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Renewable energy in Small Island Developing States (SIDS)

Modeling PV/Diesel hybrid systems in the Maldives

Master´s Thesis

of

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submitted in the partial fulfillment of the requirements for the Degree of MSc in Natural Resources Management and Ecological Engineering

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Thanks!

„Mehr als die Vergangenheit interessiert mich die Zukunft, denn in ihr gedenke ich zu leben“

» I am more interested in the future than in the past, because I intend to live in it«

Albert Einstein (1879 – 1955)

Abstract

Despite the abundant potential for electricity production from natural renewable resources, the development of renewable energy (RE) systems in small island developing states (SIDS) such as the Maldives is still at the beginning. Electricity production in SIDS depends almost entirely on fossil fuel imports. Against the background of rising crude oil prices and climate change to which SIDS are especially vulnerable, more and more efforts are put into the widespread implementation of renewable energy. A crucial precondition for the design of renewable energy systems in SIDS is the knowledge of the cost-minimal system configuration. The aim of this thesis is to determine the optimal PV/Diesel hybrid system configurations with and without storage for three case study Islands in the Republic of Maldives. In addition, Swimsol/Diesel/hybrid systems with and without storage are investigated. Swimsol is a floating solar platform in prototype stage being specially designed for the usage on the sea surface in shallow lagoons of tropical islands. The technical performance and economic viability of PV and Swimsol hybrid systems are modeled using HOMER, an optimization model for renewable energy systems developed by the National Renewable Energy Laboratory (NREL). Moreover, the conditions for renewable energy development in the Maldives are examined with stakeholder interviews and desktop research to identify barriers for development. The model results show that PV and Swimsol/Diesel hybrid systems are more economically viable than the current diesel stand-alone systems. Furthermore, it was found that PV/Diesel/Battery hybrid systems achieve considerable savings in diesel fuel and CO_2 emissions at even lower Net Present Cost than the current diesel stand-alone systems. Swimsol/Diesel/Battery hybrid systems were found to be slightly more expensive than the diesel stand-alone systems. However, if diesel prices increase, Swimsol hybrid systems with battery storage become cheaper than diesel stand-alone systems as well.

Kurzfassung

Trotz ausgezeichneter Voraussetzungen für den Einsatz von erneuerbaren Energien, ist dieser in kleinen Insel-Entwicklungsstaaten wie den Malediven noch sehr gering. Die Stromproduktion in diesen Inselstaaten ist nahezu 100%ig von Importen fossiler Energieträger abhängig. Aufgrund steigender Rohölpreise und fortschreitendem Klimawandel, werden vermehrt Bemühungen in die Verbreitung erneuerbarer Energien gesetzt. Eine wichtige Voraussetzung für die Planung erneuerbarer Energiesysteme ist die Kenntnis über kostenminimale und bedarfsgerechte Konfigurationen. Das Ziel dieser Arbeit ist es, optimale Konfigurationen für Photovoltaik/Diesel Hybrid Systeme mit und ohne Batteriespeicher zu identifizieren. Dabei werden drei maledivische Inseln genauer untersucht. Zusätzlich werden Swimsol/Diesel/Hybrid Systeme mit und ohne Speicher erforscht. Swimsol ist eine schwimmende Solarplattform im Prototypenstadium, welche speziell für den Einsatz in flachen Lagunen tropischer Inseln entwickelt wird. Die Wirtschaftlichkeit und technische Effizienz von PV/Swimsol Hybrid Systemen wird mit Hilfe von HOMER, einem Optimierungsmodell für erneuerbare Energiesysteme, untersucht, welches vom National Renewable Energy Laboratory entwickelt wurde. Außerdem werden die Rahmenbedingungen für erneuerbare Energien in den Malediven näher untersucht und Barrieren für die Umsetzung erneuerbarer Energie-Projekte identifiziert und beurteilt. In Bezug auf die Optimierungsergebnisse kann gezeigt werden, dass sowohl PV- als auch Swimsol Diesel Hybrid Systeme wirtschaftlicher als die derzeitigen Dieselsysteme sind. PV/Diesel Hybrid Systeme mit Batteriespeicher können die Lebenszykluskosten deutlich reduzieren und gleichzeitig beträchtliche Mengen an Diesel und CO_2 Emissionen einsparen. Die Kosten für Swimsol/Diesel/Batterie Systeme waren geringfügig höher als die Kosten für die derzeitigen Systeme. Bei steigenden Dieselpreisen werden jedoch auch Swimsol Hybrid Systeme mit Batteriespeicher wirtschaftlicher als derzeitige Dieselsysteme.

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1 Introduction

Despite the huge potential for energy production from renewable resources, the development of renewable energy technologies in small island developing states (SIDS) in the tropics is still at the beginning. Nearly 100% of the electricity production in countries like the Maldives and the pacific island countries is fuelled by non-renewable resources, mainly diesel fuel. The dependency on fossil fuel imports and the resulting vulnerability to price fluctuations along with the export of foreign currency are not advantageous for future socio-economic developments (Weisser, 2004). The reasons for the low contribution of renewable energy technologies to electricity production in these countries are multifaceted. Without international financial aid, high capital costs can make renewable energy technologies unaffordable (Weisser, 2004; Ministry of Environment and Energy, 2012). The intermittent energy supply of renewable energies such as wind or solar and relatively high prices for power storage pose challenges on sustainable future energy planning. Energy policies and legislative frameworks are often not suitable to attracting foreign direct investment in renewable energy (RE) and the local knowledge about renewable energy technologies to contribute to electricity production is scarce (van Alphen, 2004; Government of Maldives, 2009; UNDP, n.d). Against the background of climate change and volatile oil prices, the issue of renewable energies in developing countries has become more and more relevant in the national and international context of policy making and energy planning. A crucial precondition for renewable energy use in small island developing states is the knowledge about the cost-minimal energy system design.

The major aim of this thesis is to identify the cost-minimal energy mix for different types of islands within the Maldives. With the use of HOMER - a hybrid energy system modeling software developed by the U.S. National Renewable Energy Laboratory (NREL), Photovoltaic (PV)/Diesel/battery hybrid systems are modeled using the example of Maldivian islands. The simulations shall answer the following questions:

- *What is the cost-minimal PV/Diesel hybrid system with and without battery storage?*

- *What is the cost- minimal Swimsol/Diesel hybrid system with and without battery storage?*
- *What are the key parameters that influence the optimal system configurations?*

Former studies on renewable energies in the Maldives carried out by van Alphen (2004), van Alphen, van Sark and Hekkert (2007), Camerlynck (2004), Mohamed (2012) and Kesterton (2010) examined the potential of renewable energy on the basis of data of the main island Male and a range of outer islands with up to 1,500 inhabitants. This thesis focuses on types of islands which were not taken into account by the other studies. Namely, the energy systems of Maafushi, an island that belongs to the category 1,500 - 2,500 inhabitants, Hulhumale´ with 15,000 inhabitants as well as a resort island are surveyed in this thesis. The latter island type is responsible for more than 50% of the country´s energy consumption and is therefore regarded as critical to reduce diesel consumption and CO_2 emissions of the Maldives. Moreover, this thesis can be seen as an actualization of the findings of previous studies on renewable energy deployment in the Maldives. It is expected, that changes in prices for crude oil, photovoltaic components and energy storage components as well as increased energy usage will lead to quite different results compared to the findings of the former studies. Only first hand up to date price information derived from Swimsol GmbH, the solar company the author is working in is used. In addition to desktop research, general information on the Maldives, information on its energy sector and the conditions for renewable energies has been derived from interviews with stakeholders and experts during my visits to the Maldives.

Due to the fact that former studies have shown that more than two renewable energy generation technologies cause operational problems in Remote Island States (van Alphen, 2007) and because of the resource endowment of the Maldives, this thesis focuses on the modeling of PV/Diesel hybrid systems with and without storage. PV stand-alone systems are not considered as the cost for storage is still too high to be competitive against diesel stand - alone systems. In addition to land-based PV systems, Swimsol, a floating PV-energy platform, is introduced and modeled in HOMER. Furthermore, the national energy legislation and regulatory requirements in the Maldives and the effects on RE development is briefly illustrated as well.

The structure of the thesis is as follows. After the introduction, chapter 2 sets the scene for this thesis. Background information on the country is given. Geographic and socio-economic data are presented and prevailing trends are illustrated. In addition, an overview of the electricity market in the Maldives is given and electricity production and consumption patterns as well as costs of energy supply and electricity prices are presented. The chapter concludes with a general idea of the resource endowment of the Maldives. Chapter 3 provides the reader with an introduction to photovoltaic energy, its underlying principles and the functioning of a solar PV energy system. Swimsol, the floating solar energy platform in prototype stage, is presented in more detail. The methodology is introduced in chapter 4.1, while the case study islands are presented in chapter 4.2. The configuration of the energy systems and the assumptions and model inputs are presented in chapters 4.3 and 4.4. In chapter 5, chapter 6, and chapter 7 the optimization model results are presented and discussed. A sensitivity analysis shows how the optimization model results are influenced by some of the key parameters. Chapter 7.2 deals with the conditions to renewable energy in the Maldives. In this chapter, former initiatives to spread renewable energy technologies in the Maldives funded by, amongst others, the EU and the UNDP are reviewed and their outcomes are assessed. Moreover, the current energy policy and potential barriers to renewable energy production are presented and evaluated from a private sector perspective. Chapter 8 concludes the thesis.

2 Background Information

The Maldives is one of the world´s most geographically dispersed countries. The archipelago is comprised of nearly 1,200 small coral islands which are grouped into 26 atolls. These atolls stretch over 860 km in North-South direction in the Indian Ocean, around 1,000 km away from the southern tip of India (see Figure 2.1). The islands are surrounded by coral reefs that protect them from strong waves (Ministry of Home Affairs, Housing and Environment, 2001). Only around 200 of the islands are inhabited by the local population and another 100 islands have been developed as resort islands exclusively for touristic purposes (Ministry of Economic Development, 2012). The population structure of the islands is quite different. 20 islands have a population of more than 2,000 inhabitants, 50 islands are inhabited by 1000 - 2000 inhabitants, 80 islands host between 500 and 1,000 people and 50 islands have a population of less than 500 inhabitants (Figure 2.2) (Ministry of Environment, Energy and Water, 2007).

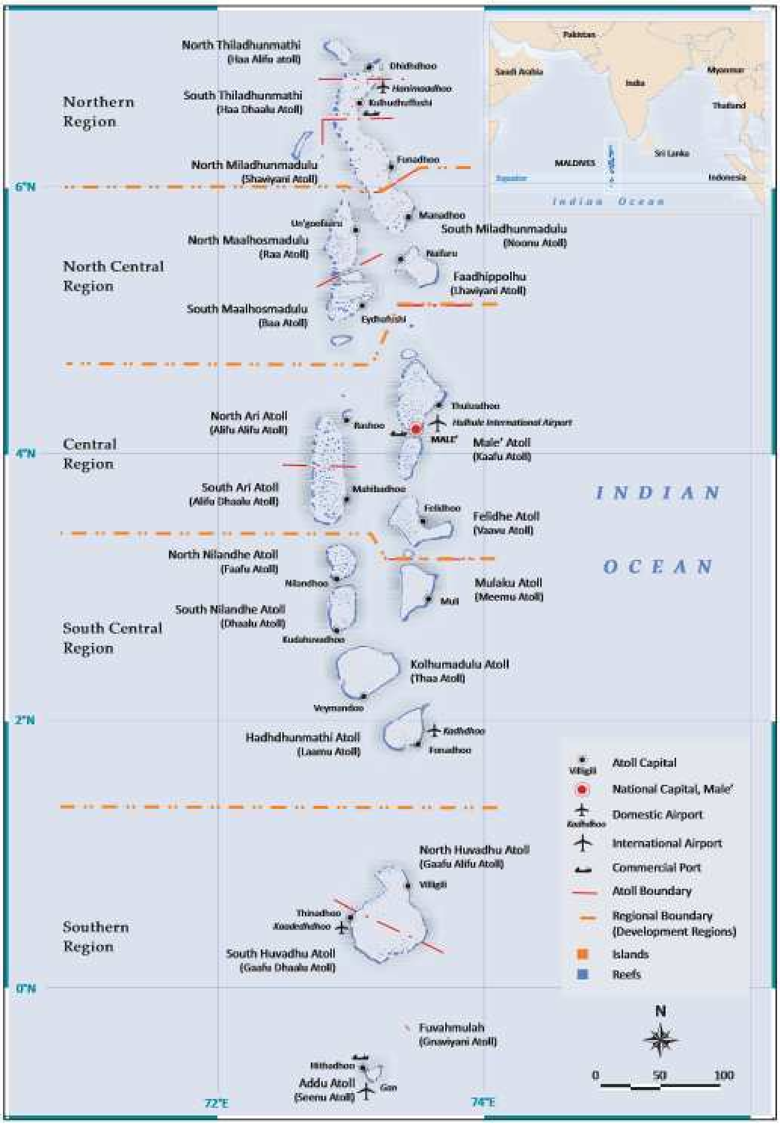


Figure 2.1: Map of Maldives (Ministry of Planning and National Development, 2007)

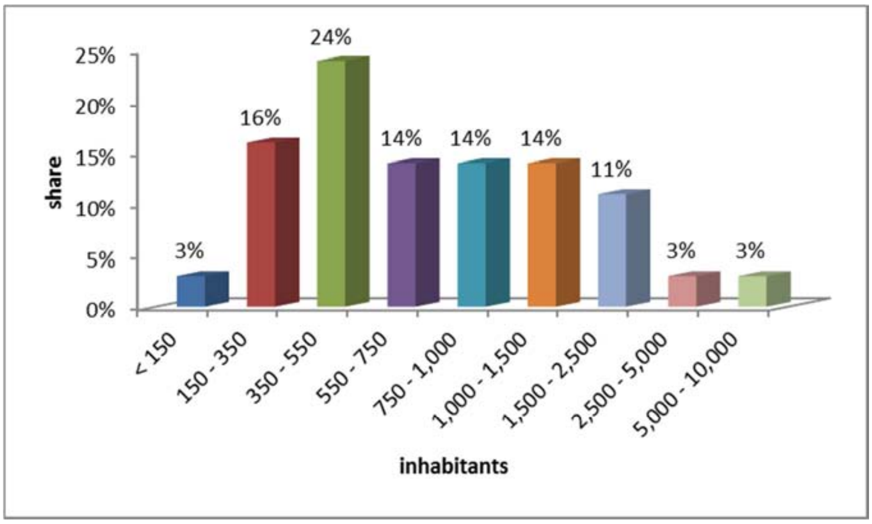


Figure 2.2: Relative breakdown of outer islands according to their population (van Alphen, 2004)

All the islands are very low lying, with over 80% of the land mass lying less than 1 m above sea level. The highest point in the Maldives can be found on the island Viligili, lying 2.4m above sea level (MHAHE, 2001; CIA, 2013).

The Maldivian population – largely Muslim - totaled to 394,451 in July 2012 (CIA, 2013). Nearly one third of the population lives in Male´, the capital of the Maldives and the city with the world´s highest population density (see Figure 2.3 and Figure 2.4). Approx. 100,000 people are living on an island with a total area of 2.5 km^2 (CIA, 2013). The population density of Tokyo, for comparison is around 13,000 inhabitants per km^2 (Welt - Blick.de, 2013).

Figure 2.3: Aearial photo of Male´ (wikimedia.org, 2013)

Figure 2.4: Male´ 2012

The second largest population center is Addu City in the South, with an estimated 19,940 residents (MEEW, 2012). The land mass of the Maldives (300 km^2) comprises only a small portion of the state territory which totals to 859,000 km^2 including ocean territory (UNDP, 2012).

The Maldives are located in the tropical climate zone. The climate is a warm and humid tropical climate dominated by the two monsoon periods with a mean annual temperature of 28.5 °C and a mean annual rainfall of 162.3 mm. The annual average relative humidity is about 80% (MHAHE, 2001).

The biggest contributor to the Maldivian Economy is Tourism. It accounted for 33% of GDP and a quarter of total employment in 2006 (EU, 2007). Figure 2.5 illustrates the correlation between tourist arrivals and GDP quite impressively.

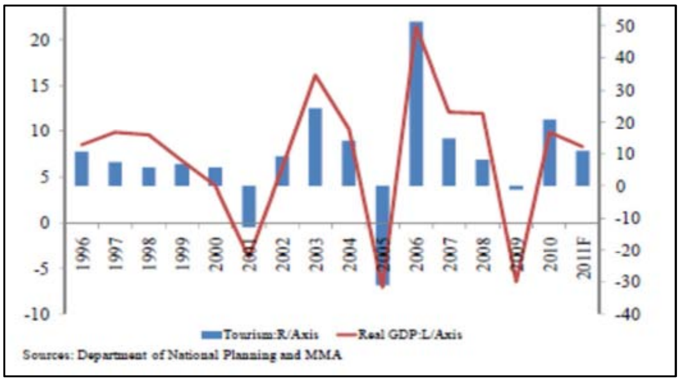


Figure 2.5: Growth in Tourism and GDP (World Bank, 2011, p. 2)

Economic Indicator	2007	2008	2009	2010	2011
per capita GNI, Atlas method	4,610	5,440	5,230	5,750	…
GDP growth (% change per year)	10.6	12.2	-4.7	5.7	7.5
CPI (% change per year)	7.4	12.3	4.0	4.7	9.7
Unemployment rate (%)	…	…	…	…	…
Fiscal balance (% of GDP)	-3.6	-11.2	-21.0	-16.1	-10.2
Export growth (% change per year)	1.2	45.2	-49.0	6.5	-4.3
Import growth (% change per year)	18.3	26.6	-30.3	14.9	17.4
Current account balance (% of GDP)	-28.4	-36	-21.6	-22.3	-31.9
External debt (% of GNI)	59.1	52.2	57.3	53.0	…

Table 2.1: Economic indicators for the Maldives, 2007 – 2011 (ADB, 2011)

Fisheries employed another 19% of the labor force but accounted for only 6% of GDP in 2006. Another 15% of the GDP was earned by industrial activities which mainly consist of garment production, boat building and handicrafts. The remaining share was earned in the services sector. The Gross National Income was $5,750 in 2010. Growth of GDP was between 5-12% per year in the period from 2007-2011, again mainly driven by the tourism sector (see Table 2.1). Agricultural production is limited by the hypercalcic soils as well as scarce land resources (World Bank, 2011).

In 2011, the Maldives graduated from the Least Developed Country Status and has now the status of a developing country (World Bank, 2011). Although GDP growth of 5-12% is quite competitive on an international level, the small size of the Maldivian economy as well as the huge dependency on two sectors - fisheries and tourism - makes the Maldives vulnerable to external shocks. The import dependency of virtually the entire economy causes further dependence on foreign exchange earnings (Ministry of Economic Development, 2012).

2.1 Energy supply in the Maldives

Since the Maldives lacks land based natural resources and the development of renewable energy is just at the beginning, the energy sector is almost completely dependent on fossil fuel imports. In addition, the lack of land limits the possibilities for renewable energy installation. These facts clearly pose challenges to the 2020 goal of carbon neutrality, a goal set up by the former president Nasheed in the year 2009.

In 2006, petroleum products accounted for more than 16% of the total imports in the Maldives (van Alphen, 2007). 7% of GDP was spent on diesel to generate electricity in 2011. Projections for 2020 expect the expenses for oil based imports to be $700 million which would approximately account for 33 - 36% of the GDP (MEE, 2012).

Followed by petrol and jetfuel for transportation purposes, the main contributor with 83% to fossil fuel imports is Diesel for electricity production (see Figure 2.6).

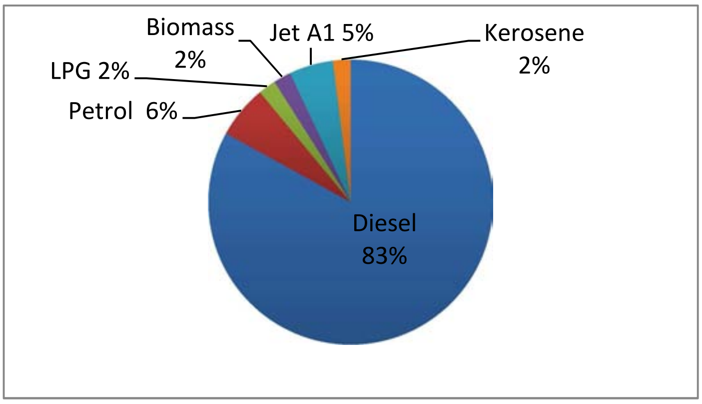


Figure 2.6: Breakdown of energy mix Maldives (MEEW, 2007)

Around 56% of the diesel oil for electricity production is used in the resort islands, 29% is utilized for electricity production by STELCO - the State Electric Company, and the remaining 15% is used in other inhabited islands and for industrial purposes

(MEEW, 2007). While Petrol, Kerosene and jetfuel is used for transportation purposes, LPG and biomass is mainly used for cooking purposes (MEEW, 2007).

According to van Alphen the total installed power of the Maldives in 2004 was 106 megawatts (MW) (van Alphen, 2004). In 2012, the Maldives had a total installed capacity of roughly 240 MW of diesel generators for electricity generation, divided into the three main types of islands (see Table 2.2) (MEE, 2012). That means the installed capacity more than doubled in a period of 8 years.

Types	**Installed Capacity (MW)**
Inhabited Islands	120
Tourism Resorts (estimated)	105
Industrial Islands	20
Total	**245**

Table 2.2: Total installed power of the Maldives, 2012 (MEE, 2012)

The greater Male' region has an installed capacity of 30 MW, with a further 8-10 MW installed for industrial purposes, while government utilities across the island chain have an installed capacity of 18 MW. The tourist resorts privately run another 105 MW of diesel generators (MEE, 2012).

Due to the high transportation costs, the almost total dependency on imported fossil fuels and the small scale of the electricity generation systems, the cost of electricity generation in the Maldives is compellingly high compared to other developing countries (A. Ibrahim, personal communication, January 30, 2013). A more detailed description of the energy prices in the Maldives is given in chapter 2.3.

2.2 The Maldivian Electricity Sector

The Maldivian electricity sector is divided into four distinct sectors and governed by the Maldives Energy Authority (MEA). Besides other duties, MEA regulates the sector and sets technical standards. It is also responsible for the resolution of conflicts between electricity providers and customers (A. Musthafa, personal communication, November 2012). The four sectors named above are the greater Male´ area, the outer islands, the industrial islands and the resort islands (Republic of Maldives, 2012).

Before the beginning of the regularization process of the electricity sector in 2008, four different types of suppliers - the State Electric Company (STELCO), Island Development

Committees (IDCs), Independent Power Producers (IPPs) as well as Non-Government Organizations (NGOs) - provided electricity to their customers (N.N, 2011). Tourist resorts as well as industrial islands have always had their own private power production. IDCs and IPPs supplied power to the inhabited islands apart from the greater Male´ region, which is being supplied by STELCO since 1949 (STELCO, 2009). Generator sizes typically range from less than 100 kilowatt (kW) of installed capacity in the outer islands up to 2-3 MW in the greater Male´ region and the resort islands (N.N, 2011). The fact that nearly all islands have had their own power supply managed by either an Island Development Committee or an Independent Power Producer led to a high degree of fragmentation and a whole range of inefficiencies. Namely, these inefficiencies are lack of technical, financial and managerial capabilities as well as small scale production and high operation and maintenance costs. In 2008, the Government of the Maldives (GoM) set up seven regional utilities to overcome inefficiencies and losses in electricity production, which were caused by lack of knowledge and technical skills as well as to improve the utility services (MEE, 2012). These regional utilities took over most of the power systems that were formerly operated by IDCs and the IPPs. STELCO, as one of the regional utilities remained by far the largest one, supplying Male´ and the surrounding islands (MEE, 2012). Despite various incentives for foreign direct investment and a Call for Expressions of Interest for public-private partnerships (PPP) in the regional utilities in 2009, all utilities remained 100% in state ownership (MEA, 2012).

With the change in government administration in 2012, newly ´elected´[1] President Waheed established a new government owned company named FENAKA Cooperation Limited merging all the regional utility companies apart from STELCO (MEE, 2012). The key objective of FENAKA is to *"ensure sustainable primary services to the populace in the regions of the country other than Male'; supply of clean water, sewerage and electricity, and to establish an environment friendly waste management system"* (Bosley, 2012). To date, FENAKA provides power to 115 out of the around 200 inhabited islands, another 73 islands are still supplied by IDCs and 6 islands are supplied by private power producers. Yet, it is planned that FENAKA will take over all the facilities that are still managed by IDCs or IPPs (MEE, 2012).

[1] Former President Nasheed was dispossessed as the result of a coup in the year 2012

2.3 Electricity generation, supply and consumption

Despite the geographic dispersion of the islands, which, besides other challenges, makes it impossible to connect all islands to one single grid, all Maldivians have access to electricity (MEE, 2012). As indicated, all inhabited islands have their own power supply, mostly accomplished by a central power house with several diesel generators and a mini grid that connects the consumers to the powerhouse. Generally, these systems have not been designed to the highest possible efficiency and most if not all of them are manually controlled. As a result, costs for electricity are high. On islands with industrial activities such as fish canneries or ice making, electricity is produced privately by the factory owners (MEE, 2012). The pictures below shall give an impression of how the power generation facilities look like on the main island (Figure 2.7) and on one of the outer islands (Figure 2.8).

