain neutral in avoidance of disagreeing or agreeing with interviewee, in order to retain biased results originating from critical interjections as suggested by Maccoby [210] and Schnell et al. [211], otherwise personal interest biases the study [212]. The previous categorization of the barriers assists in analyzing the interview results to elaborate patterns for identifying additional barriers [203]. To derive the final list of barriers a mere comparison is necessary, followed by possible amendment or reduction of barriers, or change of hypotheses or meanings of certain barriers [213]. For a better traceability of this process the interviews are transcribed and attached in Appendix A.2.

Before the final results are shown the interviewed "super-experts" are briefly introduced in the following. As already explained three such experts are identified representing the main important stakeholders of renewable power generation on Caribbean islands: Utilities (by CARILEC), politicians (by CARICOM), and private sector and initiatives (by GIZ / CREDP).

CARILEC - represented by Mrs. Allison A. Jean - Executive Director

Mrs. Jean is a former official member of the board of directors of Caribbean utilities and holds the position as executive director CARILEC since 1st of August 2013. Before that she has been the Permanent Secretary of Infrastructure, Port Services and Transport in St. Lucia and has broad experience in energy and infrastructure related issues.

CARICOM - represented by Mr. Joseph Williams - Programme Manager CARICOM Energy Desk

Mr. Williams has a long history of working in the field of power generation and renewable energy on Caribbean islands. In 1990 he became Director of Generation Department of Jamaica Public Service Company (JPSCo) followed by the position as Manager Marketing And Energy Services Department at JPSCo responsible for renewable energies and energy efficiency. In 2008 he got promoted as Programme Manager of the CARICOM Energy Desk.

GIZ / CREDP - represented by Mr. Sven Homscheid - CREDP/GTZ Technical Advisor

Mr. Homscheid has been working for the CREDP for more than ten years as project manager and consultant. As an expert for renewable energy technologies he is specialized in hydropower, but also covering PV, wind, and other renewable energies. During his career he has been project manager of several projects, such as PV installations on various Caribbean islands and he guided an LED street light pilot project in St. Vincent.

After this brief introduction of the three "super-experts" the results of the interviews are presented in the next sub-section. Additionally, the final list of barriers for evaluation is revealed.

6.3.2 Results of interviews

In the following the changes of the list of barriers to implementing renewable energies on Caribbean islands are documented. The previously identified barriers are compared to the interview outcomes. The transcribed interviews can be found in Appendix A.2.1 for Mrs. Allison Jean, in the following referred to as AJ, in Appendix A.2.2 for Mr. Joseph Williams, in the following referred to as JW, and in Appendix A.2.3 for Mr. Sven Homscheid, in the following referred to as SH. Similar to the results of the literature survey the results of interviews are presented along the four main categories of barriers.

Technical barriers

The first technical barrier called *limited availability of land* is changed to *land use competition on islands*. Basically the meaning is the same but it is more precisely adapted to the circumstances on Caribbean islands as it is stated by SH: "Land is available but it comes with certain problems. You can't put up a wind farm in the midst of a hotel development area." *Limited natural resource availability* is totally erased from the final list of barriers as it was not mentioned as important by any of the three "super-experts". *Renewable energy plants' impact on landscapes and ecosystems* emerges from the previously listed *environmental externalities from renewable energies.* This especially refers to the visual impact of wind turbines on the landscape which is underlined by SH: "The footprint of a windmill is maybe 50 square meters? But you would see the windmill for kilometers." As last natural barrier for renewable energies the natural disasters are confirmed as crucial on Caribbean islands. SH explained: "The natural disasters are not hampering the development of renewable energies, they make it more expensive." In addition JW said: "...[W]e also need to get some new consideration for the vulnerability to natural disasters, when we come to implementing this. It is also expensive, we have to make sure that we minimize any risk when implementing and operating some of these technologies."

As new technical barrier the *lack of evidence-based assessments of renewable energy potentials* is introduced, which means feasibility studies, cost comparisons and LCOE calculations. The idea is created by JW saying "we don't have a very good assessment of renewable resources." and by SH stating "so it really needs some knowledge to prepare options against each other. I don't have the feeling that the utilities will provide this knowledge to compare geothermal and hydropower and PV and wind power, and storage that would be needed to complement wind and solar. I have not seen any study that was looking at the complex economics comparing one versus the other one, looking at the scaling effect."

Focusing on technological aspects the *efficiency constraints* are taken off from the list of barriers as there is no specific mentioning in the interviews. The *immaturity of island energy systems with a high renewable energy share* is changed to a *lack of technical expertise and experience* based on the statements of SH: "...[T]here's a combination of a lack of technical understanding of things, [... and] on the technical advisor side. [...] the technical understanding is something that is missing." And of JW: " [...] the need for applied research in terms of understanding some of the integration issues to get the optimal performance from some of the equipment."

The next technological based barrier is the *low availability of renewable energy technologies.* This barrier emerges from the previously identified barrier *non-existence of local manufacturers* and it is changed among other reasons due to JW's proposition: "That's a technical barrier because there could be the opportunities to invest in variations of technologies that are suitable for different countries with different needs, especially when we think about waste to energy it comes up as a big matter. We don't have the technical capacity to do some of these assessments." Thus, it is not only about the lack of local manufacturers but also about the problem that existing technologies are not adapted to Caribbean needs.

As next topic the infrastructural barriers are elaborated. Both infrastructural barriers defined within the literature survey are confirmed by the interviews. Firstly, the *inappropriate transport and installation facilities* are verified as a barrier by JW: "So because then the island states also have small road infrastructure, so the infrastructure is limited. You will find that some of the options will have to be by-passed. [...] Especially some of those off-shore options relate to infrastructure." And by SH: "Transportation costs are the main factors why these islands have that high exploration costs." Secondly, the electrical infrastructure is mentioned as barrier, more specifically the *unsuitable transmission system and grid stability issues with decentralized renewable energies*. This is confirmed by JW stating: "We have cases where the transmission infrastructure needs so much upgrading that a project would not be considered overall." Also SH underlined this barrier saying "[...] how much variable renewable electricity can be fed into the grid as it is right now, without creating grid instability in terms of voltage and frequency?"

For the technological barriers most of the ones defined by the literature survey are confirmed by the interviews. One is completely erased and one is newly added to the list. All new findings are based on comments of JW and SH only as AJ stated that "she is not the one talking about the technical side of barriers." Nevertheless, the final list of technical barriers can be seen as valid based on the reviewed literature and experts' input.

Economic barriers

High initial investments are confirmed as the first economic barrier. SH gave an example for hydropower: "You will see stranded assets. [...] Small hydropower is quite expensive, even more so on these small islands." High investments are followed by *high transaction costs* as next economic barrier. "It is still a very big problem, the transaction costs, yes and is related to the scale of the projects. And then it becomes a big issue." is what JW said to the issue of transaction costs.

Diseconomy of scale is confirmed by SH as a prevailing barrier on Caribbean islands: "Your installed capacity of power plants is much larger if you are going for dispersed systems. I think thought needs to be put into that issue as well, if you are looking at the overall economics of the electricity sector in the Caribbean small island systems." and "Most likely you will not find a geothermal project on a small island. If you visualize the cost curve as a linear graph, the cost curve for geothermal starts much higher, and then the gradient is much smaller, as opposed to [e.g.] hydro power."

Compensating the high costs is challenging for example due to the barrier *lack of access to low cost capital.* One of the reason is the high foreign dept situation of Caribbean countries. This is verified by JW: "The governments are significantly constrained by immediate crises or issues related to their fiscal arrangements, as well as their debt situation." and "[...] there is a big gap [...] with regards to financing by commercial banks, we need significant resources, especially for the feasibility study side." Furthermore, SH stated: "Governments are involved to invest and they have limited borrowing capacity."

In addition, the barrier *lack of understanding of project cash flows from financing institutions* limits the available capital as well. Two statements underline this. Firstly, by JW: "The availability of appropriate financing, especially with regards to some of these new innovative infrastructure projects. The criteria and the requirements still reflect a lack of awareness, which is a nature of the risk aversion. Importantly, there is a huge lack in terms of some of the smaller development banks, national development banks, and the commercial banks in confidence which could finance viable projects. But because this is risky, even though the projects have good economic and financial profiles." Secondly, by SH: "They [researchers comment: commercial banks] have an interest in lending money, and of course to see and limit the risks. But they wouldn't be afraid to take a risk in the investment if they were able to factor price and risk into the project." This presented barrier rises from the previously described barriers of *short terms of procurement contracts* and of *uncertainties around project cash flows* which both target the weakness of financing institutions to assess and to long-term finance renewable based projects.

Lack of private capital is another confirmed economic barrier which is shown along the quotation of AJ: "Furthermore, there is an absence of available financing, and a significant lack of private capital to invest in renewable energy projects."

In the following the different barriers based on market distortions are listed with regards to the respective statements by the interviewees. The first barrier is the *utility monopoly of production, transmission, and distribution of electricity*. SH confirmed this along the example of Grenada: "Grenada [...] is a de facto monopoly because the feed-in conditions in Grenada are so unfavorable that private investors are not interested to put up renewable energy systems themselves." AJ mentioned that a monopolistic utility in St. Lucia hindered the private development of geothermal plants: "The utility had a monopoly and so it would not have been possible to feed the energy into the grid."

As next barrier the *small market size* on Caribbean islands is validated. SH stated: "Private sector, small scale decentralized renewable energy doesn't make sense on those islands. [...] Those markets are small on these islands in particular, if you look at St. Kitts, Montserrat and so on."

The *lock-in dilemma* as a barrier is especially interesting to discuss with the "super-experts" as they have also long experience in the conventional power generation sector. JW confirmed this barrier along this example: "For example, in some cases governments derive significant taxes revenue from the importation of fuel. And so that can be a challenge and a barrier to renewable energies." And SH raised the topic of the role of PetroCaribe: "Fuel sales in the Caribbean are more like a political decision. It is not something in which the utility would have much influence, in particular when you look at PetroCaribe. These agreements between governments are made on the political level, and not on the level of the CEO of the electricity utility." Thus, this confirms the unwillingness of the decision makers to change the existing status quo - called lock-in dilemma.

Similar to that the *fossil fuel subsidies and fuel surcharge* is named as next barrier. JW described the effect of the fuel surcharge as following: " they [researchers comment: the utilities using conventional power plants] are competitive doing their businesses because most of the fuel cost is passed on to the customer. In most countries, all of the fuel cost is passed on to the customer. When fuel prices go up, the consumers will complain, but the utility is not really going to be affected by that." This shows that the fuel surcharge disincentives the utilities in investing in renewable energies which is confirmed as an important barrier.

The interview findings approve the identified political barriers in general. Besides the merging of two barriers to one single barriers no changes are conducted for this category. Overall a broad consensus among the "super-experts" could be noticed evaluating the economic barriers by qualitative interviews.

Political barriers

All six political barriers from the literature are confirmed by the "super-experts". In the following their specific point of view is presented underlining the literature based selection and showing some different perspectives on the interpretation of these barriers. The *gap between policy targets and implementation* is confirmed as barrier to implementing renewable energies on Caribbean islands, but with a slight different meaning. SH stressed the point that policies themselves have no direct influence by saying "policy cannot be the key driver for the development of renewable energies. [...] Policy needs to lead to regulation and to legislation." Thus, this barrier does not only mean the gap between policy and implementation but also the gap between policy and legislation.

This is picked up by the following political barrier called *no prioritization of renewable energies*. After discussions with the "super-experts" it is renamed to *lack of incentives or subsidies for renewable energies* to put the focus on the policy side as prioritization is seen as too general. The reluctance of governments to financially support renewable energies is formulated by JW: "There is a lack of mission. [...] current policy in most countries still assumes and still has as a de facto position that it is the conventional form of energy which will form the backbone of the energy supply in a country. It does not provide sufficient priorities for the diversification for renewable energies by far." The issue of incentives is contradicted by SH: " [...] I would like to exclude incentives. If you are a business man and you see a business opportunity you don't need incentives." Even though one of the "super-experts" denies this barrier it is kept in the list for later evaluation of the importance to find out if his special opinion on it is valid for all other stakeholders.

The next two barriers additionally emphasize the missing legal frameworks and legislation. One is the *lack of regulatory framework and legislation for private investors*. This was specially repeated by JH: "But it [researchers comment: the framework] is not sufficiently attractive for investment until we have the kind of legislative and regulatory framework in place that can allow businesses to have a fair price for their generation, and clear access to the grid so that they can benefit from sale of generation of energy." This is supported by SH's statement: "[...] the framework conditions are the single most important barrier for private investors to do large scale renewable energy generation in the countries. [...] if private investors would be interested, they would run into a concrete block with regards to the legal ability for them to realize projects and connect them to the grid."

The *lack of legal framework for independent power producers and power purchase agreements* is the other barrier targeting the issue of legislation. This is confirmed by a practical example given from AJ: "[...] another barrier was the absence of an independent power producer. [...] Some states have independent regulators, some have state regulators, but a unification of the system is absolutely necessary to promote and implement renewable energies. This is the way forward, everyone must agree on a tariff, so better regulation is possible [...]." And SH confirmed what is missing on a business to business level: "The primary factor here would be legislation and regulation."

Apart from policy and legislation the *lack of formal institutions* is another political barrier, which is especially described by this quotation of SH: "I think a department that specializes in energy is necessary. [...] So in the short, it is very important, yes, that you have energy departments in the ministries, but it is hard to equip those departments with profound expertise and knowledge because of the small size of the populations of the countries." In the second part of the quotation the last political barrier is already mentioned, the *lack of renewable energy experts on governmental level*. This is confirmed by JW: "There is a significant challenge, because even at the level of the policy makers, there's a significant deficit in terms of being able to analyze and to understand some of the technology, and integrating some of this technology, the options of renewable energies."

For the political barriers no change in numbers is applied based on the qualitative results. The topic of one barrier is modified to avoid misunderstandings in the following analyses. Anyhow the "super-experts" show some different perspectives on certain topics so the evaluation of the importance is especially important for these barriers.

Social barriers

As last category social barriers are discussed within the interviews. The first barrier is the *lack of social norms and awareness*. All three interviews verified especially the lack of awareness as social barrier to implementing renewable energies which is quoted for each of them in the next sentences. SH: "So there is definitely a gap there when it comes to willingness. And this may have different reasons. One is lack of awareness." JW: "If it were possible to begin to educate the consumers, or the consuming public, the general citizens, so that they can begin to make the kinds of demands for the transition, then that could be a source, a big source for the change and transition that needs to happen. [...] so you need to increase awareness across board so that people can see the opportunities." AJ: "The critical mass to demand and implement effective projects is not yet there."

The lack of awareness is also based on the *lack of educational institutions*, which is the next social barrier affecting the implementation of renewable energies in many ways. For the specific case of St. Lucia SH stated: " St. Lucia doesn't have a university, so where should this expertise come from?" In addition JW referred to the consequence of lacking education, the lack of knowledge: "It is weak in terms of the specific knowledge and capacity. Knowledge as well as human resources that are necessary, is missing in a very big way."

One additional social barrier, the *lack of renewable energy initiatives* is verified by SH with the exception of Barbados: "Apart from Barbados, I have seen very little initiatives by the people in the various islands to develop renewable energy generators." However, not only the missing renewable energy networks hinder the implementation of these technologies. *Strong fossil fuel lobbies* are named as additional social barrier which is previously listed under the barrier *missing renewable energy networks.* As the issue of fossil fuel lobbies is especially stressed by the "super-experts" it is listed now as single barrier, which is underlined by for example SH: "There is a strong lobby, there are generator manufacturers and they are selling stuff, flying around from island to island in the Caribbean selling new generators. I think there are definitely kickbacks that are coming to the CEOs coming from their end." And JW framed it in the following words: "The players who should be pushing for the change actually have vested interests in the overall situation [researchers comment: conventional power supply]."

Another mentioned social barrier is the *lack of local / national champions / entrepreneurs.* AH pointed directly at this barrier saying "a local champion would definitely be needed to show and demonstrate that renewable energy projects are viable and necessary, so that would greatly help." In addition this is supported by SH: "You will have a champion, someone who attracts public attention, who creates public awareness. [...] So having a champion in the media, talking about the advantages of renewable energy generation for electricity, about the advantages for everyone's household and every person's budget, is definitely something that would work." Summarizing the statements involvements of local champions are missing on the business level and as general role models.

From the sub-category cultural barriers the *dominance of energy over environmental issues* is seen as next social barrier in the literature. This is quite frankly confirmed by AJ: "I have to say that most people don't care where their energy comes from, people just want cheap electricity." Nevertheless, this is not necessarily a barrier as she stated in her next comment: "And there is the possibility to produce electricity cheaper with renewable energy, so that is an opportunity." Anyhow this issue is kept as a barrier for further evaluation not least based on JW's remark: "The populous is very price sensitive. [...] So in that regard, they prefer to stay with the conventional power because in the short-term it would represent a lower cost for them."

Finally, the *preference for status quo* is confirmed by the interviewees as last barrier from the literature survey based list. SH described the historical bias with the following words: "They are all eager to learn how that worked. Yet, they are not doing those developments themselves. [...] Looking at geothermal in Nevis, which came to a halt now, developers are alarmed so to speak, and they are more cautious how they go about things. [...] In general, it is also an element of setback. People are getting cautious." Thus, the preference for status quo is based on missing pilot projects and experiences with renewable energies which holds back their implementation and therefore is a relevant social barrier.

Summarizing the statements on social barriers the validation confirmed all previously identified barriers. In addition one extra barrier is found based on the analysis of the interviews which is called *strong fossil fuel lobby*. Mostly all three "super-experts" agreed on the topics beside the issue of costs versus environment.

After the presentation of the social barriers the final list of barriers is completed. Most of the barriers determined by the literature survey are confirmed throughout the empirical analysis and the number of barriers was slightly reduced from 32 to 31. This is based on one erased technical and one erased economic barrier while the political barriers remain similar and one additional social barrier is introduced. The final list of barriers based on literature survey and empirical validation is presented in Fig. 6.3. These barriers are evaluated according to their importance of blocking the implementation of renewable energies on Caribbean islands in the next section.

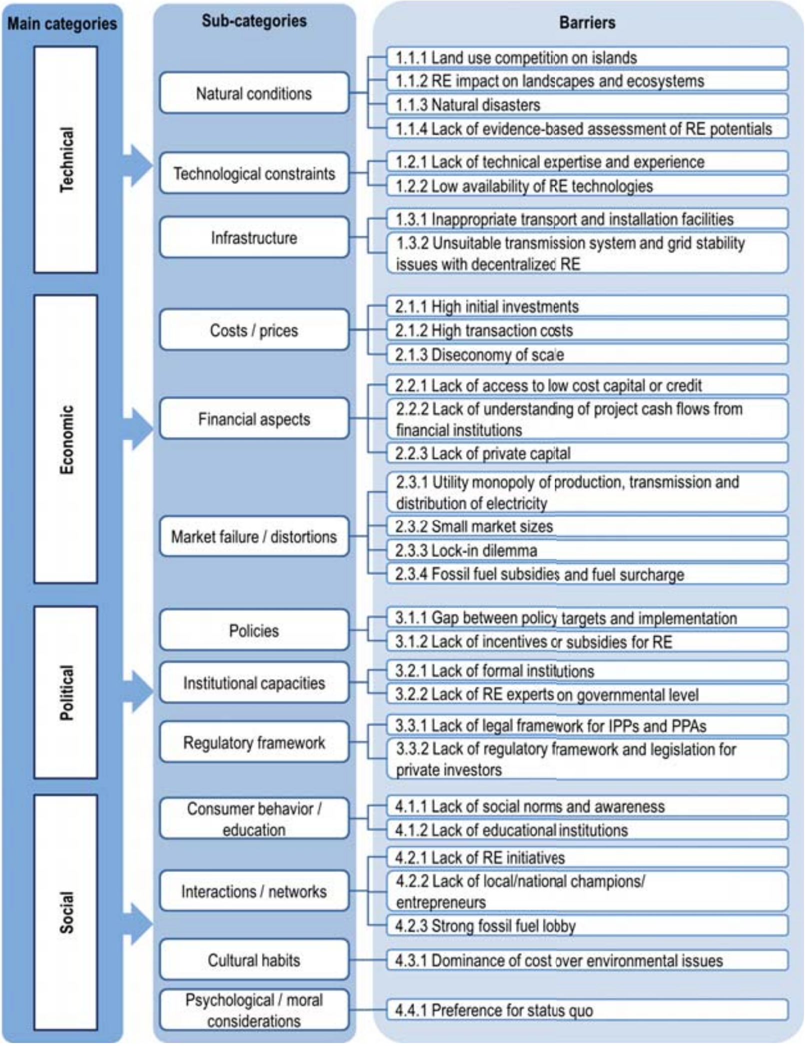


Figure 6.3: *Complete list of barriers to implementing renewable energies on Caribbean islands based on literature survey and empirical validation*

6.4 Evaluation of barriers

Within this section the evaluation and ranking of the identified barriers of implementation is presented. Firstly, a theoretical introduction into the quantitative analysis is given and the applied questionnaire is shown. This is followed by revealing the results of the weighting and discussing them.

6.4.1 Quantitative approach and questionnaire

Quantitative approach

As indicated in Sec. 6.1 a quantitative survey serves as final instrument to evaluate the previously identified barriers according to their importance for hindering the implementation of renewable energies on Caribbean islands. The advantage of quantitative research is the opportunity of an exact comparison of the results to derive for example rankings. Such a ranking is crucial to target the main important barriers by the development of a strategy roadmap.

It is not only accepted but recommended to combine qualitative and quantitative research as the following statements show. The applied across method triangulation from qualitative to quantitative research allows a more holistic, complete, and contextual understanding of the barriers [214]. In addition, different perspectives are connected, as well as different aspects of the barriers are treated by adding the quantitative research to the qualitative at this step [215]. Finally, this combination adds another validation round on the research of barriers [216].

A quantitative analysis helps to derive reliable statistical and comparable results [217]. To compare the relevance of the identified barriers certain measurements have to be performed. As no experimental or historical based data on the forms and developments of the relevance of each barrier are available an empirical approach is chosen to derive comparable numerical values. A recognized methodology is to ask experts within the research field with the help of questionnaires to evaluate each barrier along a certain scale. This has been successfully performed for example to weight policy instruments for greenhouse gas reduction in the power sector of Trinidad and Tobago (cf. [71]). Based on these considerations a questionnaire is developed to collect measurable expert opinions on the importance of barriers.

Questionnaire

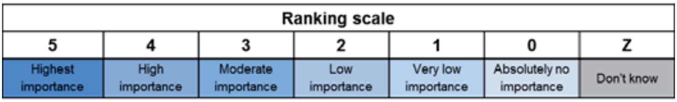
As previously discussed questionnaires are applied to gain the relevant data for the ranking of barriers. This instrument allows to approach a high number of experts without personally interviewing them. It is especially advantageous for this research as the experts are located on many different islands or countries in the Caribbean or worldwide. By electronic questionnaires a high number of renewable energy experts with linkages to the Caribbean could be approached. The questionnaire can be found in Appendix B and is explained in the following.

The layout of the questionnaire is designed according to the experiences made during the empirical research work for policy instruments in Trinidad and Tobago [71]. The content and description follows the findings during the literature survey and the quantitative validation. To ensure a clear and understandable structure and design of the questionnaire it is suggested to perform pre-testings. Such pre-tests help to eliminate mistakes, check consistencies, and evaluate potential cognitive difficulties [211]. For this questionnaire they were performed by researchers at the Reiner Lemoine Institut giving very valuable feedback by detecting and correcting misleading wordings and aesthetic errors.

The applied questionnaire starts with the introduction of the research project and of the researchers. This is important to provide background information on the project and to motivate experts to respond. As they do not receive any financial compensation for the effort to respond to the questions they have to be motivated by creating interest in the research project. The motivation can come from interest in the research topic, from the idea to support the researchers personally, and from the option to show the personal view on the important issue of barriers as one of the selected experts.

This is followed by the instructions to fill out the questionnaire. After a more detailed description, the instructions are repeated in five concise bullet points to ensure the correct way of filling out the questionnaire. The instructions are very important as a wrong handling of the questionnaire would lead to not utilizable results. Afterwards, it is asked for contact data of the respondent and he/she has to state in which of the following categories he/she perceives to belong to: Government, utility, private sector, researcher, public organization, or other. This is important to compare the different perspectives of the stakeholder groups on the importance of the various barriers.

On the next six pages of the questionnaire the barriers have to be evaluated according to their importance for hindering the deployment of renewable energies on Caribbean islands. The options are on a scale from 5 to 0 - highest importance to absolutely no importance - for each of the barriers. If the respondent has no opinion on a certain barrier, a "Z" for "don't know" can be used (cf. Fig. 6.4).



Ranking scale						
5	4	3	2	1	0	Z
Highest importance	High importance	Moderate importance	Low importance	Very low importance	Absolutely no importance	Don't know

Figure 6.4: *Scale to evaluate importance of barriers*

The ranking scale is based on on a Likert scale as in the empirical research work of barriers for renewable energies in the United Kingdom [177] and Hong Kong [178]. The Likert scale is a psychometric and summated scale to measure importance of multiple barriers through attitudes, intensity of feelings, and attitudes about the single barriers by the respondents [218]. The "Z" is introduced as option to avoid misleading answers in the case that the respondent is not sure about the subject. Questions answered with "Z" do therefore not influence the overall score of the related barrier by the respondent.

Within the questionnaire each barrier is listed with a short description and related category and sub-category as presented in Fig. 6.3. In addition, a brief explanation of each barrier is given to clarify their meaning. This is even further elaborated in the appendix of the questionnaire where the respondent can find a detailed description of each barrier as hereby presented along the example of *land use competition on islands*: Due to the small expansion of the Caribbean islands' territories, land and water resources that are suitable for renewable energies compete with mostly tourism, but also agriculture. As a result, prices for land are very high. A renewable energy development might therefore face challenges with respect to land availability. These effects are summarized under "land use competition" and have to be evaluated according to their importance as a barrier to implementing renewable energies.

The example shows that in the detailed description the barrier is firstly explained and secondly an instruction is given what directly has to be evaluated. By this direct guidance the chance of misunderstandings of barriers is minimized. Furthermore space for comments exists at each barrier to allow the respondents to give additional insights to their simple evaluation of the barrier's importance.

After the section for evaluation of barriers it is asked for the opinion on certain statements about climate change, CARICOM's renewable energy targets, and renewable energies in general followed by five statements about the personal attitude towards renewable energies. The results of these questions are not applied in this thesis but serve as contribution for further research projects.

The questionnaire is concluded with the description how to return it. In addition the respondent can state whether he/she wants to receive the final version of the study. This is another incentive for experts to fill out and return the questionnaire. This page is followed by the appendix with the aforementioned detailed descriptions of the barriers.

Method of evaluation

With the help of the questionnaires the importance of each barrier hindering the implementation of renewable energies on Caribbean islands is evaluated along the Likert-scale. In theory this scale provides ordinal data which include a ranking, whose intermediate values cannot be assumed equal [219]. Nevertheless for further analyses these data are often treated as interval data by most researchers to enable statistical analyses [220]. This means applying the scale from five to zero with the same metric value in between and assuming that there is no feeling in between for example "moderate" and "low importance". By this commonly accepted assumptions parametric and non-parametric statistical analyses are possible [219, 221].