Figure 2.7: STELCO powerhouse in Male´ (MEEW 2007)

Figure 2.8: powerhouse on a local island

In the past, electricity production has been one of the fastest growing sectors in the Maldives. Yearly electricity production in the public sector increased from 29 million kWh in 1990 to over 735 million kWh in 2011 and is expected to grow further (MEE, 2012). The greater Male´ region together with Addu City in the south of the Maldives hosts almost half of the country´s population. Consequently, these two regions account for 50% of the total installed capacity in inhabited islands. The power consumption of Male´ accounts for 72% of the all the electricity produced in inhabited islands (excluding tourist resort islands) and is growing at a yearly rate of 11% (Government of Maldives, 2009). With an average yearly electricity consumption of 1,678 kWh per inhabitant, compared to 400 kWh/inhabitant in the inhabited islands, the Male´ region accounted for the biggest share of the state electricity production (71%) and consumption (~237 GWh) in 2009 (MHE, 2010). There is a close relationship between the ambient temperature and electricity demand in Male´ because of the higher penetration of Air Condition (AC) and the higher cooling demand for refrigeration (Kesterton, 2010). The second biggest region regarding electricity generation was the Southern Province with 29.8 GWh or 9% of the country´s electricity production in 2009, followed by the Upper North province (7%), the Northern Province (6%) and the Upper South Province with 3%. The South Central Province and Central Province accounted for 2% each (see Figure 2.9) (MHE, 2010).

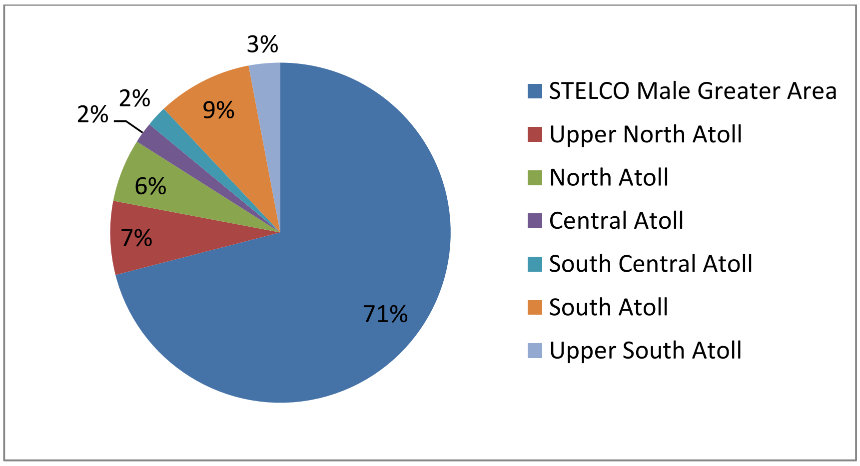


Figure 2.9: Electricity generation by province, 2009 (MHE, 2010)

The 105 islands that are currently exclusively used for touristic purposes all have their private power generation facilities with an estimated installed capacity of 1-2 MW each. Thus the tourism sector directly accounts for around 50% of the country´s total electricity consumption (van Alphen et al., 2008). Estimates from resort islands show the following contributions to electricity consumption: air conditioning ~50%, freezing ~10%, desalination ~10%, lighting ~10%, and laundry 5-20%” (N.N., 2011).

The key drivers of the electricity consumption in private households obtained from a household questionnaire on Maalhos Island, conducted by Kesterton (2010), are in the order of magnitude: refrigeration, household cooling, entertainment equipment, and cooking.

The prices for electricity in the STELCO operated areas (the greater Male´ region) as of July 2012 range between US$ 0.34/kWh and US$ 0.42/kWh (see Figure 2.10) and up to US$ 0.49/kWh in islands like Maafushi, Thulusdhoo, Guraidhoo and Himmafushi (see Figure 2.11), located between 50 and 100 km from Male´ in Kaafu Atoll in the North Central Province (see Appendix for detailed map). Prices for electricity in the outer islands can go up to US$ 1.16/kWh (Government of Maldives, 2009). The STELCO tariffs are structured according to consumption bands and allow for a fuel surcharge every time the price for diesel exceeds a certain price.

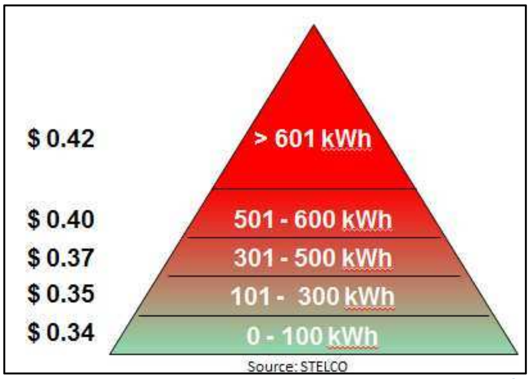


Figure 2.10: Electricity tariff structure Male´, 2012[2]

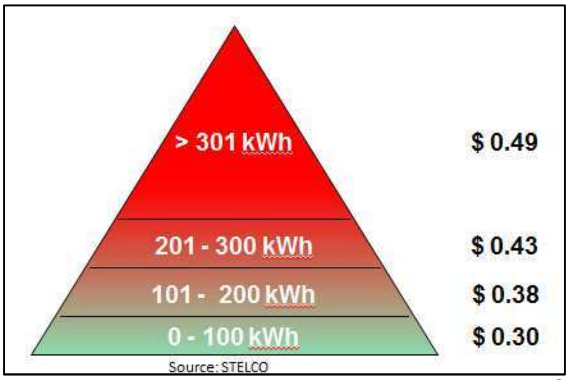


Figure 2.11: Electricity tariff structure Kaafu Atoll, 2012[3]

The pricing structure of electricity is based on the supply costs, but electricity prices in the outer islands are subsidized to lower the price inequalities throughout the country (van Alphen et al., 2008). According to the National Social Protection Agency, a total of $25M/year of fuel subsidies was paid to customers in the year 2011. This amounts to an estimated average of over $0.05/kWh" (MEE, 2012).

With a share of up to 90% of the electricity generation cost in Male´, Diesel is by far the biggest contributor to the retail price of electricity (A. Ibrahim, personal communication, January 2013). This fact causes electricity prices to be unpredictable and highlights the need for renewable energy (RE) installations. However, due to the lack of knowledge and skills as well as financing, the use of renewable energy in the Maldives is minimal (Ministry of Economic Development, n.d.). Apart from sporadic solar water heating in resort islands only few renewable energy pilot projects were carried out with technical and financial help of the United Nations Development Programme (UNDP), the World Bank (WB) and Japan International Cooperation Agency (JICA). These were to test the technical viability of RE installations such as solar and wind power (MEEW, 2007).

2.4 Natural Resource Assessment

To give an overview of the resource endowment of the Maldives, the following chapters present the resources that might be used for future sustainable energy generation.

[2] prices including a fuel surcharge of as of 07/18/2012 http://www.stelco.com.mv/tariff.php
[3] prices including a fuel surcharge of as of 07/18/2012 http://www.stelco.com.mv/tariff.php

2.4.1 Biomass and waste

Due to the limited land area and the hypercalcic soils that prevent intensive agriculture, the biomass resources in the Maldives are very limited (Republic of Maldives, 2012). Although the importation of biomass has been considered and found to be cheaper than diesel, as Mr. Mason, former Energy Advisor of the Maldives stated in Minivan News[4]: *"Biomass generation fits us rather well, as even if the most expensive form of biomass was imported from Canada it would represent 50-66 percent the current cost of diesel. It is cheap but can only be used at scale, such as Male' and possibly Addu […]."(*Robinson, 2011). Although the use of biomass for electricity generation might be cheaper than diesel, there are several problems connected to it. Apart from environmental problems connected to the intensive production of biofuels (soil degradation, biodiversity loss and high pesticide usage) the energy density of biomass is low, so large storage facilities as well as a special wharf to unload it would be needed. Furthermore, biomass has to be kept in dry condition which might pose a problem in the Maldivian Climate. In addition to that, the prices for biomass are expected to increase so energy prices are again not predictable with this renewable energy technology (ADB, 2007). Another option would be the use of seaweed to produce biofuels, but studies on this topic are still at the beginning (Kesterton, 2010).

The collection of waste is hindered by the mere distance between the islands and the low population densities in all areas apart from Male´ and Addu (Republic of Maldives, 2012). Generally, there is no solid waste collection in the outer islands and less than 2% of the islands have a service fee for waste management in place. Although waste to biogas would theoretically be an option for the outer islands, there is no reasonable animal or food waste generation that would allow for an economic operation of such facilities (Kesterton, 2010). In Male´, waste is collected in regular intervals and shipped to Thilafushi – an island approx. 5 km east of Male´. On this island, which is entirely made of garbage, the waste is burned as an open fire (see Figure 2.12).

[4] Minivan News is an English-language news website that according to its statutes provides independent and unbiased coverage of news in the Maldives (http://minivannews.com/about-us)

Figure 2.12: Burning piles of waste on Thilafushi (2013)

2.4.2 Marine energy

The current regime in the Indian Ocean is strongly influenced by the biannual monsoon seasons. The swells and wind waves are conditioned by the monsoon winds, and are typically strongest during the southwest monsoon (MHAHE, 2011). Data from the Maldivian Hydrographic office show that the current speeds of 1.5-2.6 m/s in the channels through the rims of the atolls can be strong enough for marine power generation (CUSP, 2011).

Because former research conducted by Robert Gordon University, Aberdeen, had shown that sufficiently strong marine currents for energy production (>2.5 m/s) do exist in the Maldives, the Scottish Centre for Understanding Sustainable Practice (CUSP) conducted another study on the potential of marine energy usage in the Maldives in 2011. The model used in this study identified several sites that may have large amounts of extractable marine power. However some of them cannot be used for marine energy installations due to environmental protection areas (CUSP, 2011). Even though marine energy has the advantage of being completely submerged and therefore with no visual effects connected to it, the marine currents in the Maldives are driven by the monsoon winds and therefore expected not to be available constantly throughout the year. That is why marine energy technologies have not been considered relevant to the renewable energy development of the Maldives (Republic of Maldives, 2012). However, the current state of knowledge is not sufficient for an ultimate assessment of this resource. As the former Energy advisor Mike Mason stated in Minivan News: *“We can forget ocean currents for now,” he said, explaining that as the currents were wind driven and* *therefore seasonal, marine current generators would only generate significant electricity for half the year"* (Robinson, 2011).

2.4.3 Wind

The wind resource in the Maldives is rather poor. A wind resource assessment of Sri Lanka and the Maldives carried out in 2003 by the U.S National Renewable Energy Laboratory (NREL), found that the average wind speed of 4.5 m/s is "poor to marginal" according to the NREL´s wind power classification (Kesterton, 2010). Generally, the wind pattern is dominated by the monsoon seasons with the strongest winds coming from west / northwest and east / northeast (MHAHE, 2001). Furthermore, the data produced by the NREL of United States of America indicate three wind zones in the Maldives. The region with the highest annual average wind speeds is in the upper middle of the Maldives with a "fair" resource potential (6.4 – 7.0 m/s) according to the wind power classification[5]. This region extends from just north of Male´ to the North Miladhunmadulu Atoll and experiences a stronger northeast monsoon than all other areas (NREL, 2003). It was also found that the maximum wind speeds occur at night by trend (MEEW, 2007). These results indicate that it might be worthwhile to tap these wind resources for power generation alongside with photovoltaics. A 20 MW wind project is contracted for Male´ region but it is not known at what stage the project is at the moment (Republic of Maldives, 2012). During talks with general managers of tourist resorts, it has been found that wind is not an option for power generation near resort islands, as tourists dislike the visual impact of wind farms.

2.4.4 Solar

As for wind resources, the NREL also carried out a solar resource assessment for Sri Lanka and the Maldives in 2003. It found that the seasonal variability of the solar resource is higher than the spatial variability across the country and the period with the highest solar resource is March to April with values of up to 7 kWh/m2/day (NREL, 2003). Average yearly solar radiation is 5.2 kWh/m2/day and therefore more than 50% higher than in Austria for instance. The measurements were carried out using fixed

[5] NREL´s wind power classification ranks the wind resource potential according to the wind power density and wind speed in classes from 1-7 and poor to superb, respectively (Kesterton, 2010).

plate collectors tilted at latitude which best represents the irradiation on an installed PV system. Surface solar energy data for Maafushi (one of the case study islands) obtained from the NASA Surface Solar energy data set[6] shows that daily radiation ranges between 4.8 kWh/m2/day and 6.1 kWh/m2/day with an average of 5.3kWh/m2/day (see Figure 2.13). The radiation is evenly distributed throughout the year.

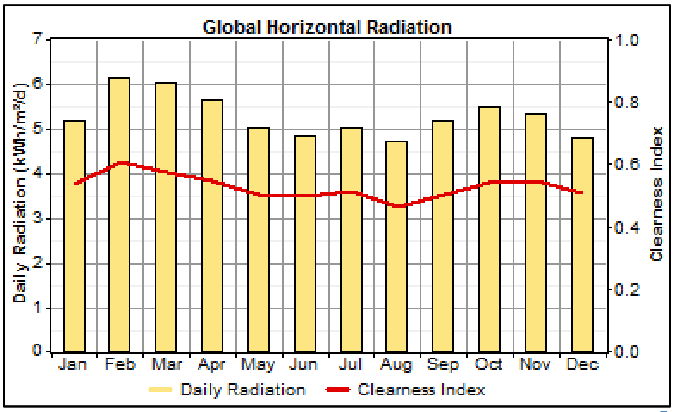


Figure 2.13: Global Horizontal Radiation for Maafushi (NASA, 2012[7])

Summing up, the solar resource is of reasonable quality and consistent across the country and throughout the year.

3 Solar Energy technology in the Maldives

Since several initiatives and development programs such as the SMILES (Strengthening Maldivian Initiatives for a long term energy strategy) co-funded by the European Union (EU) or the recent Scaling-up Renewable Energy Plan (SREP) issued by the World Bank (WB) and the Asian Development Bank (ADB) concluded that solar power is the most promising renewable energy technology in the Maldives, this thesis focuses on modeling of PV/Diesel/Hybrid systems with and without storage (MEE, 2012; MEEW, 2007; ADB, 2011; EU, 2007). The authors employment in a company that plans and installs PV systems, access to high quality cost data for all photovoltaic (PV) components as well as the involvement in a PV research and development project called SWIMSOL are further reasons for the focus of this thesis. SWIMSOL is a floating platform that carries a PV system specially designed for the usage on the sea surface in tropical island regions such as the Maldives.

[6] NASA's Surface Solar Energy Data Set provides monthly average solar radiation data for everywhere on earth at http://eosweb.larc.nasa.gov/sse/. The solar data in HOMER is retrieved from this website.
[7] Data obtained via HOMER software from NASA's Surface Solar Energy Data Set (Maafushi, 3°N, 73°E)

Although biomass and wind power might be feasible solutions for Male´, all the outer islands have little other options than solar PV for renewable power generation. For the islands in the upper middle region, small scale wind power is an option but for resort islands and islands that are not located in the favorable wind zones, wind power is not feasible due to aesthetic and efficiency reasons (Republic of Maldives, 2012). Wind power systems involve higher investment-, training- and maintenance costs and are therefore not seen as an alternative for the widespread use in the Maldives (van Alphen et al., 2007). Also wind/PV/diesel/hybrid systems are not considered in this work because prior projects have shown that more than two electricity generation components cause operational problems in hybrid systems (van Alphen et al., 2007). Solar power due to its relatively low operation and maintenance needs and modularity is highly replicable across the islands as well as expandable when future electricity demand increases.

The recently published SREP Investment Plan states that solar PV power could deliver up to 20% of the peak day time electricity demand without the need for sophisticated system control equipment (MEE, 2012). That agrees with the findings of Lilienthal (2007), who states that the maximum peak instantaneous renewable energy penetration should not be more than 15% at any given time without system control (Lilienthal, 2007). But before we go into detailed power system modeling, section 3.1 provides the reader with some basic knowledge on solar power and the functioning of a photovoltaic system. Also Swimsol is presented in more detail.

3.1 Solar Photovoltaic Energy

The term photovoltaic is attributed to *Phos* (Greek for light) and *volt* (the unit of measurement for electric potential) (Gehrlicher Solar AG, 2013). The photovoltaic effect has been discovered in 1839 by Alexandre-Edmond Becquerel, a French physicist. It describes the conversion of radiation energy into electric current and voltage in photovoltaic elements and is directly related to the photoelectric effect which relates to the discharge of electrons from the surface of semiconductor material upon exposure to radiation (Solarserver, 2010).

The first photovoltaic cells made from silicon were produced in 1954, after the discovery of the semiconductor technology. Triggered by the energy crisis in the 1970s and increased environmental awareness, the commercial development of solar cells commenced (WeizSolar, 2010). Due to the high investment costs for silicon mines and manufacturing facilities, the costs for PV technology only came down after the global demand kept on rising, so that more and more investors considered it worthwhile investing into a silicon mine. As a result, silicon prices came down, and with it prices for solar systems. Figure 3.1 shows the historical cost development for PV panels.

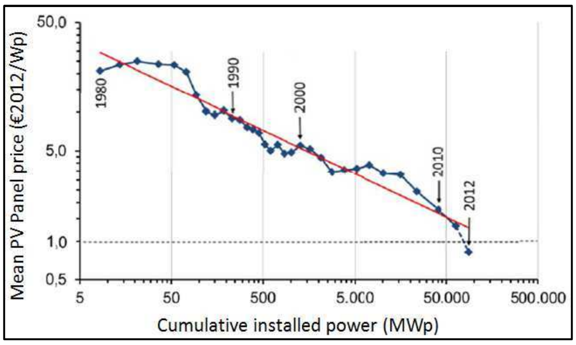


Figure 3.1: PV panel price development (adapted from Fraunhofer ISE, 2013)

A PV cell is composed of two layers of semiconductors that are doped with impurity atoms to alter their properties (see Figure 3.4). The doping with Boron creates an electron shortage and thus a positively charged layer. The insertion of phosphorus creates a surplus of electrons and thus a negative layer which is facing towards the light. The combination of these two layers creates a so called ´p-n junction´ that serves as a kind of an isolating layer between the positive and the negative pole inducing an electric field. The antireflection coating prevents reflectance and increases the transmission of the light. When photons of a wavelength up to 1,130 nm (see Figure 3.2) are absorbed by the semiconductor, electrons are ejected from the upper layer and move through the material into the p layer.

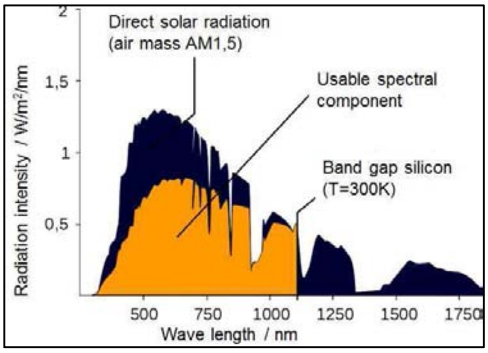


Figure 3.2: Absorption spectrum for PV panels (Mayer, 2008)

This process induces the creation of a corresponding positive charge, called a ´hole´. The separation of charges through the p-n junction induces an electric field and the charges can be collected by the metallic contacts on each side of the solar cell in the form of DC current (Mayer, 2008). The resulting voltage depends on the semiconductor material; for silicon, the commonly used material for PV cells, the voltage is 0.5 V. While the voltage is hardly influenced by irradiation, the electric current increases with the irradiation intensity. The resulting power (the product of voltage and electric current) depends on the cell temperature and decreases at increasing temperatures (Solarserver, 2010).

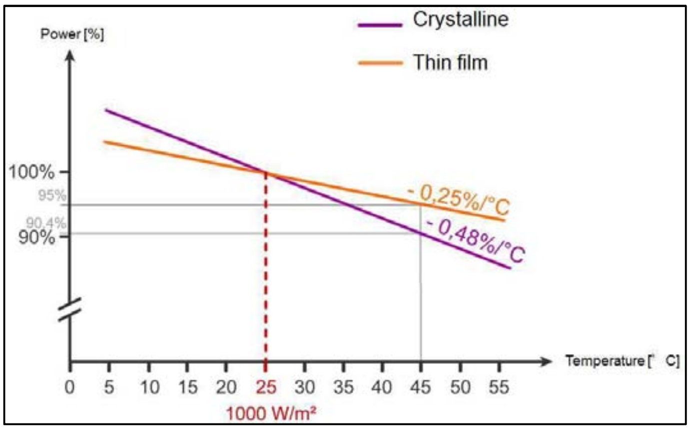


Figure 3.3: Temperature coefficients of crystalline and thin film PV panels (Swimsol, 2012)

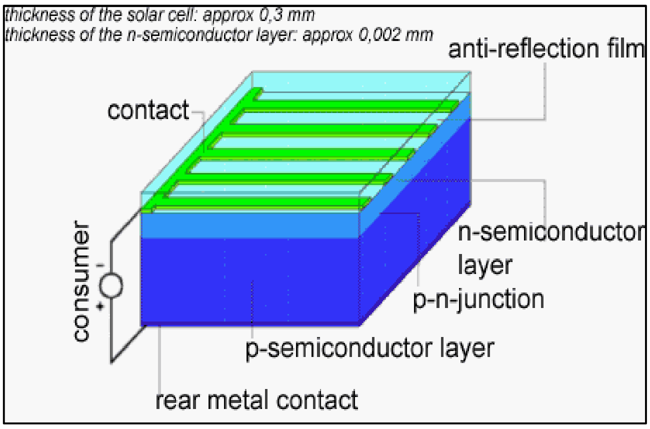


Figure 3.4: Functionality of solar PV energy (Solarserver, 2010)

The characteristics of photovoltaic panels are given at standard test conditions (STC). STC refer to an irradiation of 1,000 W/m^2 with a light spectrum Air Mass (AM) 1.5 and a cell temperature of 25 °C.

Examples for electrical characteristics that can be found on a solar panel data sheet are:

- Maximum power (maximum output at STC)
- Module efficiency (13-17% for panels made of crystalline silicon solar cells)
- Temperature coefficient

The temperature coefficient, one of the specifications of solar panels is around

- 0.48%/°C for crystalline and around – 0.25%/°C for thin film modules (see Figure 3.3)

3.1.1 Cell types

Since the market share of photovoltaic modules made of silicon is over 95% (2010), only these cell types are described in this section. Apart from silicon based PV technologies there are yet other cell types, such as organic solar cells made from hydrocarbon material and multi-junction solar cells with several p-n junctions tuned to different wavelengths of light. In addition, there are different types of thin film modules. Within the solar cells made of silicon three main types are distinguished: mono crystalline, poly crystalline and thin film/amorphous.

The manufacturing of mono crystalline silicon solar cells requires high purity semiconductor material. A block built up of one single silicon crystal is the basis for the production (Gehrlicher Solar AG, 2013). Out of this block, slices of 0.18-0.3 mm thickness are cut and contacted. These plates are called wafer. The efficiency of mono crystalline cells is over 20%. With a market share of 51% mono crystalline cells are the most common ones (WeizSolar, 2010).

Poly crystalline also multi crystalline silicon cells are made from crystals produced from a silicon smelter. Blocks are founded from a silicon smelter and wafers are produced. During the process of solidification many small crystals are formed. That is the reason why cells made with this production process are called poly crystalline. The production of poly crystalline cells is cheaper but the formation of differently sized crystals during the consolidation process leads to defects that cause lower cell efficiencies (Solarserver, 2010).

Due to the fact that the production of thin film or amorphous cells requires far less energy and silicon material compared to the other manufacturing technologies, they represent the cheapest alternative within the silicon technologies. For the production of thin film cells, silicon is evaporated onto a supporting plate (for instance glass) at a thickness of the silicon film of only around 1µm (thickness of a human hair: 40-120µm). The downside of amorphous cells is their efficiency. With only 5-7% outside the laboratory, thin film cells are far away from the cell efficiencies of the other cell types (Solarserver, 2010).

The market share of amorphous silicon cells is the biggest within the thin film sector. Other materials that are used to produce thin film cells include cadmium telluride, gallium-arsenide or copper indium gallium sulfur selenium compounds (CIGS). CIGS and CIS cell efficiencies currently range from 11 to 17.8% and up to 20% in the laboratory, respectively. Table 3.1 summarizes the key facts of the popular photovoltaic cell types.

Type	lifetime [a]	Average cell efficiency [%][8]	Temperature coefficient [% W_{mpp} / K]	Market share [%][9]	Area per kW peak [m^2]
Mono crystalline	30	13, max. 25	-0,46	51	6-9
Poly crystalline	30	12, max. 19	-0,46	35	7-10
Amorphous[10]	20	Max. 11	-0,32	10	11-18

Table 3.1: Summary of key indicators of different types of PV panels (WeizSolar, adapted and translated, 2010)

3.1.2 Functionality of a solar PV system

To provide suitable voltage and output power for different applications, solar cells are interconnected to form solar panels. A solar panel consists of the interconnected solar cells (typically 48 – 60 cells in series) embedded in Ethylene Vinyl Acetate (EVA) foils, a back-sheet with cable outlets, a cover glass on the front and a frame made of aluminum (see Figure 3.5). Glass-glass panels consist of another cover glass on the backside instead of the back sheet and are more resistant against corrosion.

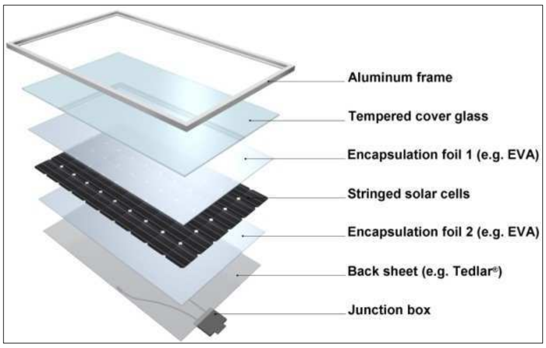


Figure 3.5: Composition of a glass-foil PV panel (Swimsol, 2010)

The DC/AC inverter, the other important component in a PV system converts the direct current (DC) produced by the solar panels into alternating current (AC) that can be used by standard electrical appliances or fed into the public electrical grid.