For this thesis a lack of large sample size and limited scope of the work leads to an analysis using descriptive statistical analysis only. This means the average value of the importance $\mathrm{Imp_{total}}$ and the variance Var for the overall sample and the single stakeholder groups are calculated as presented in Eq. 6.1 and 6.2.

$$\mathrm{Imp_{total}} = \frac{\sum\limits_{i=1}^{n} \mathrm{Imp_{expert_i}}}{n} \tag{6.1}$$

$$\mathrm{Var} = \frac{\sum\limits_{i=1}^{n} (\mathrm{Imp_{expert_i}} - \mathrm{Imp_{total}})^2}{n} \tag{6.2}$$

The average value $\mathrm{Imp_{total}}$ measures the central tendency and serves as ranking order of the barriers by sorting the averaged importance. It is comprised by all valid responses of experts $\mathrm{Imp_{expert_i}}$ divided by the number of experts n. In addition the variance measures the spread and accounts for deviation of data from average and their frequency of its deviation. Var is calculated by summing up the square of the difference between each expert's response $\mathrm{Imp}_{\mathrm{expert}_i}$ and the mean importance $\mathrm{Imp}_{\mathrm{total}}$ again divided by the number of experts n. This allows to interpret the homogeneity of the perspective on the importance of each barrier. The lower the variance is the higher is the consensus in respect of the evaluated level of importance.

Expert sample

Experts related to renewable energies on Caribbean islands were selected for the quantitative evaluation of the importance of barriers to implementing renewable energy. Stakeholders from all relevant professions were chosen which means from utilities, governments, private companies, researchers, and organizations and institutions. The identification of the experts was conducted via various sources.

Firstly, the personal contacts based on previous research projects and conferences were asked to participate within this study. Such personal contacts have the advantage of high response rates. Experts cited in other papers about renewable energies in the Caribbean were contacted as well as others with matching geographical and professional context identified via internet research (e.g. members of CARILEC). Further contacts were taken from lists of participants from CREDP, Organisation of American States (OAS), or CARICOM events and in addition the Alliance of Small Island States (AOSIS) distributed the questionnaire within their members.

Overall 110 experts were contacted coming from various practical and scientific backgrounds but focusing on renewable energies on Caribbean islands. 30 of them are politicians or working in ministries or governments. The private sector is represented by 29 experts, all from private companies besides private utilities, which are listed in an extra category. For the category utilities, 21 experts were asked to respond to the questionnaire. 15 experts from organizations and institutions and 12 experts from the academic sector were contacted to conclude the expert sample. Details on the response rate and the results of the quantitative analysis are given in the next sub-section.

6.4.2 Results of the questionnaires

This sub-section reveals the results of the evaluation of the previously identified and validated barriers according to their importance. The evaluation is based on the responses of the renewable experts asked by questionnaires. Out of the 110 asked experts 30 have sufficiently responded by sending back the filled out questionnaire. The distribution of the participants among the five stakeholder groups can be depicted in Fig. 6.5.

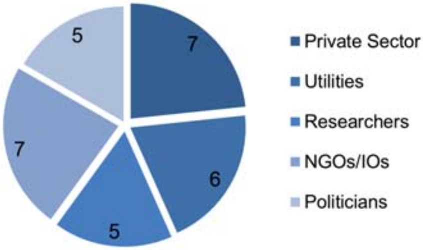


Figure 6.5: *Distribution of participants at quantitative study among stakeholder groups for renewable energies on Caribbean islands*

The different stakeholder groups are almost equally represented in the number of participants. Experts from private companies and consulting firms are leading the list of participants together with experts from non-governmental and international organizations. Both groups provide seven participants, followed by the renewable and power generation experts from local utilities. These are represented by experts of the following six utilities: Trinity Power Limited (Trinidad and Tobago), Aqualectra (Curacao), VINLEC (St. Vincent and the Grenadines), GRENLEC (Grenada), DOMLEC (Dominica), and BLPC (Barbados). Only five experts responded from the academic and the governmental sector. Compared to the number of asked experts the politicians represent the lowest and the researchers the highest response rate.

After the collection of all 30 questionnaires of the described stakeholder groups the importance of each barrier can be evaluated. The results of the evaluation are revealed along the main categories of barriers to implementing renewable energies on Caribbean islands. Results show the total importance as an average value of all responses and the respective variance is listed. Additionally the evaluation of each barrier's importance by each stakeholder group. Afterwards the overall ranking is presented to give an idea about the most important barriers which should be targeted first to implement renewable energy plants.

Technical barriers

The average total importance of all technical barriers is calculated as 2.93 which is almost moderate important on the ranking scale as shown in Tab. 6.1. An average variance of 1.5 is revealed which equals to a standard deviation of 1.22. Researchers evaluate the technical barriers with the highest and private companies with the lowest importance compared to the other stakeholder groups.

Table 6.1: *Results of empirical evaluation of technical barriers. Abbreviations stand for: Importance (imp.), variance (var.), private companies (pri.), utilities (uti.), researchers (res.), organizations (org.), politicians (pol.)*

Nr.	**Barrier**	**Total**		**Imp. by stakeholder**				
		Imp.	**Var.**	**Pri.**	**Uti.**	**Res.**	**Org.**	**Pol.**
1.1.1	Land use competition on islands	3.45	1.14	3.17	3.83	3.80	3.14	3.40
1.1.2	RE impact on landscapes and ecosystems	2.86	0.81	3.33	3.00	2.40	2.71	2.80
1.1.3	Natural disasters	2.86	1.57	2.83	2.83	3.20	2.43	3.20
1.1.4	Lack of evidence-based assessment of RE potentials	2.39	1.60	2.86	1.83	2.60	2.20	2.40
1.2.1	Lack of technical expertise and experience	3.23	1.51	3.00	2.17	4.00	3.43	3.80
1.2.2	Low availability of RE technologies	2.97	1.83	2.57	2.00	4.00	3.29	3.20
1.3.1	Inappropriate transport and installation facilities	2.66	1.61	1.67	3.00	3.00	2.57	3.20
1.3.2	Unsuitable transmission system and grid stability issues with decentralized RE	3.00	1.93	2.29	3.17	4.40	2.20	3.20
	Average	**2.93**	**1.50**	**2.71**	**2.73**	**3.43**	**2.75**	**3.15**

Barrier *1.1.1 land use competition on islands* is overall evaluated with 3.45 which is between moderate and high importance. It is the most important technical barrier with a low variance of 1.14. Experts from utilities and researchers put the highest emphasis on it. With 2.86 barrier *1.1.2 renewable energies' impact on landscapes and ecosystems* is weighted below moderate importance. The very low variance of 0.81 shows a strong consensus on this barrier. Barrier *1.1.3. natural disasters* is evaluated with the same total relevance as the previous barrier, but with a variance twice as high. The significance of this barrier is underlined mostly by representatives of the academic sector. The overall lowest important technical barrier is *1.1.4 the lack of evidence-based assessment of renewable energy potential* with 2.39 which is closer to low than to moderate importance. It receives the lowest rating by experts from utilities.

In the sub-category technological barriers, the barrier *1.2.1 the lack of technical expertise and experience* is rated with 3.23. This means a little more than moderate importance mostly pushed by researchers seeing this barrier as highly influential. The same importance by researchers is set for the barrier *1.2.2 low availability of renewable energy technologies* which receives a total average weighting of 2.97.

The barrier *1.3.1 inappropriate transport and installation facilities* is evaluated below moderate importance especially due to the low weighting by private companies of 1.67. With 3.0 the barrier *1.3.2 unsuitable transmission system and grid stability issues with decentralized renewable energies* is exactly rated as moderately important. For researchers this barrier is highly crucial and reaches a 4.4.

Economic barriers

Table 6.2 shows that for all economic barriers the average importance is 3.42 which is between moderate and high. The derived variance is 1.77 with a respective standard deviation of 1.33. Researchers weight the economic barriers with high importance while experts from utilities give them only low to moderate importance. The other stakeholder groups evaluate economic barriers on average between moderate and high importance.

Barrier *2.1.1 high initial investments* is assessed with 3.87 and therefore the most important economic barrier with a relatively low variance of 1.18. Politicians put the most emphasis on this barrier compared to the other stakeholders. The barrier *2.1.2 high transaction costs* is described as moderately to highly important with the exception of private companies' stakeholders giving it low to moderate importance only. With 0.92 barrier *2.1.3 diseconomy of scale* has the lowest variance of all economic barriers and a relatively high importance of 3.71. This is especially driven by researchers evaluating it with 4.4, but all other experts give still more than moderate importance.

From the sub-category financial barriers, *2.2.1 lack of access to low cost capital or credit* is weighted with a total importance of 3.21 and a very high variance of 2.16. Experts from private companies and from organizations assign it a high importance

Table 6.2: *Results of empirical evaluation of economic barriers. Abbreviations stand for: Importance (imp.), variance (var.), private companies (pri.), utilities (uti.), researchers (res.), organizations (org.), politicians (pol.)*

Nr.	**Barrier**	**Total**		**Imp. by stakeholder**				
		Imp.	**Var.**	**Pri.**	**Uti.**	**Res.**	**Org.**	**Pol.**
2.1.1	High initial investments	3.87	1.18	3.71	3.33	4.20	3.86	4.40
2.1.2	High transaction costs	3.47	1.12	2.86	3.33	4.20	3.71	3.40
2.1.3	Diseconomy of scale	3.71	0.92	3.60	3.83	4.40	3.57	3.20
2.2.1	Lack of access to low cost capital or credit	3.21	2.16	3.57	2.67	3.20	3.83	2.60
2.2.2	Lack of understanding of project cash flows from financial institutions	3.41	1.41	3.71	2.17	4.00	3.33	4.00
2.2.3	Lack of private capital	3.37	1.90	3.29	2.50	4.00	3.57	3.60
2.3.1	Utility monopoly of production, transmission and distribution of electricity	3.62	2.30	4.17	1.83	4.20	4.14	3.80
2.3.2	Small market sizes	3.32	1.50	3.83	2.33	3.80	3.33	3.40
2.3.3	Lock-in dilemma	3.25	2.47	3.71	1.50	4.20	4.00	3.00
2.3.4	Fossil fuel subsidies and fuel surcharge	2.96	2.68	3.17	1.67	4.25	3.71	2.20
	Average	**3.42**	**1.77**	**3.56**	**2.52**	**4.05**	**3.71**	**3.36**

while experts from utilities and governments assign it only a low to moderate importance. Barrier *2.2.2 lack of understanding of project cash flows from financial institutions* is weighted on average with 3.41. Researchers and politicians evaluate it with high importance while experts from utilities give it low to moderate importance only. A similar weighting receives the barrier *2.2.3 lack of private capital* with a total importance of 3.37.

Three of the four barriers assigned to the sub-category market distortions show very high variances. It starts with the barrier *2.3.1 utility monopoly of production, transmission, and distribution of electricity* showing a variance of 2.3 and a total importance of 3.62. Utilities weight this barrier below low importance while all others evaluate it around high importance. For barrier *2.3.2 small market sizes* the total importance is 3.32 with all groups giving moderate to high importance beside the utilities' experts evaluating it between low and very low. The next barrier showing a very high variance is *2.3.3 lock-in dilemma* with 2.47 and a moderate to high relevance of 3.25. Again experts of utilities give the lowest importance with 1.5 which is exactly between low and very low. In opposite researchers and representatives of organizations rate it as highly important. The highest variance bear the evaluation of barrier *2.3.4 fossil fuel subsidies and fuel surcharge* with 2.68. The overall importance of this barrier is moderate (2.96) with the lowest weighting by utilities (1.67) and the highest by researchers (4.25).

Political barriers

The results of the evaluation of political barriers are presented in Tab. 6.3. Their average total relevance is 3.56 which means between moderate and high importance and slightly higher than the economic barriers with a slightly lower variance of 1.67. Overall the political barriers are seen as most important by representatives from governments followed by them from the academia, from organizations, and from private companies concluding with the ones from utilities giving the lowest importance.

Table 6.3: *Results of empirical evaluation of political barriers. Abbreviations stand for: Importance (imp.), variance (var.), private companies (pri.), utilities (uti.), researchers (res.), organizations (org.), politicians (pol.)*

Nr.	**Barrier**	**Total**		**Imp. by stakeholder**				
		Imp.	**Var.**	**Pri.**	**Uti.**	**Res.**	**Org.**	**Pol.**
3.1.1	Gap between policy targets and implementation	3.97	1.70	4.43	3.67	4.00	3.86	3.80
3.1.2	Lack of incentives or subsidies for RE	3.47	1.78	3.86	2.83	3.40	3.71	3.40
3.2.1	Lack of formal institutions	2.87	1.92	2.57	1.67	3.80	3.00	3.60
3.2.2	Lack of RE experts on governmental level	3.17	2.21	3.14	1.67	3.00	3.71	4.40
3.3.1	Lack of legal framework for IPPs and PPAs	3.86	1.36	4.00	2.67	4.20	4.33	4.20
3.3.2	Lack of regulatory framework and legislation for private investors	4.03	1.03	4.29	3.33	4.40	4.00	4.20
	Average	**3.56**	**1.67**	**3.71**	**2.64**	**3.80**	**3.77**	**3.93**

Barrier *3.1.1 gap between policy targets and implementation* is seen as highly important with a value of 3.97. This is mainly pushed by representatives from private companies evaluating it between high and very high relevance and by researchers evaluating it as highly relevant. With 3.47 barrier *3.1.2 lack of incentives or subsidies for renewable energies* is evaluated as moderately to highly important again driven by private companies and in addition by organizations.

The barrier *3.2.1 lack of formal institutions* is weighted below moderate importance (2.87) and has a high variance of 1.92. This is mainly based on the divergence of the perspective of utilities setting only a 1.67 and researchers setting a 3.80 as importance value. A little higher than moderate importance is the evaluation of barrier *3.2.2 lack of renewable energy experts on governmental level* with 3.17 and a very high variance of 2.21. The spread of the assessment of the importance ranges from almost very low (1.67) by utilities to almost very high (4.4) by politicians.

Another important barrier is *3.3.1 lack of legal framework for independent power producers and power purchase agreements*. Only from utilities it is evaluated with 2.67 which means below moderate relevance while all other stakeholder groups evaluate it with high importance and more. The political barrier with the highest importance is *3.3.2 lack of regulatory framework and legislation for private investors* showing a total value of 4.03. In addition a strong consensus can be observed as four stakeholder groups weight it with high importance or more resulting in a total variance of just 1.03.

Social barriers

The results for the fourth category of barriers - the social barriers - are listed in Tab. 6.4. They show on average the same overall importance as the technical barriers with 2.93, but have a higher total variance of 1.80. The highest weighting for social barriers is given by representatives of organizations and institutions and the lowest by experts from utilities and by researchers.

For the first social barrier *4.1.1 lack of social norms and awareness* a moderate importance of 2.97 is assigned with the highest support by politicians. Experts from utilities rate it as quite unimportant (1.67). The same is true for barrier *4.1.2 lack of educational institutions* which is also low rated by utilities. In addition all other importance values are quite similar to the previous barrier with a total importance of 2.93.

Barrier *4.2.1 lack of renewable energy initiatives* has exactly the same importance. Nevertheless the weighting among the stakeholder groups is different and the vari-

Table 6.4: Results of empirical evaluation of social barriers. Abbreviations stand for: Importance (imp.), variance (var.), private companies (pri.), utilities (uti.), researchers (res.), organizations (org.), politicians (pol.)

Nr.	Barrier	Total		Imp. by stakeholder				
		Imp.	Var.	Pri.	Uti.	Res.	Org.	Pol.
4.1.1	Lack of social norms and awareness	2.97	1.83	3.29	1.67	2.40	3.57	3.80
4.1.2	Lack of educational institutions	2.93	1.86	3.14	1.67	2.40	3.71	3.60
4.2.1	Lack of RE initiatives	2.93	1.46	3.00	2.33	2.60	3.29	3.40
4.2.2	Lack of local/national champions/ entrepreneurs	3.07	1.60	2.86	2.17	3.00	3.57	3.80
4.2.3	Strong fossil fuel lobby	3.07	2.51	3.71	1.33	3.50	4.20	2.80
4.3.1	Dominance of cost over environmental issues	3.47	1.72	3.71	3.83	3.40	2.86	3.60
4.4.1	Preference for status quo	2.04	1.61	3.00	1.00	1.60	2.71	1.80
	Average	**2.93**	**1.80**	**3.24**	**2.00**	**2.70**	**3.42**	**3.26**

ance is lower (1.46). Politicians evaluate this barrier with the comparatively highest significance. Again mainly promoted by politicians and researchers the barrier *4.2.2 lack of local / national champions / entrepreneurs* has a total importance slightly higher than moderate. Barrier *4.2.3 strong fossil fuel lobby* has a moderate importance (3.07) as well with an extraordinary high variance of 2.51. For organizations and private companies this barrier is highly important while for politicians it has only moderate and for utilities even very low importance.

The highest importance of all social barriers has barrier *4.3.1 dominance of cost over environmental issues*. Experts from utilities, private companies, and governments weight it between moderate and high importance and higher while organizations assess it as just below moderate importance. As last barrier *4.4.1 preference for status quo* is evaluated. It results in the lowest total importance with 2.04 and a variance of 1.63. This barrier is moderately important for private companies while all others rate it lower. Especially experts from utilities which assign very low importance (1.00) to this barrier.

By that description all results for all barriers along the four main categories are presented. These results are used to form the final ranking which is revealed in the following sub-section and afterwards discussed in Subsec. 6.4.4.

6.4.3 Final ranking of barriers

The ranking of the barriers to implementing renewable energies on Caribbean islands is based on the total importance of each barrier. All barriers sorted by the highest to the lowest total importance are listed in Tab. 6.5 showing the total importance and related variance.

The most important barrier based on the questionnaires' results is *3.3.2 lack of regulatory framework and legislation for investors* with a total importance of 4.03 and a medium variance of 1.03. Another five barriers follow with an importance between 3.5 and 4.0 which means they can be considered as highly significant. This list is led by *3.1.1 gap between policy targets and implementation* (3.97) followed by *2.1.1 high initial investments* (3.87) and *3.3.1 lack of legal framework for independent power producers and power purchase agreements* (3.86). In a little distance but still rated as highly important are to mention barrier *2.1.3 diseconomy of scale* (3.71) and barrier *2.3.1 utility monopoly of production, transmission, and distribution of electricity* (3.62). The latter has the highest variance among the top six barriers rated with high significance.

14 barriers are evaluated with a score from 3.0 to 3.5 which equals to moderate and moderate to high importance. The first three in this group have all the same significance of 3.47, therefore they are sorted by the second criterion the variance. The lower the variance the higher is the barrier ranked as a stronger consensus on the topic is expected. Based on that barrier *2.1.2 high transaction costs* is placed on rank seven followed by *3.1.2 lack of incentives or subsidies for renewable energies* and by *4.3.1 dominance of cost over environmental issues*, which is the most important social barrier in the final ranking. On the next rank the most important technical barrier *1.1.1 land use competition on islands* appears with an importance of 3.45. The following barriers in the group of moderately and moderately to highly important barriers are not described on detail but can be depicted from Tab. 6.5.

The next cluster of barriers includes the ones with low to moderate and moderate importance (2.5 up to 3.0). Within this cluster nine barriers are identified on the ranks 21 to 29. Rank 21 and 22 can be considered as similar as barrier *1.2.2 low availability of renewable energy technologies* and *4.1.1 lack of social norms and*

Table 6.5: *Final ranking of barriers according to total importance. Showing total importance (Imp.) and total variance (Var.) of each barrier*

Rank	Nr.	Barrier	Imp.	Var.
1	3.3.2	Lack of reg. framework and legislation for private inv.	4.03	1.03
2	3.1.1	Gap between policy targets and implementation	3.97	1.70
3	2.1.1	High initial investments	3.87	1.18
4	3.3.1	Lack of legal framework for IPPs and PPAs	3.86	1.36
5	2.1.3	Diseconomy of scale	3.71	0.92
6	2.3.1	Utility monopoly of prod., transm. and distrib. of el.	3.62	2.30
7	2.1.2	High transaction costs	3.47	1.12
8	4.3.1	Dominance of cost over environmental issues	3.47	1.72
9	3.1.2	Lack of incentives or subsidies for RE	3.47	1.78
10	1.1.1	Land use competition on islands	3.45	1.14
11	2.2.2	Lack of underst. of project cash flows from fin. inst.	3.41	1.41
12	2.2.3	Lack of private capital	3.37	1.90
13	2.3.2	Small market sizes	3.32	1.50
14	2.3.3	Lock-in dilemma	3.25	2.47
15	1.2.1	Lack of technical expertise and experience	3.23	1.51
16	2.2.1	Lack of access to low cost capital or credit	3.21	2.16
17	3.2.2	Lack of RE experts on governmental level	3.17	2.21
18	4.2.3	Strong fossil fuel lobby	3.07	2.51
19	4.2.2	Lack of local/national champions/ entrepreneurs	3.07	1.60
20	1.3.2	Unsuitable transm. system and grid stability issues	3.00	1.93
21	1.2.2	Low availability of RE technologies	2.97	1.83
22	4.1.1	Lack of social norms and awareness	2.97	1.83
23	2.3.4	Fossil fuel subsidies and fuel surcharge	2.96	2.68
24	4.1.2	Lack of educational institutions	2.93	1.86
25	4.2.1	Lack of RE initiatives	2.93	1.46
26	3.2.1	Lack of formal institutions	2.87	1.92
27	1.1.2	RE impact on landscapes and ecosystems	2.86	0.81
28	1.1.3	Natural disasters	2.86	1.57
29	1.3.1	Inappropriate transport and installation facilities	2.66	1.61
30	1.1.4	Lack of evidence-based assessment of RE potentials	2.39	1.60
31	4.4.1	Preference for status quo	2.04	1.61

awareness are evaluated with exactly the same importance and variance. Directly after these two follow the barrier *2.3.4 fossil fuel subsidies and fuel surcharge* which has the highest total variance of 2.68. Especially barriers with such high variances are discussed ahead in Subsec. 6.4.4. Again the details of the remaining barriers of the third cluster can be seen in Tab. 6.5

The ranking is concluded by two barriers: *1.1.4 lack of evidence-based assessment of renewable energy potentials* has an importance of 2.39 which is between low and moderate to low. Finally, the least important barrier is *4.4.1 preference for status quo* which is only rated with low significance (2.04).

Combining Tab. 6.1, 6.2, 6.3, and 6.4 with the ranking in Tab. 6.5 allows an elaboration of the differences in ranking and evaluation for the different barriers along the stakeholder groups. The comparison is based on the number of barriers evaluated with high importance or more. 14 barriers are evaluated as highly or very highly important by researchers, while representatives of organizations and governments evaluate five barriers with 4.00 or higher. Experts from private companies follow with four barriers seen as highly important. In contrast no single barrier has a high or higher importance for experts from utilities. The different perceptions of the stakeholders are part of the discussion in Subsec. 6.4.4 as well.

To finalize the ranking all barriers are illustrated in Fig. 6.6. This figure gives an overview on the total importance and variance of all barriers at a glance. In addition the barriers are differently colored according to their respective main category.

Among the most important six barriers only economic and political barriers can be found. This phenomenon is further discussed, but it already indicates that the most improvements are needed according to economic and political conditions to implement successfully renewable energies on Caribbean islands. Only in the second group of barriers with moderate and moderate to high importance the barriers are almost equally distributed along the four main categories of barriers. Consequently the lower part of the ranking is dominated by technical and social barriers.

Looking at the variance it becomes evident that three of the four barriers with the highest variance are of economic nature. All are part of the sub-category market failure / distortions which seems to be a controversial issue. Such characteristics and the entire ranking itself are discussed in the next sub-section. The discussion finalizes the ranking to enable the deduction of solutions to overcome the most important barriers.

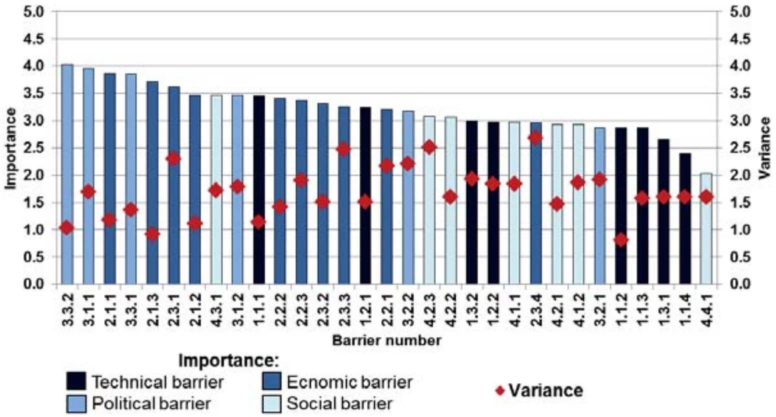


Figure 6.6: *Final ranking of barriers according to importance. Barriers are marked based on the four main categories: technical, economic, political, and social barriers*

6.4.4 Discussion of ranking and limitations

The calculated total importance of each barrier allows a clear quantitative ranking as presented in Tab. 6.5. Nevertheless, a pure focus on the numerical value might neglect other circumstances and specific comments by the asked experts. In addition, the numerical values are often quite similar and differ only on the second decimal place which makes a ranking less stringent thinking of the Likert scale as ordinal scale [219]. For all these reasons the ranking and the barriers are further discussed and limitations in the methodology are debated within this sub-section before practical recommendations can be given.

Discussion

The first six barriers in the ranking can all be considered as crucial hindering the implementation of renewable energies. For these crucial barriers solutions have to be derived firstly. Especially the most important barrier *3.3.2 lack of regulatory framework and legislation for private investors* is underlined by comments in the questionnaires such as: "Yes. Biggest challenge. Too risky for foreign investors and local investors." or "[...] this is the single most significant impediment to the development of renewable energies in the region." As aforementioned all the first six barriers are seen as most important hindering the deployment of renewable energies which is mostly supported by comments of the experts. Anyhow, two of them have to be especially discussed as diverse comments for them are collected.

One of them is barrier *2.1.1 high initial investments*. This barrier is evaluated as very important, but it also indirectly points to other barriers. As stated in one of the comments high initial costs are only problematic if financing is an issue: "This can be solved with low interest loans which are available now." Thus the importance of this barrier is based on other financial barriers for example *2.2.3 lack of private capital* and *2.2.1 lack of access to low cost capital or credit* which are both evaluated as moderately to highly important. Overcoming these barriers would also help to overcome the even more important barrier of high initial investments which increases the need to derive solutions for the financial barriers, even though they are rated less important.

The other barrier to discuss is*2.3.1 utility monopoly of production, transmission, and distribution of electricity*. The high variance indicates many different extreme responses for this barrier evaluating it either with high / very high or low / very low importance. This barrier is especially low rated by experts from utilities as they might not want to see a change of this situation (rating of experts from utilities: 1.83). For this barrier special solutions should be derived as the directly concerned responsible stakeholders of the power generation system do not consider it as important.

In general, utilities' experts evaluate barriers lower than the average importance, but it is particularly noticeable for barriers concerning the current energy system as the aforementioned barrier utility monopoly of production, transmission, and distribution of electricity. This is also true for three other barriers: *2.3.3 lock-in dilemma* (rank 14), *4.2.3 strong fossil fuel lobby* (rank 18), and *2.3.4 fossil fuel subsidies and fuel surcharge* (rank 23). All of them have a very high variance and are quite low rated by utilities. In addition, governmental representatives evaluate them significantly lower than the other three stakeholder groups as well. Thus, these barriers arising from the current ruling political parties and economical powerful utilities are not seen as relevant by them. Even though, the three discussed barriers have a medium overall importance. Solutions to overcome them should be derived to break through the prevailing power structures potentially blocking a fast deployment of renewable energies.

Looking at the overall results of the quantitative analysis it becomes evident that no barrier is rated with absolutely no or very low importance. This underlines the validity of the qualitative approach and the literature analysis leading to mostly important barriers to implementing renewable energies on Caribbean islands. Thus, for the practical recommendations and solutions the entire variety of barriers is kept in mind with a special focus on the previously discussed six most important barriers. To derive appropriate solutions it is suggested to cluster certain barriers and to consider the special focus of the stakeholder groups.

The first cluster are barriers from the sub-category regulatory framework. They are both within the top six most important barriers and action to overcome them is required mostly from politicians. This shows the relation to the institutional political barriers. If governmental experts and politicians are required to overcome lacking regulatory framework the institutional capacities have to be strengthened as well. This is especially important as politicians rate the barriers *3.2.1 lack of formal institutions* and *3.2.2 lack of renewable energy experts on governmental level* as highly and very highly important which shows an interesting sense of self-criticism. In addition, the barrier *3.1.1 gap between policy targets and implementation* fits also into this cluster and has a similar correlation to the institutional political barriers.

The second important cluster is based on barrier *2.1.1 high initial investments* of renewable energies. As previously discussed this barrier is strongly related to the issue of financing, but also other barriers influence the initial investment costs. Additional direct cost drivers are barrier *2.1.3 diseconomy of scale* (rank 5), barrier *2.1.2 high transaction costs* (rank 7). Indirect drivers can be found in barrier *1.1.1 land use competition on islands* (rank 10) as pointed out in one comment: "Renewable energies compete with other land use especially real-estate development where property is priced on a square meter basis." All these high ranked barriers are clustered under the topic of costs and combined with financial barriers to derive matching solutions.

As third cluster all barriers related to the prevailing conventional power supply system and its power structures are taken. They are previously discussed according to the role of the utilities and governments and can be found under *2.3.1*, *2.3.3*, *4.2.3*, and *2.3.4*. Thus, this cluster combining four barriers is used to derive special solutions for this politically sensitive issue.

Another interesting finding is that technical and social barriers are of secondary importance. Anyhow, they might influence indirectly other more important barriers. Thus, they should also be considered within the derived solutions as a general recommendation focusing on the cluster technical and social barriers. Two of them can be especially underlined. Firstly, barrier *4.2.2 lack of local / national champions / entrepreneurs* (rank 19) is mentioned in the literature as important, because social activities can push change on local level (cf. [19]). Secondly, barrier *1.1.4 lack* *of evidence-based assessments of renewable energies* (rank 30) is weighted low, but LCOE comparison supports financial and political experts in their decision making which might help to overcome some institutional gaps.

In conclusion, it can be stated that economic and political barriers are the most important impediments to the implementation of renewable energies on Caribbean islands according to the identified ranking. This is congruent to the results from the literature review underlining these crucial barriers (cf. [11, 18, 172]). To derive solutions the three presented clusters should be considered, which are mainly comprised of economic and political barriers.

Limitations

By the comparison with the comments and other research results the identification of the most important barriers as baseline to derive solutions can be considered as quite robust. Nevertheless, the following limitations remain within the quantitative analysis.

The first limitation can be found in the sample size. Only 30 filled-out questionnaires are used for the analysis of each barrier's importance which apparently does not allow a detailed statistical analysis [220]. Anyhow, the specific selection of the experts ensure the quality of the results. For this thesis it is more important to choose well experienced experts in the field of renewable energies on Caribbean islands than to broaden the experts sample size.

Based on the evaluation method another limitation can be detected. As aforementioned the Likert-scale is based on ordinal data and does usually not allow an interpolation of results between the ordinal numbers as it is performed for the final ranking. This issue is neglected by many researchers (cf. [220]) and for this thesis it is presumed that the respondents understand the Likert-scale as continuous. Thus, the ranking according to nominal numbers is valid under the aforementioned assumption.

Other restrictions are based on different biases: In the general comments section of the questionnaires one expert pointed out that the suggested barriers include an "European bias". This means the identified barriers are not specific enough for the Caribbean and therefore the results are valid. As this issue is only raised by one expert and the barriers are validated by Caribbean experts during the qualitative research step this bias is not seen as crucial.

Another bias is based on the simplification to evaluate all Caribbean islands at once and not country by country. Different circumstance occur in the different countries which might change the importance of certain barriers for certain countries. As the scope of this work can only consider a region wide analysis this bias has to be accepted, but it is recommended for further research to look at single countries only.

In conclusion most of the limitations are acceptable for this thesis and do not affect the overall validity of the identified barriers and their importance. Thus, recommendations to overcome the most important barriers are given in the following section.

6.5 Practical recommendations

As a final step all previous analyses lead to practical recommendations how to overcome the barriers of implementation and therefore how to foster the deployment of renewable energies on Caribbean islands. Before that, three case studies are analyzed to validate the impact of the identified barriers or clusters of barriers on specific renewable projects or on the realization of projects in specific countries. The knowledge gained within the best practice examples increases the practical relevance of the final recommendations.

6.5.1 Best practice examples

Three different examples are chosen to show the relevance of certain barriers on the success of renewable energy projects. The first is the implementation of PV installations in the country Grenada. Secondly, the key factors for the successful implementation of the Wigton wind farm on Jamaica are determined. As last example the geothermal development on Guadeloupe is investigated. The locations of the three best practice examples are illustrated in Fig. 6.7.

Showcase Grenada - decentralized PV

Grenada has one monopolistic utility, GRENLEC, which supplies the main island (GRD01) and the two smaller islands Carriacou (GRD02) and Petite Martinique (not considered in the techno-economic analysis). The overall demand is met by diesel based power plants in a total capacity of 33 megawatts leading to very high power generation costs and high tariffs for end-customers. These tariffs are comprised by a fixed rate of approximately 0.15 USD/kWh and a variable surcharge of 0.15 USD/kWh in the beginning of 2015 [222]. Looking at the results in Fig.

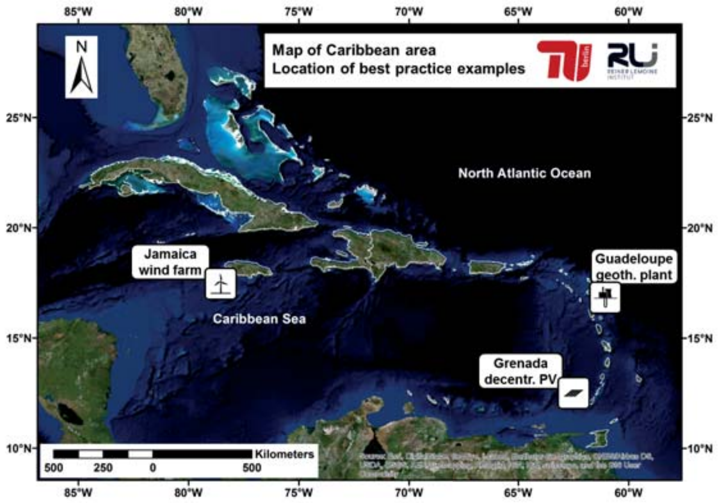


Figure 6.7: Location of best practice examples for renewable energies on Caribbean islands

5.12 the enormous techno-economic potential for renewable energies on the main island Grenada can be seen. Studies have been conducted to exploit the geothermal potential, but for this case study it is focused on solar PV.

In the year 2007 GRENLEC launched the pilot phase of its interconnection policy allowing each customer point to connect small PV plants up to ten kilowatts. For such PV plants a net-metering scheme has been applied. According to the high end-customer tariff this system has been economically very attractive. The pilot phase ended in 2011 reaching the limit of 300 kilowatts installed PV capacities. The following key parameters are identified as main drivers for this success story of PV implementation.

Regulatory framework: Within the interconnection policy clear guidelines have been given for the independent power producers how to apply for the interconnection of renewable plants and how to connect them. This regulation simplifies the entire process of applying for, installing, and operating a PV plant. In addition, it secures the revenues of the investor by guaranteeing a net-metering system for the entire project lifetime [168, 222].

Costs / financing: As a direct consequence of the secure investment conditions by the regulatory framework private capital was available to overcome the lack of financing options. The high initial costs have been compensated by the attractive net-metering conditions allowing low amortization times. Additionally, these costs could be reduced by low transaction costs through the simple application process and through a local distributor importing modules in higher quantities [223].

Local champion: The aforementioned local distributor and installer had a great influence on the successful implementation of the first PV systems. He is seen as a trustworthy person on Grenada due to his profession as a medical doctor. Based on this leap of faith private customers bought PV systems even though they had no experience with this technology on Grenada [168].

After the first effective phase a new interconnection program has been implemented in 2011. For this new phase the net-metering scheme has been substituted by a net-billing system. Within this billing system all generated solar energy is directly fed into the grid by the customer while he / she consumes all his / her electricity from the central grid. The grid tariff is substantially higher than the feed-in tariff. In addition, the feed-in tariff is only guaranteed for ten years which makes the net-billing scheme overall unattractive. Politicians and people have tried to change this new interconnection program, but the utility cannot be forced to do this as long term contracts strengthen the utility's bargaining power. Thus, the monopolistic energy supply by only one utility can impede the further implementation of renewable energies if no incentives are set for the utility to promote them.

The reason why the interconnection policy changed is that the utility looses money in a simple net-metering system, because it has to provide the grid and back-up power capacities while the customer can just reduce his / her electricity bill via feeding in all this generated power. In principle a net-billing system can work very properly if all stakeholders are satisfied by a proper tariff setting (cf. [224]).

In summary, the showcase for PV in Grenada reveals potential measurements to overcome barriers but also some limits of certain instruments to support the implementation of renewable energies. Similar cases can be observed for Martinique and Guadeloupe, where high feed-in tariffs led to a quick increase of PV installations until the tariff has been adjusted for French oversea departments by the government [225].

It has to be discussed if small decentralized plants are the most effective way for such a small island as stated by SH: "In my opinion utility RE generation makes sense, whereas private sector, small scale decentralized RE doesn't make sense on those islands." Thus, incentives and regulatory frameworks have to be set to push the utility using more renewable technologies or allowing independent power producers to operate large scale renewable plants. In the next example such a large scale plant is investigated.

Showcase Jamaica - wind farm

In 1978 a wind mapping project started for Jamaica to analyze the natural potential for wind power projects. Due to increasing oil prices the Government of Jamaica decided to increase its renewable energy targets and to support the implementation of independent wind power projects. The electricity market were liberalized in 2001 allowing independent power producers to sell electricity to the national grid. Anyhow, the power purchase agreement has to be negotiated individually with the utility and confirmed by the Office of Utility Regulation. Thus, the baseline for independent wind power projects has been laid out in Jamaica and is analyzed along the example of the Wigton wind farm in Manchester, Jamaica [226].

For this specific case a subsidiary of the publicly owned Petroleum Corporation of Jamaica (PCoJ) has been founded to purchase and operate the wind farm. With the help of international experts and financing 38.7 megawatts of wind capacities are erected at the Wigton wind farm. The operating wind power capacities feed the generated electricity into the central grid. The project has been a technical success from the beginning, but struggled financially due to low feed-in rates, which have been adjusted for now. The key parameters for the successful integration of wind power into the electricity supply system of Jamaica are listed in the following paragraphs [107].

Liberalization / regulatory framework: The liberalization of the power generation sector enabled independent power producers to enter the Jamaican electricity market and to sell electricity to the grid. A regulatory authority has to approve the rates of power purchase agreements. This should ensure competitive tariff levels but has been failed in the past for the Wigton wind farm [227].

Costs / financing: Implementation costs have been low due to sponsored prefeasibility studies and wind measurements. In addition land acquisition issues could easily be solved by the parent company PCoJ due to existing land rights for the wind farm area. The project is 100 percent debt financed by the PetroCaribe Development Fund which reduces the risk for the operator who has not to provide any equity. The secure power purchase agreement in combination with revenues from the clean development mechanism convinced the creditors financing this project [107].

International support: As a pilot project this wind farm has especially been profited from international support. Firstly, technical support of international experts for pre-feasibility studies and planning were given with a clear focus on knowledge transfer. Secondly, international financing and support mechanisms strengthened the economic viability of the project.

Overall, the Wigton wind farm sets a promising example for the initial deployment of large scale renewable energy projects by independent power producers. Lessons learned concern mainly the tariff setting of the power purchase agreement which almost led to bankruptcy of the wind farm operator. For future projects a more competitive tariff has to be set. For initial projects international support seems necessary but with subsequent projects more and more responsibilities can be taken over by locals. This is underlined by the new planned third phase of the Wigton wind farm in which the operator pays 20 percent of the initial investment by equity. By that equity share the project can be seen as a sustainable business model which can be multiplied for the entire country or even the region under the aforementioned circumstances.

Showcase Guadeloupe - geothermal plant

As third showcase the first geothermal plant on Caribbean islands is taken: the geothermal plant Bouillante on Guadeloupe. Starting with 5 megawatts in 1986 it has been extended to 15 megawatts in 2005 [228]. The initial exploration took place by the bureau de recherches géologiques et minières (BRGM), which is a French public entity, and by EURAFREP, which is a private French oil drilling company. After successful exploitation EURAFREP has been operating the drilling well and the local utility Électricité de France - Guadeloupe (EDF) has been operating the related geothermal plant. Up from 1996 a new company called Geothermie Bouillante were formed by BRGM and EDF to take over both operations and to invest into it and implement the additional geothermal capacities [229]. In this showcase the utility invested directly into renewable energies without any known governmental incentives. Key success parameters are described in the following.

Fossil fuel surcharge: The results in Ch. 5 reveal the enormous cost advantage of geothermal energy over the project lifetime. Thus, it is overall beneficial for the utility to generate power by geothermal plants instead of using expensive diesel fuel.

Nevertheless in many Caribbean countries the tariff system with fossil fuel surcharge hinders the utility to benefit from theses cost advantages. As in Guadeloupe only one tariff exists and the utility profits directly from its investment into renewable energies.

Costs / financing: Especially geothermal projects require high initial investments combined with high project risks. For the case of Guadeloupe the large international corporate group EDF is able to back-up such project risks which are small compared to the overall turnover of this company. In addition, exploitation and drilling, which involves the highest risks, has partly been financed by the governmental owned BRGM [229].

In conclusion it can be stated that under certain circumstances utilities invest initially by themselves into renewable energy projects on Caribbean islands. It has to be assured that these projects are economically profitable, that they know the technical and financial risks, and that they are able to mitigate theses risks.

On other islands with similar abundant geothermal resources the development of plants has not taken place yet. Utilities are mainly not powerful enough to exploit the resources by themselves, but they would not allow independent power producers cutting of their market shares. During the interviews AJ explained the situation for St. Lucia: "As you may know, St. Lucia harbors a volcano, so they were exploring the potential of deriving energy from these volcanic activities. The costs for this exploration were very high, and another barrier was the absence of an independent power producer. The utility had a monopoly and so it would not have been possible to feed the energy into the grid. [...] Overall barriers to renewable energies are the absence of legislation and regulation, very clear. Also, the lack of funding I presume are other barriers. Especially for geothermal, the exploration costs are very high and developers need funding for that."

An implementation of a collaborative fund for geothermal development on Caribbean islands could support the smaller utilities to share the risks and to attract financing. Additionally, the tariff setting to refinance investments into renewable projects need to be adjusted as well. Finally, regulation and legislation could be changed to facilitate the market entry for financially strong independent power producers. The latter ideas are further discussed in Subsec. 6.5.2.

Finally, all best practice examples are presented. The correlation of previously identified barriers and critical key success parameters becomes obvious by analyzing the showcases. In the following sub-section a strategy roadmap is developed showing practical recommendations and measurements to overcome existing barriers and to push the implementation of renewable energies on Caribbean islands.

6.5.2 Solutions and strategy roadmap

Solutions to overcome the identified barriers are derived and an overall strategy roadmap is developed in this final sub-section of the empirical analysis. Within the first part possible solutions for the previously clustered main important barriers are shown. In the second part the strategy roadmap for three potential renewable energy project developers - utilities, private companies, and private persons - is drawn.

Solutions

The solutions are derived along the three clusters of most important barriers to implementing renewable energies on Caribbean islands: regulatory frameworks and policies, costs and financing, and clout of conventional power system. For each of them the dependencies within the related barriers are shown as well as solutions for all of them.

Cluster I - Regulatory frameworks and policies: Two of the most important barriers are *3.3.2 lack of regulatory framework and legislation for private investors* and *3.3.1 lack of legal framework for independent power producers and power purchase agreements*. These are partially caused by barrier *3.1.1 gap between policy targets and implementation*. Changes in regulatory frameworks and policies are difficulty to conduct based on *3.2.2 lack of renewable energy experts on governmental level* and *3.2.1 lack of formal institutions*. These relations are illustrated in Fig. 6.8 together with the matching solutions.

Suggested solutions for the previously named barriers target primarily the two most important ones, the regulatory barriers. As shown in the example of decentralized PV on Grenada, the introduction of interconnection guidelines for private producers would enable a stable investment framework for renewable energy projects. The main important issue is the allowance to feed the generated electricity into the central grid. Nevertheless, grid stability issues should be considered for large scale plants especially when high shares of renewable energies are reached within the system. For example certain ramping criteria for PV or wind power plants have to be set or storage technologies have to be mandatory [230]. This could be defined in standardized power purchase agreements.

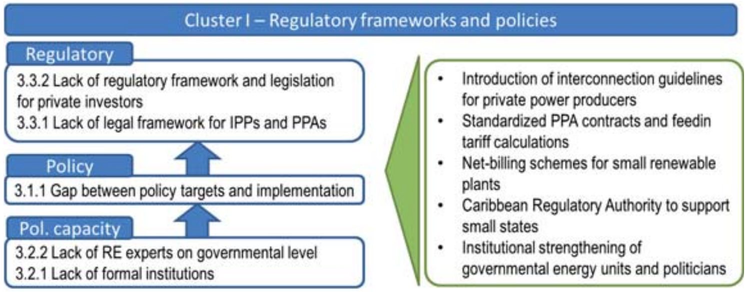


Figure 6.8: *Cluster I - Regulatory frameworks and policies - barriers and solutions*

These standardized power purchase agreements are presented as second solution to overcome regulatory and legal barriers. For independent power producers they should define the technological requirements for grid connection including for example power ramping, remote shutdowns by the utility, and reactive power provision. In addition, the calculation of feed-in tariffs or rates for the independent plants into the utilities' grid should be properly defined. It is important to find a competitive rate for both sides recovering the costs of the independent operator as well as the expenditures of the utility for transmission, distribution, and sale to the end-customer.

In a simplified way these matters should also be defined in net-billing schemes for small scale decentralized renewable power generation of private persons or small and medium enterprises. Again, the example of Grenada has shown how a simplified interconnection guideline can facilitate the implementation of renewable energies by the private sector. Nevertheless the main adjustments can be done via the length and the level of the guaranteed feed-in tariff schemes (cf. [224]).

The introduction of the aforementioned regulatory framework requires strong political will and capacities. The barrier *3.1.1 gap between policy targets and implementation* underlines the problem of implementing proper regulatory frameworks. For many small countries this gap is based on the lack of institutional capacities and renewable energy experts within the governments (cf. barrier *3.2.1* and *3.2.2*). Two primary solutions exist to overcome these political barriers.

Firstly, the Eastern Caribbean Energy Regulatory Authority (ECERA) could be reinforced to support smaller countries in the development of interconnection guidelines and standardized power purchase agreements. Until now ECERA has not gained sufficient influence to cover these tasks. But if it became more powerful and acknowledged by more countries as it is aimed within one World Bank supported project [231], the ECERA could play a crucial role in the implementation process of renewable energies on Caribbean islands.

In general, formal institutions which cover the ECERA as well as energy units or ministries within Caribbean governments should be strengthened to give the needed support for implementing regulatory frameworks. This can be done either by clustering administrative units of single countries to superordinated authorities such as the ECERA. Subsequently, less renewable energy experts would be needed as they work more concentrated in one superior authority. In addition, capacity building within local governments and support in legal or regulatory questions should continuously be given by international organizations as it has been performed in the Caribbean Renewable Energy Development Program.

In summary, the barriers of cluster I are targeted by the introduction of proper regulatory frameworks with competitive feed-in conditions for renewable energy. This introduction has to be supported by regional authorities and international collaborations strengthening the expertise and capacities of Caribbean islands' governments.

Cluster II - Costs and financing: The next important cluster of barriers focuses on costs and financing. The highest importance within this cluster has barrier *2.1.1 high initial investments.* It is followed by two direct costs drivers, *2.1.3 diseconomy of scale* and *2.1.2 high transaction costs.* More indirect cost drivers are *3.1.2 lack of incentives or subsidies for renewable energies*, which would act as cost reducer, and *1.1.1 land use competition on islands.* The whole issue of costs is also related to difficulties in financing which are reflected in the barriers *2.2.2 lack of understanding of project cash flows from financing institutions*, *2.2.3 lack of private capital*, and *2.2.1 lack of access to low cost capital.* All presented cost associated barriers and the suggested solutions can be found in Fig. 6.9.

For the presented barriers of cluster II the derived solutions firstly aim at reducing the high initial investments by direct or indirect ways. With overall only 41 million people and no local renewable technology manufacturing capacities the analyzed Caribbean islands miss opportunities to decrease initial costs for renewable technologies during production. Thus, they depend upon the world market prices for renewable plants. Nevertheless, one solution to reduce initial investments for investors could be the removal of barrier *3.1.2* which means the introduction of incentives or subsidies for renewable energies. Such subsidies could be tax reductions

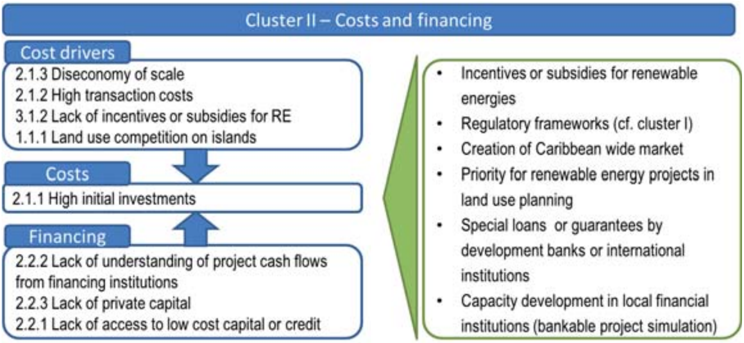


Figure 6.9: *Cluster II - Costs and financing - barriers and solutions*

or grants to reduce the initial investment costs as it has been successfully applied for solar water heaters in Barbados [232].

As previously discussed renewable power is already competitive comparing it on LCOE basis with conventionally generated power. Thus, providing secure investment frameworks for the entire project lifetime could play an important role as well as reducing the initial costs directly. These frameworks are discussed in cluster I and would also partly remove the cost related barriers.

It makes sense to keep the initial investments as low as possible. Another potential solution is the introduction of a Caribbean wide market for renewable energies with free trade among the participating countries. By that an international or local supplier of renewable energy technologies does not necessarily need to have branches in every country he wants to supply. One main hub could be installed within one country and large scale imports could take place for this. Up from there an unbureaucratic way of distributing the renewable energy products to other Caribbean countries could be applied. Thus, these countries benefit from the cost competitive large scale imports as well. The smaller the island the less possible is it to avoid diseconomies of scale. Thus, for smaller islands a centralized approach of implementing higher shares of renewable energies should be chosen to keep the diseconomies low.

If the cost driver is based on land use competition the politicians should give priority for renewable energy projects in land use planning. This either means to save governmental property for renewable energy investors or private property development plans should be assessed if they are in competition to renewable energy projects. In such cases the renewable energy projects should be prioritized without increases in the land acquisition costs to keep them competitive.

Renewable power plants are economically characterized by high initial and low operational expenditures while conventional plants show contrary cost structures due to high continuous fuel expenditures. Thus, net present values of investments in renewable energy projects are highly affected by the capital costs driven by return on equity and loan interest rates [233]. The hampering effect of high initial investments is even more crucial if low cost capital or financing is lacking.

Based on this relation, solutions for the three financial barriers are derived to overcome the most important economic barriers and to enable an economically viable project implementation. The first measurement is the introduction of special loans by development banks or international institutions. For large scale projects international financing institutions could set up competitive interest rates compared to the prevailing high interest rates on Caribbean islands (cf. Tab. 4.9). In addition, such institutions could give guarantees to secure power purchase agreements of local utilities with foreign investors. This reduces the investor's risk of payment losses and can therefore reduce the risk premium on the projects. Thus, the overall capital costs for large scale renewable energy projects decrease by direct or indirect activities.

Usually, development banks set requirements for the lowest possible project size which is financed by them. Due to high transaction costs of applying for internationally supported financing it is more viable to provide local loans for small scale renewable projects. Thus, local financing institutions have to be strengthened to allow them to assess the bankability of renewable energy projects. The better they can assess the risks of such projects the more competitive local loans will be for renewable energy projects. One way to do this is to provide capacity development by international organizations or to provide methodologies and tools to determine projects' future performances. For example such methodologies can be found in the mini-grid policy toolkit [234] or an integrated energy and finance simulation tool can be applied as developed by the Reiner Lemoine Institut (cf. [233]). These tools are not only useful for local banks. They can support the international financing institutions as well.

The increased availability of small loans by locals banks will probably increase the private investments as well. Cheap loans in combination with secure payback conditions by the described regulatory frameworks and incentives can attract a lot of private capital to invest into renewable energy projects. On many Caribbean islands a high level of private capital exists due to the immigration of wealthy people. This private capital can be direct towards investments into renewable energies by the aforementioned instruments.

In conclusion, the economic barriers can be overcome by different ways. Firstly, the initial costs can be reduced by direct or indirect measurements. Secondly, low cost financing should be provided throughout international or local financing institutions to reduce capital costs for renewable energy projects. Thirdly, regulatory frameworks would further reduce the risks of investing in renewable energies on Caribbean islands which would on the one hand decrease the capital costs and on the other hand attract more private capital.

Cluster III - Clout of conventional power suppliers: The third cluster is the clout of conventional power suppliers and utilities. This means all barriers which are related to the power structures of the prevailing system hindering the deployment of renewable energies are covered within this cluster. Namely these are barrier *2.3.1 utility monopoly of production, transmission, and distribution of electricity* and barrier *2.3.3 lock-in dilemma* as typical market failures. They are underlined by the social barrier *4.2.3 strong fossil fuel lobby* supporting the prevailing system. Another barrier which hinders the turn towards more renewable energies is *2.3.4 fossil fuel subsidies and fuel surcharge* which sets disincentives for investing into fuel saving technologies such as renewable power plants. An overview of the presented barriers and related solutions is given in Fig. 6.10.

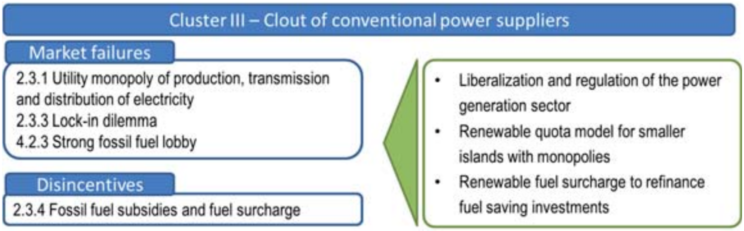


Figure 6.10: *Cluster III - Clout of conventional power suppliers - barriers and solutions*

The presented barriers can be targeted in two ways. One is to solve the market distortions and increase the competition within the power generation sector. A liberalization and regulatory frameworks allowing independent power producers could support investments into renewable energies if they are competitive under the market conditions.

For smaller countries or islands it is not necessarily possible to create a liberalized power generation market due to the small market size and the low availability of power generation experts. Under these circumstances a regulatory authority could set certain quotas of renewable capacities to force the implementation of renewable power plants within monopolistic markets. Within such quota models the utilities can decide whether to implement the capacities by themselves or to buy renewable electricity from independent power producers.

The aforementioned measurements are strong interventions into the existing business strategies and models of the existing utilities. Regulatory authorities and politicians have to show strong will to enforce these measurements which might be difficult considering the strong fossil fuel lobby and the lock-in dilemma. In addition, some utilities have long term contracts which would allow high compensation payments if their business model based on conventional power supply is endangered [168].

One final solution would be to use the existing tariff of fixed rate and fuel surcharge system and adapt it to the requirements of a renewable energy dominated supply system. Currently investments into fuel saving technologies such as renewable power plants can only be recovered by the fixed tariff as the fuel surcharge only applies for burned fuel. Thus, it is mostly more economically attractive to use low cost technologies with high fuel consumption as they are easily covered by the fixed rate and all fuel costs can be passed to the end-customer. To overcome this disincentive it is suggested to implement a renewable fuel surcharge. It means an additional tariff is introduced on top of the fixed rate and fossil fuel surcharge.