Basically, applications for solar PV energy can be divided into two main categories; off -grid and grid-connected applications. Figure 3.6 shows a typical residential grid-connected PV system. The DC power produced by the roof mounted solar panels is converted into AC current by the inverter. The amount of power produced is recorded by the electricity meter and energy that is not used up by the appliances is directly fed into the electrical grid. At times where PV electricity production is not high enough to

[8] cell efficiency in practice
[9] The rest of the market, around 4% is covered by special solar cells (see above).
[10] amorphous refers to amorphous silicon cells only

meet the demand, electricity is provided by the electrical grid. The second category within on-grid applications are central ground mounted PV systems with areas of several hundred hectares and output powers of up to several hundred megawatts.

Legend:

1 Solar panels

2 DC/AC Inverter

3 Electricity meter

4 Appliances

5 Electrical grid

Figure 3.6: Components of a solar PV system (Swimsol, 2010)

Off - grid PV systems are typically operated in remote and/or isolated areas such as thinly populated regions and islands without a connection to a public electrical grid. Off-grid systems can be designed as stand-alone or hybrid systems. The term ´hybrid system´ refers to systems with a renewable energy generator and a diesel generator that meets part of the load requirements and provides higher reliability. A typical PV/diesel/battery hybrid system consists of a PV array, a control device, an inverter, a backup diesel generator and - depending on the size of the PV array and the load requirements – a battery bank sized to store and provide energy for a certain amount of time.

Off - grid stand-alone systems typically consist of a PV array, a control device and batteries. Excess energy is thus stored in the battery bank and discharged in times when the PV array is not able to meet the load requirements. The control device takes care of the power quality and the state of charge of the batteries.

In the case of the Maldives mini-/ or micro grids are most commonly used to power the outer islands (valid for all islands apart from Male´ and Addu). The challenge to supply these islands with a maximum amount of renewable energy is to find the optimal PV/diesel/(battery) hybrid configuration – an attempt undertaken in this thesis. To increase the amount of solar energy for these islands is the aim of Swimsol.

3.2 Swimsol – a floating solar platform

"Lack of land constraints the possibility of installing renewable energy in many places. However, the atolls contain vast areas of very shallow lagoon. Building over lagoons is common for tourist resorts and may become a key component of any renewable installations also" (MEE, 2012).

Swimsol is a concept for a swimming solar power plant. It is being designed for the usage in the shallow lagoons of tropical island countries such as the Maldives, where almost the entire electricity is generated with diesel generators. As described before, the integration of solar power into the existing diesel stand-alone systems would not only be more environmentally friendly but also cheaper than electricity produced by diesel stand-alone systems. However, land is scarce and limits the possibilities to install solar PV systems on the islands. In Male´ for instance, over 25% of the area would have to be covered by PV panels if diesel generators were largely replaced by solar power. On resort islands, the area that would be needed to meet the energy demand by solar power often exceeds the area of the entire island. But most islands feature lagoons less than 50 m deep and sheltered by coral reefs. The Swimsol platform will be developed to operate in such lagoons. It will consist of floating elements made of plastic, a stabilizing structure with integrated panel fastenings and a corrosion-proof photovoltaic system. The system will be designed to withstand waves of up to 1 m and wind speeds of up to 120 km/h. All components will be produced from non-hazardous materials that are resistant against the corrosive climate in these regions with high air temperatures and air humidity as well the high salt content in the air. Figure 3.7 shows some drafts of what the Swimsol platform can look like. Due to the fact that development is still in the prototype phase, the final decision on the design of the platform has not yet been made.

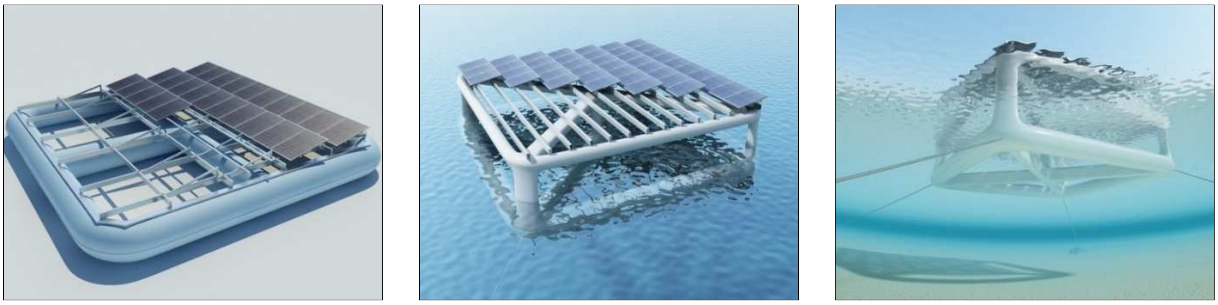


Figure 3.7: Concepts of Swimsol platforms

The overarching development goal is an electricity generation cost of less than 0.25 €/kWh and therefore cheaper than the current electricity production in tropical regions. In order to achieve this goal, Swimsol must not cost more than 3,500 $/kWpeak ($kW_p$) at a lifetime of at least 20 years. That equals to 100 $/m^2 for the platform including the stabilizing structure and 650 $/kW for the adaptation of the photovoltaic system and all its components. The adaption of the PV system includes the use of glass-glass panels instead of conventional panels with back-sheet foil, the encapsulation of the cable outlets with a specially designed resin and the sealing of the panel edges with a special rubber that prevents water from permeating the panel. In addition, all cables as well as the inverter have to comply with off - shore standards. Thus, the innovations with Swimsol are on the one hand the development of a robust, warp resistant and seawater resistant platform and on the other hand a PV system designed for the long-term usage on the sea surface.

A company-internal market research (see Table 3.2) conducted in 2010 shows a market potential for Swimsol of about 60 MW for the Maldives and roughly 500 MW globally. The research is a first estimate based on a power consumption of 250 kWh/inhabitant and year, 3000 yearly full load hours per diesel generator, an installed power per room on resort islands of 10 kW, a PV cover ratio of 20% and a yearly yield of 1,400 kWh/kWp of installed solar power. Yet, it has not been evaluated if there are enough suitable lagoons in regions outside of the Maldives (Swimsol GmbH, 2010-2012).

	inhabited islands	suitable islands	inhabitants/rooms on suitable islands	power consumption in MWh	power consumption in kWh per head	installed capacity	global market potential for Swimsol
Maldives	253	147	97.291	522.052	1.598	176.730 kW	57.410 kWp
Maldives - Male and environs	4	1	46.853	147.157	1.304	44.000 kW	8.887 kWp
Maldives - Resorts	53	107	10.460	330.300	30.000	110.100 kW	44.826 kWp
Maldives - inhabited islands	196	39	39.978	44.595	220	22.630 kW	3.696 kWp
Oceania	939	39	114.769	5.118.120	630	1.271.000 kW	22.229 kWp
Carribean	73	1	6.489	2.852.000	694	809.667 kW	5.706 kWp
Indian Ocean	18	0	272	272.000	3.056	95.333 kW	124 kWp
South East Asia	11.324	64	2.796.756	533.259.459	885	113.316.000 kW	428.512 kWp
TOTAL							513.981 kWp

Table 3.2: Market research summary (Swimsol, 2010)[11]

[11] Sources: Maldives: STELCO and other Utilities; French Polynesia, South East Asia and other: CIA Fact book, UN etc.

The Swimsol platform is being developed in cooperation with several institutes of the Technical University Vienna, and with industry partners such as Centrotherm photovoltaics AG, Lenzing Plastics GmbH and Sunpor. In 2012 a first prototype on a scale of 1:4 has been launched into a lake in Upper Austria to test the swimming characteristics of the platform (see Figure 3.8).

Figure 3.8: Swimsol „Prototype 0.5“

In the beginning of 2013 a further prototype on a scale of 1:1 will be thoroughly tested on Lake Balaton in Hungary which features a wind and wave regime quite similar to the Maldives. The market entry is planned for 2015 after a demonstration project and pilot installations in the years 2013 and 2014, respectively. Figure 3.9 shows what Swimsol installations will look like on the site of operation. The aim is to keep the system´s visual footprint as small as possible.

Figure 3.9: Visualizations of Swimsol platforms
(Swimsol 2010)

4 Energy System Modeling

The Energy System Modeling carried out in this thesis focuses on PV/diesel hybrid systems with and without battery storage on Maldivian Islands. The islands under examination are Maafushi and Hulhumale´ with 2,000 and 15,000 inhabitants, respectively. In addition, the energy system of Meeru Island Resort - a tourist resort is investigated. The aim is to determine the cost-minimal system designs for the case study islands and the parameters influencing the outcomes. It is expected that the implementation of PV hybrid systems has a range of advantages compared to the current diesel stand – alone systems.

The configurations that are analyzed for each of the islands mentioned above are:

- Present Diesel stand – alone systems
- PV/Diesel systems with and without battery storage
- Swimsol/Diesel hybrid systems with and without storage

Detailed information on the different configurations and the model inputs and assumptions are given after the research questions, the methodology and the case study islands have been presented.

4.1 The HOMER model

To answer the research questions named in the introduction of this thesis, U.S. National Renewable Energy Laboratory´s (NREL) Hybrid Optimization Model for Electric Renewables (HOMER) is used. It was decided to use this model because it allows the system designer to simulate large numbers of system configurations on an hourly resolution and provides a detailed idea of the most favourable systems and the adjunctive cost parameters. Therefore HOMER is considered as a suitable tool to model the island energy systems. HOMER is a simulation software package for energy system analysis and optimization for both off-grid and grid connected power systems. The model is a widely used tool and has been successfully applied in former studies on energy systems in remote locations and in SIDS such as van Alphen et al. (2007), Rehman and Al-Hadhrami (2010) who did a study on remote area in Saudi Arabia, Lau et al. (2010) who carried out a study on the performance of PV hybrid energy systems in Malaysia or Phuangpornpitak and Kumar (2007) who used HOMER to evaluate PV hybrid systems for rural electrification in Thailand.

HOMER *"[…] is a powerful tool for designing and analyzing hybrid power systems, which contain a mix of conventional generators, combined heat and power, wind turbines, solar photovoltaics, batteries, fuel cells, hydropower, biomass and other inputs"* (HOMER Energy, 2012). It helps to determine how intermittent energy resources can be optimally integrated into hybrid energy systems.

"*HOMER performs three principal tasks: simulation, optimization and sensitivity analysis"* (HOMER Energy, 2012). In the first step, the simulation process, HOMER compares the electric demand and the electricity production from RE for each hour of the year and determines the technical feasibility and life-cycle cost of the different configurations (Lambert, Gilman and Lilienthal, 2006). It takes into account the electrical load to be served, the availability of intermittent resources for each hour of the year, reliability requirements and all kinds of costs (Givler & Lilienthal, 2006). In the second step, the optimization process, HOMER simulates various system configurations to find the lowest cost combinations that are technically feasible. In the third step, the sensitivity analysis, the software steps through the optimization process again to determine the effects of changes in input parameters that are uncertain and/or out of the control of the system designer. Examples for such variables are solar irradiation, fuel prices or the interest rate. In this way, the user can assess the optimal system configurations under different uncertainty factors (Givler & Lilienthal, 2006).

So, the inputs are the electric demand at an hourly basis, solar radiation and the energy conversion equipment. For all components of the energy system, the system designer can specify the capital costs, the replacement and O&M costs as well as the properties of the components such as fuel efficiency for the diesel generators, the efficiency of the solar cells or the conversion efficiency of the converter.

After performing these steps, HOMER ranks the feasible system configurations to their Net Present Cost (NPC). The NPC represents the lifecycle cost of a system. It aggregates all the costs that occur within the specified project lifetime into one lump sum of today´s dollars. The future cash flows are discounted back to the present using the discount rate specified by the modeler (Lambert et al., 2006). The NPC includes the initial investment cost, operation and maintenance costs, replacement costs and penalty costs such as emission penalties.

The NPC is calculated according to the following equation (1):

$$NPC(i,N) = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \tag{1}$$

Where C_t is the cost in year t, N is the project lifetime, and i is the annual real interest rate (discount rate) given by equation (2):

$$i = \frac{i^{´} - f}{1+f} \tag{2}$$

with $i^{´}$ being the nominal interest rate (the interest rate for a loan) and f being the annual inflation rate (Lambert & Lilienthal, 2006; Homer Energy, 2004). In HOMER all prices escalate at the same inflation rate.

NPC calculation in HOMER also takes into account salvage costs, which is the remaining value of the system components at the end of the lifetime. Salvage costs are calculated by equation (3):

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{3}$$

where S is the salvage value, C_{rep} is the replacement cost of the component, R_{rem} is the remaining life of the component and R_{comp} is the lifetime of the component (Homer Energy, 2004).

The levelized Cost of Electricity (COE) is calculated by HOMER using the following equation (4):

$$COE = \frac{TAC}{E_{served}} \tag{4}$$

Where E_{served} refers to the total amount of useful energy the system produces over the lifetime and TAC refers to the total annualized costs given by equation (5):

$$TAC = CRF\left(i, R_{proj}\right) \times NPC \tag{5}$$

With R_{proj} being the project lifetime and CRF is given by the following equation (6):

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{6}$$

The COE [$/kWh] is a useful metric to determine the average cost per kWh produced by an energy system (Lambert & Lilienthal, 2006).

Further outputs of the modeling process include initial capital needed to install the system, the yearly running costs, the amount of fuel needed and other information such as the energy production from renewables, the amount of excess energy, the running times of the diesel generators and the emissions from energy production.

Summing up, the outcome of the simulation process is a list of possible system configurations for each system type in the order of NPC. Detailed results can be output as a range of graphs, plots and tables and the designer can compare the configurations on the basis of different uncertainty parameters. A detailed overview of the input parameters and assumptions used for the energy system modeling in this study can be found in section 4.3 and 4.4 after the description of the case study islands. HOMER is maintained by Homer Energy and version 2.68 beta of the program can be downloaded free of charge at: http://www.homerenergy.com (accessed 23/02/2013). The simulations in this thesis were done with version 2.68 beta and the latest version of the software 2.81. Version 2.81 can be downloaded for a free-trial of two weeks and must be purchased after that (Homer Energy, 2012).

4.2 The case study analysis

As mentioned in the introduction of this thesis, van Alphen (2004), van Alphen, van Sark and Hekkert (2007), Camerlynck (2004), Mohamed (2012) and Kesterton (2010) conducted research on RE on Maldivian islands. Namely the capital Male´ and outer islands of up to 1,500 inhabitants were the topic of research of these studies. In contrast, this work focuses on islands with more than 1,500 inhabitants. In addition, energy system modeling is carried out for a resort island, the type of island that contributes to over 50% of the country´s total power consumption. Electrical load data for the local islands Hulhumale´ and Maafushi was collected directly from the

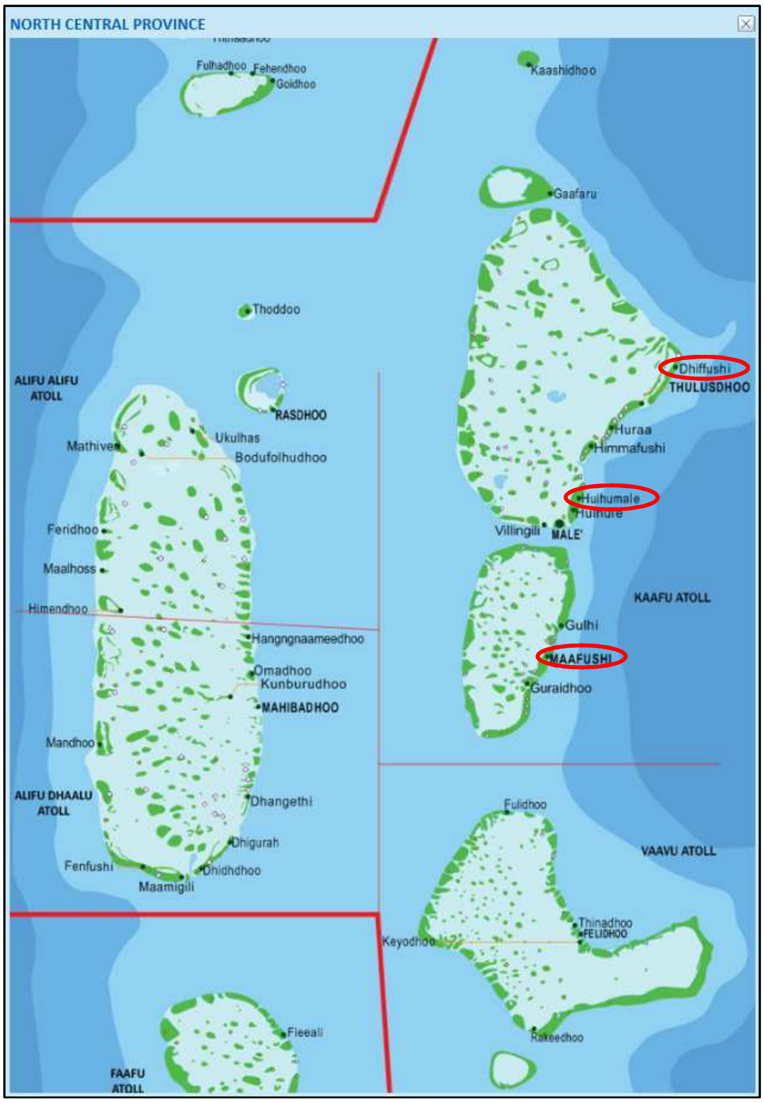


Figure 4.1: Locations of the case study islands (adapted from GoM, 2013)

State Electric Company (STELCO) who is the sole electricity provider in these islands. Electrical load data for the tourist resort Meeru Island was obtained with support of Mr. Walter Kauffmann, the general manager of the resort. Figure 4.1 shows the location of the islands in the North Central Province of the Maldives.

4.2.1 Maafushi

Maafushi is an inhabited island that falls into the category of 1,500 – 2,500 inhabitants. It is located approx. 26 km south of Male´ in the Kaafu Atoll in the North Central Province of the Maldives (3.56° North, 73.29 East). The travel from Male´ takes about an hour in speed boat. With a length of about 1,200 m and a width of about 250 m, the total area of 23.3 hectares hosts alongside to residential homes several guest houses for travelers, two schools, a hospital, a mosque and a jail (GoM, 2013b). The population census in 2006 counted 2,000 inhabitants (Department of National Planning, 2013). The energy system of the island consisted of 5 diesel generators with a total capacity of 1,870 kW in 2010 (see Table 4.1). The electricity production in 2010 amounted to 2,995,144 kWh.

Figure 4.2: Aerial photo of Maafushi (GoM, 2013b)

Generator type	capacity	Total capacity
Cummins NTA 855 G2	250 kW	**1,870 kW**
Cummins NT 855 G2	200 kW	
Cummins KTA 19 G3	380 kW	
Cummins KTA 19 G4	400 kW	
Cummins KTA 38 G2	640 kW	

Table 4.1: Energy system of Maafushi

Figure 4.3 shows the island´s daily load curve obtained from STELCO data from 24/03/2010 (weekday) and 02/10/2010 (weekend). While the lowest loads can be observed at 7 am, the peak load of just over 600 kW and 340 kW occurs at 8 pm for weekdays and weekends, respectively. As can be observed, the load on weekends follows approximately the same pattern as on weekdays but at a lower level at each time of the day. The total daily demand is 12,110 kWh and 5,957 kWh on weekdays and weekends, respectively.

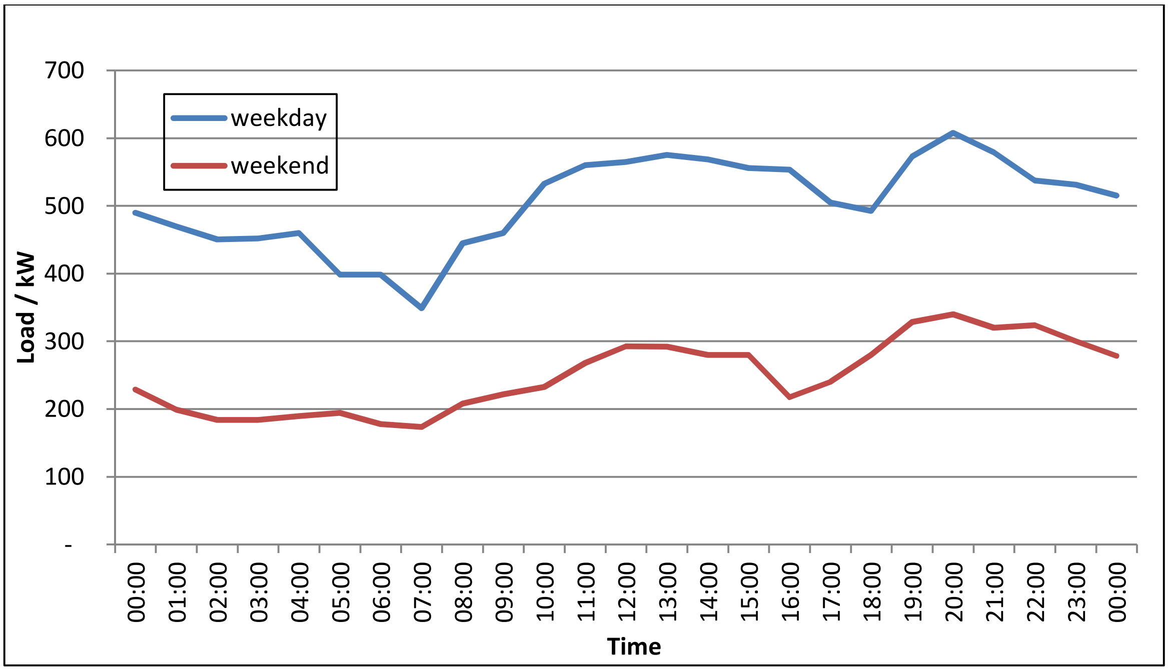


Figure 4.3: Maafushi – daily load curve

Both load curves have been entered into HOMER. As the hourly load data was only available for two days in 2010, a "standard deviation in the sequence of daily averages" of 7.31% was input into HOMER to create randomness in the daily load curves throughout the year. This was done to cater for seasonal variations in electricity consumption. The standard deviation was calculated in MS Excel based on the monthly minimum and maximum values in the year 2010 obtained from STELCO.

A Cost of Energy (COE) of 0.323 $/kWh and an annual operating cost of 1,173,748 $ for the diesel stand-alone system of Maafushi was calculated with HOMER. This configuration is as the baseline scenario to which the RE energy systems are compared to.

4.2.2 Hulhumale´

Hulhumale is an artificial island in the North Central Province of the Maldives. It is located approx. 5.3 km NNE from Male´ (4.20° North, 73.54° East). The island is the product of a land reclamation project that started in 1997 mainly to create new land for housing to decrease population stress in the capital and to facilitate growth. The reclaimed area as of 2002 was 188 hectares (see Figure 4.4). The first settlement of the island commenced with a population of just over 1,000 people in 2004. Hulhumale is a rapidly developing island and changes in population data can be observed almost daily. To match electricity data with population current population data was obtained separately from Hulhumale´ Development Corporation (HDC), the institution responsible for the development of the island. The data gathered from HDC showed roughly 15,000 inhabitants in 2011 (Department of National Planning, 2013, HDC, 2011). The island energy system consisted of four diesel generators with 4 MW of total installed capacity (see Table 4.2) in 2011. The electricity production in 2011 was 12,493,598 kWh.

Figure 4.4: Aerial photo of Hulhumale´ (GoM, 2013b)

Generator type		Capacity	Total capacity
Cummins	KTA 50 G2	800 kW	**4,000 kW**
Cummins	KTA 50 G2	1,000 kW	
Cummins	KTA 50 GS8	1,200 kW	
Cummins	KTA 50 G3	1,000 kW	

Table 4.2: Energy system of Hulhumale´ (STELCO 2011)

The daily load curves for one weekday and one day on the weekend in the year 2011 were obtained from STELCO which is the sole power provider on the island. Similar to the load pattern of Maafushi, the peak demand occurs in the evening hours and the load pattern for weekends is roughly the same as for weekdays but on a lower load. Peak load of the island is 1,980 kW and 1,650 kW at weekdays and weekends, respectively (see Figure 4.5). The total daily demand is 37,730 kWh on weekdays and 34975 kWh on weekends.

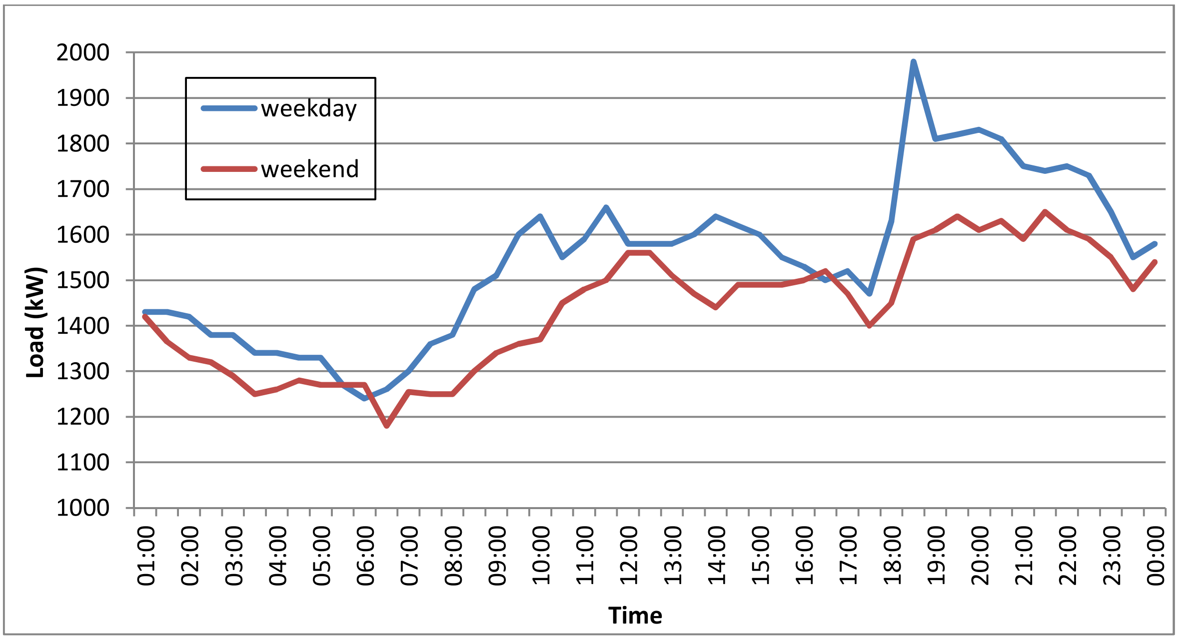


Figure 4.5: Hulhumale´ - daily load curve

To take into account load variations throughout the year, a randomness factor of 4.54% which was calculated in MS Excel on minimum and maximum monthly values of the year 2011 has been added to the simulation process. This randomness factor was calculated as the standard deviation in the sequence of daily averages, based on the monthly minimum and maximum values for the year 2011 which were obtained from STELCO. A levelized cost of energy of 0.310 US$/kWh and an annual operating cost of 4,059,313 $ was calculated with HOMER for the baseline scenario which is used for comparisons to the PV/diesel hybrid systems.

4.2.3 Resort – Meeru Island

Figure 4.6: Aerial photo of Meerufenfushi (Google maps, 2012)

Meerufenfushi (4.27 North, 73.43 East), the real name of Meeru Island resort is an island exclusively developed for touristic purposes. It is located in the upper north of Kaafu Atoll in close proximity to Dhiffushi, a local island 200 m south of the island. The distance to Male´ is around 37 km. The total area of the island is approx. 90 acres with a length of 1200 m and a width of 350 m (see Figure 4.6). The resort island consists of 600 beds and reports a yearly capacity utilization of over 99% (W. Kauffmann, personal communication, November 1, 2012). So the island is inhabited by 600 tourists almost all year round. This leads to a fairly similar daily load profile throughout the year (see Figure 4.7). In addition, there is obviously no difference in the load curves of weekdays and weekends. This proves the findings of Bohdanovicz and Martinac (2007) who showed that *"load patterns for tourist destinations differ from commercial and domestic operations due to their relatively high power demands for extensive periods […]"* (Bohdanovicz and Martinac, 2007). The total number of staff that works on the island is 600. The average daily energy production is approx. 34 MWh with a diesel consumption of approx. 8000 liters per day. Meeru island, like most tourist resorts in the Maldives produces its own drinking water with a desalination plant and it takes care of the sewerage water with an own treatment plant. MHE (2010) who conducted a survey in resorts found the electricity breakdown of resorts to be as follows:

- Air conditioning: ~50 %
- Freezing: ~10 %
- Desalination: ~10 %
- Lighting: ~10 %
- Laundry: between 5 % and 20 % (MHE, 2010)

These numbers above were roughly confirmed during talks with the General Manager of Meeru Resort (W. Kauffmann, personal communication, November 1, 2012).

In 2012 the island energy supply consisted of 5 diesel generators with a total capacity of 4,050 kW (see Table 4.3).

Generator type	Capacity	Total capacity
Cummins	450 kW	**4,050 kW**
Cummins	450 kW	
Cummins	900 kW	
Cummins	1,125 kW	
Cummins	1,125 kW	

Table 4.3: Energy system of Meeru Resort Island 2012

The figure below shows the electrical data the author obtained during his visit to the Maldives in November 2012. To create a realistic load curve, unusual spikes due to blackouts have been eliminated. As it can be seen, the daily load curves for 10 different days in April 2012 follow a quite similar pattern.

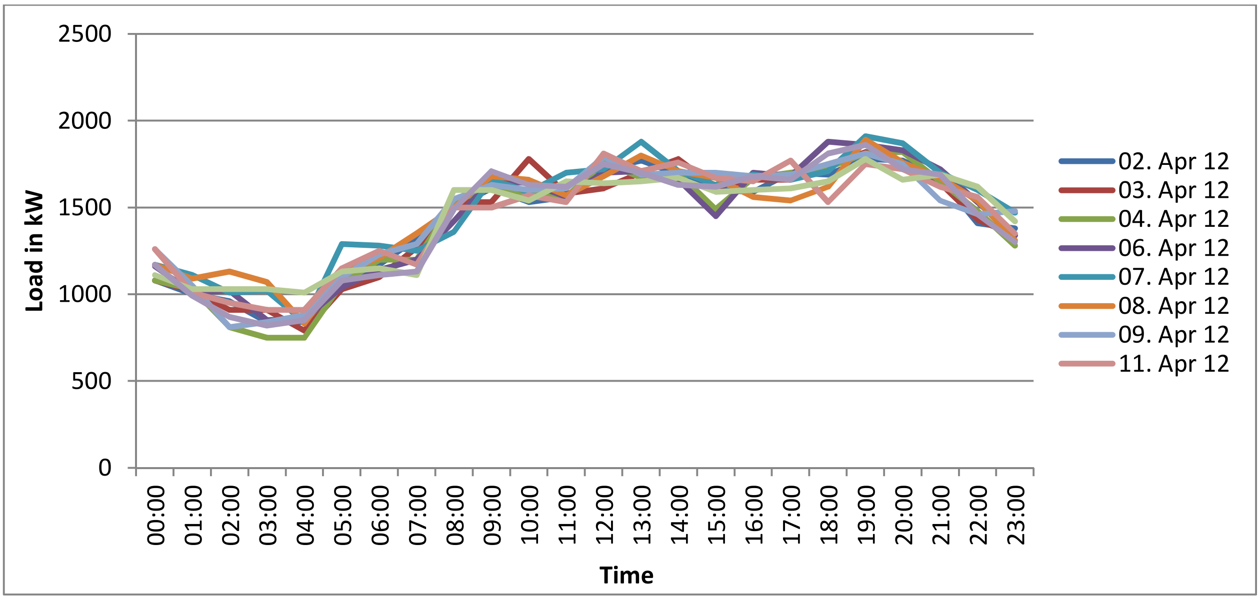


Figure 4.7: Daily load profiles – Meeru Island Resort (April 2012)

Out of these load profiles, an average daily load profile was generated (Figure 4.8). This load curve was used for the simulation runs with HOMER.

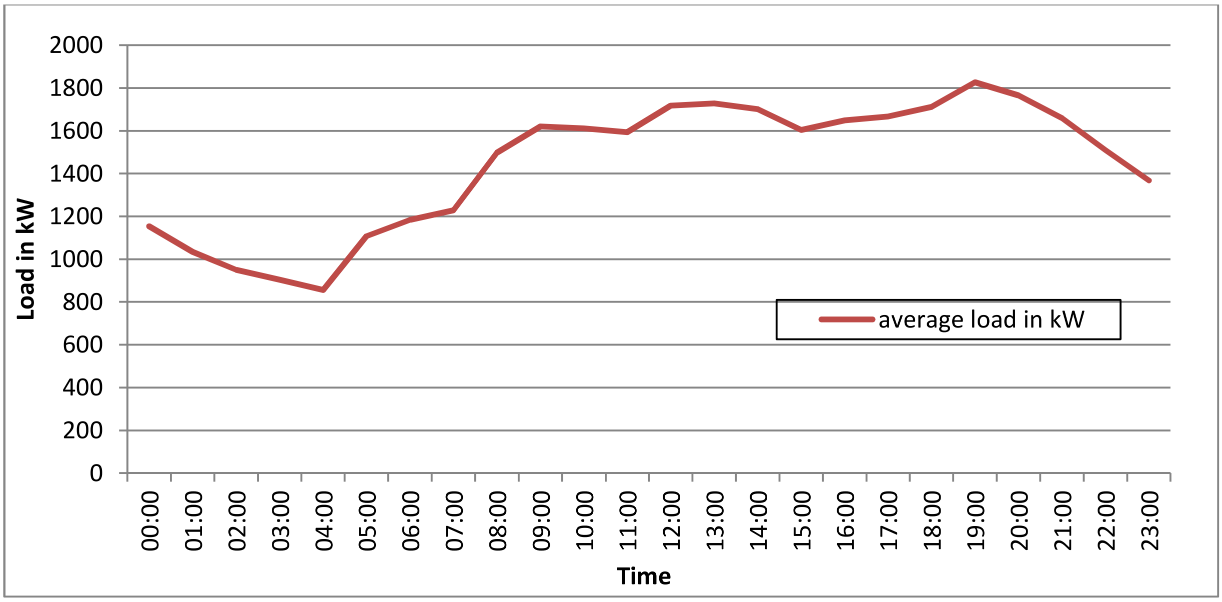


Figure 4.8: Average load profile – Meeru Island resort (2012)

To cater for differences in the daily load profiles a randomness factor of 1.47% was added for the simulations. HOMER calculated a levelized cost of energy of 0.308 US$/kWh and an annual operating cost of 3,741,550 $ for the diesel stand - alone configuration which is used for comparisons to the PV/diesel hybrid systems.

4.3 Energy System Configurations

The system configurations HOMER was run with can be found below (see Figure 4.9). The baseline scenario consists of diesel generators only. The PV/Diesel hybrid system and the Swimsol/Diesel hybrid system comprise a PV array/Swimsol platform, a converter and diesel generators. PV/Diesel/battery hybrid systems consist of a PV array/Swimsol platform a battery bank, a converter and diesel generators.

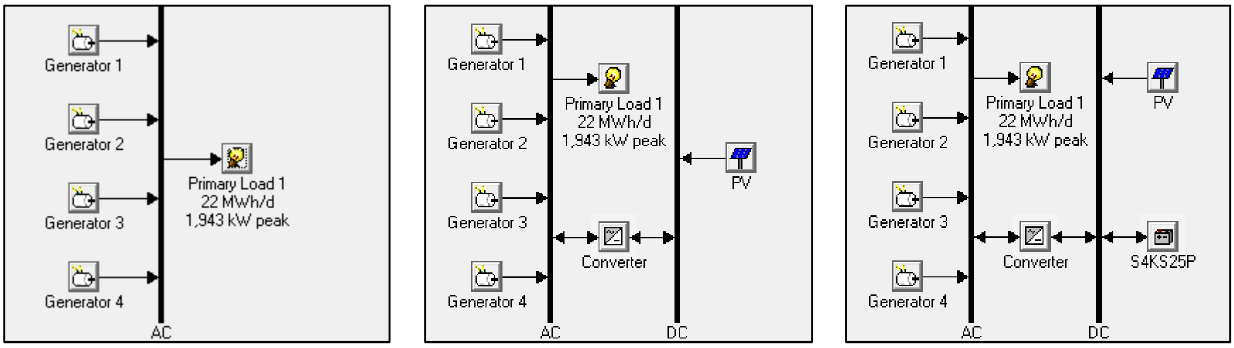


Figure 4.9: Exemplary System configurations

These configurations were modeled and analyzed for all individual islands to find the lowest cost energy production system.

4.4 Assumptions and input parameters

The assumptions and model input parameters are - apart from the island specific data such as the load profile, the number and types of diesel generators and irradiation data - the same for all modeling cycles. These specifications are presented in the following chapters. Details on the mathematics and the functioning of HOMER software are given where appropriate. For the modeling, it is assumed that constraints such as social, institutional or financial barriers do not exist.

4.4.1 Economic inputs

As the Inflation rate in the Maldives was between -2.8% and 12.3% between 2000 and 2010 and the interest rate for loans in 2013 is about 12% (Indexmundi, 2013; BoM, 2013), the annual real interest rate input into HOMER was set to the default value of 6% for the baseline scenarios. HOMER uses the annual interest rate to convert all future cash flows into annualized costs (Lambert & Lilienthal, 2006). Obviously, the correct value for this variable depends amongst other factors on macroeconomic conditions and the political and financial situation of the country. That is the reason why the interest rate is dealt with in more detail in the subsequent sensitivity analysis of this paper.

The project lifetime was assumed to be 20 years. System fixed capital cost, system fixed O&M cost and capacity shortage penalty were set to 0.

Parameter	**Value**
Annual real interest rate	6%
Project lifetime	20 years
System fixed capital cost ($)	0
System fixed O&M cost ($/yr)	0
Capacity shortage penalty ($/kWh)	0

Table 4.4: Economic inputs summary

The system fixed capital cost refers to fixed costs that occur independently of the system composition. The system fixed O&M cost is a cost that refers to fixed expenditures for the operation and maintenance of the system independently of the system components and the runtime hours of the individual components. The capacity shortage penalty is a cost penalty HOMER applies to the system cost for any capacity shortage that occurs during the year (Lambert & Lilienthal, 2006).

4.4.2 System control inputs

The system control inputs determine how the software models the battery bank and the diesel generators (Lambert & Lilienthal, 2006). The dispatch strategy, which determines how the system charges the battery bank was set to *load following*. With this strategy the generators produce just enough power to meet primary load requirements. Recharging the batteries will be satisfied by the renewable energy components and the time the load is fully or partially satisfied by discharging the batteries is optimized depending on the load properties for each day of the year (Lambert & Lilienthal, 2006). Furthermore, systems with multiple diesel generators with capacities less than peak load that operate simultaneously were modeled in HOMER. This was done to reproduce current conditions on the islands. The other system control inputs available in HOMER do not apply to the type of simulations that were run for this thesis.

4.4.3 Operating reserve

The operating reserve is a constraint to be specified by the designer. It is the additional reserve capacity required for a system to account for sudden decreases of RE power output or sudden increases in the load (Homer Energy, 2004). The operating reserve constraint was set at the default value of 10%, for PV a reserve of 25% was set due to the inherent variability of solar irradiation.

4.4.4 Solar Resource

Solar radiation data used for the simulations were obtained from the NASA Langley Research Center Atmospheric Science Data Center[12] using an automatic link in HOMER that gathers the radiation data on the basis of the GPS coordinates entered in the solar resource interface of the software. The data are monthly averages with a spatial resolution of 40x40 km with the GPS coordinates entered into HOMER as cell midpoints. HOMER synthesizes a set of 8,760 solar radiation values, one for each hour of the year using the Graham algorithm. These data sequences have realistic day-to-day and hour-to-hour variability and autocorrelation suitable for the use in solar simulation design (Homer Energy, 2004).

The clearness index is calculated based on the latitude and the daily radiation data. The clearness index is a measure of the clearness of the atmosphere. It is a dimensionless value between 0 and 1, defined as surface radiation divided by extraterrestrial radiation (Homer Energy, 2004).

4.4.5 Photovoltaic System

HOMER calculates the output of the PV array for each hour of the year using the following equation (7):

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right) \left[1 + \propto_P \left(T_C - T_{C,STC}\right)\right] \quad (7)$$

where

Y_{PV} is the rated capacity of the PV array, meaning its power output under Standard Test Conditions (STC) [kW]

[12] http://eosweb.larc.nasa.gov/cgi-bin/sse/global.cgi

f_{PV} is the PV derating factor [%]; a factor that accounts for reduced output in real-world operating conditions

G_T is the solar radiation incident on the PV array

$G_{T,STC}$ is the incident radiation at STC

$\propto_P$ is the temperature coefficient of power [%/°C] (see chapter 3.1 of this thesis)

T_C is the PV cell temperature [°C]

$T_{C,STC}$ is the PV cell temperature under STC [25 °C] (Homer Energy, 2004)

The input parameters for the PV system are summarized in Table 4.5.

Parameter	**Value**
Capital cost per kWp	$ 2,500
Replacement cost	$ 2,500
Yearly O&M cost (1.5% of investment)	$ 37.50
Lifetime	20 years
Derating factor	85%
Slope	Default to latitude (optimum)
Azimuth	0° (optimum)
Ground reflectance	20%
Temperature coefficient of power	-0.44%/°C
Nominal operating cell temperature	47.5 °C
Efficiency at standard test conditions	15%

Table 4.5: Input parameters for PV system

Due to the highly corrosive climate in the Maldives, prices for the energy system modeling were calculated for a PV system with glass-glass panels instead of a system with conventional panels. Prices for systems with glass-glass panels are about 20% higher than for systems with glass-foil panels. Due to climatic issues, PV systems with tracking were not considered an option for the system modeling. Moreover, tracked PV systems need even more space to prevent them from shading each other.

The costs for the PV system excluding the inverter are 2,500$ per kW_p readily installed. This figure includes PV panels, the mounting system, substructure, shipping, installation, etc.[13] Yearly Operating costs for PV systems are usually 1.5% of the investment and include cleaning, insurance, administration and a replacement of the inverters after 10 years. Due to the corrosive climate and high salt content in the air 1.5% operating costs excluding the replacement of the inverter after 10 years were assumed. Other technical

[13] Prices are based on a company internal cost calculation of Swimsol GmbH and are the regular selling prices for systems from 50 kW in the Maldives.

parameters such as the temperature coefficient and the panel efficiency at STC were derived from a data sheet of Sharp Solar. The area needed to install one kilowatt peak of solar energy is approximately 6 – 8 m^2 depending on the chosen technology and the cell efficiency. Due to the severely constrained land resources on many of the islands of the Maldives, this issue is discussed in more detail in chapter 7 of this thesis.

4.4.6 Swimsol platform

The Swimsol platform is modeled as a PV array with the input parameters shown in Table 4.5 with the following alterations:

The capital cost is $ 3,500 instead of $ 2,500. This is due to the higher cost for the swimming platform, the substructure, mooring, underwater cables and adapted electrical components. Due to the higher costs for cleaning, insurance and maintenance, yearly O&M costs are assumed to be 2% instead of 1.5% of the investment. Ground reflectance is assumed to be 25% instead of 20% because reflection of solar beams on the sea surface is expected to be higher than on the ground or on roofs.

4.4.7 Inverter

The inverter efficiency was assumed to be 98%, which is a common value for solar inverters. The lifetime was assumed to be 10.5 years. Inverter costs depend on the size of the inverter and were derived from company internal wholesaler price information as shown in Table 4.6:

Size	Capital cost	Replacement cost
5 kW	$ 2,000	$ 2,000
10 kW	$ 2,625	$ 21,250
100 kW	$ 21,250	$ 21,250

Table 4.6: Cost summary inverter

In Europe, inverters usually have to be replaced at approx. 20% of the investment costs after 10-12 years lifetime. This is due to the failure of the capacitor which “dries out” after this period of time. Due to remoteness and the small size of the Maldivian PV market, it was assumed that replacement costs are similar to the investment costs. O&M costs of the inverter were assumed to be incorporated in the O&M costs of the PV array.

4.4.8 Diesel generator

During talks with persons on several islands in charge of the diesel generators the author learned that the prices for diesel generators are between 250$ and 350$ per kW (P. Latzka, W. Kauffmann, R. Fernandez, personal communication, November 2012 and February 2013). Therefore the capital cost for the generators was assumed to be $300 per kW. Replacement costs were assumed to be 100% of investment costs.

The cost of electricity production with diesel generators is comprised of approx. 90% fuel costs and approx. 10% O&M costs (A. Ibrahim, Senior Engineer at STELCO, personal communication, January 2013). The kWh generated out of one litre of diesel as well as the diesel cost is known for all islands under examination and therefore the O&M costs per kWh were calculated using the following equation (8):

$$C_{op} = \frac{c_{op,kWh} \times N_{kWh}}{t_{op}} \tag{8}$$

where

C_{op}	is the O&M cost per hour [$/hr]
$c_{op,kWh}$	is the O&M cost per kWh [$/kWh]
N_{kWh}	is the amount of kWh produced per year
t_{op}	is the total operating hours per year

O&M costs are therefore assumed to be 5$/hr. These costs account for operating personnel, lubricants, maintenance and spare parts. The reason why the O&M costs are calculated as $/hr is mere the fact that HOMER can only deal with this format.

Generator lifetime was set to 25,000 hours. This value represents the best fit to information the author got during his visits to the Maldives that generators have to be replaced every 5 - 6 years (W. Kauffmann, personal communication, November 2012). Table 4.7 summarizes the input parameters for diesel generators.

Parameter	Value
Capital cost	300 $/kW
Replacement cost	300 $/kW
Lifetime	25,000 hours
Minimum load ratio	50%
Maximum load ratio	80%

Table 4.7: Generator input parameters

The partial load efficiency of diesel generators is another important parameter that HOMER uses to calculate fuel consumption, generator runtime and output. The minimum load the generators were allowed to run at was set at 50%. This value was the common understanding of all persons I talked to. At loads smaller than 50% O&M costs as well as maintenance go up and lifetime decreases significantly. The same applies for loads above 80% of the nominal load of DG (A. Ibrahim, P. Latzka, W. Kauffmann, R. Fernandez, personal communication, November 2012 and January 2013). That is why the generator sizes for the simulations were adjusted accordingly. The fuel curve and the efficiency curve of the generator that determine the fuel consumption and efficiencies at different loads were calculated individually for each generator size on the basis of information of diesel service & supply (2011) (see Figure 4.10 and Figure 4.11 for examples).

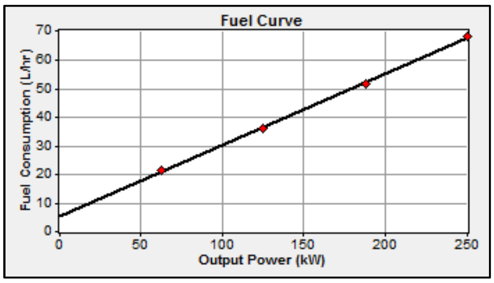


Figure 4.10: Fuel curve of a 250 kW generator

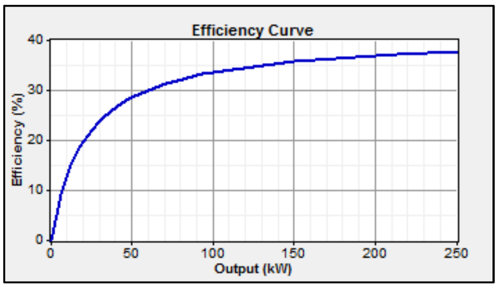


Figure 4.11: Efficiency curve for a 250 kW generator

4.4.9 Battery bank

The battery bank is a collection of one or more batteries connected to strings to attain the desired voltage. In this case Hoppecke 24 OPzS 3000 lead - acid deep cycle batteries were connected to strings of 120 batteries each to reach a voltage of 240 V on the DC bus.

Due to the results of literature research and consultations with colleagues from ESEA from the Technical University Vienna, it was decided to only use lead - acid batteries for the system modeling in this thesis (unpublished research report for Swimsol GmbH 2012; M. Chochole, personal communication, June 2012). The main reasons for this decision were the cost efficiency and matureness of lead acid batteries compared to other storage technologies. Also, lead - acid batteries are the ones most usually used in off-grid systems and therefore regarded as the best technology for the system design on Maldivian islands.

HOMER models the battery as a device capable of storing DC electricity at a fixed round-trip efficiency with limits as to the charge and discharge properties and how much energy can cycle through the battery before it needs to be replaced (Homer Energy 2004, Lambert & Lilienthal, 2006). The key physical parameters for the modeling software are the batteries´ nominal voltage, capacity curve, lifetime curve, the minimum state of charge and the round trip efficiency (Lambert & Lilienthal, 2006).

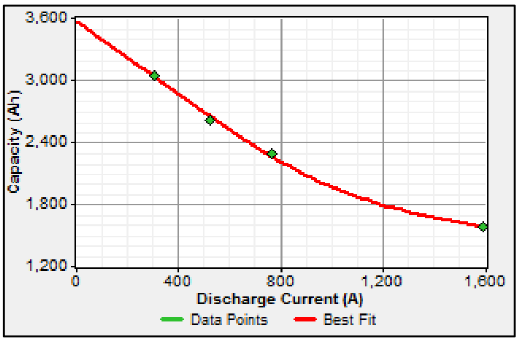


Figure 4.12: H 3000 battery capacity curve

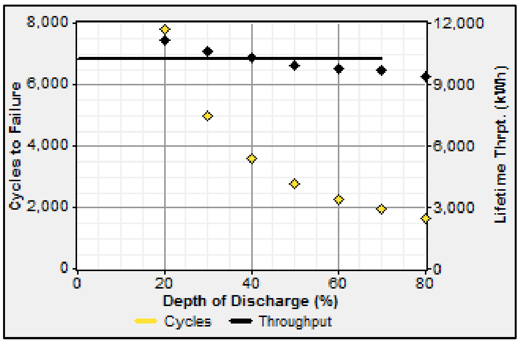


Figure 4.13: H 3000 battery lifetime curve

The capacity curve determines the discharge capacity in ampere hours versus the discharge current in Amperes. Typically, discharge capacity decreases with increasing discharge current (see Figure 4.12). The lifetime curve shows the number of charge - discharge cycles to failure as a function of the depth of discharge as a percentage of the battery´s total capacity (see Figure 4.13). The number of cycles to failure typically decreases with increasing depth of discharge (Lambert & Lilienthal, 2006).

As for battery costs real market prices were derived from Phaesun GmbH - a wholesaler for off - grid components[14]. Battery O&M costs were assumed to be incorporated in the O&M costs of the PV system and the diesel generators. Table 4.8 shows a summary of the battery parameters used for simulation.