This renewable surcharge could either be a fixed rate per kilowatthour over a certain project lifetime similar to feed-in tariff schemes or a flexible rate per kilowatthour based on the fossil fuel surcharge level - for example 75 percent of the fossil fuel surcharge. In both cases only the renewable energy which is fed into the grid and consumed should be compensated. Excess energy could potentially not be covered by the renewable fuel surcharge to keep the overall costs for the end-customers low. Utilities would have to invest into system stability and storage technologies to use as much of the generated renewable energy as possible. This renewable surcharge is also important when looking at the solutions for the regulatory barriers. It becomes obvious that these would allow private investors to generate and sell electricity to the local utility. Again the utility would not be able to refinance the feed-in payments to the independent power producers just by the fixed part of the end-customer tariff. Thus, for these cases a renewable fuel surcharge should be applied as well.

Summarizing the solutions for the barriers of cluster III reveals that a combination of regulatory measurements and economic incentives have to be used to turn the conventional power generation sector towards renewable energies. A balance between enforcement and incentives has to be found to realize these measurements successfully.

Hereby the solutions for the three main clusters of barriers are presented. The removal of these barriers would certainly facilitate the implementation of renewable energies on Caribbean islands. Anyhow, various other barriers - especially technical and social - are identified in the previous analyses. They are rated with lower importance but they could still influence the implementation of renewable energies.

For the technical barriers it is suggested to increase the knowledge transfer between higher developed countries and the Caribbean countries. Studies such as conducted in the first part of this thesis should be made available to underline the cost competitiveness of renewable energies. In addition, renewable technologies adapted to the special needs on Caribbean islands should be provided, for example storage technologies and hurricane proofed wind turbines. Training by international institutions for local energy experts to understand these new technologies would also support the deployment of them. Thus, international organizations and companies should ensure a proper knowledge exchange between local Caribbean experts and international experts.

In terms of social barriers a constant increase in awareness and education would support the transformation of the power sector towards renewable energies in various ways. The more the people demand renewable energies the higher is the pressure on the politicians and utilities to implement changes. Additionally, pilot projects by local champions or initiatives could evolve from higher awareness. Campaigns removing the social barriers should be supported by international and local institutions and governments to set the foundation for the shift of paradigm in the Caribbean energy sector.

After presenting the whole variety of measurements and solutions to remove or overcome the identified barriers a final strategy roadmap is developed. This roadmap could serve as a blueprint to implement the presented solutions in certain Caribbean countries.

Strategy roadmap

For the implementation of the solutions it is important to distinguish between small, medium, and large islands. The smaller the island the better is an all-in-one solution. This means the local utility should transform the power supply with the help of a few local or international partners into a renewable energy based system without too many decentralized solutions. On medium size islands a mixture of large scale projects combined with some private decentralized investments could be feasible. On large islands a real liberalization of the energy market could take place and different utilities, private companies, and private persons could realize renewable energy projects under the a proper regulatory framework politically fixed in advance.

As listed in Fig. 6.11, three main investor groups can be responsible for the successful implementation of renewable energy projects: utilities, private companies (independent power producers), and private persons. All of them should be interested to invest into renewable energies if the right measurements are taken to overcome the existing barriers. A roadmap to do this for a single Caribbean country is drawn in Fig. 6.11.

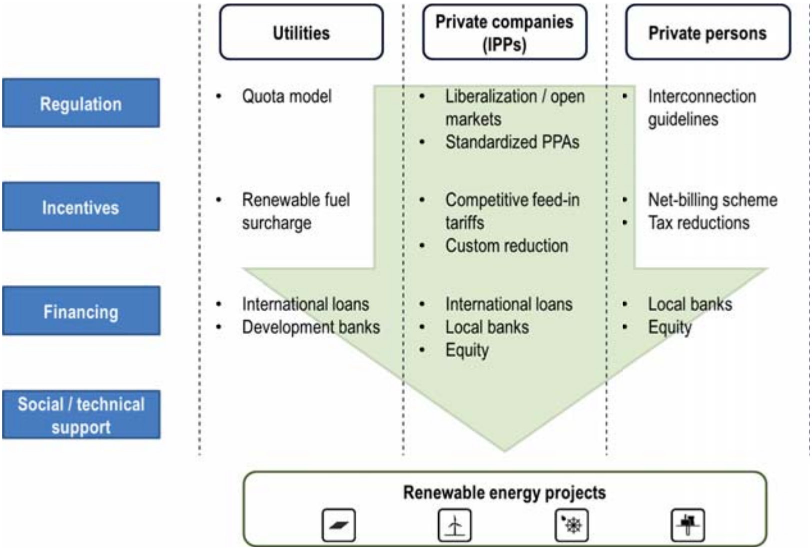


Figure 6.11: Roadmap for successful implementation of renewable energy projects on Caribbean islands

Within the presented roadmap the specific measurements and solutions to implementing renewable energies are distributed along the three levels of regulation, incentives, and financing. The solutions differ among the three investor groups. As fourth level the social and technical support listed has to be given by the local people and by local and international organizations. For this level no specific measurements are written as it refers to the general support of the implementation of renewable energy projects.

If utilities are targeted a quota model have to be introduced as regulatory framework supported by the aforementioned renewable fuel surcharge as incentive. The financing for utility based projects would mainly have to come from international and development banks providing cheap loans for such investments.

For private companies it is important to liberalize the power sector market or at least opening it for independent power producers. In addition, standardized power purchase agreements should be included into the regulatory framework. The most important incentive for independent power producers is a competitive feed-in tariff level within the power purchase agreements which could be supported by reduced custom charges for renewable technologies. Low cost capital from international or local banks is important to keep the private projects economically viable and to attract enough equity from private companies.

A decentralized approach to foster the deployment of renewable energies on Caribbean islands relies on the action of private persons. A clear and simple interconnection guideline is the regulatory prerequisite for them to install and operate their own renewable energy plants. To guarantee revenues a proper net-billing scheme could stimulate investments and the attractiveness could be furthermore increased by tax reductions. With further institutional developments local banks could provide special loans to finance private renewable energy projects. For some of them it might even be feasible to pay them by 100 percent equity.

As presented, the roadmap in Fig. 6.11 summarizes the right application of the derived solutions to implementing renewable energies. The roadmap is drawn for single countries and excludes the interactions among them. Nevertheless the creation of Caribbean wide markets and an acknowledged regulatory authority should further support the implementation of renewable energies.

With these final practical recommendations the empirical part of this thesis is concluded. Barriers are identified and evaluated according to their importance and matching solutions are derived. In the following last chapter the analysis of the techno-economic potential of renewable energies is merged with the empirical analysis of barriers and solutions to derive a final synthesis of this thesis.

Chapter 7

Conclusions

In the final chapter the conclusion summarizes the main findings of this thesis. It connects the two previously presented research parts, the techno-economic potential and the barriers to implementing renewable energies on Caribbean islands. During this final conclusion future research needs are identified and outlined as well.

7.1 Conclusions and summary

This thesis consists of two independent research parts which are strongly connected. There is no need to even look at the empirical evaluation of barriers unless there is a proven techno-economic potential of renewable energies. The research work has been guided by the following two hypotheses:

- A huge untapped techno-economic potential of renewable energies exists on Caribbean islands.
- Different technical, economic, political, and social barriers block the deployment of this potential.

The six research questions which were raised in Ch. 1 helped to test these two hypotheses. Answers to these questions were found by means of several different scientific methods, such as energy system simulations, literature reviews, and empirical data collection. An enormous techno-economic potential for renewable energies was found on 60 out of 62 analyzed Caribbean islands. Additionally, the most important barriers to implementing this potential are identified and even solutions are recommended to overcome them. In the rest of this chapter the applied methods and achieved results are summarized more specifically with regards to each of the six research questions.

What is the natural resource availability of renewable energies on Caribbean islands?

A detailed resource assessment was used to figure out the availability of renewable resources on Caribbean islands. For this assessment data from meteorological and water flow models were used to determine the natural renewable resources for each analyzed island. By modeling these resources an electrical feedin time series can be derived. These feedin time series represent hourly power generation of the renewable power plants applying the typical efficiency values for the respective technologies. The investigation includes solar, wind, hydro, and geothermal resources.

Solar irradiation and the related PV feedin time values show excellent results on all Caribbean islands. The irradiation ranges from 1,850 to 2,300 kWh/m^2/year. Correspondingly, modeled PV plants reach 1,600 to 1,900 full load hours, whereby the highest values are found on Eastern Caribbean islands. Wind resources are more varied among the 62 analyzed islands. Average wind speeds start at 4.7 m/s and go up to 9.8 m/s. The resulting wind full load hours have the lowest values on the largest of the Caribbean islands and on the Bahamas with around 700 to 2,000 hours per year. On most of the other Caribbean islands 2,000 to 3,000 wind full load hours were detected. The highest wind yields were found on the ABC-islands (Aruba, Bonaire, and Curacao) with up to 6,000 full load hours.

Hydropower resources were analyzed by applying theoretical discharge values from the waterGAP model. Developed hydropower potential exists on eight Caribbean islands with on average 2,600 full load hours. A promising gross hydropower potential was found on many more Caribbean islands but was not further explored in this thesis. The revealed geothermal potential often exceeds the electricity demand of the respective island many times over. Such geothermal potential was identified for ten islands.

To conclude, abundant natural resources exist for the use renewable energy technologies on Caribbean islands as presented in Sec. 4.2. Solar irradiation is excellent for all of them while wind resources are more heterogeneously distributed. Hydro and geothermal resources can only be found on some of the Caribbean islands. In cases in which such resources are found the opportunities for renewable energy technologies are huge.

How can technological solutions be applied to utilize these resources?

This thesis demonstrates the technological solutions for utilizing the abundant resources available. In general, the working principles of the renewable plants are the same whether applied on islands or in large centralized systems on the mainland. The island energy supply systems require fast and flexible power plants because of the lower and more varying loads especially if high shares of fluctuating renewable energies are introduced. For this reason, diesel or oil fired power plants has been the most successful of conventional power generation on islands. In addition, stability criteria such as the spinning reserve have to be met within island energy supply systems. This reserve can be provided by on demand power plants (diesel or geothermal) and / or by battery systems.

All necessary components - diesel, PV, wind power, hydropower, and geothermal plants and battery systems - and their application for such island energy supply systems were theoretically explained in Sec. 2.2. After the theoretical introduction, a detailed description was given for modeling these components. Simulations are necessary to analyze technical and economically feasible renewable energy options for Caribbean islands.

The survey of existing simulation tools has shown that none of the previously available tools meets all the requirements for simulating renewable energy supply systems on Caribbean islands sufficiently (cf. Subsec. 3.1.1). Thus, for the purposes of this thesis a simulation tool had to be developed in Matlab. It allows for the simulation of all previously mentioned components of an island energy supply system plus technological and economic input parameters. The derived feedin data from Sec. 4.2 can be fed into the model to simulate one reference year in hourly time steps. A certain dispatch strategy was programmed to ensure that the load and all stability criteria are met for every time step. The simulation tool provides technical and economic output values and further allows for techno-economic optimizations. Within such optimizations the supply option with the lowest LCOE can be determined. A detailed description of the structure and functions of the developed simulation tool can be found in Sec. 3.2. To test this simulation tool it was compared to two other simulation tools and it showed full functionality. In addition, the simulation tool was used to determine the output value for two existing island energy supply systems and it successfully calculated the actual energy output as seen in Sec. 5.1.

In conclusion, technological solutions for utilizing renewable resources for power generation can be explored and evaluated with the help of the developed simulation tool. The applied dispatch strategy and technical constraints ensure that all simulated supply options would operate without interruptions. The simulation tool thus allows for exploring various combinations of renewable technologies and battery systems to determine the best technological solutions to implementing renewable energies on Caribbean islands.

To what extent can renewable energy technologies compete with the current conventional power generation system on Caribbean islands?

The previously presented simulation tool was applied to figure out the techno-economic potential of renewable energies on Caribbean islands. Optimized systems with renewable energies were proven to be highly competitive compared to current conventional supply systems.

To compare renewable energies with the status quo, a simulation of this status quo of all considered 62 Caribbean islands had to first be carried out in Subsec. 5.2.1. The simulation included all known existing fossil, hydro, wind, and geothermal power plant capacities. PV plants were excluded because precise geographic information was not available. Almost all Caribbean islands are dominated by fossil fuel based power generation. These conventional power plants consume in total approximately 19 billion liters of diesel per year which results in 50 million CO_2 emissions per year. The average power generation costs add up to 0.30 USD/kWh. The lowest values were found on Trinidad (TTO01) and Tobago (TTO02) with around 0.07 USD/kWh due to very low fossil fuel prices. The highest values were detected on the smaller Virgin Islands (VIR02 and VIR03) and Montserrat (MSR01) with more than 0.40 USD/kWh. In general, it can be observed that the power generations costs increase for smaller islands because of higher transportation costs for fuel and the lower efficiencies of small scale plants. The current number of renewable energy plants is extremely low. Less than one gigawatt renewable capacities are currently installed leading to an average share of renewable energies of 1.1 percent.

Taking the status quo as a basis the energy supply system of each island was optimized. This means the systems' configurations were techno-economically optimized to reach the lowest possible LCOE through the use of identified renewable resources. In Subsec. 5.2.2 a huge techno-economic potential was detected for renewable energy technologies on Caribbean islands. The results showed that the average power generation costs can be reduced down to 0.215 USD/kWh which is a reduction of 27 percent underlining the competitiveness of renewable power plants. Overall, this requires 760 MW of hydropower, 8,880 MW of photovoltaic, 6,300 MW of wind power, and 530 MW of geothermal power plants. These capacities are supplemented by 3,120 MWh of battery systems. An additional investment of 35 billion USD is needed to implement these capacities. With that investment the fossil fuel consumption can be reduced by 8.5 billion liters per year and 22 million tons of CO_2 emissions can be saved respectively.

Optimizing the Caribbean island energy supply systems would increase the absolute renewable energy share of the overall consumption to 45 percent. The islands' average renewable share is higher with 62 percent, as the low consuming islands have higher shares of renewable energies which are less weighted in the absolute case. The islands with geothermal resources (MTQ01, GLP01, GRD01, LCA01, MSR01, BES02, KNA01, KNA02, DMA01, and VCT01) reach the highest renewable energy shares with 93 to 99 percent leading to the highest cost savings as well. Among the islands without geothermal resources the ones bearing the highest wind potential also have the highest renewable energy shares, higher than 60 percent. Islands with a potential share of renewable energies lower than 60 percent are often dominated by PV installations which are less competitive than wind plants because of their high full load hours.

The island with the highest total potential is Puerto Rico (PRI01) where 3.3 GW PV and 4.1 GW wind power can be economically implemented. Only two islands do not have any techno-economic renewable energy potential: TTO01 and TTO02 based on their low conventional LCOE. Renewable resource availability and local fuel costs were identified to be the most important factors for reducing LCOE. Sensitivity analyses were performed as well, showing the influence of several factors in implementing renewable energies such as battery technology, fossil fuel costs, and risk-based higher interest rates. It is especially important on islands with high geothermal potential to develop stringent implementation roadmaps as geothermal plants result in high renewable share supply systems (cf. Subsec. 5.3.4).

Finally, it can be stated that the extensive implementation of renewable energies has significant economic and ecological advantages on Caribbean islands. Fuel consumption and CO_2 emissions can be reduced by 45 percent by implementing the most cost competitive systems under the current economic conditions. If fossil fuel costs increase renewable energy shares will probably increase beyond 45 percent renewable energy share which is based upon the current conservative assumption that fossil fuel prices will remain stable.

The recommended implementation of 15 GW renewable energy capacities is both an enormous step forward in establishing renewable energies and most importantly very economically viable in comparison to the existing one gigawatt. The calculated techno-economic potential is based on current realistic cost assumptions and technical considerations. Thus, renewable capacities should be developed further on Caribbean islands due to economic and environmental benefits. Furthermore, the untapped potential suggests that overcoming the barriers to implementation requires research beyond the energy system simulations.

Which barriers hinder the implementation of the existing techno-economic renewable energy potential?

31 barriers to implementation of renewable energies were detected. These barriers were identified by literature reviews and expert interviews. They are categorized into technical, economic, political, and social categories.

Firstly, a literature synthesis matrix was applied and 32 barriers are found in scientific papers and reports as seen in Sec. 6.2. These were adjusted and / or validated by three interviewed "super-experts" representing the main important stakeholders in the Caribbean power generation sector: the utilities (by CARILEC), the politicians (by CARICOM), and the private sector and institutions (by GIZ / CREDP) (cf. Sec. 6.3). The adjustment led to a final list of 31 barriers which are named below.

Technical barriers
1.1.1 Land use competition on islands
1.1.2 Renewable energies' impact on landscapes and ecosystems
1.1.3 Natural disasters
1.1.4 Lack of evidence-based assessment of renewable energy potentials
1.2.1 Lack of technical expertise and experience
1.2.2 Low availability of renewable energy technologies
1.3.1 Inappropriate transport and installation facilities
1.3.2 Unsuitable transmission system and grid stability issues with decentralized renewable energies

Economic barriers
2.1.1 High initial investments
2.1.2 High transaction costs
2.1.3 Diseconomy of scale
2.2.1 Lack of access to low cost capital or credit
2.2.2 Lack of understanding of project cash flows from financial institutions

2.2.3 Lack of private capital
2.3.1 Utility monopoly of production, transmission and distribution of electricity
2.3.2 Small market sizes
2.3.3 Lock-in dilemma (conventional energy supply structures block renewable energies)
2.3.4 Fossil fuel subsidies and fuel surcharge

Political barriers
3.1.1 Gap between policy targets and implementation
3.1.2 Lack of incentives or subsidies for renewable energies
3.2.1 Lack of formal institutions
3.2.2 Lack of renewable energy experts on governmental level
3.3.1 Lack of legal framework for independent power producers and power purchase agreements
3.3.2 Lack of regulatory framework and legislation for private investors

Social barriers
4.1.1 Lack of social norms and awareness
4.1.2 Lack of educational institutions
4.2.1 Lack of renewable energy initiatives
4.2.2 Lack of local/national champions/ entrepreneurs
4.2.3 Strong fossil fuel lobby
4.3.1 Dominance of cost over environmental issues
4.4.1 Preference for status quo

What are the most important barriers?

With the help of questionnaires an empirical evaluation has resulted in a ranking of barriers as written in Sec. 6.4. Of the six most important barriers three are economic and three are political. A comprehensive analysis of the barriers led to identifying three new fields which cover the most important barriers of implementation. Cluster I is related to the regulatory frameworks and policies, cluster II is based on costs and financing, and cluster III deals with the clout of conventional power suppliers.

Among all barriers the most important is *3.3.2 lack of regulatory framework and legislation for private investors* which can be found in cluster I. Additionally, barrier *3.1.1 gap between policy targets and implementation* (rank 2) and barrier *3.3.1 lack of legal framework for independent power producers and power purchase agreements* (rank 4) are part of this cluster. Both are rated with high importance and are among the top six barriers. Barrier *3.2.2 lack of renewable energy experts on governmental level* (rank 17) and barrier *3.2.1 lack of formal institutions* (rank 26) are both seen as of medium importance. Nevertheless, they are also crucial because governmental experts and institutions are needed for overcoming the three previously named barriers.

Cluster II contains the third most important barrier, *2.1.1 high initial investments*. This barrier is influenced by *2.1.2 high transaction costs* (rank 7), *2.1.3 diseconomy of scale* (rank 8), *3.1.2 lack of incentives or subsidies for renewable energies* (rank 9), and *1.1.1 land use competition on islands* (rank 10). This underlines the importance of costs and cost drivers as barriers to implementing renewable energies. In addition, financing instruments are missing to cope with these high initial costs. Thus, barriers related to financing are part of this cluster as well: *2.2.2 lack of understanding of project cash flows from financing institutions* (rank 11), *2.2.3 lack of private capital* (rank 12), and *2.2.1 lack of access to low cost capital or credit* (rank 16).

For cluster III only one barrier is rated among the six most important: *2.3.1 utility monopoly of production, transmission, and distribution of electricity*. Nevertheless, this cluster is crucial as all barriers within are related to the clout of conventional power suppliers which is very powerful. Three other barriers with around medium importance form cluster III: *2.3.3 lock-in dilemma* (rank 14), *4.2.3 strong fossil fuel lobby* (rank 18), and *2.3.4 fossil fuel subsidies and fuel surcharge* (rank 23). All listed barriers in this cluster show an exceptional high variance as they are very low ranked by utilities and very high by other stakeholders.

Finally, it can be concluded that political and economic barriers are the most important ones to implementing renewable energies on Caribbean islands. Barriers from technical or social categories are mainly important in so far as they hinge on very crucial economic and political barriers.

What strategies have to be pursued to overcome these barriers?

The solutions for overcoming the most important barriers were based on the three identified clusters as described in Subsec. 6.5.2. The most urgent solutions are to introduce regulatory frameworks, to support policies, and incentives favoring renewable energies, and to enable financing. These measurements need to be applied differently for the potential investors or operators which are utilities, private companies, and private persons.

A quota model can be used as a regulatory framework to force utilities to implement a certain share of renewable capacities. This should be supported by a renewable fuel surcharge which is an instrument for setting economic incentives to generate power by renewable resources instead of burning fossil fuels. Such a renewable fuel surcharge would strengthen the current tariff system in most of the Caribbean islands where the fossil fuel surcharge disincentivizes the implementation of renewable energies. Additionally loans with low interest rates need to be available for utilities by international development banks.

For private companies it is most crucial to have an open and / or liberalized market in order to be able to enter the power generation sector to sell renewable energy. Standardized power purchase agreements can promote the private sector activities. Such regulatory standards would reduce transaction costs and decrease the risks of investments. Within these standardized contracts a transparent methodology should be suggested to calculate competitive feed-in tariffs for independent power producers. A decrease in import taxes for renewable technologies can further support their introduction. Low cost loans by international or local banks could be backed up by local governments which would solve the financing gap for private companies. In addition, a secure investment framework could increase the equity share reducing the financing needs.

The third group - private persons - needs also assistance in overcoming their specific barriers to implementing renewable energies. A regulatory framework to connect private renewable power plants to the central grid is required. In addition, net-billing schemes with attractive feed-in tariffs should be implemented to guarantee secure paybacks. Tax reductions could be set as further incentive to reduce the high initial costs of renewable energy technologies. Local banks should provide special loans and attractive net-billing schemes can attract more private capital for sustainable investments.

As a result of the previous analyses proper solutions to overcome barriers can be recommended. Focusing on regulatory frameworks and secure payback or feed-in schemes would accelerate the implementation of renewable energies on Caribbean islands.

Summary

To summarize the main findings of this thesis it can be stated that both hypotheses are confirmed. Firstly, a huge untapped techno-economic potential of renewable energies exists on Caribbean islands. To prove this an island energy supply system model was developed and applied with realistic economic, technical, and resource input data. The results demonstrate that it would be economically feasible to increase the renewable share from one to 45 percent, but implementation of renewable capacities continues to lag behind. Secondly, different technical, economic, political, and social barriers stands in the way of exploiting this potential, which was validated by empirical research. Caribbean renewable energy experts corroborated this correlation and helped to rank identified barriers according to their importance. Solutions, which were based on this ranking, should enable the Caribbean decision makers to increase the number of renewable energy power plants on Caribbean islands. It is strongly recommended that the stakeholders of the power generation sector on Caribbean islands work together to implement the suggested solutions and measurements. The entire local economy would profit from the introduction of further renewable power plants because this would significantly reduce the LCOE on almost all of the analyzed islands.

7.2 Research recommendations

This thesis has given a detailed view of the techno-economic potential for renewable energies on Caribbean islands. Furthermore barriers blocking this potential were identified and solutions were derived for overcoming them. Acknowledged scientific literature and methodologies were used in formulating practical recommendations. Nevertheless, there were some limitations to the energy system simulation and the empirical analysis which are discussed in Sec. 5.4 and in Subsec. 6.4.4. Based on these previous considerations and on the overall results of this thesis future research needs are outlined in this section. The section starts with research recommendations regarding the assessment of the techno-economic potential and ends with recommendations for improving the empirical research into barriers and solutions to implementing renewable energies on Caribbean islands.

Modeling and simulation of island energy supply systems on Caribbean islands

The conducted simulations and optimizations can be seen as a pre-feasibility study for implementing renewable power plants on the analyzed islands. For further studies the level of detail could be increased in three exemplary ways.

Firstly, renewable resources should be studied further. For hydropower the detected gross hydropower potential could serve as baseline for further deployment of hydropower plants. Although not part of this thesis it would be worthwhile to consider researching larger islands such as Hispaniola (HTI01 and DOM01) and Puerto Rico (PRI01). The use of biomass as a renewable resource could be included in future island energy supply models as well.

Secondly, it would be interesting to allow more electrical nodes within the energy supply system model. This enables the analysis of different power plant locations to reveal balancing effects as well as grid connection costs on larger islands. Furthermore the interconnection of single islands could be investigated with multi-node models to understand the technical and economic benefits of such interconnections.

Thirdly, the capability of the simulation model could be increased to provide a more detailed technical and electrical analysis of island energy supply systems. One step was already performed by developing the 1min Matlab model (cf. Subsec. 5.1.1) which can be applied for specific islands now. Another step is to include voltage and frequency into the model instead of just looking at the energy flows. By this step the grid infrastructure and frequency behavior could be studied as it is allowed by tools such as PowerFactory.

To summarize the improvements for techno-economic feasibility studies of single island energy supply systems should consider more resource options, different locations of power plants, and potential interconnection between islands. Additionally the grid infrastructure, the equipment, and the capability of integrating high shares of renewable energies need to be assessed before the simulated results can be implemented in reality. The pathways of implementation can be studied more specifically as well as performed by Plessmann [164].

Empirical research on barriers and solutions to implementing renewable energies on Caribbean islands

To improve the empirical results of this thesis more specific data could be collected and / or different methodologies could be applied. As recommendation the following three aspects could be targeted.

Firstly, more renewable experts could be asked to gain more insights on barriers and solutions. This specifically makes sense if the research objective is narrowed to single islands or island clusters in the Caribbean. Then more local barriers could be elaborated and the respective solutions fit better to the local circumstances. This could be supported by increasing the number of case studies as well.

Secondly, when more detailed solutions are available, the focus can be changed to more concrete implementation plans. Detailed practical recommendations need to be formulated with the help of political and legal experts. Additionally further research is needed in tariff schemes for power purchase agreements or net-billing systems. These tariffs need to be developed in collaborations with local and international experts using methodologies similar to Blechinger et al. [224].

Thirdly, inclusion of the identified barriers into the techno-economic energy supply model could allow for a more specific calculation of the potential of renewable energies on Caribbean islands. Besides the further integration of technical and economic constraints, political and social aspects could be considered in such a combined model as well. One example for combined socio-techno-economic modeling can be found within a research project of IZT and University of Flensburg [235].

In conclusion, it is important to derive more and more specific solutions for the identified barriers. More detailed data would allow more specific solutions and enable a clear implementation plan. The identified barriers should be considered on an early stage of techno-economic pre-feasibility studies already.

Final statement

This thesis reveals that a huge techno-economic potential for implementing renewable energies on Caribbean islands exist. Renewable power plants could help both to reduce power generation costs and CO_2 emissions in the Caribbean. However, a high variety of technical, economic, political, and social barriers hinders the implementation of sustainable power generation technologies. Among them the most important are missing regulatory frameworks and policies as well as high costs and difficult financing conditions. In addition, the clout of conventional power suppliers slows down the transition towards renewable energies.

In this last section different future research recommendations were given to improve and confirm the derived results and solutions. Despite the fact that methodologies could be improved this research demonstrates the urgency to start implementing the suggested solutions and measurements as soon as possible. These measurements, summarized in the strategy roadmap in Fig. 6.11, will definitely improve the framework conditions for implementing renewable energies on Caribbean islands. The faster the share of renewable energies is increased the more fossil fuel based expenditures and CO_2 emissions are saved. Thus, implementation of these recommendations should not wait for future research. Immediate action is not only possible but it is urgently needed to transition the Caribbean islands to a more economically and ecologically sustainable future.