[14] www.phaesun.com (accessed 12 January 2012)

Parameter	Value
Capital cost	1,200 $
Replacement cost	1,200 $
O&M cost	0 $
Nominal capacity	3,000 Ah
Nominal voltage	2 V
Round trip efficiency	86%
Min. state of charge	30%
Float life	20 years
Lifetime throughput	10,196 kWh
Suggested value	10,241 kWh
Max. charge rate	1 A/Ah
Max. charge current	610 A

Table 4.8: Summary of battery parameters

4.5 Summary of input parameters[15]

The following table summarizes the input parameters used for the energy system modeling in HOMER.

Control Parameters	Annual real interest rate	6% (3%, 9%, 12%)
	Project lifetime	20 years
	Diesel price	$1.04 (1.14, 1.25, 1.35 $/l)
	Dispatch strategy	Load following
	Operating reserve	as percent of load: 10% as percent of solar output: 25%
	Emission penalty	$0 ($10)
PV array	Cost of PV array	$2,500/kWp
	Cost of Swimsol	$3,500/kWp
	Replacement cost	100% of investment cost
	O&M cost	PV: 1.5% of investment cost Swimsol: 2% of investment cost
	lifetime	20 years
Power converter	Cost of power converter	5 kW: $2,000 10 kW: $2,625 100 kW: $21,250
	Replacement cost	100% of investment cost
	O&M cost	$0, included in O&M of PV
	Lifetime	10.5 years
	efficiency	98%
Diesel generators	Cost	$300/kW
	Replacement cost	100% of investment cost
	O&M cost	$5/hour
	Lifetime	25,000 hours
	Minimum load ratio	50%
Battery bank		See Table 4.8

Table 4.9: Summary of input parameters

[15] Values in brackets are considered in sensitivity analysis

5 Optimization Results

Based on the assumptions and input parameters presented in chapter 4.4 and summarized in chapter 4.5, simulations with more than 40,000 different system configurations and 24 combinations of sensitivity parameters for each system configuration and each island were run to determine the optimal PV/diesel hybrid system and the optimal PV/diesel/battery system. According to the findings of Lilienthal (2007) and MEE (2012), the maximum PV capacity for systems without battery storage has been constrained to 20% of the peak load of the island. The size of the converter for systems without storage was chosen to meet the entire PV production at all times to limit excess energy and maximize solar energy penetration. The results are presented and compared to the existing systems. Optimal system configurations refer to the systems with least Net Present Cost (NPC), the metric HOMER uses to rank systems. For the ease of reading, only the key results are presented in this section while an example of a detailed system report can be found in HOMER – System Report of this thesis.

5.1 Maafushi – 2,000 inhabitants

Table 5.1 shows the base case system with 5 diesel generators and a total installed capacity of 1,870 kW. The present fuel consumption is 1,024,719 litres per year with a total cost of 1,056,708 $ per year. The total annual cost for this system is 1,173,665 $ and the COE is 0.323$/kWh, respectively. The average fuel consumption to produce one kilowatt hour of electric energy is 0.27 litres[16]. This value is comparably low compared to real figures because in contrast to the human operators of the diesel generators on the islands, HOMER optimizes runtimes and load ratios for all diesel generators. In reality diesel generators are often run in a more inefficient way, leading to higher relative fuel consumptions. This is mainly due to the lack of technical equipment such as power analyzers, which precisely measure the load at any given time and allow the operator to optimize generator runtimes.

[16] This is valid for all system configurations

Baseline scenario – Diesel stand-alone		
	Value	metric
Diesel Generators	1,870	kW
Cost parameters[17]		
Investment cost	561,000	$
Operating cost	65,605	$/yr
Fuel cost	1,056,708	$/yr
Replacement cost	51,352	$/yr
Salvage	-102,275	$
Total NPC	14,023,808	$
COE	0.323	$/kWh
Energy output		
Diesel generators	3,779,938	kWh/yr
Fuel consumption	1,024,719	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	2,698	t/yr

Table 5.1: System characteristics: Diesel stand-alone system

Figure 5.1 illustrates the great contribution of fuel costs to the total Net Present Cost of the system. The contribution of the gensets to the total NPC also indicates the runtime hours of the individual gensets in this configuration.

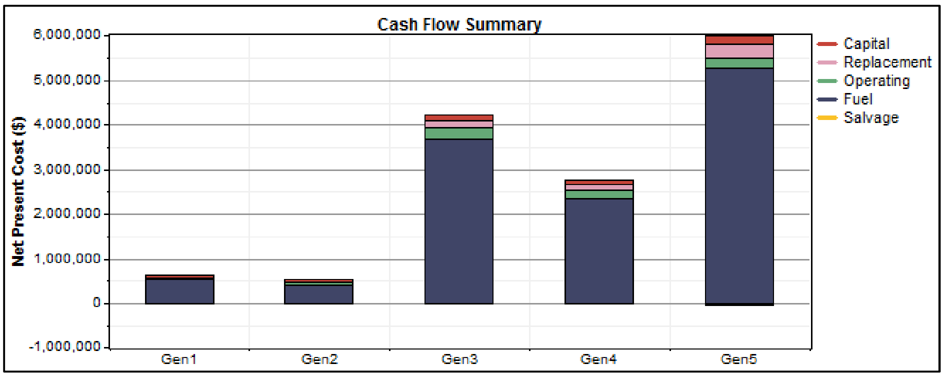


Figure 5.1: Net Present Cost Summary – Diesel stand-alone system

5.1.1 PV/Diesel hybrid system

Table 5.2 and Table 5.3 give the optimal PV/diesel system and the optimal Swimsol/Diesel system of Maafushi, respectively. As described earlier, the installed PV capacity has been constrained to 20% of the island´s peak load which is approximately 150 kW in this case. The total NPC of the PV/Diesel system is 13,739,702 $ and the Cost of Electricity (COE) is 0.317 $/kWh. Although the investment costs as well as the O&M costs for the Swimsol platform are higher than for a regular PV system, total NPC of 13,944,692 $ and COE of 0.322 $/kWh of the Swimsol/Diesel system are still slightly

[17] Values are annualized cost with the exception of investment cost and salvage for all simulation results.

lower in comparison with the baseline scenario. The yearly diesel consumption can be reduced by approx. 58,000 liters or 6% per year with both configurations.

Optimal PV/Diesel system		
	value	metric
Diesel Generators	1,620	kW
PV	150	kW
Converter	150	kW
Cost parameters		
Investment cost	907,597	$
Operating cost	69,095	$/yr
Fuel cost	1,005,623	$/yr
Replacement cost	49,322	$/yr
Salvage	-60,539	$
Total NPC	13,739,702	$
COE	0.317	$/kWh
Energy output		
Diesel generators	3,556,847	kWh/yr
PV	227,726	kWh/yr
Excess Electricity	84.0	kWh/yr
%	0	
Fuel consumption	966,945	l/yr
Average fuel efficiency	0.27	l/kWh
CO_2 emissions	2,546	t/yr
Renewable fraction[18]	6	%
Savings compared to baseline		
CO_2 emission reduction	152	t/yr
%	5.6	%
Diesel savings	57,744	l/yr

Table 5.2: Optimal system configuration – PV/Diesel

Optimal Swimsol/Diesel system		
	value	metric
Diesel Generators	1,670	kW
PV	150	kW
Converter	150	kW
Cost parameters		
Investment cost	1,057,597	$
Operating cost	73,895	$/yr
Fuel cost	1,005,618	$/yr
Replacement cost	49,322	$/yr
Salvage	-60,547	$
Total NPC	13,944,692	$
COE	0.322	$/kWh
Energy output		
Diesel generators	3,556,835	kWh/yr
PV	227,739	kWh/yr
Excess Electricity	84.1	kWh/yr
%	0	
Fuel consumption	966,940	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	2,546	t/yr
Renewable fraction	6	%
Savings compared to baseline		
CO_2 emission reduction	152	t/yr
%	5.6	%
Diesel savings	57,779	l/yr

Table 5.3: Optimal system configuration – Swimsol/Diesel

Due to the similarity of both systems, the graphical representation of the results is only given for the PV/Diesel system (Figure 5.2 and Figure 5.3).

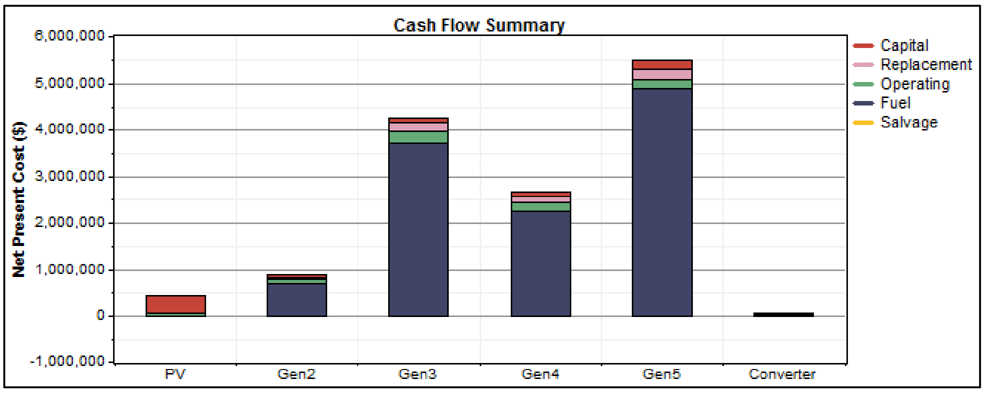


Figure 5.2: Net Present Cost Summary – PV/Diesel system

[18] Renewable fraction is calculated by HOMER as the fraction of the total energy output from renewables to the total energy production of the system

Figure 5.3 shows the graphical representation of the solar PV fraction for each month of the year. This figure again demonstrates the even distribution and therefore PV energy production throughout the year.

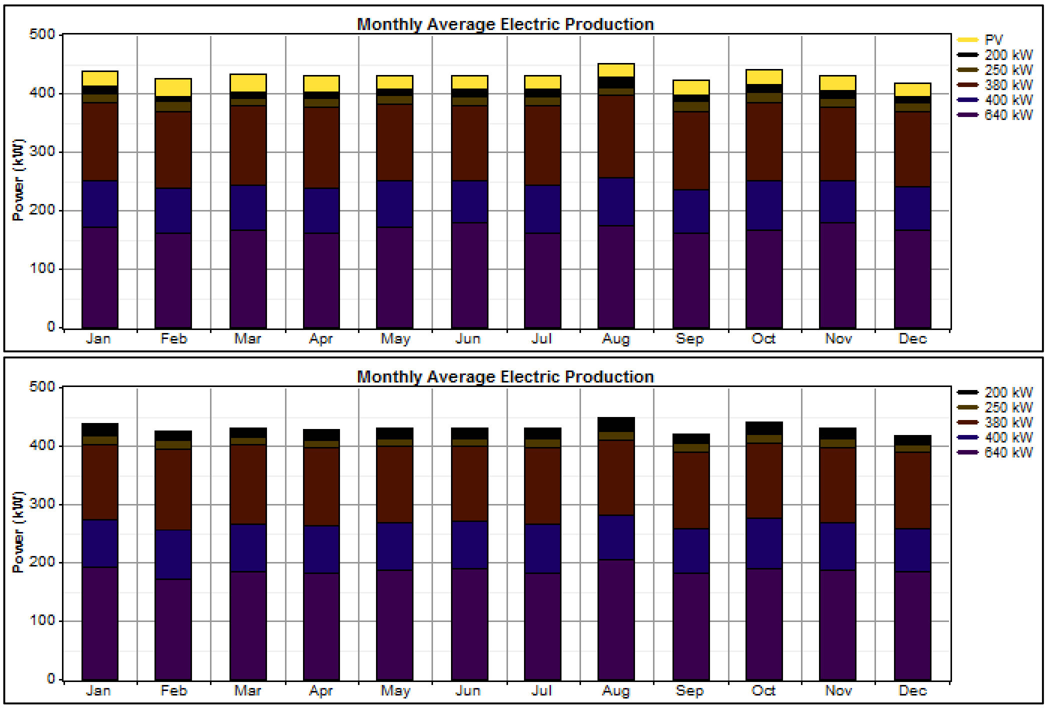


Figure 5.3: Electric production for diesel stand-alone and PV/Diesel systems

5.1.2 PV/Diesel/Battery hybrid system

Table 5.4 summarizes the characteristics of the optimum PV/Diesel/Battery hybrid system for the island of Maafushi. In this configuration with a RE fraction of 59% only 1,220 kW of diesel generator capacity is needed. In addition, the cost minimal PV/Diesel system with battery storage consists of a PV capacity of 1,600 kW, 10 strings à 120 batteries and a 700 kW converter. The total NPC of 12,718,653 $ and the COE of 0.293 $/kWh in this system are considerably lower compared to the baseline scenario. The yearly diesel savings amount to nearly 600,000 litres. Emission reductions of more than 1,500 tons per year or 58.2% can be achieved.

Optimal PV/Diesel/battery system		
	value	**metric**
Diesel Generators	1,220	kW
PV	1,600	kW
Batteries	1,200	pcs
Converter	700	kW
Cost parameters		
Investment cost	5,951,417	$
Operating cost	90,390	$/yr
Fuel cost	445,222	$/yr
Replacement cost	81,596	$/yr
Salvage	-312,084	$
Total NPC	12,718,653	$
COE	0.293	$/kWh
Energy output		
Diesel generators	1,565,305	kWh/yr
PV	2,429,078	kWh/yr
Excess Electricity	43,360	kWh/yr
%	1.09	
Fuel consumption	428,098	l/yr
Average fuel efficiency	0.27	l/kWh
CO_2 emissions	1,127	t/yr
Renewable fraction	59	%
Savings compared to baseline		
CO_2 emission reduction	1,571	t/yr
%	58.2	%
Diesel savings	596,621	l/yr

Table 5.4: Optimal system configuration – PV/diesel/Battery

Optimal Swimsol/Diesel/Battery system		
	value	**metric**
Diesel Generators	1,220	kW
PV	1,000	kW
Batteries	600	pcs
Converter	700	kW
Cost parameters		
Investment cost	4,731,417	$
Operating cost	114,695	$/yr
Fuel cost	666,293	$/yr
Replacement cost	42,891	$/yr
Salvage	-70,317	$
Total NPC	14,110,928	$
COE	0.325	$/kWh
Energy output		
Diesel generators	2,340,608	kWh/yr
PV	1,518,258	kWh/yr
Excess Electricity	7,290	kWh/yr
%	0.19	
Fuel consumption	640,666	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	1,687	t/yr
Renewable fraction	38	%
Savings compared to baseline		
CO_2 emission reduction	1,011	t/yr
%	37.4	%
Diesel savings	384,053	l/yr

Table 5.5: Optimal system configuration – Swimsol/Diesel/Battery

The installation of 1,600 kW of solar PV would need an unshaded area of about 12,800 m^2 which would be approx. 4.3% of the total area of Maafushi[19]. It is not clear, whether this amount of space would be available on the island. However, the island features a vast lagoon area with plenty of space for a Swimsol installation (see Figure 5.4). The optimal configuration of a Swimsol/Diesel/Battery system is shown in Table 5.5. It consists of a PV array of 1,000 kW alongside of 600 batteries, 1,220 kW of diesel generators and a

Figure 5.4: Maafushi and its lagoon (Google maps, 2012)

700 kW converter. In this configuration with a RE fraction of 38% the total NPC of 14,110,928 $ as well as the COE of 0.325 $/kWh are slightly higher in comparison with the baseline scenario. Nevertheless, considerable amounts of diesel savings and CO_2

[19] Based on an area of 8 m^2 per kWp installed.

emission reductions are achieved. This lowers the dependence on diesel fuel and leads to a reduced vulnerability to increases in diesel prices. A more detailed analysis of rising fuel prices and emission penalties are given in chapters 6 and 7. It is worth noting, that the excess electricity with these systems is relatively high in comparison with PV/Diesel/Battery systems on the other islands. This could not be eliminated even by multiple runs of the model. Figure 5.5 illustrates the solar energy production for each month of the year for both systems. 200 kW, 380 kW and 640 kW in these figures refer to the generator sizes[20].

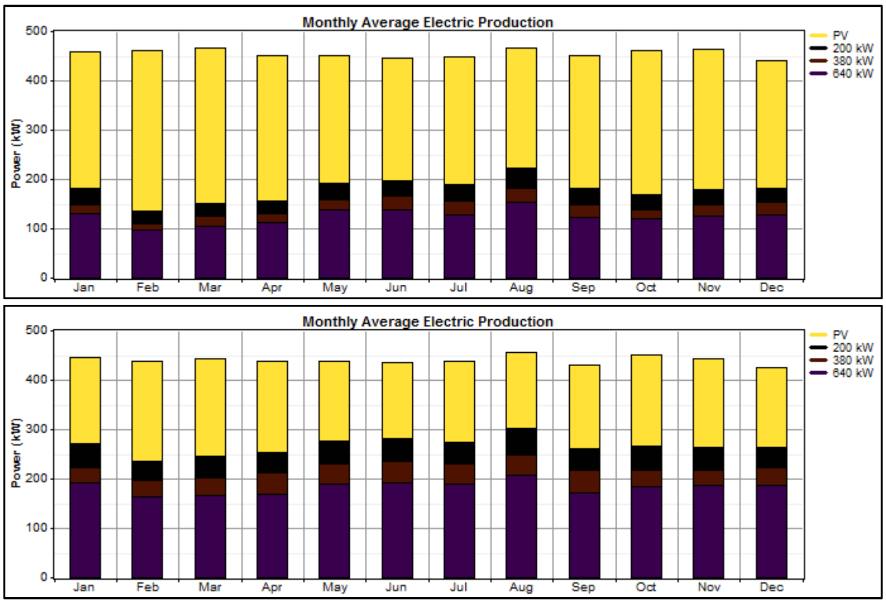


Figure 5.5: Monthly average electric production for PV/Diesel/Battery and Swimsol/Diesel/Battery system

5.1.3 Summary of the simulation results for Maafushi

The following table summarizes the optimization results for the island of Maafushi. It is worth noting, that apart from the Swimsol/Diesel/Battery system, all systems are cheaper than the base case system in terms of NPC and COE.

[20] This is valid for all figures that show the monthly average electric production.

	Base case	PV/Diesel	Swimsol/ Diesel	PV/Diesel/ Battery	Swimsol/ Diesel/ Battery
System configuration					
Diesel generators (kW)	1,870	1,620	1,670	1,220	1,220
PV Panels (kWp)	-	150	150	1,600	1,000
Converter (kW)	-	150	150	700	700
Batteries (pcs)	-	-	-	1,200	600
Cost Summary					
Investment (1000$)	561	968	1,058	5,951	4,731
Total NPC (1000$)	14,024	13,740	13,945	12,719	14,111
COE ($/kWh)	0.323	0.317	0.322	0.293	0.325
RE Fraction (%)	-	6	6	58	37
emission reduction (tCO_2/yr)	-	152	152	1,571	1,011
Required land area for PV installation ($1000m^2$)	-	0.9 – 1.2	-	9.6 – 12.8	–-

Table 5.6: Summary of simulation results for Maafushi

The cost-minimal system for Maafushi consists of a 1,600 kW PV array, 12 strings à 120 batteries, a 700 kW converter and 1,670 kW of diesel generators. COE of this system is 0.03 $/kWh lower than for the diesel stand-alone system. However, the required land area for this system would be 9,600 – 12,800 m^2 or about 4% of the area of the island. It yet has to be clarified if this amount of suitable space is available on the island.

5.2 Hulhumale´ - 10,000 inhabitants

Table 5.7 shows the base case system for Hulhumale´ with 4 diesel generators and a total installed capacity of 4 megawatts (MW). According to HOMER, the present fuel consumption is 3,625,829 litres per year with a total cost of 3,770,864 $. The total annual cost for this system is 4,059,313 $ and the COE is 0.310 $/kWh. The COE in this system is lower than the one in the base case system of Maafushi due to the larger size of the generators which are usually slightly more efficient. Also it is assumed, that HOMER is able to run the generators in a more efficient way than on Maafushi.

System architecture – Diesel stand-alone		
	value	**metric**
Diesel Generators	4,000	kW
Cost parameters		
Investment cost	1,200,000	$
Operating cost	103,115	$/yr
Fuel cost	3,770,864	$/yr
Replacement cost	214,131	$/yr
Salvage	-330,269	$
Total NPC	47,760,004	$
COE	0.310	$/kWh
Energy output		
Diesel generators	13,450,640	kWh/yr
Fuel consumption	3,625,829	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	9,548	t/yr

Table 5.7: System characteristics – Diesel stand-alone system

Figure 5.6 summarizes the contributions of the individual gensets to the total NPC of the system. Again, the biggest contributor to NPC by far is fuel cost.

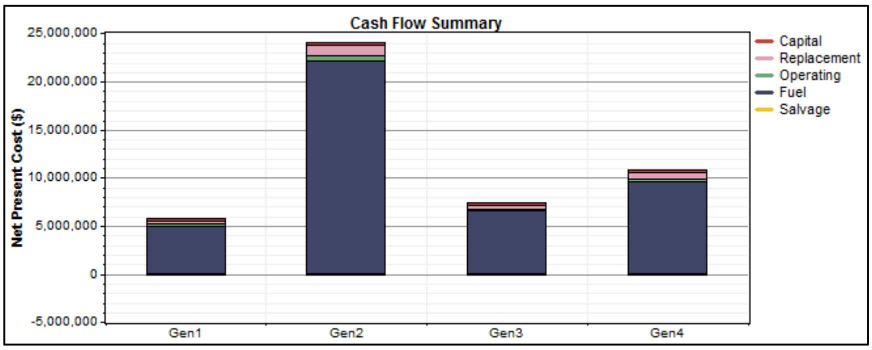


Figure 5.6: Net Present Cost Summary – Diesel stand-alone System

5.2.1 PV/Diesel hybrid system

Table 5.8 and Table 5.9 show the characteristics of the optimal PV/diesel system and the optimal Swimsol/Diesel system, respectively. Again, the installed PV capacity has been constrained to 20% of the island´s peak load which is approximately 450 kW on

Hulhumale´. The installed capacity of diesel generators is similar to the base case for both configurations. According to HOMER, the total NPC of the PV/Diesel system is 46,843,172 $ and the COE is 0.304 $/kWh. Therefore, NPC can be brought down by 916,832 $ with the PV/diesel system in comparison to the diesel stand-alone system. NPC as well as COE for the Swimsol/Diesel system are again higher than for the PV/Diesel system but still slightly below the costs for the base case system. The reduction in diesel consumption is about 5% for both RE/Diesel configurations and the emission reduction is 483 t/yr and 458 t/yr, respectively.

System architecture – PV/Diesel hybrid		
	value	**metric**
Diesel Generators	4,000	kW
PV	450	kW
Converter	450	kW
Cost parameters		
Investment cost	2,418,681	$
Operating cost	115,360	$/yr
Fuel cost	3,580,047	$/yr
Replacement cost	188,655	$/yr
Salvage	-125,404	$
Total NPC	46,843,172	$
COE	0.304	$/kWh
Energy output		
Diesel generators	12,779,912	kWh/yr
PV	684,418	kWh/yr
Excess Electricity	0.0738	kWh/yr
%	0	
Fuel consumption	3,442,352	l/yr
Average fuel efficiency	0.27	l/kWh
CO_2 emissions	9,065	t/yr
Renewable fraction	5	%
Savings compared to baseline		
CO_2 emission reduction	483	t/yr
%	5	%
Diesel savings	183,477	l/yr

Table 5.8: Optimal system configuration – PV/Diesel

System architecture – Swimsol/Diesel		
	value	**metric**
Diesel Generators	4,000	kW
Swimsol	450	kW
Converter	450	kW
Cost parameters		
Investment cost	2,868,681	$
Operating cost	129,970	$/yr
Fuel cost	3,589,887	$/yr
Replacement cost	188,869	$/yr
Salvage	-10,593	$
Total NPC	47,579,968	$
COE	0.308	$/kWh
Energy output		
Diesel generators	12,814,172	kWh/yr
PV	684,463	kWh/yr
Excess Electricity	0.0753	kWh/yr
%	0	
Fuel consumption	3,451,813	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	9,090	t/yr
Renewable fraction	5	%
Savings compared to baseline		
CO_2 emission reduction	458	t/yr
%	5	%
Diesel savings	174,016	l/yr

Table 5.9: Optimal system configuration – Swimsol/Diesel

Again, the graphical representation of the simulation results is only given for the PV/Diesel system (see Figure 5.7 and Figure 5.8). The cost portions of the PV system show the high capital cost in comparison with the O&M cost in contrast to the cost shares of the diesel generators, where capital costs are negligibly low in comparison to the running costs.

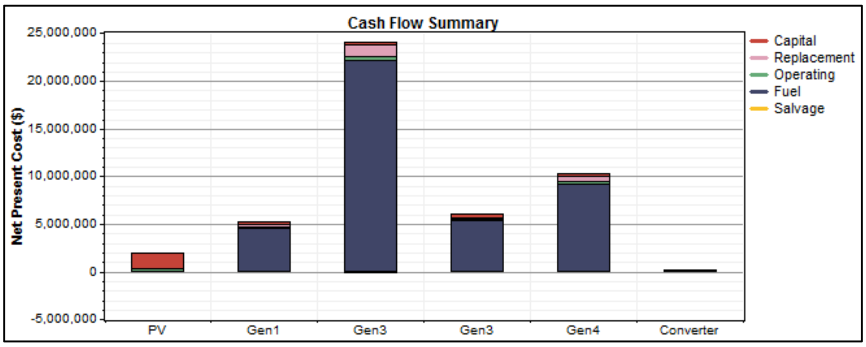


Figure 5.7: Net Present Cost Summary: PV/Diesel System

Figure 5.8 shows the production of the PV system for each month of the year.