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One love!

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Appendix A

Appendix - Interviews

A.1 Interview guide

I. Introduction

Introduction of research project and researchers.

Ask for permission to record.

Ask for permission to quote the interviewed person.

II. Personal Experience

Could you briefly introduce yourself?

Could you tell us about your professional background of the last ten years of working within the energy sector in the Caribbean?

Specifically, what is your work experience within the RE sector in the Caribbean?

What were the most exciting projects?

Which problems did you encounter at each project?

Which were the biggest problems (political, economic, social?)

Which were the enabling factors (to these projects)?

What lessons have you learned?

What are the responsibilities of your current position?

How does your current position relate to the advancement of RE in the Caribbean?

if yes:

What is your vision for RE in the Caribbean?

What is your strategy for the implementation of RE throughout the region?

III. Barriers

What do you think are the main barriers to the development of RE in the Caribbean?

In which area do you see the biggest potential for improvement in the next years?

How do you evaluate current efforts to remove the barriers to RE?

With who do you think lies the responsibility for the advancement of RE?

How realistic do you think is the 47 % RE share in electricity production by 2027 set by the CARICOM members? (What are the most urgent areas in need of change in order to achieve that goal?)

general exploration:

How do you think natural conditions in the Caribbean inhibit the implementation of RE (e.g. with regards to land and resource availability, potential negative environmental impacts of some RE or natural disasters)?

specific exploration:

How do you think land and resource characteristics of Caribbean islands inhibit the implementation of RE?

How important do you consider the potential negative environmental impact of some RE technologies? (e.g. risk of toxic spills and deforestation from geo-thermal, disturbance of migratory birds and noise pollution from off-shore wind parks)

How about the impact of natural disasters?

general exploration:

What do you consider the main barriers relating to technical aspects of RE implementation in the Caribbean (e.g. systemic and individual)?

specific exploration:

What are the biggest efficiency constraints? (i.e. low efficiency of RE requiring more spatial expansion)

How do existing island energy systems inhibit a higher RE share? (think of supply chains, grid stability and structure, transmission capacity)

What are the consequences of the non-existence of local RET manufacturers?

special question to CARILEC: Do the utilities or regulators set a cap on the maximum electricity production by RE? (If so, why and what are the implications for the development of RE?)

general exploration:

What do you think are the main economic hurdles to the implementation of RE?

specific exploration:

Can you tell us specifically about the effects of prices and investment costs on the implementation of RE?

In what ways are international funding institutions enabling the implementation of RE?

What are the problems that arise from the involvement of international institutions?

What do you think are the challenges that investors face when financing RE projects?

Can you tell us about the role of electricity utilities in national markets and developing grid infrastructure for RE, for instance?

Can you tell us about the role of current (fossil based) institutions and technology with regards to the widespread application of RE?

What do you think of fossil fuel subsidies and the fuel surcharge with regards to sustainable development in the Caribbean?

general exploration:

How does national and/or regional policy relate to the development of RE?

Can you give an assessment of the institutional capacity of regional and national authorities to advance RE?

What is your opinion on the existing legal framework for regulating and stimulating RE development?

specific exploration:

What is your personal assessment with regards to the success of the implementation of RE policies?

In what ways you think current policy prioritises the conventional, FF based system over RE?

How do you assess the role of ministries and specialised institutions that ought to implement RE in the Caribbean?

How is the private sector currently involved in the electricity production from RE? (think of self-consumption, investment, net-metering etc. - how could this be incentivised further?)

general exploration:

What role do you think social norms and consumer awareness play in the development of alternative energy production systems?

In what ways do you think social innovation networks or individuals are currently preventing the development of RE?

specific exploration:

How important do you consider social capital in the promotion of RE in the Caribbean?

In what ways do you think is the success or lack of success of RE tied to the existence of local entrepreneurs/champions?

Which do you consider more important for the successful implementation of RE - local entrepreneurs or the external regulatory framework of the business environment?

How do you think the success of a RE project relates to a sense of ownership over the project? (i.e. is there a perceived loss of control over externally funded projects, and if so, what are the consequences?)

In what ways do negative experiences in the past affect the development of RE?

Ad-hoc Questions

How could these barriers be removed?

Have recent attempts to remove these barriers been successful?

How could this be incentivised further?

What were specific problems? etc.

IV. Finish

Is there anything you would like to add?

Who do you think we should talk to/consult for our next step, the questionnaire with the weighting of the barriers? Who are the experts in this region?

Would you like to receive a transcribed version of this interview within the following week?

THANK YOU!

A.2 Interview transcriptions

A.2.1 Executive Director CARILEC

Participants:

Allison A. Jean [AJ]
Executive Director, CARILEC

Philipp Blechinger [PB]
Doctoral Candidate, TU Berlin
Researcher, Reiner Lemoine Institut

Katharina Richter [KR]
Research Assistant, Reiner Lemoine Institut

Date: 17. February 2014

Length: 58 minutes

Interview

[PB] Thank you very much for taking your time to participate in this interview. Could you briefly introduce yourself?

[AJ] I have been with the CARILEC since August 2013, as the Executive Director. Before that, I was Permanent Secretary at the Ministry of Infrastructure, Port Services and Transport in St. Lucia. So I can report from the policy, not so much from the implementation side. You can say that I am now in the learning stages of the practical side of RE. I can present to you the government side and the CARILEC side.

[PB] Specifically, what is your work experience within the RE sector in the Caribbean? And what were the most exciting projects?

[AJ] I have been with two projects - one wind farm and one geothermal exploration in St. Lucia.

[PB] For the wind farm - did the development take place?

[AJ] No, it didn't.

[PB] What were the barriers, or the reasons for why the project didn't take off?

[AJ] For the wind farm, it was the case that the land was just too expensive. It was private land and it was very expensive because it was in competition with tourism. The planners didn't know if they should buy up the surrounding land, but we could not have built a wind turbine. So there was a land use conflict, because there was a lack of appropriate land use planning. The biggest factor was the lack of agreement between stakeholders.

[PB] And for the geothermal project?

[AJ] As you may know, St. Lucia harbors a volcano, so they were exploring the potential of deriving energy from these volcanic activities. The costs for this exploration were very high, and another barrier was the absence of an IPP. The utility had a monopoly and so it would not have been possible to feed the energy into the grid.

[PB] What other barriers were there?

[AJ] Overall barriers to RE are the absence of legislation and regulation, very clear. Also, the lack of funding I presume are other barriers. Especially for geothermal, the exploration costs are very high and developers need funding for that.

[PB] So there is a lack of regulation and legislation that impedes RE development. Do you think the utilities on these islands promote or rather hinder RE?

[AJ] CARILEC assists members to promote RE. Utilities are in promotion of RE, but there are different levels of development for different states

[PB] Okay. So we'll proceed to the economic barriers then, before we come to the social and political side of the issue.

[KR] What do you think are the main challenges that investors face when financing RE projects?

[AJ] The critical mass to demand and implement effective projects is not yet there. The Caribbean consists of small islands and small populations. Furthermore, there is an absence of available financing, and a significant lack of private capital to invest in RE project. There are uncertainties when it comes to financing, too, and a lack of experience.

[KR] So apart from the general lack of capital, would you say that the access to such capital is of equal importance? Or would you say that commercial, as well as public banks are quite willing to finance RE projects as it is right now?

[AJ] The lack of access to capital is a more important barrier than its availability. The access to funding is a major barrier. There is only one commercial bank in the Caribbean to give out loans, that is First Caribbean. So it is mainly the access to capital at the moment, that inhibits RE projects.

[KR] Why do you think commercial banks are so reluctant to fund these projects?

[AJ] I would say it is a lack of awareness, and also mostly a lack of knowledge about the benefits of these projects.

[KR] So moving on to the political side - you have already talked about the lack of regulation and legislation. We have been hearing about the Eastern Caribbean Energy Regulatory Authority. We would like to know how you asses the role and the future potential for this authority to push forward RE?

[AJ] The ECERA has great potentials, despite only St. Lucia and Grenada being on board. Some states have independent regulators, some have state regulators, but a unification of the system is absolutely necessary to promote and implement RE. This is the way forward, everyone must agree on a tariff, so better regulation is possible and so that we can bring down our high electricity prices.

[KR] So in the light of the high expectation you have for ECERA, the increase of regional cooperation within the Caribbean in terms of stakeholder networks, in terms of technical cooperation and in terms of regulation is the way forward?

[AJ] Yes, definitely.

[PB] What do you think about the role of national interest? Or how do you explain that there are only two countries participating at the moment?

[AJ] I think many countries are pursuing a wait and see policy, so once the project takes off, we will have more countries joining.

[KR] And you think that the tariff-setting is something that the member states would willingly hand over to a higher, regional authority.

[AJ] Yes, I believe they would have to do so.

[KR] You have been talking about a wind farm project in St. Lucia, where you said that one of the reasons why this project didn't take off was a lack of agreement between the stakeholders. So what role do you think the very static, fossil fuel based stakeholder network we have at the moment plays in maintaining the fossil fuel based system as it is right now?

[AJ] Not much. No, I don't think this plays a role, not in the Caribbean.

[KR] So you also wouldn't say that because of the presence of a strong fossil fuel stakeholder network, RE can't take off?

[AJ] No, not in the Caribbean.

[KR] To go the other way and again coming back to the fact that there is a lack of agreement, and that projects don't take off, how do you assess the role of a local or regional champion, or entrepreneur, in promoting RE?

[AJ] Yes, a local champion would definitely be needed to show and demonstrate that RE projects are viable and necessary, so that would greatly help.

[PB] Could you tell us a bit about the technical barriers to the development of RE?

[AJ] Unfortunately, I cannot talk about this aspect. I am not the one to talk to about the technical side.

[KR] In what ways does current policy prioritize the conventional, fossil fuel based system over RE?

[AJ I don't think that the one is prioritized over the other. Every country has policies for RE in place, as well as strategy and targets, so I don't think you can say that the conventional system is being prioritized over the RE system. It is not the case.

[KR] In the context of existing policies then, how do you assess the role of ministries and specialized institutions in promoting RE in the Caribbean?

[AJ] The ministries are very knowledgeable, and very resourceful for the implementation of RE. The only barrier I see there is that they should have more consultations with the service providers and major stakeholders, to guarantee that everyone can come to an agreement. There should be more dialogue in the form of consultations, so that everyone knows about the policies.

[PB] What role do you think corruption plays in maintaining the fossil fuel system?

[AJ] I cannot comment on that.

[KR] Something we have come across in our literature review, and in other interviews is that sometimes the utilities or regulators set a cap on the amount of energy that is allowed to be produced from RE. Can you tell us something about this?

[AJ] I don't think we can talk of a cap. Every state has targets, there are RE targets that the states work towards, so we cannot talk of a cap on RE production, the cap is not the problem. All islands have targets that they must achieve.

[KR] To quickly come back to the social aspects of RE, and especially with regards to consumers in the Caribbean - how do you think people are prepared for RE? Is this something they willingly accept?

[AJ] I have to say that most people don't care where their energy comes from, people just want cheap electricity. And there is the possibility to produce electricity cheaper with RE, so that is an opportunity. And so yes, people are prepared for RE in a way.

[PB] Would you say that this concern with energy is mainly environmental, or mostly about the price?

[AJ] The concern is mostly with price, I have to say.

[KR] Is there any negative experience in the past that might affect the present development?

[AJ] No, I don't think so.

[PB] So we talked about all the barriers from our side, is there anything you would like to add? And how do you think these barriers can be overcome?

[AJ] What I have to say is that there is a significant multi-lateral agency interest in developing RE in the Caribbean. There are a lot of organizations, a lot of public banks, like the African or Asian Development Banks that all want to push forward RE in the Caribbean. However, for a consolidation of all projects, and to identify the limits of the specific countries when it comes to RE, all of this money and effort should go into project implementation. There is too much paper work done, and there exists too much documentation, to the point that there is a duplication of efforts. What we really need are pilot projects to attract more investors, and to finally implement projects.

[KR] Would you say that relates to a somewhat heavy reliance on donor money for RE projects in the past? That then leads to a lack of RE initiatives?

[AJ] Yes, I would think so.

[PB] So maybe we can talk about targets, to conclude this interview. Which role do you see the CARILEC plays in achieving these targets?

[AJ] Well let me say that the CARILEC is a non-profit, private organization. We are not a public organization, and we are member based. Our members are being prepared for RE, but there is also support on the individual utility basis. However, some of them operate below profit, and there is no linear implementation for every country. The goals for the future must include country by country roadmaps to RE. To find out - what are the gaps, and how to address these gaps, so that assistance can be given to countries in implementing RE. An effort there has been made in the Renewable Energy and Energy Efficiency Technical Assistance project REETA, and we must continue with this to push forward RE.

[PB] Thank you so much for these interesting insights.

A.2.2 Programme Manager CARICOM Energy Desk

Participants:

Joseph Williams [JW]
Programme Manager, Energy Programme CARICOM

Philipp Blechinger [PB]
Doctoral Candidate, TU Berlin
Researcher, Reiner Lemoine Institut

Katharina Richter [KR]
Research Assistant, Reiner Lemoine Institut

Date: 27. January 2014

Length: 1h 16 min

Interview

[PB] We are very glad you are sharing your experience with us. Could you briefly introduce yourself and your current activities, especially you involvement with RE?

[JW] I have been working with the programme for five, six years now, the CARICOM Energy Programme. And of course, there are challenges for our countries, mostly in terms of renewables and energy efficiency. The programme covers all aspects of renewable capacity energy matters in the CARICOM region. So my thrust is energy, and obviously energy is a really big area of opportunity for our country, so it has to be the focus. In that context, energy policy also plays a role. My background is that I am a mechanical engineer so I spent time in the industry in Jamaica. I was working in a water utility, in a manufactory, and then I got to the electric utility. I spent some time in the electric utility, on the demand side management programme, and I later managed the renewable energy post and energy efficiency matters for about six years. So for ten years I have been in energy management in the region. What else. I have also done occasional work at the embassy; I did energy policy and planning, and writing.

[PB] That's a huge record. Have you been involved with the Wigton wind farm in Jamaica?

[JW] Indirectly. I was with the utility, I had to review submissions, and we were also negotiating pricing for the project.

[PB] Could you tell us about the most exciting projects you have been involved with, in terms to RE? And, what were the major barriers for implementing renewables during these projects?

[JW] Let me think. The most exciting projects. I have not been involved with a lot of implementation, I have been mostly on the project preparation on the side of the institutions.

[PB] This is also interesting for us. Let's also see the preparation process, or the policy process.

[JW] I think that there is extensive involvement at the CARICOM secretariat. I was involved in the early stages of the CREDP. I had to manage a CREDP project with the UNDP controlling the credit of the project in the final stages. The most interesting part about it involved finding projects that needed financing and technical assistance and facility. So that involved screening and assessing the projects that we would support. Then we also provided the technical assistance support. It was interesting because it gave me a good sense about projects of this kind, and it led to an understanding of some of the issues for developing this project.

[PB] What have been the criteria you have applied to assess these projects?

[JW] First, we established the expenses and what the objectives were for this project. That was an assessment of the potential feasibility of the project, and the potential for capacity and implementation. We looked at how likely this thing is to be implemented given all the constraints. We looked at the capacity and objectives of the project, but then we also had to look at some of the risks within the project, as well as the policy and regulatory framework within the country, as well as the attitude at the national level for supporting the development.

[PB] This is very interesting because I think this is what we could call the barriers. This is directly what you have been checking - what barriers do exists, or have been removed that make a project more or less feasible.

[JW] Let me say this. The CREDP project has been going because of the technical assistance. Overall, the CREDP project was overcoming certain barriers already, including finance, policy, capacity. What we tried was to get some projects to the point where they could be bankable, which means get some prefeasibility work done, to the point where it can be taken to get solid financing for the implementation. We were trying to get these bad projects bankable. So the basic premise or idea of getting these projects bankable was part of overcoming barriers because the idea is that we wanted to at least get some credits on the go, so that the region can see the benefits and so on. That's where we wanted to go. So initially, just being able to get a project financed was a barrier in and of itself because it allows for credit for demonstration effects that would hopefully attract developers further down the road. So the overall CREDP project was targeting barriers in and of itself, but it was this intervention within CREDP, where we really tried to at least get some finance, to get them bankable. So they at least become a catalyst. So that's the problem.

[PB] Now the question is, from your experience, what are the main barriers to get these projects to the status in which they are bankable?

[JW] Okay. There are some general barriers, and then there are some specific issues which are more permanent or more dominant in one territory than in another. The

Caribbean is not homogeneous. Different countries have different attitudes and different levels of development. Even if they are not, at the point of putting in place the support policy and regulatory framework, there are different levels of attitudes and so on. Even though I must also say over the last five years, some countries have made progress. Having said that, let's come back to the barriers. General barriers, I would say still persist as were defined in the context of CREDP. CREDP creates the first major RE development intervention in the region, and it's to overcome barriers in the area policy and regulation. Policy because regulator and legislator bind themselves to it. And then, financing, capacity and intervention rules. All of these barriers have made significant progress in the area of policy. Five countries have started some kind of draft policy of how to implement approved policy in terms of actually creating and enabling an environment. But a lot more needs to be done there. Jamaica and Barbados are possibly most advanced in terms of actually legislating and work on the ground. Other countries, Antigua, Bermuda, St. Vincent and the Grenadines, and a few others are making significant stride. But in terms of how to do interventions in the ground, and enabling to have barriers removed, even though they have documentation, the approval in some cases at the level of the parliament, the legislative changes that need to take place are a little bit slow. I think Barbados and Jamaica are possibly most advanced in terms of legislative changes in some of the areas. In terms of capacity, they have not had at significant advances. There is a significant challenge, because even at the level of the policy makers, there's a significant deficit in terms of being able to analyze and to understand some of the technology, and integrating some of this technology, the options of RE. There's a significant lack, a great lack at the level of the financing institutions. That is a huge barrier at that level. Because many projects are viable, financially and economically viable, but the financial institutions just lack any kind of knowledge and capacity to advance it. That is a huge barrier. Even when the projects don't require a support at the legislative level, because they can be permitted through an existing framework in some cultures, there is just no financing available, especially at the commercial level because of lack of capacity within those institutions, as well as awareness in terms of how to assess and appraise a lot of these projects. There is a huge amount of work to go over to the next levels. The issue of awareness has increased significantly in a general way. But especially in terms of understanding the benefits, the limitations, as well as some of the impacts at the national level. Projectary impacts in terms of potential interventions by governments in terms of fiscal measures. There is a lack of awareness there that is linked to lack of capacity of some of the policy-maker's understanding of what are the real benefits, the potential impacts and how some of these interventions can even be revenued in the future. They need to do things but they lack some of the awareness to then take some of the hard decisions that need to be taken.

[PB] Let's just ask some specific questions about this. Would you say the lack of capacity is within the ministries, for example that there are professionals or experts missing, or that they need more knowledge? This is what I understand from this.

And the second one, would you say that the institutions themselves are missing, or that there should be more specific ministries? Or let's say that the next step would be talking about a Caribbean energy regulatory authority? Is this something that would overcome an institutional barrier?

[JW] Yes, but the CARICOM level is another level. I'm just saying even within countries, within their own energy sector, the regulatory framework is very weak. So let me clarify that. Even as it stands now, in regulating the sector, before we even talk about RE, the framework is very weak. It is weak in terms of the specific knowledge and capacity. Knowledge as well as human resources that are necessary, is missing in a very big way. But when it comes to RE, there is no requirement to set up specific skills to understand the issues around various technologies and how we integrate those into the current systems. That is right when we're talking about issues of the feed-in, the different mechanism, the different instruments and how to manage those. There's the issue of performance based advice, which is sometimes very important in order to give the occurring level of benefits to the system and to the society. What renewable energy brings. That kind of analysis is sometimes not possible to be done because we don't have the technical capacity, within the government and the renewable sector. We speak generally, but even when we come to RE, the gap is even more stark because of the specific need for development.

[PB] So this is not only a lack in the government, but also for utilities and companies, you would say?

[JW] That's correct.

[PB] In what ways do you think current policy prioritises the conventional system, compared to the RE system? Is this a barrier too, or would you say the prioritisation is towards RE at the moment?

[JW] There is a lack of mission. But we have to move into a certain direction and improve and increase the contribution of RE. That recognition is expressed in draft policies or approved policy documents. But not by itself will that make it happen. The governments need to move to the next step. Which is really to change the legislation of those for the RE parks, the generation, especially as it relates to cities. So that is right up there. To answer the question specifically, even though there is a recognition that is expressed in different ways, there is still some ways to go in terms of actually changing the legislations to ensure that RE can participate in a fair setting. So I would say yes, the current policy in most countries still assumes and still has as a de facto position that it is the conventional form of energy which will form the backbone of the energy supply in a country. It does not provide sufficient priorities for the diversification for RE by far. There is a recognition, and now we are trying to move that process forward. But it is not fast enough for us recently.

[PB] This is similar to the experience we made in our current research. There are different steps, and first there's this mission and the policy, but policy is just stating targets without pushing the implementation, but then it needs the regulation to get these projects to a real status. There is still a lot of work to be done.

Let's move to different aspects of these barriers. We are also looking at the social side. You already said that the awareness is missing; also I would say human resources which might be a problem within the educational system. But the question is more general. What role do you think social norms and consumer awareness play in developing RE production systems?

[JW] I think it is critical because in the Caribbean, energy is a very political matter. Highly political. We are talking about sovereign states where energy is a big issue in these countries. So governments can win or lose elections depending on the price of energy. If for example, in a particular country, the electricity tariffs were to be adjusted close to elections, then that could be the difference between a government staying in office or a change. These are important details. I say political because most of the countries are dependent on imports, and so a lot of the energy security to the extent that they can call it that comes from political arrangements with those states. So energy is political. Having said that, it means that to the extent that the populous, the general citizen, have an appreciation or make demands for a certain transition, for certain changes, the political electorate can't move in that direction. The populous is very price sensitive. As you know, us Caribbean citizens, we are among the world's highest electricity tariffs. So businesses, their competitiveness, it's affecting everything of it. If it were possible to begin to educate the consumers, or the consuming public, the general citizens, so that they can begin to make the kinds of demands for the transition, then that could be a source, a big source for the change and transition that needs to happen. So that is one reason. Let me just elaborate about education. One, it has to be able to help to appreciate the long-term benefits, even if we could ignore investment, frankly, if we can have people to appreciate life cycle cost, to understand what is level source cost, that in the long-run, they will be better off. To point out the importance of issues that are not so critical to them, but are important for us to encourage change and the link between energy systems. Then more and more people would make the choice, then when more and more people demand a choice we will have critical mass that would make a demand politically, for the change, for the politicians, for the political electorate to do the right thing and to implement the policy. So that is one level. The other level has to do with business opportunities. There is significant opportunities for small business, for the household sector and so on, and they can identify the benefits of clean energy in the context of the global movement towards RE, that more opportunities are coming up along with it, then more forces would seek to find themselves into organization, push the ropes to make demands for the changes that are necessary to enable a business environment market that is more supportive of RE. The third is that ultimately, governments do not have the funds to support even in the context of subsidy the introduction as well as the market for RE. So the market has to be brought to a point where it functions, where there's an equated supply and demand and activities for a market to function. For that to happen, it means awareness of the opportunities.

It means awareness in terms of the technology and of the issue, awareness in terms of pricing, in terms of marketing. So you need to increase awareness across board so that people can see the opportunities and begin to see a business opportunity, opportunities for enterprise and entrepreneurship in this area so that the market can develop. So awareness has to come from different levels. But we already mentioned in terms of the institutions and the human resources, we have said that. But on the side of citizenry, it has to come from different levels because we need opportunities that will the market work.

[PB] Would you say that investment conditions right now are favorable for entrepreneurs? Would they be able to start a renewable business?

[JW] Definitely not as favorable as it ought to be. There are arising opportunities because prices have come down significantly but regardless of whether or not some of the environmental law for integration of RE into the grid, regardless of that. But it is not sufficiently attractive for investment until we have the kind of legislative and regulatory framework in place that can allow businesses to have a fair price for their generation, and clear access to the grid so that they can benefit from sale of generation of energy.

[PB] Just one remaining question about the social barriers. Do you think people are prepared for the change already, or do you think they prefer the current status? Sometimes people are just kind of scared in this transition process. Do you see this as a barrier?

[JW] Well, are people prepared? I think this is a process, and I moved along the process, and now I can say that people are far more prepared than five years ago, far more. The big trouble has been a lack of affordability, or the cost. And the recognition that we are vulnerable because of our over-dependence on imports, and as a result, of any move in prices. Those are the drivers as to why they are more prepared for the transition. Having said that, the most of the populations in most of the territories are very price sensitive. They hesitate. Even if they think that in the long-term it would be better for them. But they are hesitant to pay anymore for energy today, even though it might be better for them in a very short term. So in that regard, they prefer to stay with the conventional power because in the short-term it would represent a lower cost for them. So yes, there is a lot more preparedness and awareness in a part of the populous, and I can give you a little sense of that. But no if it means paying any more immediately, they would rather stay with the conventional system. That is general the case for across the region.

[PB] Do you think that local initiatives promoting RE have increased in the last few years because of an increased RE demand? Also with regards to initiatives setting up networks, talking to each other and trying to push it.

[JW] Definitely, there is no question about that. Regionally, we have done a number of things to help that process. For example, we have what is known as a CARICOM energy week. That is a programme week in November, in that we seek to mobilise the CARICOM member states, we try to support various member states in their own effort because it celebrated a series of concurring national energy weeks. So yes, there is significant efforts there. Yes a number of cases we've had where persons have shown that it has been very beneficial and that has been very helpful. At the CARICOM level we are doing pilot demonstration projects especially in the context of government.building and production. So yes, it's come a long way, yes it's playing a significant role, yes in terms of strategy, but it is also a market place for a significant strategy changing market perceptions and creating the critical demand. We need to find some empirical approach which would then progress over time to create regional energy awareness, looking at the different dimensions of the sector. Awareness is changing over time, and that is important in the market in terms of demand. There is some more work to do, especially at the regional level.

[PB] We hope to support your work with our research. That you can really see what is going to happen, which barriers are already kind of removed, and which ones are the most critical to target next.

[JW] Yes. That is important for our strategies. Our strategies need to be evidence based.

[PB] Let's go back to the financial aspects on the market perspective. I have asked you about local entrepreneurs and if they would be able to start to create their businesses and you have said definitely no. So let's get a more detailed look on this.

[JW] Let me clarify. In some territories, especially in Jamaica and Barbados, they have made progress in terms of their legislative and regulative frameworks. Quite a bit of small businesses are there, especially in solar and micro mini-grid. Solar hot water is generally moving forward, too, by itself, because that generally doesn't require grid feed-in. But generally, speaking, the answer to the question is no. We don't have an environment that encourages small businesses to take up things and generally, this is not taking up as permanently as we would wish. We have some progress now that there is significant movement in terms of the difference in price for some of the technologies over the past five years. That has been a topic impetus, the uptake of small businesses.

[PB] Then let's look at the more large-scale businesses, and at the utilities. I mean they would have the ability to move towards RE, but it is happening very slow. What do you think of barriers at the utility scale, looking at the energy and electricity markets?

[JW] Well utilities fall under three categories. There's government owned utilities. Then you have the partially government owned and partially private utilities. Then there is almost totally private utilities. So let us categorize these two areas. The government and private. In the case of the government, by and large, governments need to agree to go into the same direction. Where the government is the owner, they recognize that some of the interventions require incentives. There is a lack of understanding of input of such incentives, or the need for such incentives or an incentives framework, and the revenue stream for the utility and their overall budget. Because some of them have to support the utilities for their budget and do budget transfers. So for the public utilities, for the government owned utilities, it's a little bit a lack of awareness, a little bit of lack of information. This is particularly staff in the areas where they have really elaborated premises. They need more information to move to the next level. They need more capacity and help to move to the next level, right. It's really capacity and information and so on. And then when we look at the private utilities. They have no real incentives because they have a license which guarantees them a certain market, and they are competitive doing their businesses because most of the fuel cost is passed on to the customer. In most countries, all of the fuel cost is passed on to the customer. When fuel prices go up, the consumers will complain, but the utility is not really going to be affected by that. So they really need a reform in their own regulatory framework. But also, it is my view that the level should be such that the utilities can really share in the cost so that not only the consumers have to share the burden of the fuel cost. The utility is the single biggest player in this sector, as an entity, they need to share in that, that is my view. But that is not articulated in policy. But I think we need to incentivise that, in terms of some the changes that need to take place. Then of course, there's the issue that governments are also very cautious about tempering with the sacred contracts they have with the utilities, that it may send a signal to the investment bank that the government will not risk a contract. So the utilities use that to their advantage, because obviously these are small island states which depend a lot on the international market when it comes to investments, and they don't want to give the impression to their donor that they risk a contract. There is a need for us for us simply to bring all the parties to the table and to negotiate an approach recognising that the model we are using at the moment is not sustainable. To the extent that the customers are vulnerable and they will complain and blame the utilities that their business is not a market place. They need to recognise that it is in their interest to change the demand for a more diversified portfolio that allows for RE.

[PB] So two questions about this. Do you think that the whole production process of the conventional energy system, including transport of fuel and distribution of fuel, is also affecting the transformation of the energy system?

[JW] Two ways. This is probably a part of the answer which I have given before. And it really relates to vested interests. The players who should be pushing for the change actually have vested interests in the overall situation as it stands. For example, in some cases governments derive significant taxes revenue from the importation of fuel. And so that can be a challenge and a barrier to RE. Not in every territory, but it can be. Now to the costs and specifically for the supply chain arrangement, as it relates to conventional. I think that this is a big factor too. The fact is that a lot of the key players have a vested interest and a lack of incentive to change the current system. If you take utilities, there is a real issue of loss of revenue, and loss of business. And for that discussion to be going forward, it would need to take that into consideration without avoiding the transformation or change, but one that allows for the business structures and the business model to get involved in the market themselves. I have articulated at a personal level, but as for the government transition, the approach would be to establish certain caps and allow the market to respond to that, rather than necessarily trying to open up. For example, we could say in a particular territory, ten percent of the portfolio should be supplied by RE, and x percent should come from small distributed generators, and so much from IPPs. That would allow a framework for the utilities to see how it affects their business, how they could participate, and then depending on the framework as well how they could be moving forward. Because the territories are small, because governments don't have the money to invest, they don't want to scared private investors. But at the same time you need to get them to get to participate and be supportive of the change.

[PB] Do you think this could be done with the national authorities, or do you need this Eastern Caribbean Regulatory Authority for this? Maybe the national authorities are too much involved with the current system. Do you think it would be easier if it was on a sub-national level, like on a CARICOM level to push this?

[JW] No, I don't think approaching from a regional level, certainly from the regulatory side, would seem feasible and approachable. The regional approach is important because it lends itself to a significant amount of sharing. It lends itself to addressing some of the capacity issues and so on, because you really need a specialist for these areas and most of the countries don't have the capacity for an adequate regulatory framework. So it will be useful to understand that. But because of the political nature of energy, because no country will put themselves at a disclosure of the decision of their tariffs and so on, it has to be convinced at the national level. And then there are some dimensions, certain terms of the procurement, and certain issues in terms of the performance dimensions of the regulatory framework that can be done at the regional level. But certainly when it comes to tariff-setting and some of the other issues they will remain at a national level. So that's why response is that it is not feasible to divest to the regional level at this stage based on the level of the political arrangement now, and the implementation constraints for CARICOM. In other words, CARICOM is not like the EU. To compare issues directly, it is an association of sovereign states. So even when it makes decisions, a lot is still left to the discretion of the national governments. Even though there are moves now to change that, we are still not anywhere near where the EU is and because of that, because of the political nature of tariff-setting, I don't think it is feasible to divest the total regulatory support, regulatory action and interventions to a regional level. Even though it may be possible to do some of it at a regional level. There are some opportunities for inter-state developments, but that is to trade in energy and so on. That is where regional and sub-regional regulatory framework is imperative.

[PB] Let's also look at the financial aspects and the economics of RE. We have learned also from you that the costs of RE are significantly dropping. But you still have this high initial cost, compared to conventional systems. What do you think are the main financial barriers for implementing RE?

[JW] We touched upon them already. There are funds around in the banks, right, there are funds. The banks are not short of funds. But certainly at the lowest level, the commercial banks, there is a significant lack of awareness, and as such a significant risk aversion to support anything RE and even energy efficiency, because they are both unknown land. That is a huge barrier. Because in some cases projects are viable, financially, but the banks won't touch them. That is what I would say a large one. The second one is that the policy framework is also a factor. To the extent that you have the kind of legislative framework that would allow for grid-feeding or would allow a developer to have a price for his sale of his RE output and to earn some guaranteed access to the grid, and to allow him to enter some kind of PPA with the utility, in one case, or in other cases to have some collective standard mechanism that allows him to feed in. To say he could have those in hand, then that would form a basis with which to negotiate with the bank. The absence of that makes it difficult in terms of secure financing. So I'm saying that one, banks, and generally financing institutions, not just the commercial banks, financing institutions lack the capacity and awareness, and that's a big barrier, a huge one. But even where it could be demonstrated, that a project, even if it is seen as a low-risk, that it has the necessary instruments and the necessary guarantees for revenue streams and so on, even if it was possible to secure those, it may not be possible for some banks to consider, even notwithstanding their risk aversion. Because of the lack of those things, banks won't even look in that direction. So it's a combination I think, of the awareness issue and lack of capacity, but also the policy and the legislative framework also overlaps. The lack of adequate policy and legislative framework also overlaps and disincentives and discouraged financial institutions from considering those interventions. Obviously there are other issues. There needs to be more demonstration, and again, that would come to awareness. If you had more demonstration, then the banks could look and see that some of the works and understand it, but to require soft financing, we don't have enough development for that.

[PB] Another question is if there is enough financing available anyway? If there was a regulatory framework to secure a risk-free investment, or more or less risk-free, would there be enough financing available?

[JW] Particularly with those kind of financing, no, I'd say no. And I'll tell you why too. A lot of that comes to the region as concessionary development financing. Largely by studies, in some cases it is not even early stage development, so this is more the usual assessment here and there. What is needed is more financing that is geared towards buying down the cost of putting hardware on the ground. So that we would have more tangible demonstration and pilots, in some areas there would be pilots, to understand the integration issues, to physically demonstrate the benefits and to show that some of the things are sustainable. So the financing is lacking from that point because no study partners will provide a place to do that. Very few of them.

[PB] This financing which would come, do you think that it fits for RE? As we said, we need long-term financing, and also the interest rates very much affect the viability of the project.

[JW] The government has nothing to do with it really. The financing we need to differ for some technologies, for example geo-thermal, hydro power, there is a different kind of scale. Overall for cases of small, decentralised RE generation that is where I think a lot of work needs to be done by the commercial banks, properties and so on. That is where the big market is. But the bigger intervention, the bigger projects that come at a larger scale, there is a big gap because for those, with regards to financing by commercial banks, we need significant resources, especially for the feasibility study side. We need significant more rules for those interventions. Especially we will need to look at interconnection and so on. There is a significant lack. But over the last year there has been significant development, there has been a significant infrastructure boom that has been established with the support of the EU, and there has been a lot of investment bankers come forward with investments which got in funding to support some of these investments. But again a big part of the challenge at this place into the access to some of these criteria and the requirements in terms of security that potential developers would have to put up and would have to meet. That is a serious disincentive again. Some of the requirements really require some of these developers and these projects to have very good balance sheets and credit rating and this is a big issue. Even with the utilities. Some of the utilities which would like to invest in some of these do have challenges in terms of their credit rating and their ability to access financing based on their balance sheet. That is one barrier in itself. The availability of appropriate financing, especially with regards to some of these new innovative infrastructure projects. The criteria and the requirements still reflect a lack of awareness, which is a nature of the risk aversion. Importantly, there is a huge lack in terms of some of the smaller development banks, national development banks and the commercial banks in confidence which could finance viable projects. But because this is risky, even though the projects have good economic and financial profiles.

[PB] Speaking about economics, for a long time the main issue that hindered RE development was that it was simply too expensive. What do you think right now are the barriers in the Caribbean, with regards to price and cost?

[JW] There is definitely technology adoptions. For solar PV, the costs have come down significantly so they are very feasible for smaller systems, for smaller generators, or even for great scale plants to be installable, so the price rate is up, very feasible. The big barrier there comes back to the policy. The greater interconnection policies would access prices as well as the issue of price. So access plus price. It needs a lower price for you to go invest and for you to take the risk and get back revenues. There could be an issue when it comes to the large-scale projects in some of the territories, but that's mainly with wind. So those prices have come down significantly and a lot of them are very feasible where the resources are available. For other technologies like geothermal only have energy demands that might be medium to large as well as insignificant micro amounts or small amounts. The first because, I mean there is still a big doubt about this development. So that requires I would imagine, some IPP where the government provides some kind of support. But I mean the government doesn't have fiscal space to provide back up to some of these larger projects, even when it has the will. It just cannot provide the kind of sovereign guarantee or support, just because it doesn't have any fiscal space for that. It's a barrier, but certainly the prices are favorable for some technologies like solar. But I would say for the others, the issue of just being able to access these scarce resources is a big issue.

[PB] When we speak about PV and wind power, the costs for the technologies themselves are low right now. But what about if you look at the smaller island states within the Caribbean, or even the smaller islands within these states? Is that a matter that transaction costs that are higher compared to a large country?

[JW] Of course. That is a very good point. So even in those countries where it is relatively lower, many countries have some form of involvement in these, can't go ahead, but especially for the bigger countries like Jamaica, Barbados, they do have some experience of that. It is still a very big problem, the transaction costs, yes and is related to the scale of the projects. And then it becomes a big issue.

[PB] That is one of the things we assume as well. How will you remove this barrier? Is it possible to combine and to have perhaps a larger market size to remove taxes for imports, or something like that?

[JW] Removing taxes from import are already under way. Most countries have already identified that that is a lot of success to incentivise industry. I think that is also a question of scale and we need to coordinate the approach we are taking, especially in terms of procurement. But it is a possibility, and would be a strategy certainly for public sector interventions. That is one of the options that are taken. It is a possibility, but it would need to be tested certainly in the context of barrier removal. But it is a big possibility in overcoming the transaction costs for a country.

[PB] I think we learned a lot about the economic barriers. As last category, we would like to talk about the technical barriers. That means in terms of the natural conditions in the Caribbean, but also technical constraints by the renewables themselves, but also the infrastructure. What do you see as the main barriers in this field?

[JW] There are lots of resources that are available to the problem with regards to RE, so there's an option, the technology option, renewable energy options. What we don't know, we don't have a very good assessment of renewable resources. For example, I can't tell you the potential for wind for most of the countries. We don't have detailed solar assessment for a thorough basis for a country over an extended period. So it is generally likely that we have so many hours of sunshine and so on. But when it comes to detailed map in terms of measurements, that is still an irritable rota because you know, we have just not been able to put it together, in a way that is comprehensive and detailed and can be looked over and influence the decision. So the resource assessment is still something to trade with. Then we haven't touched other areas like the land draw, geothermal assessment and so forth. So that is why. The other issue in terms of the technical is that we do need to correlate capacity to support some of the decision-making as well as some of the operations. For some of the technologies, for the developer to come to a government and say look, I think we have the solution to introduce in your country. We do not even have the kind of resources that we can provide to the government with some quick support process that is being presented with. That's a technical barrier because there could be the opportunities to invest in variations of technologies that are suitable for different countries with different needs, especially when we think about waste to energy it comes up as a big matter. We don't have the technical capacity to do some of these assessments. But the flip side of this is that from the beginning, developments are vulnerable to risky arrangements because of the technical failure to recognize and to do some of the due diligence. On the third level would be the need for applied research in terms of understanding some of the integration issues to get the optimal performance from some of the equipment. There are different recent performance criteria or recent performance indices or recent performance issues in different technologies, and we need to better understand this context, but we also need to get some new consideration for the vulnerability to natural disasters when we come to implementing this. Because they are so expensive, we have to make sure that we minimize any risk when implementing and operating some of these technologies. So there is need for what I would say some kind of a center that would provide regional support both in terms of assessment, assessing the technologies, and understanding them better, as well as some continuing resource research in terms of renewable deployment to ensure that we get maximum performance from these options that are available to us.

[PB] We said that there are infrastructural barriers, let's say that you would not install something based on missing transport capacities?

[JW] That's an issue. In many cases. We have good wind resources. But the smallest turbine that we could get to go that site, that was some years ago, it could not be transported by road to get to the farm. As such, the development didn't take place. So because then the island states also have small road infrastructure, so the infrastructure is limited. You will find that some of the options will have to be bypassed. And it is disappointing especially with wind. We have cases where the transmission infrastructure needs so much upgrading that a project would not be considered overall. For the rest of the examples, yes, in the context of small island states with very constrained resources to put in place the infrastructure that is taken for granted in some of the developed countries that can be a constraint. The same could be applied to marine RE. Especially some of those off-shore options relate to infrastructure.

[PB] Overall, we touched upon all the main barriers, it was really astonishing, I mean we did quite a lot of literature surveys, and looked at many older and new studies, and we covered all the important fields. So it was very enlightening for us to see it from your perspective. Is there anything from your side you would like to add?

[JW] Whereas the countries have recognized that they need to know the right direction to diversify their energy supply arrangements, mainly because of their vulnerability issue. There are other issues of course. It would provide employment opportunity to business, and then there are climate change issues. For all these reasons we need RE. The governments are significantly constrained by immediate crises or issues related to their fiscal arrangements, as well as their debt situation. And that is, to the extent that more can be done to help them make decisions in terms of critical analyses to understand the benefits, and to understand how decisions are taken and can be balanced against other competing issues. That is really what is the governments' greatest issue. Well not the greatest but relatively. The other area would have to be appropriate financing instruments to cheaply do the studies and assessments to significantly improve the demonstrations and pilots and also to provide the resources to help with project implementation on the ground. So, resources, initially. In the case of the utility, the big issue for the government is really to find a way to bring the utilities to the table in a way that doesn't present them as breaking their contractory obligation. And that is a regional approach, supported by the partners that could be useful. But it has to be in the context of the long-term sustainability of the sector, and not just necessarily the pure business interest. And it has to be created in a way of a dialogue. That really requires work and a stage approach rather than a lone-stand transformation in many cases, in terms of the open-up of the market for competition and for generation of RE. So it has to be a managed process that will require input of partners, and there is significant room for regional intervention. But the greatest barrier is really to get the governments to see that there is a specific way how the various interventions in their territories can be done in a way that doesn't derail their various quotas because of the incentives they would have to provide.

[PB] Do you think the success of a RE project relates to the sense of ownership over the project? if there is external funding, people might feel like they lose control over the project. You said that pilot projects are needed, but then the question if they are externally financed, do people still identify with this?

[JW] I don't think this is a big factor. It may have been a factor two or three years ago. It's not a big factor now. Right now I think there's a recognition that most of these interventions will have to come through support from outside, concessionary financing and foreign investments. They are needed. Governments don't have the money at all when looking at the capacity of the private sector or GDP. But it is not when it comes to financing. I think governments are open to that.

[PB] Perfect, thank you very much for this interesting discussion.

A.2.3 Technical Advisor CREDP/GTZ

Participants:

Sven Homscheid [SH]
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Length: 1h 20 min

Interview

[KR] Could you briefly introduce yourself, as well as tell us about your experience of working within the RE sector in the Caribbean?

[SH] My name is Sven Homscheid, I am technical consultant and advisor for the Caribbean Renewable Energy Development Programme, which is currently run under the GIZ. I'm also hydropower and renewable energy consultant and working for selected governments and private investors in the Caribbean.

[KR] So your main area of work is hydropower?

[SH] My background is hydropower. I am an engineer specialising in hydropower, but as the technical advisor on the CREDP I was exposed to any sorts of RE, and also energy efficiency. In particular solar power, wind power and hydro power. Also in selected countries energy efficiency in terms of EE in household appliances, energy efficiency in the building sector, EE in the hotel sector. Those were the topics I was dealing with when I was long-term advisor of CREDP. I'm not long-term advisor any more, but am rather on a contract basis from assignment to assignment, still working with CREDP. The fields I was dealing with were technical fields, like feasibility studies or supervising the establishment of tender documents, as well as renewable projects that we intended to use as lighthouse projects; as well capacity building measures, e.g. lectures, public lectures or lectures at university; then programme managing of the Eastern Caribbean Energy Labelling Project that was a sub-project of CREDP, but that comes to an end in March. It deals with the introduction of energy labels for household appliances. This is co-financed by the EU. I'm also technical advisor and assisting the programme management there.

[KR] Could you elaborate on the most exciting and successful projects from your time within CREDP, especially large-scale implementation of RE?

[SH] The most exciting one for me certainly as hydropower engineer were the feasibility studies of the upgrade of the hydropower plants in St. Vincent. This was the Richmond Hydropower Plant and the South Rivers Hydropower Plant. During the initial investigations about the refurbishment of the fifty and sixty year old hydropower plants, I came across an initial stage investigation for a new hydropower plant, just downstream from the existing plants. Suddenly, from two hydropower projects, the entire study was somewhat extended to three hydropower projects including one new. That was exciting in two ways. One, of course, it is another hydropower plant by itself that was just found, so to speak, but on the other hand it was very exciting because this was the only really new capacity that was supposed to be studied in this hydropower project in St. Vincent. The other two hydropower projects exist already. And when we're saying Renewable Energy Development Programme, I think the initial idea was not to refurbish existing plants, but to build new projects. And suddenly, the entire setting for this hydropower project changed. The entire idea or concept suddenly turned into something which I personally also considered useful for CREDP because we really were looking at new hydropower capacity. And that was for me the most exciting. The most successful project - of course the most successful always refers to projects that were implemented - and here we have to say, there were no projects that we were dealing with as CREDP that were implemented other than we are bringing in money in order to assist the implementation. After a couple of years, we got a co-financing from the Austrian Development Agency ADA. That allowed us to co-finance individual projects. We co-financed up to a maximum of I think 25,000 USD. Those were projects where we came with money physically, put it on the table. Those were realized. But I cannot remember any project that we had initiated and prepared for other investors to invest in, that were really realized. It was always donor money. No private investment was done, which is in itself a sign that something is wrong with the entire idea of developing RE the way that CREDP is seeking to do it. So basically, we were not able to remove the barriers. Otherwise private investors would have come and just jumped on the train, in particular when it comes to projects that were already prepared. That was the idea of my involvement with CREDP from day one. The team was looking for support from an engineer, and they found me as an engineer. I was told that we need someone who is preparing projects so that projects are ready for implementation. So I said fine, that sounds like you prepare projects. And then suddenly see machines in the field and then finally, you see RE generators in the field. And that never really happened, unless you bring in your own money. With the original concept of CREDP you didn't see anything coming to fruition. And that is kind of depressing as well.

[KR] Would you say that once financial assets in form of donor money had been given, these projects were implemented, or did they not take off at all?

[SH] We have now six projects that are operating. These are five PV projects and one solar hot water project in St. Lucia. So these projects are up and running, except for the solar water because the hospital which uses the solar hot water system is not yet operating. But it is installed already, the money is spent. But we had to bring the money as grant money, not even as financing. We had several projects where CREDP has organized financing, and financing banks were absolutely willing and able to lend the money for those projects. And still those projects didn't materialize.

[KR] So picking up on this, what would you describe as the main barriers to the success of these RE projects?

[SH] willingness of the project owner to do so. There is a clear difference between government projects and also utility projects, and private sector projects. Looking at Barbados, for example, the private sector has developed a vivid interest in the solar PV industry, and even before that in the solar hot water industry. Since 34 years by now I think, the solar hot water industry in Barbados is flourishing because there is private interest in these projects. Also photovoltaic systems are being installed right now, e.g. the company Williams has installed large amounts of PV on their factory roofs. They plastered the whole roofs full with PV panels. They are interested in it. So if we would have looked for projects where we would find some project owners that are interested in general, and then support those who are willing, instead of working with those who we had to convince to do a project in the first place, we would have seen more project coming to fruition as CREDP. In general I think everything starts with willingness to do things. The preparedness to do things is the first step. It is not the only step, of course, there are many more steps. You need to have technical expertise to realize projects, and you need to have the financing, and most likely with many projects you need a building permission to do those things as well, but it all starts with the willingness. Apart from Barbados, I have seen very little initiatives by the people in the various islands to develop RE generators. So there is definitely a gap there when it comes to willingness. And this may have different reasons. One is lack of awareness, granted, that is certainly one of the things. But no one can tell me now in these days that there's a lack of awareness that RE is the better way forward. Whenever you speak to people in the Caribbean, they would let you know that they are convinced that RE is the way forward that could make energy supply much cheaper. That is only partly true, but most people already believe that RE would make the electricity supply cheaper. So the headings are already there. But still people are not really doing it themselves. And here we have to ask the questions why it is that people are talking about it, but not willing to go all the way through these processes to implement projects.

[PB] I want to know something about this willingness. What level do you refer to? Is it a political level, or the private sector level - in case of the latter, do you think that if the private sector was only willing to implement, then the framework conditions would not matter?

[SH] That can never be the case when you look at energy generation because the framework conditions are the single most important barrier for private investors to do large scale RE generation in the countries. When you look at countries like St. Vincent, Grenada, St. Lucia, where the utilities still have the de facto monopoly to generate RE energy, I mean now we have to look back at Grenada and see that this is a de facto monopoly because the feed-in conditions in Grenada are so unfavorable so that private investors are not interested to put up and RE systems themselves. So if private investors would be interested, they would run into a concrete block with regards to the legal ability for them to realize projects and connect them to the grid. One example is a small windmill in Dominica. There was a windmill built without permission to connect it to the grid. Therefore this windmill was just sitting there for I think three years, spinning occasionally when the wind was too strong, but not generating any kWh electricity, because there was no permission to connect it to the grid. They had started to build something without looking at the framework conditions. And then of course they were also mal-advised because the owners of the project were of the opinion in the first place that they would be able to generate electricity just for themselves. Then they found out that the machines they bought were asynchronous machines which need to be connected to the public grid. So there's a combination of a lack of technical understanding of things, also on the technical advisor side. He messed it up completely. I mean in Dominica, theoretically, you are allowed to apply for a license because they have a completely liberalized market there. And it should have been much faster under liberalized market conditions. The reason why it took so long for this Rosalie Windmill to be connected to DOMLEC's grid were administrative barriers, lack of clear rules of how to apply for permission, lack of knowledge on the side of the regulator, how to check if everything is in order; lack on the side of the utility because it was of course also their first project buying electricity from an IPP. Everyone was moving really carefully, so it took forever. Everything took forever. The essential message is that it doesn't help if a project investor is just doing something; it has to be done in the right way.

[PB] Can you name one of the projects you said prepared initially, but that then just didn't go forward?

[SH] The Newtown hydropower Project in Dominica. The project owner is the water company. It's an existing water pipeline which was supposed to deliver water to the coastline from the mountains, from the tailrace of the existing hydropower cascade. We studied the project feasibility. I've done pipeline testing myself with a team from DOWASCO, we repaired the pipeline so that it was now finally resisting the pressure that we would have required, we fixed leaks and so on. So even DOWASCO was putting in some amounts of money in terms of pipe fittings and so on, and manpower. Everything was prepared up to the tender documents, which would have only needed to get a final review and then they would have been issued. Banks were also looking at and willing to finance the project. And then suddenly the government said, oh, by the way, DOWASCO is broke and not allowed to get a single penny from the government. And that was the end of the project. And I was asking myself, fine, what was this now for? In particular looking at the fact that this was a pipeline project from CREDP/UNDP and CREDP/GIZ who had taken over this pipeline project, but this is not a pilot or demonstration project. How many pipelines, bulk water pipelines from the mountains reaching to the sea do we have in the Caribbean? How many similar project conditions do we find in the Caribbean? This is a very unique project. So I don't know why this project hasn't been picked up, without looking at the consequences of what happens afterwards.

[PB] Just to summarize for this project. It sounds like the technical feasibility was ready, also the financial feasibility, but then it was stopped from the political side.

[SH] Essentially yes. From the political side based on financial arguments. But the financial arguments I cannot really see. You have to see, this project would have saved the water company.

[PB]. So yes, if it is economically viable in the end, there's no financial argument.

[SH] And if you find a financier, in particular, banks would be willing to finance it. The CDB is looking at it right now, again, and they are speaking of high-level conversations between the Prime Minister of Dominica and the President of the bank, CDB. Again, this is not based on an initiative by CDB, or the government. It is based on something that CREDP has initiated and the GIZ is involved in as well.

[PB] How would you explain this political intervention?

[SH] I would not be able to say the reasons because this is something where you would have to be able to look into the head of the board of directors of DOWASCO, the water company. They would be able to tell you why they decided not to go ahead and instead put a stop to the entire project. It was a very clear general statement. The CEO of the water company told me his minister has told him if they have to put even a single dollar, they would have to forget about the project. So they forgot about the project.

[PB] There are only speculations then.

[SH] Exactly. I have spoken to the people from the board. I have even made a couple of presentations to the board of directors of the water company. Whenever I showed them the revenue figures of the project for every year, they were always fascinated and said good thing, go for it, and even DOMLEC was willing to partner in the project and said we would even be a private partner in a BtB arrangement, if only it would come from behind the oven and if you stated that you had an interest in the project. With regards to the equity part of the financing, it would essentially had cost DOWASCO a fraction of what private investor would have to pay. For DOWASCO itself it would only have been manpower to manage the project. Yet it didn't come to fruition.

[PB] Did you find similar cautiousness or however you would describe it in other projects as well? That an authority somehow decides not to go forward despite technical and financial feasibility of a project?

[SH] If you had asked me last year, I would have said yes. A year ago for example, like we have done in St. Vincent. But nowadays it is different because some projects are moving slowly, maybe not in the right direction, but some do not. As for the reasons - I think if you have twenty projects, there are twenty different reasons for the projects not to go ahead. The hydropower projects in St. Vincent that we have studied, we actually identified that with the existing set-up, there is more electricity to be gained from the hydros because the river carries more water. They could install larger turbines and larger pipelines. With the lower capacity factor, they would still get more electricity out of the water, out of the rivers. It was economically and technically feasible to upgrade the hydros. And yet, VINLEC has decided to merely replace the old machines with new machines of the same size, and old pipelines with new pipelines of the same size. I don't want to go into the reasons or the history of that project because it has not much to do with the barriers, but the decision was clearly made to go for PV installations in the first place. VINLEC has by now installed around 170 kWh PV on their roofs, and they have plans to install more PVs instead of going for the more economically interesting option of hydro, which comes at a lower cost. That is something I cannot understand. The reason is lack of knowledge among the management and in particular the CEO of VINLEC.

[PB] Is it that maybe someone in charge is profiting more from PV than from hydro?

[SH] I am a little naive, thinking that this is not the case, but I don't have evidence that someone else is getting kickbacks. I would even suggest that for the PVs, it didn't seem like that. The PVs that were and would be installed by VINLEC are procured by VINLEC themselves, and are sold by VINLEC themselves, so it's all among them. The cost is fairly low. So it doesn't seem for people from outside that there is any room for any kickbacks.

[PB] If we look at conventional power generation, we would probably find much cases like these, for example somebody losing their share in the power generation.

[SH] Definitely. With PV it is different, and also with hydropower. I mean hydropower companies, in particular those that they have hired, a British hydropower company that is an equipment manufacturer, would not have a vast interest in selling larger machines. They also just went for the same size and so on. So they were not convincing themselves enough. I guess you are right with conventional power, with diesel generation in particular. There is a strong lobby, there are generator manufacturers and they are selling stuff, flying around from island to island in the Caribbean selling new generators. I think there are definitely kickbacks that are coming to the CEOs coming from their end. They have a strategy to sell their equipment that is incredibly American. They organize Golf tournaments, they sponsor CARILEC conferences and I don't know what else they are doing but they are following the same strategy. And you don't see that from solar manufacturers.