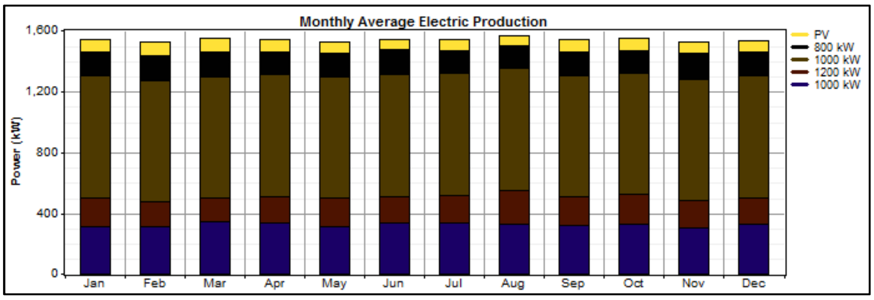


Figure 5.8: Monthly Average Electric Production - PV/Diesel System

5.2.2 PV/Diesel/Battery hybrid system

The best PV/Diesel/Battery in terms of NPC is a system configuration with 5,000 kW PV, 2,800 kW Diesel generators, a 2,200 kW Converter and 2,400 batteries and a COE of 0.280 $/kWh. The renewable fraction is 53%. This configuration is shown in Table 5.10. The total capacity of the batteries is 14,400 kWh and lasts for a system autonomy of 6.56 hours. The NPC of this system is about 4,000,000 $ lower than the NPC of the base case system and COE is 0.027 $/kWh lower than the COE of the base case system. Table 5.11 shows the characteristics of the optimal Swimsol/Diesel/Battery system with a RE fraction of 33%. Total NPC as well as COE of this system is slightly lower than NPC and COE of the base case system and diesel savings of 33% or over 1,170,000 liters per year are achieved with this configuration.

System architecture – PV/Diesel/battery		
	value	metric
Diesel Generators	2,800	kW
PV	5,000	kW
Batteries	2,400	pcs
Converter	2,200	kW
Cost parameters		
Investment cost	16,675,833	$
Operating cost	248,125	$/yr
Fuel cost	1,820,764	$/yr
Replacement cost	259,418	$/yr
Salvage	-19,578	$
Total NPC	43,156,792	$
COE	0.283	$/kWh
Energy output		
Diesel generators	6,458,282	kWh/yr
PV	7,604,637	kWh/yr
Excess Electricity	154,720	kWh/yr
%	1.10	
Fuel consumption	1,750,734	l/yr
Average fuel efficiency	0.27	l/kWh
CO_2 emissions	4,610	t/yr
Renewable fraction	52	%
Savings compared to baseline		
CO_2 emission reduction	4,938	t/yr
%	52	%
Diesel savings	1,875,095	l/yr

Table 5.10: Optimal system configuration - PV/Diesel/Battery

System architecture – Swimsol/Diesel/battery		
	value	metric
Diesel Generators	2,800	kW
PV	3,000	kW
Batteries	1,200	
Converter	2,000	kW
Cost parameters		
Investment cost	13,194,444	$
Operating cost	291,685	$/yr
Fuel cost	2,544,713	$/yr
Replacement cost	176,308	$/yr
Salvage	-15,993	$
Total NPC	47,566,504	$
COE	0.308	$/kWh
Energy output		
Diesel generators	9,061,145	kWh/yr
PV	4,563,073	kWh/yr
Excess Electricity	516	kWh/yr
%	0.0038	
Fuel consumption	2,446,838	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	6,443	t/yr
Renewable fraction	33	%
Savings compared to baseline		
CO_2 emission reduction	3,105	t/yr
%	33	%
Diesel savings	1,178,991	l/yr

Table 5.11: Optimal system configuration - Swimsol/Diesel/Battery

Figure 5.9 shows the NPC of the optimal PV/Diesel/Battery system. Costs for the PV system contribute large shares to the total NPC of this system[21].

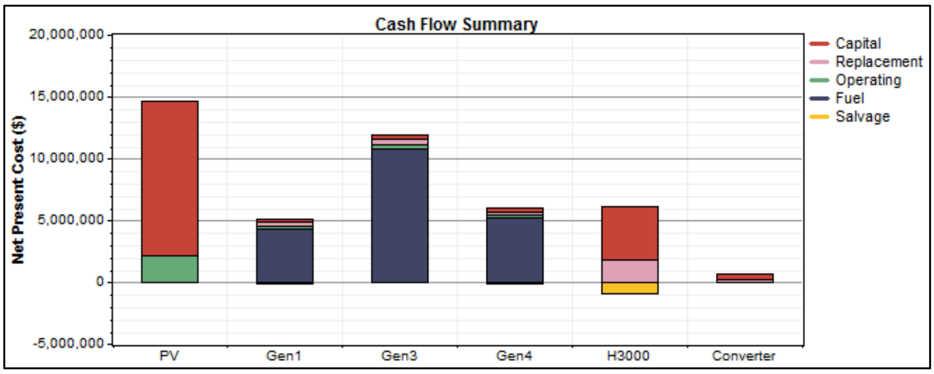


Figure 5.9: NPC Summary – PV/Diesel battery system

Figure 5.10 shows the RE fractions for the two different system configurations. Due to the higher costs for the Swimsol platform, RE fractions are smaller in the Swimsol/Diesel/Battery system.

[21] Proportions of costs are similar for the optimal Swimsol/Diesel/Battery system.

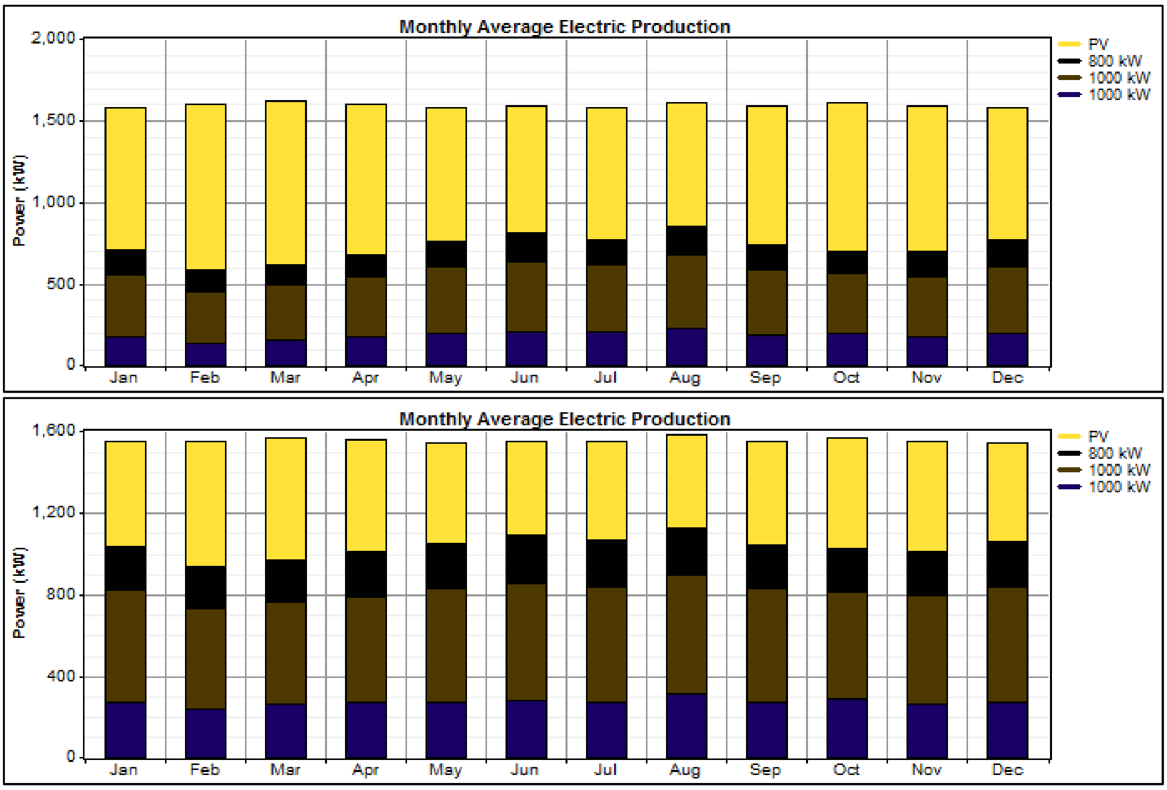


Figure 5.10: Monthly average electric production – PV/Diesel/battery and Swimsol/Diesel/Battery systems

Other interesting figures referring to systems with battery storage are presented in the following, representative for all RE/Diesel/battery systems. The figures refer to the PV/Diesel/Battery systems. Figure 5.11 shows the state of charge of the battery bank. During daytime, when PV power is produced, the batteries are charged until they reach their maximum charge of about 70-90%. In the evening hours until about 0:00pm, the batteries are discharged to the minimum state of charge of 30% to serve part of the island´s energy demand.

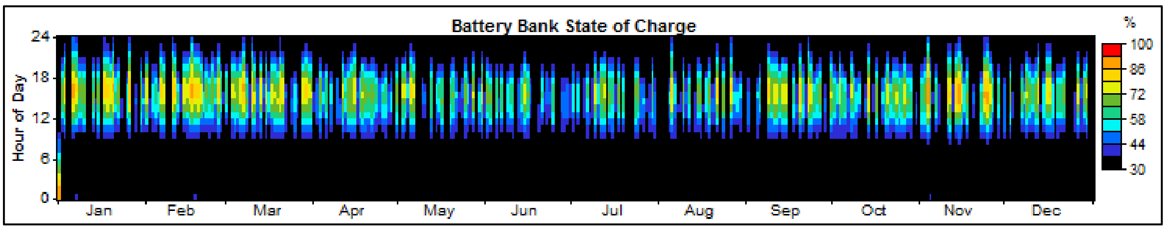


Figure 5.11: Battery bank state of charge

Figure 5.12 shows the interaction of the different power generators and the battery bank to serve the load of the island on and exemplary day (May 23). The PV power output curve indicates overcasting during parts of the day. Solar energy that cannot be used up by the island charges the battery bank which is discharged again when solar energy production goes down.

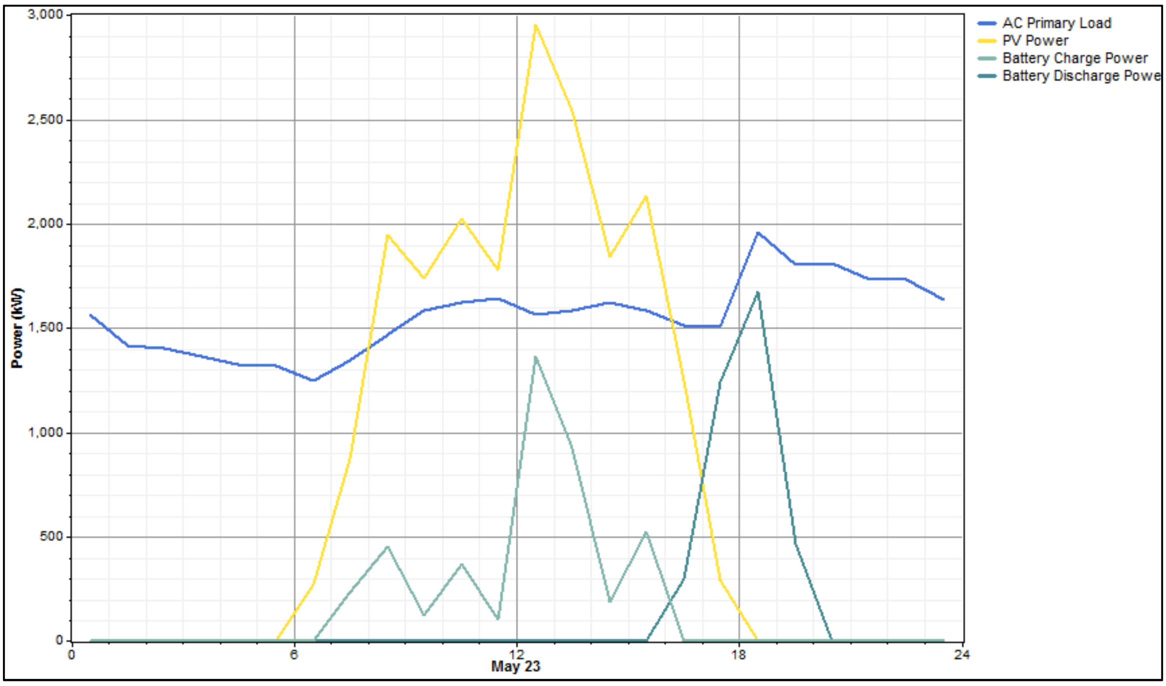


Figure 5.12: PV output, primary load and corresponding battery charge and discharge power

Figure 5.13 additionally shows the output power of the different diesel generators during the course of the day. It can be observed, that all diesel generators can be switched off during the time the PV array delivers power.

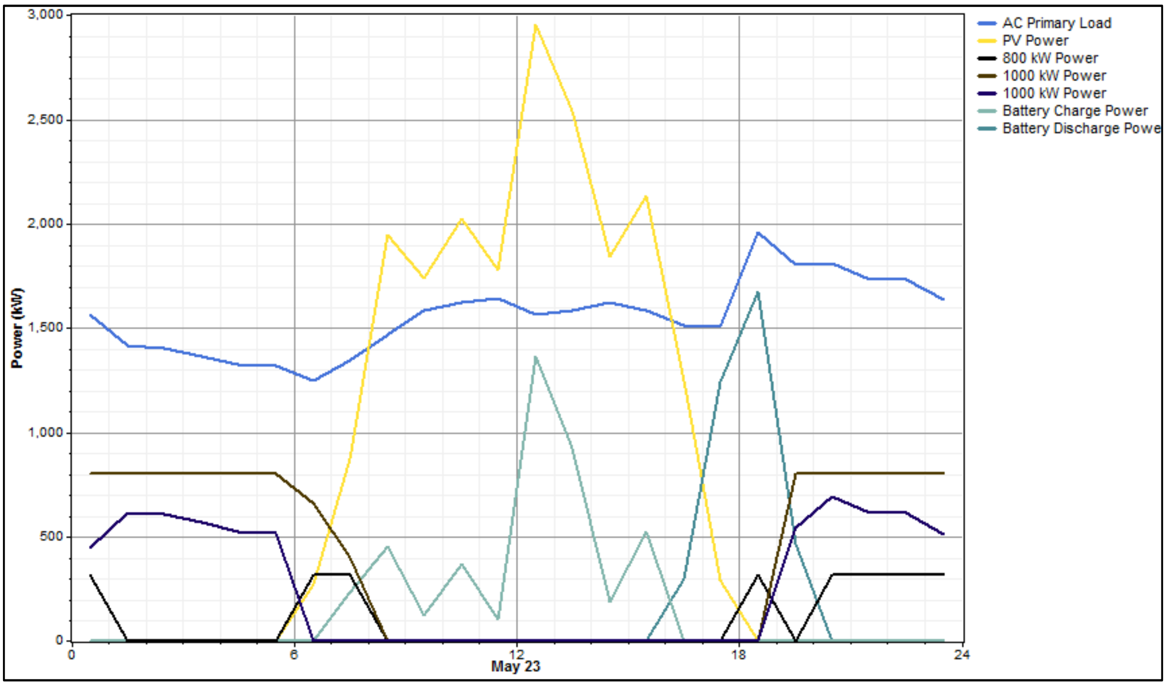


Figure 5.13: PV output, primary load, diesel generator output and corresponding battery charge and discharge power

5.2.3 Summary of the simulation results for Hulhumale´

The following table shows the optimization results for Hulhumale´. All PV/Swimsol system configurations are less expensive than the current diesel stand-alone system. However, investment costs for PV and Swimsol Diesel systems are obviously much higher than for the diesel stand-alone system.

	Base case	PV/Diesel	Swimsol/ Diesel	PV/Diesel/ Battery	Swimsol/ Diesel/ Battery
System configuration					
Diesel generators (kW)	4,000	4,000	4,000	2,800	2,800
PV Panels (kWp)	-	450	450	5,000	3,000
Converter (kW)	-	450	450	2,200	2,000
Batteries (pcs)	-	-	-	2,400	1,200
Cost Summary					
Investment (1000$)	1,200	2,419	2,869	16,675	13,194
Total NPC (1000$)	47,760	46,843	47,580	43,157	47,566
COE ($/kWh)	0.310	0.304	0.308	0.280	0.308
RE Fraction (%)	-	5	5	52	33
emission reduction (tCO_2/yr)	-	483	458	4,938	3,105
Required land area for PV installation (1000 m^2)	-	2.7 – 3-6	-	30 - 40	-

Table 5.12: Summary of simulation results for Hulhumale´

The cost-minimal system for the island of Hulhumale´ is a PV/Diesel/Battery system with 2,800 kW diesel generator capacity, a 5 MW PV array, 3,600 batteries and a 2,200 kW inverter. The COE is 0,027 $/kWh lower than for the base case system. However, the investment cost for this system configuration is more than 15-fold the investment cost for the diesel stand-alone system. The area needed to install 5 MW of PV energy is between 30,000 and 40,000 m^2. It is assumed, that there´s enough land available on Hulhumale´ to install this amount of PV capacity.

5.3 Resort – Meeru Island

Table 5.13 shows the characteristics of the base case system for Meeru Island Resort with 5 diesel generators and a total installed capacity of 4.05 MW. The present fuel consumption is 3,342,071 litres per year with a total cost of 3,475,775 $. The total annual cost for this system is 3,741,550 $ and the COE is 0.308 $/kWh, respectively. The COE for this system is again lower than the one in the base case system of Maafushi due to the larger size of the generators. Also, it is assumed, that HOMER is able to run the generators in a more efficient way than on Maafushi. The COE figure for the Hulhumale´

base case system which has comparable installed capacity of diesel generators is almost the same as for this system.

System architecture – Diesel stand-alone system		
	value	metric
Diesel Generators	4,050	kW
Cost parameters		
Investment cost	1,215,000	$
Operating cost	102,115	$/yr
Fuel cost	3,475,755	$/yr
Replacement cost	185,417	$/yr
Salvage	-249,312	$
Total NPC	44,130,296	$
COE	0.308	$/kWh
Energy output		
Diesel generators	12,494,312	kWh/yr
Fuel consumption	3,342,071	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	8,801	t/yr

Table 5.13: System Characteristics – Diesel stand-alone system

Figure 5.14 shows the Net Present Cost summary for the base case system on Meeru Island. It follows a similar pattern as the base case systems of the other islands in terms of cost proportions.

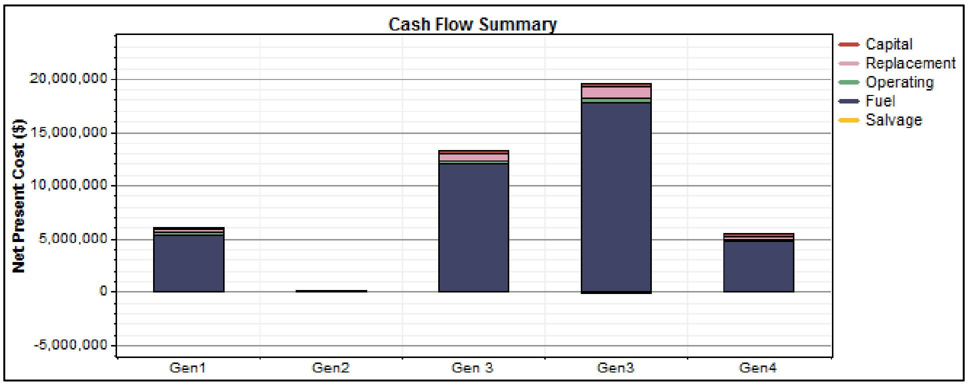


Figure 5.14: Net Present Cost Summary – Diesel stand-alone system

5.3.1 PV/Diesel hybrid system

Table 5.14 and Table 5.15 show the characteristics of the optimal PV/diesel system and the optimal Swimsol/Diesel system. Installed PV capacity has been constrained to 20% of the island´s peak load which is approximately 400 kW in these cases. The installed capacity of diesel generators is lower than in the base case system and consists of a 450 kW, a 900 kW and a 1,125 kW generator. In addition, a 400 kW converter is used in both systems. The total NPC of the PV/Diesel system is 43,493,204 $ and the COE is 0.303 $/kWh. Therefore, NPC can be brought down by 637,092 $ with the PV/diesel system. Investment cost for the Swimsol/Diesel system is higher than for the regular PV/Diesel system, but NPC as well as COE are still slightly lower than the costs for the base case system. The implementation of a PV system to cater for parts of the demand on Meeru Island Resort would result in diesel savings of almost 147,000 litres per year and a CO_2 emission reduction of 387 tons per year.

System architecture – PV/Diesel		
	value	**metric**
Diesel Generators	2,475	kW
PV	400	kW
Converter	400	kW
Cost parameters		
Investment cost	1,825,833	$
Operating cost	122,310	$/yr
Fuel cost	3,323,188	$/yr
Replacement cost	202,565	$/yr
Salvage	-175,631	$
Total NPC	43,493,204	$
COE	0.303	$/kWh
Energy output		
Diesel generators	11,904,103	kWh/yr
PV	602,246	kWh/yr
Excess Electricity	0.0744	kWh/yr
%	0	
Fuel consumption	3,195,372	l/yr
Average fuel efficiency	0.27	l/kWh
CO_2 emissions	8,414	t/yr
Renewable fraction	5	%
Savings compared to baseline		
CO_2 emission reduction	387	t/yr
%	4.4	%
Diesel savings	146,699	l/yr

Table 5.14: Optimal system configuration – PV/diesel

System architecture – Swimsol/Diesel		
	value	**metric**
Diesel Generators	2,475	kW
PV	400	kW
Converter	400	kW
Cost parameters		
Investment cost	2,225,833	$
Operating cost	135,110	$/yr
Fuel cost	3,323,178	$/yr
Replacement cost	202,565	$/yr
Salvage	-175,631	$
Total NPC	44,039,896	$
COE	0.307	$/kWh
Energy output		
Diesel generators	11,904,060	kWh/yr
PV	602,288	kWh/yr
Excess Electricity	0.0751	kWh/yr
%	0	
Fuel consumption	3,195,362	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	8,414	t/yr
Renewable fraction	5	%
Savings compared to baseline		
CO_2 emission reduction	387	t/yr
%	4.4	%
Diesel savings	146,709	l/yr

Table 5.15: Optimal system configuration – Swimsol/Diesel

Figure 5.15 illustrates the PV production for each month of the year.

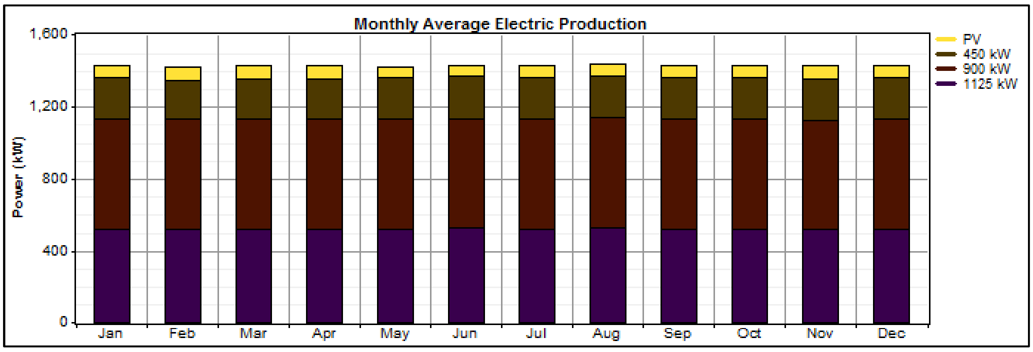


Figure 5.15: Monthly average electric production of a PV/Diesel system and a Swimsol/Diesel system

Figure 5.16 shows the NPC of the optimal PV/Diesel system. Costs for the PV system do not contribute a large share to the total NPC of this system[22].

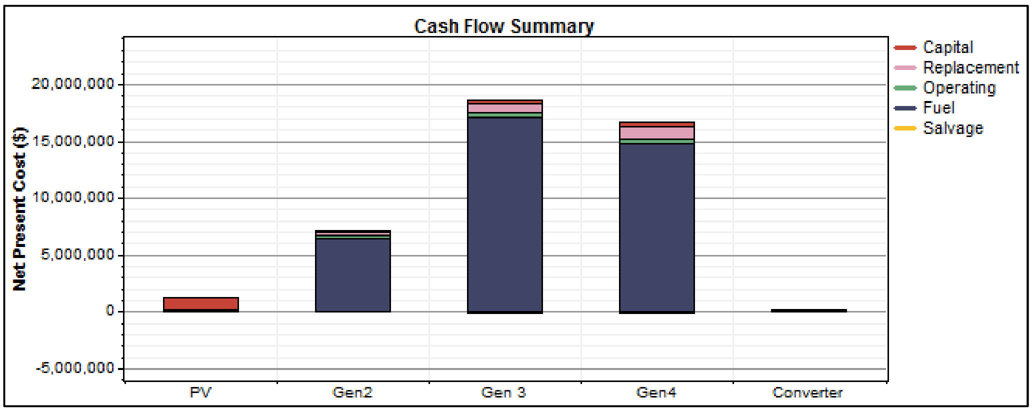


Figure 5.16: Net Present Cost Summary – PV/diesel system

5.3.2 PV/Diesel/Battery hybrid system

Table 5.16 summarizes the characteristics of the optimum PV/Diesel/Battery hybrid system for Meeru Island Resort. This system has a RE fraction of 67% and consists of 3 diesel generators with a total capacity of 2,475 kW, 6 MW of solar PV, 6000 batteries and a 1,900 kW converter. The total NPC of 41,145,112 $ and the COE of 0.287 $/kWh with this system are considerably lower compared to the baseline scenario. The yearly diesel savings amount to over 2,200,000 litres and with it an emission reduction of more than 5,800 tons per year or 66.7% can be achieved. Though, the installation of 6,000 kW of solar panels would consume an area of 48,000 m^2 or about 11.4% of area of the island[23]. The optimal configuration of a Swimsol/Diesel/Battery system, for which land area does not play a role, is shown in Table 5.17. The optimal system configuration consists of a PV array of 4,000 kW alongside of 2,400 batteries, 2,475 kW of diesel generators and a 2,000 kW converter. In this configuration with a RE fraction of 46% the total NPC of 45,049,696 $ as well as the COE of 0.314 $/kWh are again slightly higher in comparison with the baseline scenario. Nevertheless, considerable amounts of diesel savings and CO_2 emission reductions are achieved.

[22] Proportions of costs are similar for the optimal Swimsol/Diesel/Battery system

[23] Based on an area of 8 m^2/kW_p of solar PV

System architecture – PV/Diesel/battery		
	value	**metric**
Diesel Generators	2,475	kW
PV	6,000	kW
Batteries	6,000	pcs
Converter	1,900	kW
Cost parameters		
Investment cost	23,336,250	$
Operating cost	272,290	$/yr
Fuel cost	1,159,465	$/yr
Replacement cost	300,146	$/yr
Salvage	-2,055,914	$
Total NPC	41,145,112	$
COE	0.287	$/kWh
Energy output		
Diesel generators	4,128,064	kWh/yr
PV	9,033,701	kWh/yr
Excess Electricity	0.0342	kWh/yr
%	0	
Fuel consumption	1,114,870	l/yr
Average fuel efficiency	0.27	l/kWh
CO_2 emissions	2,936	t/yr
Renewable fraction	67	%
Savings compared to baseline		
CO_2 emission reduction	5,865	t/yr
%	66.7	%
Diesel savings	2,227,201	l/yr

Table 5.16: Optimal system configuration - PV/Diesel/Battery

System architecture – Swimsol/Diesel/battery		
	value	**metric**
Diesel Generators	2,475	kW
PV	4,000	kW
Batteries	2,400	kW
Converter	2,000	kW
Cost parameters		
Investment cost	18,036,944	$
Operating cost	345,250	$/yr
Fuel cost	1,893,878	$/yr
Replacement cost	203,669	$/yr
Salvage	-1,005,933	$
Total NPC	45,049,696	$
COE	0.314	$/kWh
Energy output		
Diesel generators	6,766,721	kWh/yr
PV	6,022,891	kWh/yr
Excess Electricity	0.0232	kWh/yr
%	0	
Fuel consumption	1,821,036	l/yr
Average fuel consumption	0.27	l/kWh
CO_2 emissions	4,795	t/yr
Renewable fraction	46	%
Savings compared to baseline		
CO_2 emission reduction	4,006	t/yr
%	45.6	%
Diesel savings	1,521,035	l/yr

Table 5.17: Optimal system configuration – Swimsol/Diesel/Battery

Figure 5.17 shows the NPC of the optimal PV/Diesel/battery system. Costs for the PV system contribute large shares to the total NPC of this system[24]. The term H3000 refers to the battery type used for the simulations.

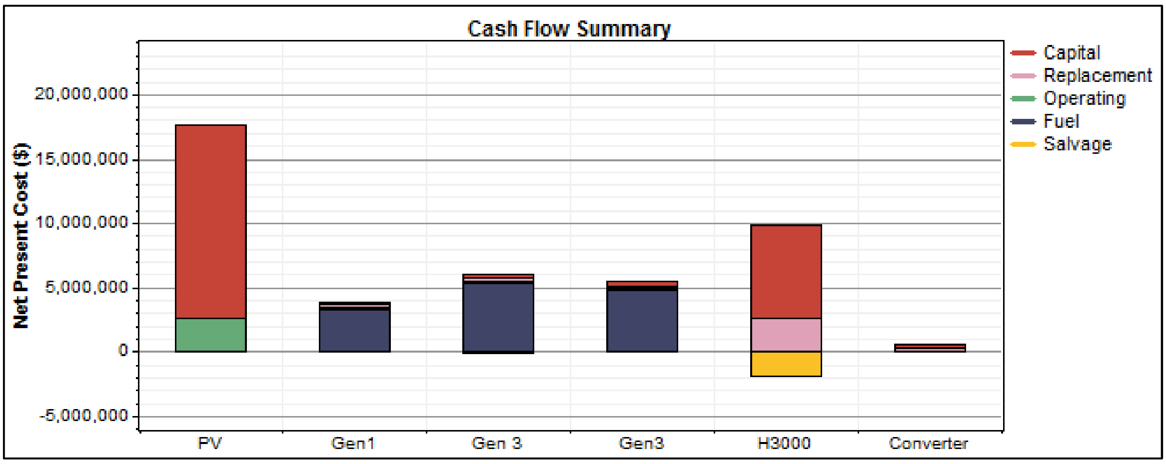


Figure 5.17: Net Present Cost Summary – PV/Diesel/battery system

[24] Proportions of costs are similar for the optimal Swimsol/Diesel system.

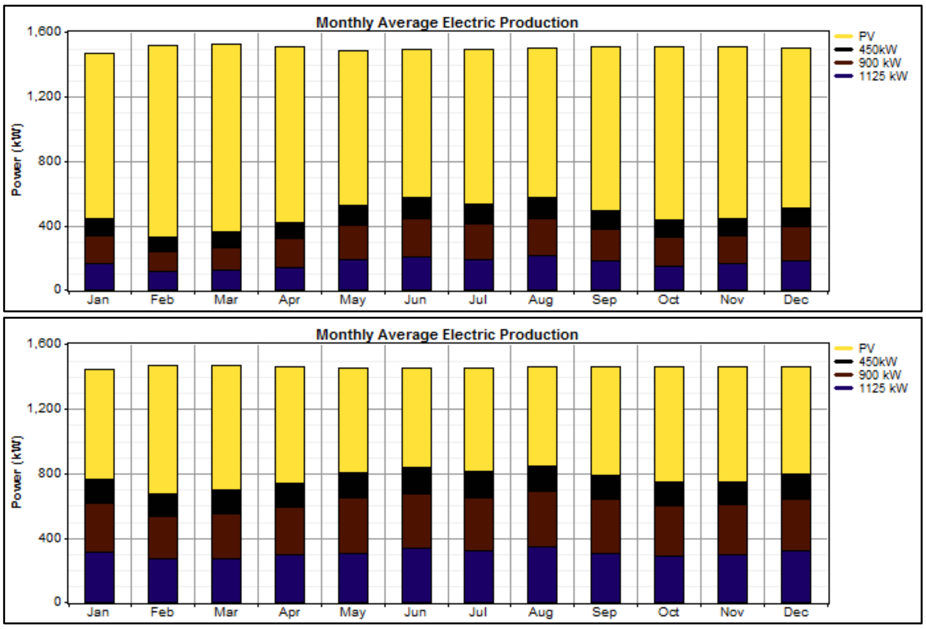


Figure 5.18: Monthly average electric production of a PV/Diesel/Battery and a Swimsol/Diesel/Battery system

Figure 5.18 shows the PV production for a PV/Diesel/Battery system and a Swimsol/Diesel/Battery system. Due to the higher investment cost the installed capacity of Swimsol is smaller and therefore the share of electricity production for this system is smaller, too.

5.3.3 Summary of the simulation results for Meeru Resort

The following table shows the simulation results for Meeru Island Resort.

	Base case	PV/Diesel	Swimsol/ Diesel	PV/Diesel/ Battery	Swimsol/ Diesel/ Battery
System configuration					
Diesel generators (kW)	4,050	2,475	2,475	2,475	2,475
PV Panels (kWp)	-	400	400	6,000	4,000
Converter (kW)	-	400	400	1,900	2,000
Batteries (pcs)	-	-	-	6,000	2,400
Cost Summary					
Investment (1000$)	1,215	1,826	2,226	23,336	18,037
Total NPC (1000$)	44,130	43,493	44,040	41,145	45,050
COE ($/kWh)	0.308	0.303	0.307	0.287	0.314
RE Fraction (%)	-	5	5	67	46
emission reduction (tCO_2/yr)	-	387	387	5,865	4,006
Required land area for PV installation (1000 m^2)	-	2.4 – 3.2	-	36 - 48	-

Table 5.18: Summary of simulation results for Meeru Resort Island

The simulation results show, that the most favourable system for Meeru Island is a PV/Diesel/battery system. NPC and COE of this system are 41,145,000 $ and 0.287 $/kWh, respectively. However, due to the constrained area of unshaded roofs, it is not realistic to install a PV system with the size of 36,000 – 48,000 m^2 on this island. The Swimsol/Diesel/Battery system is slightly more expensive than the base case system, but it would not encounter any land constraints.

The 400 kW PV array of the PV/Diesel system could be installed on roofs of the staff quarters and would deliver electricity at a lower cost than the diesel stand-alone system.

5.4 Summary

As it is shown in Table 5.19, the present diesel stand-alone systems are not optimal for all islands under examination.

PV/Diesel as well as Swimsol/Diesel hybrid systems are in the long-run more cost effective than the diesel stand-alone systems. The downside of these systems is the investment cost, which is approx. double the investment cost for the diesel only systems. PV/Diesel hybrid systems with battery storage are even more cost effective but involve investment costs that are approx. 10-fold the investment costs for a diesel stand-alone system. Another issue with PV/Diesel/Battery systems is the huge land requirement for the PV installations. In the case of Maafushi for instance, the optimal PV system would cover approx. 4% of the island. As described before, it is not realistic to install a PV system of this size on the island due to the constrained area of suitable roofs. This barrier can be overcome with Swimsol/Diesel/Battery systems, which would be installed in the lagoons of the islands. However, due to the 40% higher investment cost of these systems, they are slightly more expensive than the current systems[25]. Despite the slightly higher costs, the savings potential on diesel and CO_2 emissions are enormous. Up to 46% of fuel and CO_2 emissions can be saved.

[25] This is not the case for Swimsol/Diesel/Battery systems on Hulhumale´. Here even the Swimsol system with battery storage is slightly cheaper than the current system.

Scenario	Parameter	Metric	Maafushi	Hulhumale´	Meeru Island
Base case	Electricity demand	MWh/yr	3,778	13,451	12,494
	Investment costs	1000$	561	1,200	1,215
	Annual cost	$/yr	1,174	4,059	3,742
	COE	$/kWh	0,323	0.310	0.308
Optimum PV/Diesel system	RE-Fraction	%	6	5	5
	Fuel savings	1000 l/yr	57,8	183	147
	Emission reduction	tCO_2/yr	152	483	387
	Investment costs	1000$	908	2,419	1,826
	Annual costs	1000$/yr	1,119	3,873	3,623
	COE	$/kWh	0.317	0.304	0.303
	Required land area	m^2	900 – 1,200	2,700 – 3,600	2,400 – 3,200
Optimum Swimsol/Diesel system	RE-Fraction	%	6	5	5
	Fuel savings	1000 l/yr	57,8	1,875	147
	Emission reduction	tCO_2/yr	152	458	387
	Investment costs	1000$	1,058	2,869	2,226
	Annual costs	1000$/yr	1,124	2,309	3,646
	COE	$/kWh	0,322	0.308	0.307
Optimum PV/Diesel/ Battery system	RE-Fraction	%	58	52	67
	Fuel savings	1000 l/yr	597	1,875	2,227
	Emission reduction	tCO_2/yr	1,571	4,938	5,865
	Investment costs	1000$	5,951	16,675	23,336
	Annual costs	1000$/yr	590	2,328	1,553
	COE	$/kWh	0.293	0.280	0.287
	Required land area	m^2	9,600 – 12,800	30,000 – 40,000	36,000 – 48,000
Optimum Swimsol/Diesel/ Battery system	RE-Fraction	%	37	33	46
	Fuel savings	1000 l/yr	384	1,179	1,521
	Emission reduction	tCO_2/yr	1,011	3,105	4,006
	Investment costs	1000$	4,731	13,194	18,037
	Annual costs	1000$/yr	818	3,013	2,355
	COE	$/kWh	0.325	0.308	0.314

Table 5.19: Systems Summary

6 Sensitivity Analysis

In this section, the sensitivity of the output to changes in the input parameters used in the sensitivity analysis– fuel price, annual real interest rate and emission penalties – are analyzed and discussed. The focus is on the simulation results for PV hybrid systems on Meeru Island Resort, exemplary for all islands. As for the fuel price, it was decided to carry out scenario analysis for moderate diesel price increases. Therefore, the current diesel price of 1.04 $/l, and price increases of 10%, 20% and 30% were considered to be feasible as sensitivity variables. As for the interest rate, 3%, 9% and 12% were taken in addition to the baseline value of 6%. The last category of sensitivity variables that has been tested was an emission penalty of 10 $/t in comparison to no charges for CO_2 emissions in the baseline scenario.

Sensitivity Parameter	Value
Annual interest rate	3%
	9%
	12%
Fuel price (US$/l)	1.14
	1.25
	1.35
Emission penalty	$ 10

Table 6.1: Sensitivity parameters employed

Table 6.1 shows the sensitivity parameters that were employed to carry out the sensitivity analysis.

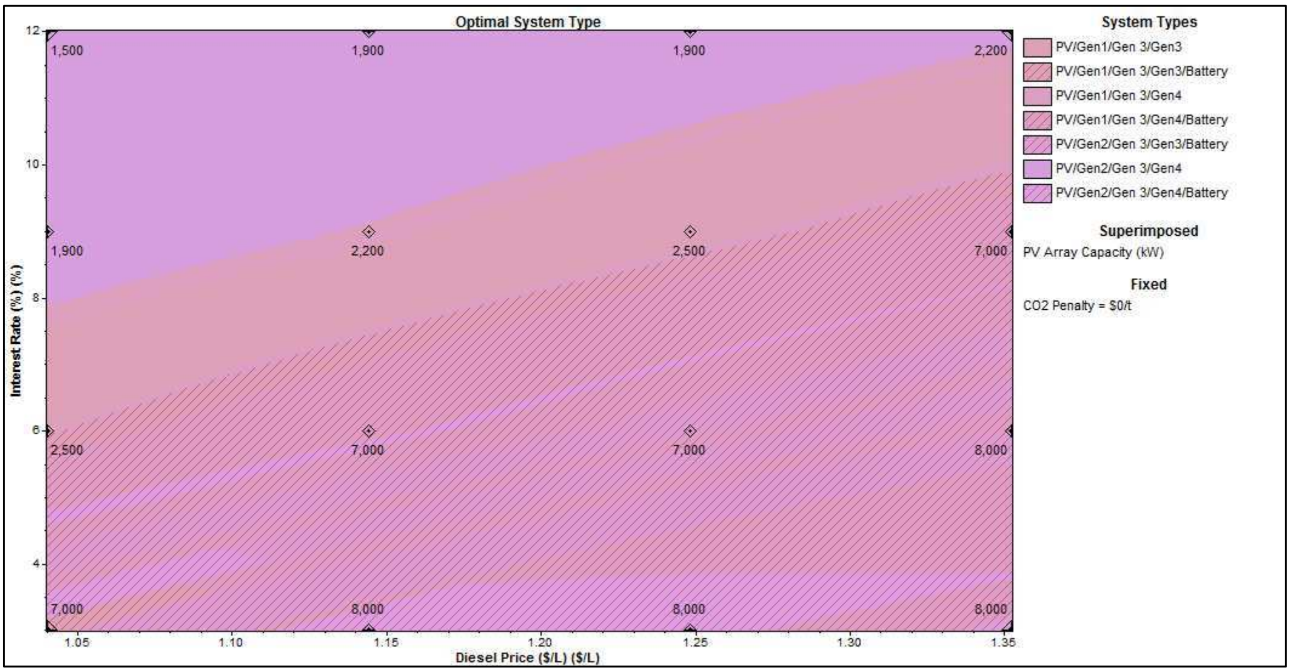


Figure 6.1: Sensitivity Results for Meeru Island Resort (CO_2 Penalty = $0/t)

Figure 6.1 shows a graphical representation of the sensitivity analysis carried out for Meeru Resort. It is worth noting, that the dashed zones represent PV/Diesel hybrid systems with battery storage while the plain-coloured areas represent PV/Diesel hybrid systems without battery storage. The superimposed values indicate the optimal PV Array Capacity. The CO_2-Penalty was set to 0 in this case.

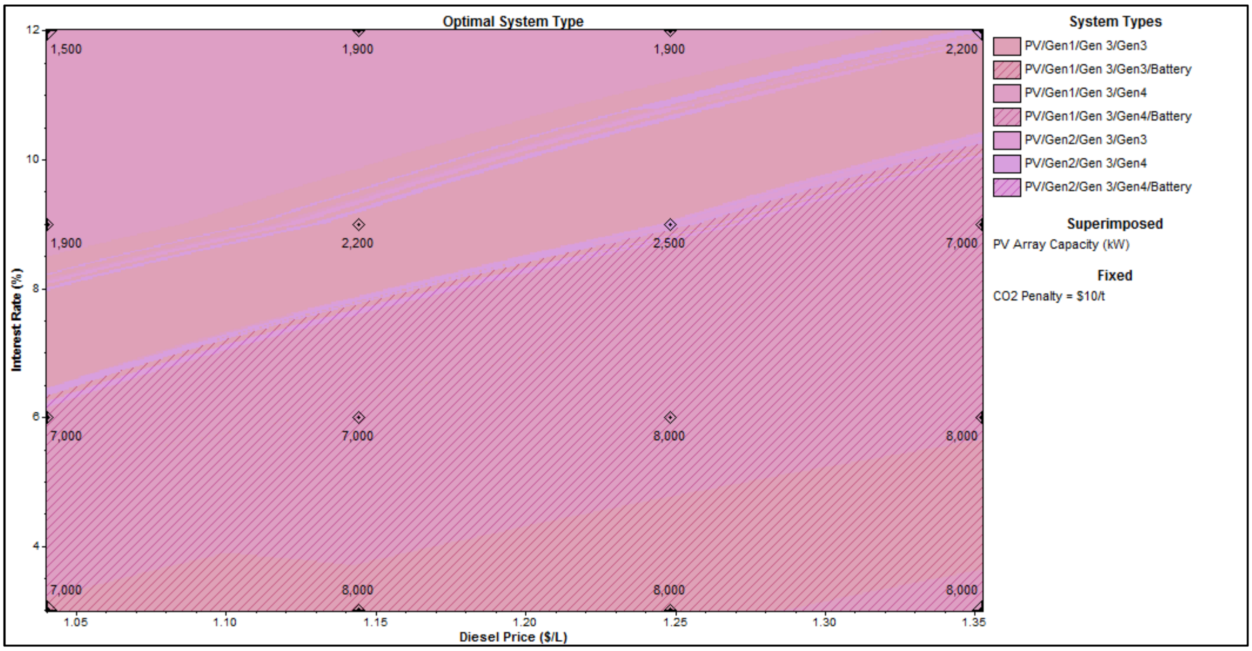


Figure 6.2: Sensitivity Results for Meeru Island Resort (CO_2 Penalty = $10/t)

Figure 6.2 again shows the results of the sensitivity analysis for Meeru but the CO_2 Penalty is set to 10 \$/tCO_2 in this case.

The first striking result for both emission penalty scenarios is that the base case configuration – a diesel stand-alone system - is not an optimal system type for none of the sensitivity cases. For all sensitivity cases, the PV/Diesel hybrid system is the better option.

Generally, higher annual interest rates favour expenses in the future more than higher initial investments, because these expenses are discounted to calculate the total NPC. If higher interest rates are applied, initial investment costs contribute relatively more to the total NPC than future expenses do. So there is a great incentive to postpone purchases because future cash flows are heavily discounted (see Figure 6.3). This is the reason why diesel generators with low investment costs and deferrable fuel payments become more favourable and the optimal PV capacity decreases as the interest rate increases[26] (Bailey et al., 2007). As Figure 6.1 and Figure 6.2 show, at interest rates above approx. 9%, PV capacity drops significantly even for the highest fuel price scenario.

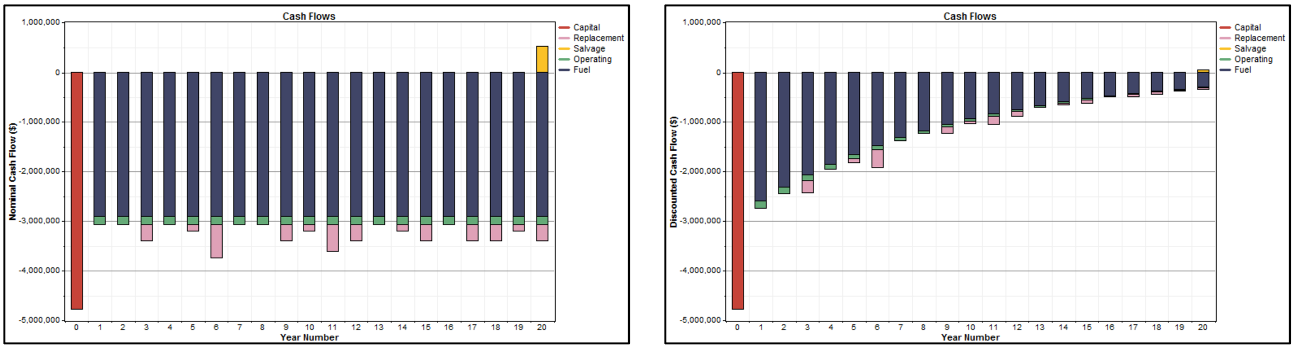


Figure 6.3: Cash flows with 0% discount rate and 12% discount rate for the same system configuration

An identical cash flow in year 20 contributes only about one tenth to the NPC at a 12% discount rate. Since relatively high annual interest rates can be frequently found in developing states and RE-technologies involve high capital costs, it can be a further drawback for renewable energy development.

As it is shown, the optimal size of the PV system increases as the fuel price goes up. At the same time, the installed capacity of diesel generators and fuel consumption decreases. This is true for both emission penalty scenarios. As for Swimsol, the previous section has shown that Swimsol/Diesel/Battery systems are more expensive in terms of NPC and COE for all islands but Hulhumale´. However, this is not true anymore for a scenario with a fuel price increased by 13%.

It is obvious that an emission penalty makes RE more favourable than diesel generators. At the same time, COE of the systems go up, as the emission of greenhouse gases involves a cost. So, an emission penalty would only make sense if it doesn´t involve additional costs for the people. Otherwise, purchasing power would go down and lead to unfavourable macroeconomic conditions.

Summing up, the higher the diesel price, the lower the interest rate and the higher the emission penalty, the higher the optimal RE fraction gets.

[26] Investment costs per kW for a PV system are almost 10 times higher than the investment costs for diesel gensets

7 Discussion

The following chapters summarize and discuss the modeling results and examine the conditions for renewable energies in the Maldives.

7.1 Modeling results

In contrast to former studies on RE in the Maldives such as Camerlynck (2004) who found that COE for PV/Diesel/battery hybrid systems were higher than for the diesel stand-alone systems, the present thesis shows that the integration of PV with and without battery storage into the existing diesel stand-alone systems in the Maldives is economically viable. The reasons for the different outcomes are the drastically decreased prices for PV systems and increased prices for fossil fuels. Costs of Electricity as well as NPC for the PV/Diesel hybrid systems are lower than the costs for the present systems and great amounts of fuel and CO_2 emissions can be saved. For systems without battery storage and grid control mechanisms the size of the PV system is constrained by the intermittent nature of solar energy and its effects on grid stability especially in small island grids. That is the reason why PV capacity was limited to 20% of the peak load for system simulations without battery storage. The present thesis shows that the overall costs for a PV/diesel hybrid system are lower than the costs for the base case for all islands. Even Swimsol/Diesel hybrid systems were economically viable for all islands, although the investment costs for the swimming system were set 40% higher than for a regular system. The maximum RE fraction in terms of RE electricity production to total electricity production achieved without battery storage was 5-6%. The savings in fuel and emissions were therefore comparably low.

PV/Diesel systems with battery storage achieve RE fractions of up to 67% and save considerable amounts of fuel and greenhouse gas emissions at a lower total NPC and a lower COE than the diesel stand-alone systems. The problem with these systems is the area needed to install the large capacities of PV on the severely land constrained islands. It is definitely not possible to install 6,000 kW of solar on Meeru Island for example. The amount of unshaded roof area estimated from aerial pictures is approx. 5,000 m^2. There would be additional roof areas available on the water villas, but the roofing made of plant material is not suitable for PV installations. Replacement of the roofs by metal sheets commonly used throughout the Maldives is not considered as a possibility. Therefore Swimsol/Diesel systems with battery storage were modeled as well. Due to the higher investment costs for the Swimsol platform, the optimal size of the PV system and with it the RE fraction is smaller in these systems. Furthermore, total NPC as well as COE was shown to be slightly higher in configurations with Swimsol and battery storage (apart from Hulhumale´). However, this is not true anymore if diesel prices go up by 13%. With increases in diesel prices Swimsol/PV/battery systems become economic viable, even though the investment cost is higher.

It was tried to model the systems as close to reality as possible. Only first-hand cost information have been used in terms of investment, replacement and O&M costs for all components, the demand curves were measured demand curves from the islands and technical specifications of the components were input as detailed and realistic as possible. However, HOMER is not designed to provide the system designer with a definite system configuration nor does it take all technical details into account. One technical issue, HOMER does not model close to reality, is the batteries. The program assumes the properties of the batteries to remain constant throughout its lifetime and that they are not affected by external factors such as temperature and other factors such as the properties of the electrolyte. In reality, the lifetime of a battery greatly depends on the charge and discharge cycles, the charge and discharge current as well as external factors like temperature, humidity and salt content in the air. The question whether the lifetime of the batteries is unrealistic in HOMER models and what lifetime should be used instead could not be finally clarified. However, it is assumed that battery lifetime can be increased drastically with air conditioned containers even in tropical climate conditions. Another technical issue that was not incorporated in the simulations was system control devices which provide for grid stability and control the different system components. Prices for control systems are difficult to obtain, as they must be designed individually, according to the particular system configurations.