[PB] They would still sell their diesel generators even if they didn't run so much. So the question is if the diesel fuel sale is a similar issue - is the system working similarly or is it more hidden?

[SH] Fuel sales in the Caribbean are more like a political decision. It is not something in which the utility would have much influence, in particular when you look at PETROCARIBE. These agreements between governments are made on the political level, and not on the level of the CEO of the electricity utility. But once a country is part of the PETROCARIBE agreement, I'm pretty sure that there is a certain obligation to take off a certain amount of fuel annually. Or anything in this direction. There will definitely be incentives to buy enough oil, diesel or fuel.

[KR] Since we have been talking about the issue of lobbying, and the conventional fuel-based system - would you say that if a local champion put in effort, and built a stakeholder network with regards to RE instead of fossil fuels, RE projects would become more successful?

[SH] Definitely yes. You will have a champion, someone who attracts public attention, who creates public awareness. Public attention is very important if you want to reduce corruption. The best thing you can do is to go public with whatever happens. Be transparent. As transparent as possible. That's the most efficient way to eliminate corruption. So having a champion in the media, talking about the advantages of RE generation for electricity, about the advantages for everyone's household and every person's budget, is definitely something that would work.

[KR] Do you see this related to overall consumer awareness in this case?

[SH] Yes. There are different means of creating consumer awareness of things. We have just finished our campaign for energy labels for ECELP. We used a media campaign, produced some video and radio clips, jingles and so on, and then broadcasted them. That is one way of creating media and public awareness. But that is certainly the least efficient one. If you look at e.g. in St. Lucia there was this Grynberg affair. There was this business man Grynberg from the US who was securing drilling rights for oil in front of the island. There was a conflict and there was debate and a legal dispute going on, and a lot of articles were published in the media about this entire thing. And although nothing has happened in terms of real development, this case got so much attention, and everyone knows about it in St. Lucia. So that is a much more efficient way - to put it in a drama, or a story and then publish it in the media, publish it in the news stories, headlines, in TV or whatever media is the right one. That's another way to do it. Then of course the government initiatives, energy awareness week and so on, that's very nice, but people aren't taking that on too serious. I don't think there are any behavioral changes coming out of energy awareness week. That is only scratching the surface. Of course you have the awareness created by people just doing things. The most efficient way of promoting solar power in Barbados e.g. was that people started installing PV systems in larger numbers. People saw those installations, people were speaking about these installations, and then suddenly everyone wanted to have one. It is like introducing a new car into the market. First of all you have to show that this car is there, create interest, and then more and more people are interested in it, and so you see more and more cars of this brand, the brand gets more and more popular. It is like a wildfire. And it is also in my opinion the best way to start a business with any kind of publicly available RE technology. If you even look at wind power, at utility style. Utilities in the Caribbean are still fascinated that all of the ABC islands in the Southern Caribbean have wind parks by now. They are all eager to learn how that worked. Yet, they are not doing those developments themselves. But it is like the ABC islands are now driving BMWs and the other islands are still going in VW Golf.

[KR] Would you say that also goes the other way, that negative experiences affect the development of RE?

[SH] Yes, in any respect. Looking at geo-thermal in Nevis, which came to a halt now, developers are alarmed so to speak, and they are more cautious how they go about things. But there's also the positive effect to learn from the experience, from the bad experience of neighbouring islands. So it is not entirely negative if someone experiences a pitfall. In the case of Dominica, e.g., the next island to look at geothermal, they were a lot more cautious. They had a different approach. They learned from the experience of the non-existing geo-thermal bill in Nevis and they tried to do first things first. There is always a positive effect, even when there is a pitfall in neighbouring islands in the development of RE. In general, it is also an element of setback. People are getting cautious. The El Dorado gold rush is being stopped by people not finding gold and losing a lot of money in attempting to do so. There are both effects.

[PB] About geothermal, would you say, Sven, that geothermal was even a barrier for other renewables?

[SH] It is definitely the excuse in St. Vincent not to go larger scale in renewable. It's a profound excuse not to move into other fields. In the case of St Vincent yes. In the case of Dominica, yes, as well. Because everyone is looking at what is coming out of this geo-thermal: This is a management decision, you have to say. If you are a utility, and are also consulting for DOMLEC, then the decision to go for a new hydropower plant in Dominica is a long term investment. You are looking at a minimum of 20 years, if not with refinancing options another ten years, so it's definitely long-term. If you are investing long-term, the first five years of running a hydropower project, or let's call it even two years, because its construction takes a while as well. So after two years, there is an alternative form of generation of electricity that is coming and stealing your business. You will see stranded assets. And that is what every utility, every businessman has to avoid. So that's a very logical decision. But on these small islands, it's more a political decision in terms of what is going to be used as electricity generator. We have a conflict here. The case in Dominica is very good for an illustration of how the economics come into play when it comes to competing between different RE technologies, in particular when you look at geothermal compared to hydropower. Now we have the scaling effect in both cases. Small hydropower is quite expensive, even more so on these small islands. You would look at specific investment costs of 6,000 to 8,000 to maybe 10,000 USD per kW installed. It is similar with geothermal. But then there's the cost curve. If you visualize the cost curve as a linear graph, the cost curve for geothermal starts much higher, and then the gradient is much smaller, as opposed to hydro power. There the initial cost is much less, but the gradient according to how larger or how much more capacity you would install, is deeper. So you'd have to look at the scaling effect, how much electricity is needed at that particular island. This is usually miniscule, which in turn leads to the fact that geo-thermal development has a higher initial cost. If you as an island cannot export electricity to the neighbouring islands over a long-term contract, it may not be the cheaper option. This is mistaken by most of the governments, since they always promised it would come at 6-7 USD Cent kWh generation costs, which they might not be able to keep up because of scaling effects. If you drill a hole for exploration, you sink the first 2 to 3 million USD. If you bore another hole for a production well, the next 2 or 3million USD are gone already. And that's half the cost of the entire comparable hydropower scheme already. So it really needs some knowledge to prepare options against each other. I don't have the feeling that the utilities will provide this knowledge to compare geothermal and hydropower and PV and wind power, and storage that would be needed to complement wind and solar. I have not seen any study that was looking at the complex economics comparing one vs. the other one, looking at the scaling effect. I think if the utilities and the governments had the facts on the table, they would be able to compare one technology's levelized cost of electricity against the other ones. It would be very obvious in which way to go. The answer would be flapping into their face. But obviously no one has done it yet.

[PB] This is part of the first part of my research. I will look at a timely resolution of one hour. I will look at energy systems and their performance over one year, so you will see the different advantages of the technologies and how they complement each other. It will be a techno-economic optimization. We will look at the load curve and then the best system supplying a load curve under certain conditions, cost assumptions and technical restrictions.

[SH] This amounts to real cost data? In particular for geo-thermal it is quite difficult because it is very rare that you see small geothermal systems being built on small islands. And we could see already in Nevis that there was a cost overrun with every day that they were drilling.

[PB] For geothermal it will just be an additional scenario. It will be the other way around, I will look at what costs have to be reached by geothermal to be competitive.

[SH] Okay but that's shooting past what people read. If you want to produce a relevant study that people will be interested in and read, they will want to know what your assumption is for the cost of geothermal. It is easier for you and more secure, to put it up as you said. You leave the residual or marginal cost to be decided. But that doesn't help any decision-maker to come to terms, neither on political nor on utility level. They still wouldn't know how expensive geothermal energy really is. And that is the key challenge here.

[PB] I have particular information on St. Vincent. There is collaboration with some smart guys in Potsdam, who could provide me with help to put some numbers on this geological data. What are the costs on drilling and such, certain rocks and so on.

[SH] Try to get the contact of geo-thermal companies who have built larger projects, Costa Rica for example. There are a lot of projects there, as well as in some projects in Africa. Most likely you will not find a geo-thermal project on a small island. The only one would be in Guadeloupe. In Guadeloupe, cost is highly subsidized so you would still have to scale it up or down. But I think what you would have to do is, you would have to analyze the cost in detail, and then look for the scaling effects. Look for transportation cost. Transportation costs are the main factors why these islands have that high exploration costs. You really would have to do like a contractor would have to. Do your cost estimate, do it as detailed as possible. For all the little elements, for drilling equipment, its rental or transportation to the island, maintaining your camp and construction site on the island, you'll get the individual cost. Then put together the construction costs, and try to come up with your own cost estimate. You wouldn't find reliable figures for realized projects. And that's the only way you can generate reliable data for your study. Then add a surcharge, or profit margin. Thereby don't consider this to be the same profit margin as you would have it for any other project since it is a high risk project. High risk means high percentage, high rate of return. So you need to be more realistic there. Then you come up with the levelized cost of electricity generation.

[PB] What you described before from the cost curve, what we'll hopefully be able to see is what amount of load would be needed for geothermal projects to be viable. If there is a certain amount of electricity produced, since it is only the initial drilling that is expensive.

[KR] Do you think there is room for improvement when it comes to financing of RE projects? For example, with regards to incentives, access to capital and maybe the duration of the procurement contracts given out by the governments?

[SH] Yes. But I would like to exclude incentives. If you are a business man and you see a business opportunity you don't need incentives. Incentives work when people are not sure about whether to go for it or not. Then you give a goodie or hand out the carrot. I think that's not needed here. Incentives is not the right word and not the right way forward. Incentives cost money. If you exempt certain technologies from tax, then that is a real loss of revenue for a government. You would have to look out how to compensate for this loss of revenue because this is pressure on your budget. We are discussing these issues currently with regards to energy saving light bulbs or energy saving equipment and the reduction of duties for more energy efficient equipment. You cannot do that without paying from your budget, because you have used you annual income. These small countries cannot afford to lose any dollar because they have tight budgets. It cannot come at a cost for a government, when you are looking at incentives. For projects that are viable, and we are not looking at non-viable projects at this moment, we are not looking at rural electrification programmes in the Caribbean: The Caribbean is electrified except for maybe most parts of Haiti, but other than that the Caribbean is electrified. We are just looking to replace diesel based electricity systems with renewable ones. So incentives are not really necessary because the projects are viable. A friend of mine usually says you carry the dogs to hunt and that is true. If you incentivise smart decisions, what's that good for? The projects are viable. But in most cases, governments are involved to invest and they have limited borrowing capacity. Antigua for example is under IMF control, Grenada is under IMF control. So they have not much flexibility in terms of how they spend their public budget. They usually are obliged to cut cost and save whatever they can. Now it is just a question of sitting down with the IMF's financial advisors, and making the point that with this project, we would annually save this much money. This is the real fact. If a project didn't save money, you would not invest in this project. And this is also the feedback you would get from the IMF or other financing institutions. If a project is so profitable that a government, company or utility would want to invest in it, then it would even be possible to approach a private commercial bank. Commercial banks live on giving out loans and getting their return plus interest, so they would make money as well. They have an interest in lending money, and of course to see and limit the risks. But they wouldn't be afraid to take a risk in the investment if they were able to factor price and risk into the project.

[K] So it is mainly uncertainties around cash flows and a lack of access to cheap capital that are preventing these either public or private institutions from giving out loans for RE projects?

[SH] Do you mean there is reluctance? I don't see reluctance from financing institutions. I have not really had this situation that a private or public developer had even approached the CDB or the national development banks for a loan yet. The only case I am aware of is in Grenada where one of the former advisors to the government has publicly said that we need 120 million USD for changing our diesel based generators for a renewable based generation - who is there to give us money? So he was not really approaching a bank, he was just saying that publicly at a conference. But if they had produced a concept that would have supported itself in terms of economics and technical feasibility, I have yet to see the bank that says no we are not interested.

[KR] You have talked about policy before, so I'd like to return to the political aspect of the barriers. How do you relate national or let's say Caribbean wide, regional policy to the development of RE?

[SH] Policy. Policy is a buzzword for me. CREDP has worked a very long time to draft policies for individual countries. We were actively involved in the policy drafting for St. Lucia, St. Vincent. We had influence in the policy drafting for Surinam. And all these policies are a piece of paper sitting there. And then, what happens next? Policies are not worth the paper they are written on, unless they are taken and put into reality. In Grenada we have seen the development of the PV sector even without a policy being in place. This is clear proof of that policy cannot be the key driver for the development of RE. For the case of Grenada, it was a private company approaching the public sector, the government, and said we want to do something. We want to be green and want to develop a PV market. And they were sitting down with the electricity company GRENLEC, who said why not. Let's do a pilot project - here you have I think it was 300kw out of our generating capacity, once installed we do a net metering agreement and it was done. There was no policy involved at that point. Government was hastening afterwards to put everything that was done in reality into a policy. So policy came afterwards. This is a clear sign that policy is not the driving force. It can be a barrier of course, if it is a policy that prevents the installation of RE, or that grants monopoly, then it would certainly hamper the development. But the primary factor here is not the policy. The primary factor here would be legislation and regulation. The key word here really is regulation. Policy needs to lead to regulation, and to legislation. Those are the powerful tools with which you can change the energy environment on islands and in countries in general. But this is not unique for the Caribbean, it is applicable for the whole world. We see it in Germany right now. A policy is one thing. Everyone is complaining about policy. The review of the renewable energy law in Germany for example. It is still policy. So everyone still kind of relaxes. Once this is turned into legal obligation, into legal papers, into laws, then people will realize that there is a change coming up.

[PB] So would you say that we need policy to come to regulation or can we leapfrog it?

[SH] If we are looking at policies, we are really wasting time. For four or six years in the first phases of CREDP, we were looking at passing policy papers in these little countries. For example, in St. Lucia the problem was that the government was not sure how to go about this policy paper. Usually I would say a government is smart enough to sit down and say we now write a policy paper. Then they just express where they want to go and how they want to go there without being too specific. Here in St. Lucia they had consultations. They even consulted with the utility, which of course said no, don't write this in a policy. We cannot keep up with these goals because we have to take care of our shareholders. In St. Lucia it is a partly private utility. And so of course everything took much, much longer, whereas a policy is a thing of two months in Germany for example. It's a policy. It doesn't hurt anyone, but is has to be done quickly and it is single-sided. It is the political decision by the policy-makers, who are the politicians. They may consult with their specialist, but they definitely do not ask the pig that is going to be slaughtered how the pig was feeling about being brought to the butcher. That is not helping anything. So therefore I would say policy should skip to regulation directly, because policy is taking up too much time.

[KR] How do you assess the situation with regards to formal institutions, such as specialized ministries fostering investment and disseminating information? I am talking about energy departments and specialized agencies within the government.

[SH] Complicated. Let me blend out the comparison to Germany. Because in Germany we don't have an energy ministry, and it still works. But we decide this individually. In the Caribbean, however, I think a department that specializes in energy is necessary. We have to see how governments in the Caribbean work. How politics in the Caribbean work. It is not the case that a ministry would have an armada of specialists for a given topic. It is not given that the ministry of health has a minister and a permanent secretary that are specialists in health aspects. There is a lot of administration. There are a couple of specialists that have knowledge about the topic itself. There are more administrators who are shifting paper from A to B. But it is not that the expertise would be available in a country because of a lack of numbers, but because of a lack of capacity. St. Lucia doesn't have a university, so where should this expertise come from? Transferring this now to the electricity sector, it would definitely be better to have a unit that is dedicated to energy topics and that is requiring knowledge and reading up articles on the internet, reading books on these things, rather than reading books about electricity, energy, infrastructure, transportation, climate change, water issues, because this is all sustainable development related, this is all climate change related, this is all being financed. For that you would need an opinion, because only if you have an opinion on climate change you are entitled to receive the international support from the international funding agencies. So in the short, it is very important, yes, that you have energy departments in the ministries, but it is hard to equip those departments with profound expertise and knowledge because of the small size of the populations of the countries. Even if you had two handfuls of specialists on each island, it is not said that out of these ten people, anyone would be willing to work for the government. Since they are specialists, they would make more money in the private sector.

[PB] How do you think could this be overcome, via a Caribbean wide authority?

[SH] You would need to consider your energy agency, or energy unit as a kind of management unit with sound background and a general overview of the energy field. But then this energy unit would need to have a budget to hire consultants for advising them. And this would be a budget for international consultants. If the St. Lucian government asked a St. Lucian consultant for expertise in the energy field, the turnout would not be high. But if you got an international consultant telling you how you are standing compared to other countries, markets around the world, e.g. compared to other SIDS in the South-Pacific, and you would allow the government to compare what they are doing, and what you are doing, I think that would help a lot more than the pure creation of energy units. So enabling energy units is the next important step.

[KR] That was also tapping a bit into the regional cooperation aspect there. If we look at the Caribbean as a region in total, would you say that there are barriers relating to natural conditions of the Caribbean, such as limited availability of land inhibiting the development of RE projects?

[SH] I have to treat the answer a little bit in a direction which indirectly relates to limited land. How much land do you need for a windmill? The footprint of a windmill is maybe 50 square meters? But you would see the windmill for kilometers. So for wind projects, looking from the experience of Barbados and St. Lucia, it is the visibility and the non-availability of vast areas of land where windmills can be hidden. For PV projects it is different. PV projects are not hampered by the lack of land because you don't necessarily have to use land, you can use roofs. Most of the islands have enough roof space to place all their technical capacity for PV on roofs. So we have to be a little bit careful if we say land availability. Land is available but it comes with certain problems. With wind, it is not the availability but the acceptance of the technology in the vicinity. You can't put up a wind farm in the midst of a hotel development area.

[KR] Is that also impacted by natural disasters?

[SH] Jamaica has a wind farm. Jamaica's wind farm has already survived two hurricanes without damage. The natural disasters are not hampering the development of RE, they make it more expensive. But the example of Jamaica is very good, because it is a regional example. People have seen that severe hurricanes have gone over the wind farm and nothing serious has happened.

[KR] Moving on to one of the last aspects, relating to technical issues that we have already tapped into: Would you say that the energy systems on the islands are not mature enough to develop a high RE share in their electricity production? In terms of supply chains, or perhaps there is a cap on the maximum share of RE production, set by the regulator or utilities?

[SH] Yes. There are technical limitations. That is something we found out from a Master thesis from St. Vincent. I had a student that was working for me using the programme digsilent and Excel spreadsheets in order to analyze how much variable renewable electricity can be fed into the grid as it is right now, without creating grid instability in terms of voltage and frequency fluctuations beyond the limits that the utilities are set to follow by the legislator. It found that 30 % variable renewables in St Vincent is an easy thing that wouldn't require any changes to the infrastructures right now. It would just lead to less diesel consumption. It would lead to more flexible operation of diesel generators. And this 30 % was calculated based on the assumption that a diesel generator would not operate below 50 % of its load, which is a very conservative assumption. You could practically go up to 35-40 %, depending on the size of the diesel generator. Then it would just operate fine. But VINLEC gave us the VINLEC 50 % and not less. This limits your flexibility in terms of how you dispatch your generators. Also the efficiency of diesel generators is decreasing with the scale percentage performance vs. peak performance. So let's say you can inject 30 % in a current system as it is right now. Then you would have to look at different counter measures for variable RE. I am stressing variable renewables because you also have dispatchable renewables, like hydropower, geothermal which are not playing a big role on the island but that would also be dispatchable. The variable renewables would reach their technical limit at some point, and then you would have to change aspects. Either you change your diesel generators to appropriate scale, e.g. several small generators instead of one large generating set, so that you have more flexibility to switch it on and off. I mean high speed generators can do much faster load-following in comparison to low-speed diesel generators and so on. But those things could be put into a strategy, fitting in perfectly well into replacing generators with expired life-time. Some of those generators are already reaching their economic life time and it wouldn't come at an additional cost, where utilities like to speak about stranded assets. They say that if our generators are not used anymore we have stranded assets, we were always catering for depreciation income for the generators, and if you take away that we cannot operate those generators economically viable. And that's a true thing. But you can have a master plan, where you plan for replacing old, large slow diesel generators with modern, quick-responding equipment. By these means, you can easily increase a 40 % margin for a variable renewable injection to 60 % just over the time replacing your old diesel generators with more flexible ones. This is one option to do a change overhaul of an old generation park. It's possible, we have theoretically proven that it is possible. Practically, Bonaire has proven that it is possible to have a high penetration system. So proof is there. Now the willingness and the technical understanding is something that is missing.

[PB] How do you assess the potential role and impact of the Eastern Caribbean Energy Regulatory Authority?

[SH] I'm a firm believer of regional regulatory agencies. For several reasons. It is economically more feasible because you need a set of around ten specialists in the field of electricity generation. You need someone who is a transmission specialist, a generation supply specialist, a specialist for other technical generators. Then you need a legal specialist, an economic one and legal administrators. So let's say around ten people. They need to be highly skilled, that means they come at a cost. They would not go home with less than 100,000 USD a year. So that means you would build a very costly enterprise. I think it is a brilliant idea if you can share those costs among several islands. It also gives the regulator a higher independence. If you are not regulating your cousin, it is more likely that you take decisions based on technical rather than family background.

[PB] Do you think the governments would allow this authority to interfere in their national legislations?

SH] They are not interfering with their sovereignty, and that is the problem with the ECERA project at the moment. And that's also something that was induced by the WB themselves, because the first concept was too rigid already. The first concept that was presented to the Eastern Caribbean governments, stated that we will do the regulation, you don't have anything to do with it anymore. To which the Prime Minister in St. Vincent said: no one is doing my regulation, I do it myself, as long I am Prime Minister, I am taking the decisions. So he is not willing to participate. The only two countries that are still on board with the ECERA are Grenada and St Lucia, and they are shaky candidates. They are not sure if they want to participate or not. Their politics are changing from time to time. After elections in Grenada for example, everything has changed over night. The government of Grenada is now looking at a parallel development of regulation because they have the feeling that ECERA is taking too long. The electricity sector has to be restructured by the end of March because the IMF was demanding a change in legislation in the electricity sector. They are under time pressure now, which makes it harder for ECERA to get a foot on the ground on these islands. But in general I think that the governments have not seen the advantage of giving up their sovereignty over the electricity sector. They feel they are giving up sovereignty, they are independent, they are proud to be independent. So to them now putting their electricity sector into the hands of a regional electricity regulator equals giving up sovereignty. For the regulator to become the successful regulator that everyone wants, that means that this field has to be addressed. The regulator needs to get a different spin, and in my opinion, the regional regulator has to provide expertise that the countries cannot provide. Other than that, the decision-making must be left to the national regulatory commissions. This would increase the willingness of the countries to allow a foreign element, a regulator from outside to take part in the decision-making process. Recommendations would be produced by the regional regulator. The recommendations would then be discussed on the national level. These recommendations would be based on evidence and facts and ideally also be discussed publicly. Then those decisions are either adopted or not by the national government.

[KR] So a sense of ownership is important in attaining legitimacy over RE projects?

[SH] Not only ownership. The countries have to be aware of the modus operandi of the regional regulator. If they have a feeling that they give up sovereignty and that they lose control over the very precious electricity sector, this will never happen. So the WB should have never been so rigid in the first place. They should have said ok, what are your requirements, how do you want it done, and how far would you be willing to give up you sovereignty. Then maybe find a stage-wise concept on how those countries' sentiments could have been recognized and accepted.

[PB] As far as I understood the issues about the regional regulator, it would be great to have one, but the national governments are not really willing to give up their sovereignty. We have also talked about the social and economic barriers. Is there anything you would like to add?

[SH] You should distinguish between distributed RE generation by the private sector and RE generation by the utilities on those small islands. There is a big difference. In my opinion utility RE generation makes sense, whereas private sector, small scale decentralized RE doesn't make sense on those islands. It's nice as kind of buy-in from the private people, but we see it even in Germany that there is only one pie to be shared among players in the market. Those markets are small on these islands in particular, if you look at St. Kitts, Montserrat and so on. There is no room for other settings apart from monopolies in order to get to the point of lowest cost generation. If you allow 30 % of the electricity generation to be done by private disperse investments, how are those private investors supposed to generate electricity cheaper than a megawatt PV field? That's not possible: Your installed capacity of power plants is much larger if you are going for dispersed systems. I think thought needs to be put into that issue as well, if you are looking at the overall economics of the electricity sector in the Caribbean small island systems. If you start off with grid-connected systems with net metering, net metering is something that's not sustainable. If you want to run the electricity company bankrupt, you go ahead with net metering. If you want to secure electricity supply sustainably, you convince the utility to go for RE generation at utility scale because that is what gives the clear economic benefits to large scale RE for the utility.

Appendix B

Appendix - Questionnaire

Barriers and solutions to the development of renewable energy projects in the Caribbean

-Questionnaire-

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Berlin, 18th February 2014

Introduction

Thank you for your participation in this questionnaire. We have identified you as one of the major experts regarding renewable energies within the Caribbean area. Therefore we very much appreciate your contribution to this study.

The study, commissioned by the Reiner Lemoine Institute, will feed into Philipp Blechinger's doctoral dissertation at Technische Universität Berlin. We furthermore seek to present its final version at the Micro Energy Systems Symposium at the University of California, Berkeley, 10-12 April 2014.

This study sets out to explore the diverse barriers and their solutions to the use of renewable energies (RE) for electricity production on Caribbean islands today. The outcome of this study will be a rating matrix of the identified and categorised barriers and sub-barriers to RE in the Caribbean. Since the ranking follows the importance and impact of the barriers, this matrix serves as a strategy instrument for their removal to political and economic decision makers. In this regard, this paper will advance the implementation of RE in the Caribbean and thus contribute to the region's energy security, access and sovereignty, as well as the diversification and decarbonisation of its energy production.

At this stage of the research, we have conducted three semi-structured interviews with Mr. Joseph Williams (Programme Manager CARICOM Energy Desk), Mrs. Allison Jean (Executive Director CARILEC) and Sven Homscheid (Technical Advisor GIZ/CREDP). In combination with an extensive preceding literature review, the results of the interviews have culminated in the production of a list of approximately 30 barriers. They are broadly categorised into technical, economic, political and social barriers. In order to validate these findings, and to ultimately rank them according to their importance, we kindly ask you to express your perception of the single barriers' importance, and your opinion about renewable energies in general. You should fill out the questionnaire according to your best knowledge, keeping in mind that the study focuses on small Caribbean island states only.

As aforementioned, you are one of the selected experts that we have contacted for this questionnaire. In appreciation of the roles and responsibilities your position entails, we are very grateful for your participation in this study. In order to arrive at a balanced conclusion, this questionnaire was sent to representatives of utilities, the private sector, government bodies, research institutions and international organisations that all play an important role in the Caribbean energy sector.

We appreciate the return of this survey at your earliest convenience. Please indicate at the end of the questionnaire whether you would like to receive a copy of the final study.

Instructions

This questionnaire starts with the evaluation of the different barriers on a scale from 5 to 0 (highest importance to absolutely no importance) for each of them. If you have no opinion on a certain barrier, please state “Z” for “don’t know”.

The ranking will look like this:

Ranking scale						
5	**4**	**3**	**2**	**1**	**0**	**Z**
Highest importance	High importance	Moderate importance	Low importance	Very low importance	Absolutely no importance	Don’t know

Please make a careful selection. Each row will contain a comment section, in which we appreciate your thoughts/suggestions/ideas with respect to the barriers. Your ranking will serve to complete the first qualitative steps of the study, and is of special importance for its end-product, the rating matrix.

Within the ranking table, each barrier comes with a short description. **Please find a more detailed explanation of the single barriers in the appendix, in case you need it.**

The list of barriers will be followed by a set of statements and questions related to the topic. We will ask you to agree or disagree on a scale from 5 to 0 (strongly agree -strongly disagree).

To summarize the instructions:

1. Use the scale from “0” to “5”
2. Use “0”, when a criterion has absolutely no importance
3. Use “Z”, when you have no opinion on a certain criterion
4. Do not leave any blanks
5. Do not forget to save the pdf after answering the questionnaire

For any questions, please do not hesitate to contact us.

Confidentiality

Your response will be treated confidential and the results are used for academic reasons only.

You may reserve your right to anonymity if you wish to do so. In case you provide us with your details, only the two above mentioned researchers will see your response.

Expert Responder Data

Name:

Company/Ministry/Organis.:

Department/Position:

Country:

Contact:

Email:

Phone:

Which one(s) of the following categories do you perceive to belong to?

☐ Government

☐ Utility

☐ Private Sector

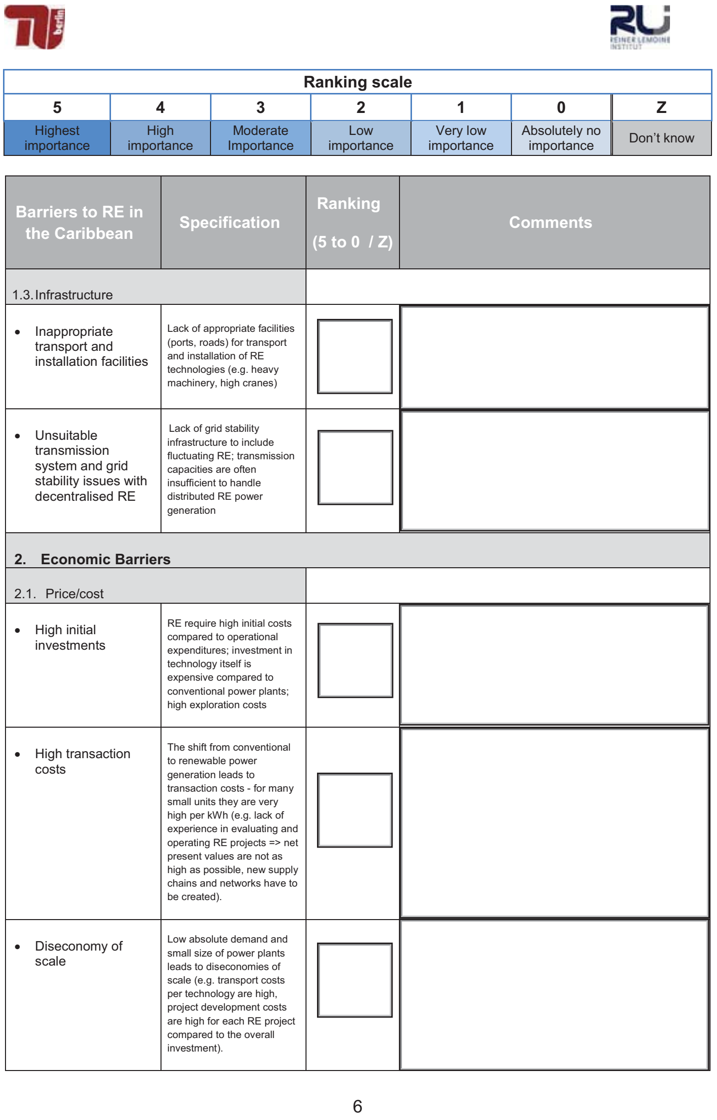
☐ Researcher

☐ Public Organisation

☐ Other (please state):

Ranking scale						
5	4	3	2	1	0	Z
Highest importance	High importance	Moderate Importance	Low importance	Very low importance	Absolutely no importance	Don't know

Barriers to RE in the Caribbean	Specification	Ranking (5 to 0 / Z)	Comments
1. Technical Barriers			
1.1. Natural Conditions			
• Land use competition on islands	Land area is limited on islands, leading to competition between RE projects and e.g. tourism or agriculture => land is getting expensive for RE.	☐	
• RE impact on landscapes and ecosystems	RE projects may affect ecosystems (e.g. hydro power => rivers, wind power => birds). Also noise and visual impacts are considered here.	☐	
• Natural disasters	Natural disasters (e.g. Hurricanes, flooding, earthquakes) increase the risk of destruction of RE plants.	☐	
• Lack of evidence-based assessment of RE potentials	Evidence based analyses on the RE potentials and cost effectiveness of different RE technologies are missing (e.g. comparison of cost, feasibility, levelized cost of electricity) => true potential of REs remains uncertain	☐	
1.2. Technical Constraints			
• Lack of technical expertise and experience	Experience and knowledge at the operation side is missing, especially for complex high share renewable energy supply systems (e.g. electrical engineer with RE experience).	☐	
• Low availability of RE technologies	Non-existence of local manufacturers leads to maintenance issues, spare parts are hard to organise; existing foreign technologies are not adopted to Caribbean needs	☐	



Ranking scale						
5	4	3	2	1	0	Z
Highest importance	High importance	Moderate Importance	Low importance	Very low importance	Absolutely no importance	Don't know

Barriers to RE in the Caribbean	Specification	Ranking (5 to 0 / Z)	Comments
1.3. Infrastructure			
• Inappropriate transport and installation facilities	Lack of appropriate facilities (ports, roads) for transport and installation of RE technologies (e.g. heavy machinery, high cranes)	☐	
• Unsuitable transmission system and grid stability issues with decentralised RE	Lack of grid stability infrastructure to include fluctuating RE; transmission capacities are often insufficient to handle distributed RE power generation	☐	
2. Economic Barriers			
2.1. Price/cost			
• High initial investments	RE require high initial costs compared to operational expenditures; investment in technology itself is expensive compared to conventional power plants; high exploration costs	☐	
• High transaction costs	The shift from conventional to renewable power generation leads to transaction costs - for many small units they are very high per kWh (e.g. lack of experience in evaluating and operating RE projects => net present values are not as high as possible, new supply chains and networks have to be created).	☐	
• Diseconomy of scale	Low absolute demand and small size of power plants leads to diseconomies of scale (e.g. transport costs per technology are high, project development costs are high for each RE project compared to the overall investment).	☐	

Ranking scale						
5	**4**	**3**	**2**	**1**	**0**	**Z**
Highest importance	High importance	Moderate Importance	Low importance	Very low importance	Absolutely no importance	Don't know

Barriers to RE in the Caribbean	**Specification**	**Ranking (5 to 0 / Z)**	**Comments**
2.2. Financial Aspects			
• Lack of access to low cost capital or credit	Due to large foreign debt and high interest rates of Caribbean countries, capital costs are high, which leads to a limited borrowing capacity of governments.	☐	
• Lack of understanding of project cash flows from financial institutions	Little or no funding is available from commercial banks due to a lack of understanding and/or pilot or demonstration RE projects that results in risk averseness.	☐	
• Lack of private capital	Insufficient investment and innovation from private sector. Previous projects have often been reliant on donor money.	☐	
2.3. Market Failure/distortion			
• Utility monopoly of production, transmission and distribution of electricity	Barrier to market entrance for RE investors; monopolistic structures hinder competition and innovation.	☐	
• Small market sizes	Due to small market sizes new competitors have difficulties to join the energy market => barrier to competition and investment opportunities	☐	
• Lock-in dilemma (conventional energy supply structures block REs)	The lock-in dilemma describes the situation that an existing technology cannot be substituted by the better innovation due to institutional bias and power structures of the old system => competitive RE technologies are not adopted due to the influence and power of existing conventional power supply systems	☐	

Ranking scale						
5	4	3	2	1	0	Z
Highest importance	High importance	Moderate Importance	Low importance	Very low importance	Absolutely no importance	Don't know

Barriers to RE in the Caribbean	Specification	Ranking (5 to 0 / Z)	Comments
• Fossil fuel subsidies and fuel surcharge	Conventional power systems are often subsidised or governmentally supported (e.g. high electricity tariffs due to fuel surcharge are reduced by subsidies). This results in price/competition distortions and disproportional consumer burden	☐	
3. Political Barriers			
3.1. Policy			
• Gap between policy targets and implementation	Most Caribbean countries have ambitious RE policy targets. Nevertheless, these RE goals are not pushing the practical implementation and a failure to meet them has no legal consequences => enforcement of targets is too weak.	☐	
• Lack of incentives or subsidies for RE	Lack of incentives for RE (e.g. governmental financed feed-in tariffs, tax reductions for RE)	☐	
3.2. Institutional Capacity			
• Lack of formal institutions	Lack of specialised government departments to disseminate information and foster investment within RE; Multi-purpose ministries cannot focus on RE.	☐	
• Lack of RE experts on governmental level	Lack of experts on government level; politicians lack specialisation and RE knowledge	☐	
3.3. Regulatory			
• Lack of legal framework for IPPs and PPAs	A regulatory framework for independent power producers that secures grid-connection and return on investment for RE projects is missing on a Business to Business level.	☐	

Ranking scale						
5	**4**	**3**	**2**	**1**	**0**	**Z**
Highest importance	High importance	Moderate Importance	Low importance	Very low importance	Absolutely no importance	Don't know

Barriers to RE in the Caribbean	**Specification**	**Ranking (5 to 0 / Z)**	**Comments**
- Lack of regulatory framework and legislation for private investors	A regulatory framework for private investors is missing to secure grid-connection and return on investment of RE projects (e.g. net-metering). Application processes are not standardised and too bureaucratic.	☐	
4. Social Barriers			
4.1. Consumer Behaviour/ Awareness			
- Lack of social norms and awareness	Acceptance and education about RE technology is missing. Full potential of REs is not understood by citizens.	☐	
- Lack of educational institutions	Lack of educational institutions (e.g. vocational training centres, colleges, universities) focusing on RE. This leads to a lack of RE experts.	☐	
4.2. Interaction Networks			
- Lack of RE initiatives	Strong local initiatives pushing the implementation of REs are missing. Informal institutions are dominated by the conventional energy supply system.	☐	
- Lack of local/national champions/ entrepreneurs	Lack of role models creating best practice examples by implementing REs (e.g. well-known personalities have positive advertisement and marketing effects for RE	☐	
- Strong fossil fuel lobby	The profiteers of existing fossil fuel (conventional) energy supply system are afraid of losing market shares. Strategic sale of diesel generators and oil to secure the conventional power supply; political agreements within PETROCARIBE bind states to buy in more oil	☐	

Ranking scale						
5	**4**	**3**	**2**	**1**	**0**	**Z**
Highest importance	High importance	Moderate Importance	Low importance	Very low importance	Absolutely no importance	Don't know

Barriers to RE in the Caribbean	**Specification**	**Ranking (5 to 0 / Z)**	**Comments**
4.3. Cultural			
• Dominance of cost over environmental issues	Electricity is a basic need. People are highly price sensitive and outweigh environmental considerations.	☐	
4.4. Psychological/Moral			
• Preference for status quo	Negative experiences with RE in the past hindering innovative projects. The existing operational status quo is preferred.	☐	

Comments/Remarks:

Please precede to the last set of statements that complete the questionnaire.

Ranking for Statements					
5	**4**	**3**	**2**	**1**	**Z**
Strongly agree	Agree	Neither/ Nor	Disagree	Strongly disagree	Don't know

Statement	**Ranking**
The Caribbean is adversely affected by Climate Change.	
In the future, the Caribbean will be adversely affected by Climate Change.	
The Caribbean Community holds responsibility for mitigating Climate Change.	
Renewable Energy is a central instrument to reduce GHG emissions.	
RE is a central instrument to create energy sovereignty in the Caribbean.	
CARICOM's target to achieve a 47% renewable energy share in electricity production by 2027 is realistic under current ***political*** conditions.	
CARICOM's target to achieve a 47% renewable energy share in electricity production by 2027 is realistic under current ***economic*** conditions.	
CARICOM's target to achieve a 47% renewable energy share in electricity production by 2027 is realistic under current ***social*** conditions.	
CARICOM's target to achieve a 47% renewable energy share in electricity production by 2027 is realistic under current ***technical*** conditions.	
Authorities at the moment are successful at increasing RE shares in electricity production.	
Private investors are reluctant to engage with RE.	
Utilities dominate fossil fuel based national energy markets.	

Personal Statement	**Ranking**
My job is to facilitate the implementation of RE.	
I maintain relationships with all stakeholders of the energy industry.	
The advancement of RE is a central task in my current position.	
Part of my work is to facilitate the affordability of electricity produced through RE.	
Part of my work is to facilitate the integration of RE into the existing grid infrastructure.	

Further Proceedings

To return the questionnaire, you have the following options:

- You can fill out the answering sections directly in this document, then save the changes and upon completion return it via email to either

  philipp.blechinger@rl-institut.de

  or

  katharina.richter@rl-institut.de

- You can print out the form, fill out the blanks per hand and then scan and email the document to the above mentioned addresses

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  Fax.: +49 30 5304 2010

Would you like to receive the final version of this study?

☐ yes
☐ no

And finally, thank you very much for your participation.

Appendix – Clarification of barriers

Technical Barriers

Natural Constraints:

1.1.1. Land use competition on islands

Due to the small expansion of the Caribbean islands territories, land and water resources that are suitable for RE compete with mostly tourism, but also agriculture. As a result, prices for land are very high. A RE development might therefore face challenges with respect to land availability. These effects are summarised under "land use competition" and have to be evaluated according to their importance as a barrier for implementing REs.

1.1.2. RE impact on landscapes and ecosystems

RE projects may give rise to environmental externalities. That is to say, regardless of their aim of producing clean and emission-free energy, RE projects might have negative effects on the environment. Examples include migratory bird disturbances and noise pollution from wind parks, toxic spills and deforestation from geo-thermal drilling, disturbance of hydrological ecosystems from hydro power. Similarly, there is a large visual impact from wind turbines, which could devalue land and hinder its development not only in a touristic zone. These effects are summarised under "RE impact on landscapes and ecosystems" and have to be evaluated according to their importance as a barrier for implementing REs.

1.1.3. Natural disasters

The vulnerability of the Caribbean to hurricanes, flooding and earthquakes increases the risk of RE projects, and might therefore deter investors. Within this barrier, the importance of these effects on the implementation of REs in the Caribbean has to be evaluated.

1.2.3. Lack of evidence-based assessment of RE potentials

To this date, no sufficient feasibility and potential studies comparing costs of RE have been conducted. There is a lack of applied research that would lead to evidence-based strategies for political decision-makers to foster the implementation of RE projects. Similarly, there is a lack of assessments that compare project costs and the levelized cost of electricity for different RE technologies, for example between hydro and geo-thermal power. Under these circumstances, the true potential for RE remains uncertain, and therefore untapped. The lack of these studies has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

Technical Constraints:

1.2.1. Lack of technical expertise and experience

RE hybrid systems are difficult to understand and operate. Especially high share RE systems require newly developed operation tools and technologies which require different expertise compared to conventional combustion power plants. The lack of experience with this kind of technology at the operational side can lead to miscalculation and failed investments. This lack has to be evaluated according to its importance as a barrier for implementing RE in the Caribbean.

1.2.2. Low availability of RE technology

There are no local manufactories for RE technologies in the Caribbean. As a consequence, maintenance becomes more difficult, both in practical and financial terms. Similarly, spare parts might be hard to organise. Small Island Developing States have therefore been described as “takers of technology”. However, the technology that is available to them via import is often not adapted to specific Caribbean needs. This could apply to for example the sizes of wind turbines and their survival wind speed. Availability of RE technology hence refers to both the original purchase and organisation, as well as to the suitability of the technology to the Caribbean islands systems. The missing availability of locally adopted technologies has to be evaluated according to its importance as a barrier for implementing RE in the Caribbean.

Infrastructure Constraints:

1.3.1. Inappropriate transport and installation facilities

Small Caribbean states lack the infrastructure to transport large RE equipment such as wind turbines, drilling equipment etc. to their destination. In particular, the lack of well-developed roads and ports pose a restraint on the implementation of RE projects. Additionally, heavy machinery and high cranes for the installation of RE plants are lacking. These infrastructural constraints have to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

1.3.2. Unsuitable transmission system and grid stability issues with decentralised RE

The current state of most islands’ transmission system inhibits a high RE share through low transmission capacities and a lack of grid stabilisation facilities. The grid stability is threatened by voltage and frequency fluctuations caused by especially variable renewables such as wind or solar. Furthermore, issues of energy storage and how to best meet consumer demand complicate the wide-spread application of RE. This technical issue of integrating fluctuating renewable resources into the existing grid has to be evaluated according to its importance as a barrier for implementing RE in the Caribbean.

Economic Barriers

Price and Cost:

2.1.1. High initial investments

RE technologies require large up-front payments compared to conventional diesel generators. As such, their initial costs are far higher than their operational expenditures. Geo-thermal especially has very high exploration costs. This cost structure of REs requires an evaluation of its relative importance compared to other barriers to implementing RE in the Caribbean.

2.1.2. High transaction costs

Transaction costs are the costs other than the money price associated with the sale of energy/electricity from the producer to the consumer. In the case of the shift from conventional to renewable power generation, these may involve exploration costs, bargaining costs for negotiating Power Purchase Agreements, grid extensions to connect RE systems, the creation of new supply chains and networks and so on. Naturally, these costs rise per kWh for many small units such as solar or wind terminals, especially when compared to the cost of a single large power plant. The lack of experience of evaluating and operating RE projects leads to a further increase in these costs. High transaction costs of RE have to be put in perspective and ranked according to their importance in relation to other RE barriers in the Caribbean.

2.1.3. Diseconomy of scale

There are several scaling factors that render the investment and implementation of RE in the Caribbean costly. Due to small island populations, the absolute demand is not high enough to achieve economic advantages from the economy of scale, i.e. producing more energy at cheaper cost. This is further inhibited by the small size of RE systems that leads to high installation and project development costs for each single small plant. As a result, electricity is produced at increasing cost per unit of energy compared to centralised large scale power plants. The effect of diseconomies of scale has to be evaluated in its importance as a barrier to RE in the Caribbean.

Financial Aspects:

2.2.1. Lack of access to low cost capital and credit

Caribbean governments experience a limited borrowing capacity as a result of their large foreign debts and high interest rates, which increase the price of capital. Financial resources to support RE developments are therefore limited. In addition, commercial banks require high interest rates from their customers, which increases the capital costs for RE projects. High interest rates and lack of access to credit have to be evaluated according to their importance as barriers to the implementation of RE in the Caribbean.

2.2.2. Lack of understanding of project cash flows from financial institutions

Financial institutions, especially commercial banks, are reluctant to provide funding for RE projects. In this respect, they act very risk averse due to a lack of understanding and knowledge about RE project cash flows. The lack of pilot projects and demonstrations inhibits a large-scale recognition of RE as viable investment opportunity. The lack of understanding and inability to assess RE project cash flows from financial institutions have to be ranked according to their significance as barriers to RE in the Caribbean.

2.2.3. Lack of private capital

There is insufficient investment and innovation from the private sector because of a limited purchasing and investment power within small Caribbean island states. In order to take off, RE projects in the past mainly relied on donor money from development banks or the Caribbean Renewable Energy Programme CREDP. Hence the absence of local private capital for RE projects has to be evaluated according to its negative impact on RE development in the Caribbean.

Market Failure/Distortion:

2.3.1. Utility monopoly of production, transmission and distribution of electricity

On most islands, the electric utility, may it be public, private or mixed, holds the monopoly for the generation and distribution of electricity. As a result, grid extension, for example, is performed by the utilities that tend to extend one big grid instead of creating several smaller ones, which are more suitable for variable renewables. This monopoly position gives the utility much bargaining power with respect to handing out permissions to connect renewables to the grid, and makes it hard for investors or independent power producers to enter the market. It acts as major market distortion, and inhibits competition in the area of electricity production, ultimately hindering the development of small and large scale RE production. The monopolistic structure of the energy supply market in Caribbean island states ought to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

2.3.2. Small market sizes

Due to their small market sizes, Caribbean island states are very dependent on the international market with respect to interest rates and investment conditions, which in turn creates an unstable investment climate within the islands. Small markets furthermore impede competition for small-scale power producers and present less business opportunities than larger ones. RE investors consequently struggle to set a foot in the door. The small size of the single countries, as well as the respective size of the power generation sector has to be put in relation with other barriers that impede RE development in the Caribbean.

2.3.3. Lock-in dilemma (conventional energy supply structures block REs)

The current energy system in the Caribbean is based on imported fossil fuels, and has been for most of the 20th century. Public institutions, trade agreements, inter-state economic transactions, subsidies, infrastructure, import quotas, electricity generation systems, political concessions etc. are all set up to support this system. Accordingly, there is an institutional and technological bias towards conventional fossil forms of energy. This lock-in refers to the inability to adopt innovation in the form of RE, due to the imperfect competition that arises out of the favouring of conventional forms of energy through the above mentioned mechanisms. Furthermore, a lack of research and development culture, which actively promotes RE, aggravates this lock-in. In order to implement RE, investors and entrepreneurs have to break these formal and informal structures that are in place, and for example negotiate tax breaks, power purchase agreements, the permission to connect their power plant to the national grid, etc. This is a lengthy and costly process, which could represent a hurdle for the wide-spread application of RE. The lock-in dilemma within the energy supply sector has to be ranked according to its importance within other barriers to RE in the Caribbean.

2.3.4. Fossil fuel subsidies and fuel surcharge

Since the Caribbean economies are dependent on the import of oil and gas, governments provide large-scale subsidy payments to enable their cheap purchase and stimulate the economy (e.g. within the Petrocaribe contracts). This market distortion results in a competitive advantage of fossil fuel based energy over RE and acts as major barrier to their deployment. Furthermore, to guarantee their revenue stream despite fluctuating world oil prices, governments allow for a fuel surcharge on behalf of the utilities. As the fuel surcharge is connected to the amount of fuel used within the power generation, it sets no incentives to invest into fuel saving technologies such as REs. The fuel surcharge and additional subsidies on fossil fuels have to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

Political Barriers

Policy Constraints:

3.1.1. Gap between policy targets and implementation

Most Caribbean island states have outlined a renewable energy roadmap and already have in place specific policy to increase the share of RE. CARICOM member states for example have committed to an increase in the share of renewables to 47% of their electricity production by 2027. In reality, however, too little is done to achieve these targets. The lack of enforcement mechanisms furthermore weakens these ambitions. The gap between policy targets and implementation of RE has to be evaluated in its importance as one of the barriers to implementing RE in the Caribbean.

3.1.2. Lack of incentives or subsidies for RE

Government incentives and subsidies, for example in the form of feed-in tariffs or tax reductions would push the implementation of REs. The lack of such incentives has to be evaluated according to its significance as one of the barriers to RE development in the Caribbean.

Institutional Capacity:

3.2.1. Lack of formal institutions

Within Caribbean governments, there is a lack of specialised energy departments or ministries, which serve to disseminate information and foster investment through the promotion of RE. Multi-purpose ministries impede RE specialisation within the energy sector in government. The lack of formal institutions focusing on REs has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

3.2.2. Lack of RE experts on the governmental level

There is a lack of RE experts on the government level. Importantly, politicians themselves lack the specialisation and knowledge that is required to effectively deal with RE matters, also partly due to the small population sizes on these islands. Hence there is an overall capacity deficit within the ministries that impedes the development of RE. This lack of RE expertise on the governmental level has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

Regulatory Constraints:

3.3.1. Lack of legal framework for IPPs (Independent Power Producers) and PPAs (Power Purchase Agreements)

The lack of a legal framework for IPPs and PPAs on a business to business level severely constrains the development of RE, since negotiations take time, are subsequently not bound by law and hence might be infringed upon. The lack of oversight and regulation can lead to arbitrary decisions with regards to connecting power producers to the public grid and guaranteeing their price, and thus can discourage investment in RE. The lack of a legal framework for IPPs has to be evaluated according to the importance in relation to other barriers to the implementation of RE in the Caribbean

3.3.2. Lack of regulatory framework and legislation for private investors

There is a lack of a regulatory framework for private investors to secure grid-connection and the net return on investment of RE projects (e.g. net-metering). Application processes are not standardised and too bureaucratic. This can lead to high upfront costs for private investors and unsecure cash flows. The lack of a legal framework for private investors to install and produce RE has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

Social Barriers

Consumer Behaviour/ Awareness:

4.1.1. Lack of social norms and awareness

The region lacks acceptance and education about available technologies, green energy and access to RE on the consumer side. On the business side, awareness and information is lacking as well with regards to rates of return and interest rates for RE projects, thus impeding private and small-scale RE development. The full ecological and economic potential of RE is not understood by the people. This deficit in awareness has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

4.1.2. Lack of educational institutions

Due to small population sizes, the region lacks trained staff for the implementation and operation of RE, both in the private and public sector. The lack of vocational training centres, colleges and universities that focus on RE leads to a lack of RE in the region. As a result, there is no institutionalised learning with regards to RE, and technology transfer centres that could enable learning processes and provide access to expertise are lacking. The lack of educational institutions creating RE knowledge has to be evaluated with regards to its importance as a barrier to the implementation of REs in the Caribbean.

Interaction Networks:

4.2.1. Lack of RE initiatives

The current fossil fuel based system has produced a very static stakeholder network when it comes to the energy production sector, which is dominated by this conventional energy supply system. Consequently, innovation and adaptation of RE fall short with respect to the incitement of strong local initiatives and the creation of new, RE stakeholder networks. This lack of RE initiatives has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

4.2.2. Lack of local or national champions/entrepreneurs

RE could be pushed very much by influential individuals regardless of the existing framework conditions. The absence of role models when it comes to RE initiatives implies an absence of best practice examples. Well-known personalities yield significant power to advertise RE and provide an information platform for more investors. The lack of local champions pushing REs has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean

4.2.3. Strong fossil fuel lobby

Due to the large amounts of oil imports, there is a strategic sale of diesel generators and oil on behalf of oil companies to secure the conventional power supply. These profiteers have significantly more resources available for the representation of their interests on decision-making levels than for example solar technology providers do. Furthermore, politically binding agreements within PETROCARIBE oblige or have obliged Caribbean states to continue crude oil purchases from Venezuela, in turn furthermore disincentivising the development of RE. The influence of the strong fossil fuel lobby has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

Cultural:

4.3.1. Dominance of cost over environmental issues

The real and perceived need for accelerated economic development outweighs ecological considerations of dwindling natural resources of oil and gas. Therefore, fossil fuel based electricity production is the currently dominant form of energy on Caribbean islands. At the same time, citizens are very price sensitive and make demands for their source of energy based on its consumer end price, rather than its environmental friendliness. Their basic need is to have cheap electricity, which could be endangered by REs. The focus on economic and not ecological issues from the customer side has to be ranked in its importance as a barrier for implementing RE in the Caribbean.

Psychological/moral:

4.4.1. Preference for status quo

Negative experiences with RE in the past might affect the public’s acceptance of these technologies in a negative way. In effect, this is to say that the willingness to change an existing functioning system is decreasing. The operating conventional system can be preferred compared to the new and unknown RE system. This preference has to be evaluated according to the importance as a barrier for implementing RE in the Caribbean.

99 % of the electricity supply on Caribbean islands is currently provided by fossil fuel based power plants which is very expensive and polluting. The use of renewable energy technologies can be a cost-effective and sustainable solution to these problems. Implementing renewable energies has been rather slow despite sufficient natural resources. This has guided the two main research questions of this PhD thesis: (1) What is the techno-economic potential for renewable energies on Caribbean islands and (2) which barriers and solutions exist in the utilization of this potential?

Firstly, a technical analysis was conducted based on a self-developed island energy supply model. 60 of the 62 analyzed islands demonstrate high to very high techno-economic potential for implementing renewable energies. The optimal renewable energy share is 45 % as opposed to the current 1 %, which would result in a decrease in LCOE from 0.30 to 0.22 USD/kWh and the added benefit of a 22m tons per year decrease in CO2 emissions. Initial investments of 35bn USD are required to reach the optimized renewable capacities in GW: 0.8 hydro, 8.8 PV, 6.3 wind, and 0.5 geothermal plus 3,120 MWh of battery storage.

Empirical analyses were conducted to answer the second research question. The most important barriers are distributed among three main clusters. The 1st cluster is regulatory frameworks and policies, for example lack of regulatory framework and legislation for private investors. The 2nd is costs and financing, of which high initial investments is the most important barrier. The 3rd cluster is the clout of conventional power suppliers. To overcome these barriers most crucial are improvements to the regulatory frameworks, incentives such as a , “renewable fuel surcharge”, and financing options.

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