The load curves obtained from STELCO are only a snap-shot of the demand curves in the course of the year. That is the reason why the analysis carried out in this thesis cannot be directly translated into reality. For instance, correlations between the availability of solar energy and energy demand cannot be taken into account with the data used in this thesis. However, a standard deviation in the sequence of averages was calculated on the basis of monthly average values and input into HOMER to artificially create randomness of the load curves throughout the year. To do exact system analysis, load curves for each day of the year would have to be obtained and entered into the simulation program.

As for the simulations carried out for the resort island, load data for 8 different days in April 2012 were obtained. Load curves in resorts with a capacity utilization of 99% do not differ that much over the year. Consequently, the results for Meeru Resort Island can be seen as the ones that are most realistic.

Another important factor especially for PV installations is the severely constrained land on many of the Maldivian islands. For systems without battery storage, the PV capacity is small enough to be installed on roofs and the land usage for these installations would therefore be non-competitive. For systems with battery storage and higher RE fractions, the availability of non-competitive land is most probably not given anymore. An approach for further studies to overcome this weakness of the analysis would be to include a hypothetical land rent in the analysis. It is assumed that, depending on the extent of the land-rent, PV systems would not be competitive anymore. Given the severely constrained land resources in the Maldives, such a land rent would consequently high. Moreover, PV systems involve relatively high investment costs already. So it would not be reasonable to introduce a land rent, if the government aims to produce 60% of the energy needs from solar by 2020.

Nevertheless, HOMER is a suitable tool to simulate large numbers of system configurations under different scenarios. It provides the system designer with a detailed idea of the cost parameters of the different systems and shows the most favourable system configurations. The simulation and optimization process is ideal for feasibility studies to determine the range of component sizes and adjunctive costs. On the basis of these simulations, detailed electrical engineering can be done to design the final system. This is exactly what HOMER software has been successfully used for by a vast number of energy system designers in the past 12 years.

But for all that, the remaining challenge is the high investment cost involved in renewable energy systems. Even if hybrid systems are cheaper than the current systems on the long run, the financing of these systems pose great difficulties for small island developing states. There needs to be policy intervention to facilitate the widespread implementation of RE in developing countries.

The following chapter therefore analyzes the situation in the Maldives, presents the current situation and the initiatives and development plans for future renewable energy development and tries to evaluate these actions from a private sector perspective.

7.2 Institutional factors in developing renewables in the Maldives

In the past, several partly inter-related international initiatives funded by the United Nations Development Programme (UNDP) and Global Environment Facility (GEF), the Asian Development Bank (ADB) and the EU amongst others, have been carried out to promote renewable energy in the Maldives. Technical and non-technical barriers to RE development (these are described in the following chapter in more detail) have been identified and programs have been developed to overcome these barriers and attract foreign direct investment (FDI). The underlying principle of all these programs was the facilitation of the widespread implementation of RE in the Maldives.

One major initiative called the *Renewable Energy Technology Development and Application Project* (RETDAP) funded by the UNDP and GEP was carried out during the years from 2004 to 2011. The program was designed to address barriers to the uptake of renewable energy technologies (RETs) and to lower or overcome them (REEEP, 2012). Financed by the GEF and the UNDP and implemented in cooperation with the former Ministry of Environment, Energy and Water (MEEW), the overarching goal was to reduce the growth rate of greenhouse gas emissions through removal of the barriers to RE development and application. Integral parts of the project were to formulate an energy policy to develop capacities, awareness and institutions to promote implementation and commercialization of RE (van Alphen et al., 2008; UNDP, n.d.). Intended outputs of the RETDAP were as follows:

- *"RE advocacy and awareness (information, education, services)*
- *RE resource assessment*
- *RE policy development and institutional strengthening (pricing schemes, …)*
- *RE technical capacity building*
- *RE project financing schemes*
- *RE system project development"* (UNDP, n.d.)

The overall rating of the RETDAP project results in the final evaluation report (UNDP, 2011) has been described as only "marginally satisfactory". Reasons for this poor overall result stated in the report were amongst others:

- *"Lack of a strategic plan to create RE public awareness, and the absence of any programmes or activities to improve local RE technical capacity of entrepreneurs and policymakers.*
- *No Resources being in place for the continued collection of wind and solar data.*
- *The lack of any plan or resources to promote RE awareness in the Maldives;*
- *The lack of system, plan or resources to build local technical capacity for developing, maintaining and operating RE systems in the Maldives"* (UNDP, 2011)

Other initiatives such as the SMILES project (Strengthening Maldivian Initiatives for a Long-term Energy Strategy, 2009) co-funded by the European commission under the so called Asia Pro Eco Programme, or an ADB funded project (2011), targeted topics such as efficiency of energy generation and utilization and improvement of the transport sector efficiency. Further objectives included the lowering of the import rate of fossil fuels and the establishment of a regulatory framework that promotes RE for private investors as well as the reduction in emissions per kWh by at least 20% by 2016 (ADB 2011b, van Sark et al., n.d.).

On the background of volatility in fossil fuel prices and increasing concern about energy security and climate change, the Government of Maldives (GoM) also stated ambitious goals for a sustainable future (ADB, 2011). Besides the carbon neutrality goal by 2020 unveiled by the former President Nasheed in 2009, several strategic papers such as the Strategic Action Plan (2009) stated ambitious goals in terms of renewable energy development (GoM, 2009).

The goals of all these government publications are quite similar - greater energy efficiency and conservation awareness as well as CO_2 reductions. Further goals stated in the strategies include:

- Provision of all citizens with access to affordable and reliable supply of electricity
- Promotion of renewable energy technologies
- Achievement of carbon neutrality by year 2020
- Promotion of energy conservation and energy efficiency to reduce costs

(GoM, 2009)

To achieve these goals, it is planned that solar energy provides 60% of the country´s primary energy by 2020 (ADB, 2011).

Given the multitude of meaningful strategies and goals to achieve greater contribution of renewables to the country´s energy supply – how does reality look like? In the past years only very few renewable energy projects have been implemented. Around 2 MW of solar PV energy have been installed with the assistance of different country programs. Funds were received for instance from the Japanese Government, Multi Donor Climate Change Trust Fund (CCTF), ADB, WB and GIZ (Gesellschaft für Internationale Zusammenarbeit) (A. Musthafa, personal communication, July 2012).

7.2.1 Current Situation

Although there is a number of additional RE projects in preparation, most of them are held up because the current situation is – after all the efforts described in the previous section – still not favorable for the widespread development of renewable energy (Republic of Maldives, 2012). One reason for this is the recent change of government through a coup from the opposition party during which President Nasheed - who has been extremely committed to climate change and sustainability issues - was dispossessed during riots in Male´ in February 2012. Although the new president of the Maldives, Mr. Waheed wants to remain committed to the previous administration´s carbon neutral goal (Merret, 2012), the barriers to renewable energy development identified during the RETDAP program as well as during the ongoing SREP Program still exist in large parts. The barriers are:

Limited involvement of entrepreneurs in producing and servicing RE systems:

This problem is attributed to lack of awareness and knowledge along with the belief that RE is no feasible source of power generation in the Maldives. The general perception is that the private sector hardly shows any interest in the RE business.

Lack of policies on the utilization of RE

Despite the commitment and encouragement of the Government of Maldives (GoM) to develop RE resources, there are still no distinct policies in place that support engagement in RE projects. There is still a clear need for policies that produce real incentives for the development of renewable energy.

Inadequate capability of the key players

Key players in government institutions and utilities do not have sufficient capability to develop, design, implement and manage RE projects. As a consequence of the total dependence on fossil fuels for electricity generation, the capacity is simply missing or very limited (UNDP, n.d.; N.N., 2011).

Lack of financing available for RE applications

There is currently no financial assistance available for RE projects (UNDP, n.d.).

Due to the poor robustness of the legal system and the little track record in the commercial sphere, foreign investors are not willing to invest in the Maldives at normal interest rates. After the change of government in March 2012 the situation has become even worse. These facts make raising capital at an acceptable price a challenge. Renewable energy such as solar PV would be economic in comparison to diesel at public or private sector discount rates in a secure, low risk economy with a well-developed legal system (Republic of Maldives, 2012). But lack of government guarantees, the poorly defined regulatory requirements together with the lack of capacities in the utilities cause problems to mobilize financial resources at normal rates of interest, making the usually high upfront costs of renewable energy an almost insuperable barrier to its development (Republic of Maldives, 2012) without external funding. In addition, subsidies for conventional energy technologies further distort the market situation. According to National Social Protection Agency an estimated subsidy of over $0.05/kWh summing up to a total of $25M/year was paid as a fuel subsidy to islands with inefficient electricity generation in the year 2011 (MEE, 2012).

Apart from these rather non-technical barriers, there are also technical barriers to overcome. Power stations are not prepared for the integration of RE into the grid. The marine transport network is fragile and in large parts not equipped to move and handle containers once they arrived at the island. These facts also add to complexity and uncertainty and might cause substantial additional costs.

In the past, the functioning of the energy regulator, the Maldives Energy Authority (MEA), which has the mandate to regulate the Energy sector and to advise the government, has been constrained by the lack of staff and finance (ADB, 2011). As a result, a regulatory framework for renewable energy does practically not exist. Apart from a Feed-In-Tariff (FIT), which did not have the desired effect of people investing into RE, regulations regarding independent power generation and pricing and use of RE technologies are currently not in place (GoM, 2009).

The existing FIT program was established in March 2011 to encourage private investments in renewable energy. But due to the fact that it was not published in the gazette, it is not yet an official regulation (A. Musthafa, personal communication, November 2012). The utilities were instructed to buy electricity from RE sources at a rate of US$ 0.22/kWh. In addition to that the government provided for another US$ 0.03/kWh. Apart from one single contract signed between STELCO and Renewable Energy Maldives Ltd., a private company, no other projects were implemented under this scheme. When government officials realized that this incentive scheme did not bring the desired effects, a revised FIT taking into account regional variations in fuel prices and fuel efficiency (see Table 7.1) was introduced 6 months later (MEE, 2012).

Utility Services Provider	Existing FIT (US$/kWh)
1. State Electric Company Limited: Greater Male´ Region	0.22
2. Upper North Utilities Limited: Upper North Region (Ha, HdH, Sh)	0.29
3. Northern Utilities Limited: North Region (N, R, B, Lh)	0.29
4. Central Utilities Limited: Central Region (M, F, Dh)	0.26
5. South Central Utilities Limited: South Central Region (Th, L)	0.35
6. Upper South Utilities Limited: Upper South Region (Ga, Gdh)	0.35
7. Southern Utilities Limited: South Region (Gn, S)	0.26

Table 7.1: Revised Feed-In Tariff Rates (MEE, 2012)

Despite all efforts, new project development in the RE sector is still not taking place. The barriers named before can be held responsible for this situation. For instance, most people do not have funds to purchase a solar PV system for their homes even if it would save 50% of the cost for electricity at a period of only 5-6 years. As a consequence, along with the existing FIT there are additional financial incentives necessary to cover part of the initial investment costs for RE installations. Currently, utilities and investors are requesting to revise the existing FIT and set clear regulatory requirements to make further contracts a win-win for each side (MEE, 2012).

The current overall situation for renewable energy development in the Maldives is still neither beneficial for the achievement of the government targets and nor for utilities, project developers, investors or independent power producers (IPPs). But there are indications that, in the foreseeable future this situation will change in a positive way.

7.2.2 Initiatives and concepts for future renewable energy development

The government is currently in the process of formulating a new electricity structure. In parallel, a new Feed-In-Tariff (FIT) and a net metering program are being established. According to the MEA, the new FIT will be more transparent and attractive for investors (A. Musthafa, personal communication, November 2012). The new FIT will be introduced for larger installations (sizes to be defined). It will set different tariffs depending on the RE technology, the project size and the region the system is installed in. Features like a land rent and a capacity charge are considered for the new FIT scheme, but the implementation of those is subject to a revision by external experts from the ADB so it might well be that they are not implemented or additional features are added.

Feature 1 - Land Rent

Due to the fact that land is extremely scarce in the Maldives, efficient land use is indispensable. Consequently, it is planned that a substantial land rent, payable by the project owner to the government, is introduced. In parallel, the usage of space that cannot be used for future development shall be actively encouraged.

Feature 2 - Capacity Charge

Because even relatively small RE installations can be potentially very large in proportion to any individual island grid and therefore one installation denies a proportionally large capacity to another RE installation, a capacity charge is proposed. The capacity charge is to be paid by the project owner to the utility. It compensates for decreased “free” grid capacity due to the insertion of renewable energy into the island grid. Therefore the lost opportunity to install another renewable energy project priced. Furthermore, the utility needs a clear understanding of the power production, because it has to reserve the grid capacity to absorb it. A sufficiently high capacity charge will provide a strong incentive for project developers to actually utilize the reserved capacity. If a project is not performing as planned, it will result in a loss for the developer. Another reason for a capacity charge is the need for an even distribution of power supply over time instead of a single peak. Evenly distributed power supply reduces storage and voltage stabilization requirements. In order to be effective, the capacity reservation charge needs to be high, but the feed-in-tariff itself will be set high enough to compensate for the capacity charge as well as the land rent if the proposed project performs as planned (MEE, 2012).

In addition to the FIT, it is planned to introduce a Net Metering scheme which allows electricity customers that generate renewable energy to connect to the distribution network and feed the excess electricity into the grid. Instead of a payment for the electricity sold by the customer to the grid, all exports will be set off against the customer´s electricity bill. Besides the FIT and Net Metering program a Renewable Portfolio Standard (RPS) policy and regulations will be introduced to obligate large power consumers (such as tourist resorts) and utilities to generate a portion of their energy needs by renewable energy technologies (MEE, 2012).

In regard to initiatives for future renewable development, the Maldives is one of the countries participating in the *“Scaling Up Renewable Energy Program”* (SREP) already mentioned earlier in this work. The program commenced in January 2011 and is one of the most promising programs to have a real impact on the conditions for renewable energy in the Maldives. To date, an investment plan (IP) has been prepared by the Ministry of Environment and Energy (MEE) which will support the goals of the program (43). The overall objective of the SREP is to demonstrate the economic, social and environmental viability of a low carbon development using renewable energy (A. Musthafa, personal communication, November, 2012). This will generate new economic opportunities, secure access to energy services and benefitting the country´s future development (REEEP, 2012). These goals are commonly agreed upon by all public and private stakeholders.

The underlying principles of the SREP Investment Plan (IP) are adjusted to the National Energy Policy and Strategy focusing on the creation of an enabling environment for the growth of a reliable and sustainable energy sector and the reduction on the overreliance on fossil fuels.

Despite some negative headlines regarding the SREP after the change of government earlier this year, (Robinson, 2012), Mr. Musthafa from MEA states that the Maldives was given an indicative allocation of US$ 30 million of funds to design and implement programs for the transformation of the energy sector through the use of renewable energy. These funds are expected to leverage additional resources on a scale of 1:4 up to US$120 million. According to the MEA this additional fund is to be mobilized by

Multilateral Development Banks, bilateral donors and the private sector (A. Musthafa, personal communication, November 2012).

In addition to the SREP Investment Plan, a press release from October 15th, 2012 states that the current government is going to continue with the carbon neutrality program and has committed itself to a US$ 138 million project to install 16 MW of renewable energy within five years. According to the press article, the funds will be used to power ten islands entirely with renewable energy. Furthermore, 30% of the total energy demands of another 30 islands will be supplied by renewable energy (Merret, 2012).

So there´s a base for qualified optimism that conditions for the development of renewable energy will change in the near future. And in fact, the Government of Maldives called for tenders for several solar projects with a total volume of about 1 MW of installed power financed through the SREP Program in January and February 2013 (Swimsol 2013). So one can say, the development efforts come to fruition.

7.2.3 Evaluation of the proposed actions from a private sector perspective

"The promotion of competitive and open markets for RETs is a necessity for private sector participation and the availability of investment capital" (van Alphen et al., 2008).

"Access to capital is widely recognized as one of the primary barriers to renewable energy deployment" (Milford et al. 2011).

From the perspective of investors, be it foreign investors or local businessmen, the investment in renewable energy technologies in the Maldives needs to be projectable and future cash flows need to be relatively predictable to make it attractive. Thus, well-defined, predictable, and well-enforced regulations regarding technical, licensing and financial issues as well as an explicit legislation on taxes, codes and standards needs to be set up (ADB, 2011). Only with these factors in place, the perceived risks and the expected returns go in hand and make it an attractive investment for people willing to invest. If the new "electricity structure" (see previous chapter) the government is currently working on, is able to provide a well-defined regulatory regime and set clear laws and standards for renewable energy, this would in fact reduce the perceived risks from an investor perspective. Together with the proposed FIT for larger installations, which would guarantee for continuous income from the renewable energy investment, (foreign) direct investment in RE installations can surely be attracted. Solar PV energy for instance would be financially viable with a guaranteed FIT of US$ 0.27/kWh (Swimsol 2012).

To assess the land rent as a proposed feature of the new FIT, one would need to know the exact design of it. Generally, in a country like the Maldives where land resources are scarce, a land rent makes perfect sense. But only if the actual design is made in a way that treats different RE technologies accordingly. For instance, if there would be an identical land rent for all RE technologies, technologies with a low output per square meter such as PV would be at a disadvantage compared to e.g. wind power, regardless if wind power would or would not be the optimal technology for a given site. In addition, land rent would make PV systems even more expensive.

Since the most promising RE for the Maldives – solar PV and wind – are intermittent sources of energy, the capacity charge as it is described in the previous section would mean even higher initial costs for RE systems due to either tracking devices in the case of solar PV or storage. Tracking of PV systems means following the altitude of the sun to get a higher and more even energy yield across the day, but the installation of tracking system involves higher investment costs, higher operation and maintenance costs and the tracking devices are subject to corrosion which can make them less reliable.

The better option would be to provide for grid stabilization with the help of a cascading set of diesel-generators and short time storage together with smart control systems (Swimsol, 2012).

As they all have their own power supply through diesel generators, for resorts, the FIT would not serve as an incentive to invest in RE. Often, the operators, owners and land owners of tourist resorts are different entities with different time horizons and different priorities. For instance, operating licenses or planning horizons may be much shorter than the lifetime of a solar PV installation (Republic of Maldives, 2012). That makes it more difficult to convince the resorts to convert their energy supply to RE. Therefore, "*a phased approach where resorts are given a time frame to comply with energy regulations complemented with demonstration could be considered*" (N.N., 2011, p.10).

The Renewable Portfolio Standard, which seeks to obligate utilities and large power consumers such as tourist resorts to generate parts of their electricity through renewable energy installations, would serve as such a phased approach as proposed in the SREP Investment Plan.

From a private household perspective, the proposed net metering scheme is not sufficient to overcome the barriers related to renewable energy installations for small households. This is due to the fact that the savings from solar energy would not be enough of an incentive to invest into a solar energy system for a private household. Such a scheme would need additional financial incentives such as investment subsidies or soft loans. These instruments are necessary to overcome the relatively high upfront costs of RE not only in countries with low average incomes. An investment subsidy in the form of a grant covering a certain percentage of the investment together with promotional activities would surely be a good incentive for investments in RE even for financially weak private households. Soft loans with low interest rates, long grace periods and long durations are another good instrument that converts the high capital cost of RE installations into affordable operating costs. Ideally, these loans do not require any other type of collateral than the RE system itself. These loans could be paid back by the savings generated from the RE system.

Funds out of the SREP Investment Plan could be partly used to provide for the instruments named above and therefore provide real incentives even for small enterprises and private households.

Furthermore, the current subsidies for conventional energy (~US$ 25 million) could be gradually eliminated and shifted towards subsidies for RE. In this way, prices for energy from fossil fuels would reflect the real production cost for electricity and the savings would contribute to RE development (van Alphen et al., 2008).

8 Conclusion

The performance and economic viability of RE systems in small island developing states were investigated using three Maldivian islands as a case study. It was shown that PV/Diesel systems as well as Swimsol/Diesel hybrid systems are more cost effective than the diesel stand-alone systems that are currently used on all the islands. PV/Diesel hybrid systems with battery storage are even more cost effective but due to the severely constrained land resources not easy to implement. Swimsol overcomes the barrier of constrained land area at an investment cost 40% than for regular PV systems. However, if diesel prices increase by only 13%, Swimsol/Diesel/battery systems also become more cost effective than diesel stand - alone systems. The integration of PV/Swimsol into existing systems leads to fuel savings and CO_2 emission reductions of up to 67%. With it, the dependency on fuel imports is decreased and the vulnerability to price shocks is mitigated. Moreover, electricity generation prices remain more and more constant throughout the lifetime as PV penetration increases.

The overarching barrier to the implementation of these systems is the investment cost and the relative political and regulatory instability that causes investors to ask for high interest rates and short payback periods in SIDS. For that reason the development of RE systems in the Maldives cannot be done without international financial aid and policy interventions. There is a strong need for a stable regulatory and legislative framework that mitigates the risks involved in a long term investment in a renewable energy system.

As for the resorts, an option for policy intervention would be the implementation of a gradually increasing duty on fuel consumption together with tax incentives for RE systems. The problem of high capital costs for RE systems is not valid for resorts anyway as they are most often owned by foreign investment companies.

If, and only if the actions proposed by the Government of Maldives presented in the previous chapter are implemented and the barriers to renewable energy development can be lowered, there is a great potential for RE and solar PV in particular to contribute to the country´s energy supply and the goal of carbon neutrality by 2020.

9 Bibliography

ADB (2007). Maldives Environment Assessment. Retrieved from http://www.adb.org/sites/default/files/environment-assessment-maldives.pdf [accessed: 20th October 2012]

ADB (2011). Asian Development Bank Maldives: Fact Sheet. Retrieved from http://www.adb.org/sites/default/files/pub/2012/MLD.pdf [accessed: 20th October 2012]

ADB (2011b). Technical Assistance Report: Capacity Development of the Maldives Energy Authority. Asian Development Bank (2011). Retrieved from http://www2.adb.org/Documents/TARs/MLD/45079-001-mld-tar.pdf [accessed: 20th October 2012]

Bailey, P., Chotimongkol, O., Isono, S. (2007). Demand Analysis and Optimization of Renewable Energy: Sustainable Rural Electrification of Mbanayili, Ghana. (Master´s Thesis). University of Michigan, Ann Arbor, U.S.A

Bohdanowicz P, Martinac I. (2007). Determinants and benchmarking of resource consumption in hotels–case study of Hilton International and Scandic in Europe. *Energy and Buildings 2007* 39(1). 82–95

BoM (2013). Personal loans. Retrieved from http://www.bankofmaldives.com.mv/PBanking/Pages/Personal_Loans.aspx. Bank of Maldives (2013) [accessed: 20th October 2012]

Bosley, D. (2012, June 19). President Waheed creates centralized utilities corporation FENAKA. Minivan News. Retrieved from http://minivannews.com/politics/president-waheed-creates-centralised-utilities-corporation-fenaka-39349 [accessed: 20th October 2012]

Camerlynck, J. (2004). Modelling of Renewable Energy Systems in the Maldives. Utrecht, Netherlands: Department of Science Technology and Society, Utrecht University

CIA (2013, February). The World Factbook: Maldives. https://www.cia.gov/library/publications/the-world-factbook/geos/mv.html [accessed: 25th October 2012]

CUSP (2011). Marine Energy in the Maldives: Pre-feasibility report on Scottish Support for Maldives Marine Energy Implementation. Aberdeen, Scotland: Centre for understanding sustainable practice

Department of National Planning (2013). Statistical Yearbook 2010. Retrieved from http://planning.gov.mv/yearbook2010/yearbook/1_geography/1.5.htm. Republic of Maldives (2013) [accessed: 23th October 2012]

Diesel Service and Supply (2011). Approximate Diesel Fuel Consumption Chart. Retrieved from http://www.dieselserviceandsupply.com/Diesel_Fuel_Consumption.aspx.

European Community (2007). The Maldives: European Community Strategy Paper 2007 – 2013. Retrieved from http://eeas.europa.eu/maldives/csp/07_13_en.pdf [accessed: 25th October 2012]

Fraunhofer ISE (2013). Aktuelle Fakten zur Photovoltaik in Deutschland. Retrieved from http://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/aktuelle-fakten-zur-photovoltaik-in-deutschland.pdf

Gehrlicher Solar AG (2013): Funktion und Komponenten: Der Begriff Photovoltaik. Retrieved from: http://www.gehrlicher.com/fileadmin/content/pdfs/de/technik/Funktion_Komponenten_Photovoltaik.pdf [accessed: 30th November 2012]

Givler, T., Lilienthal, P. (2006). Using HOMER® Software, NREL's Micropower Optimization Model, to Explore the Role of Gen-sets in Small Solar Power Systems: Case Study: Sri Lanka. Golden, Colorado: National Renewable Energy Laboratory

GoM (2013). Isles. Retrieved from http://isles.egov.mv/. Government of Maldives (2013)

GoM (2013b). Isles. Retrieved from http://isles.egov.mv//Island/?lid=2&id=442. Government of Maldives (2013) [accessed: 30th November 2012]

Government of Maldives, The President´s Office (2009). The Strategic Action Plan: National Framework for Development 2009-2013. Male´, Maldives. Retrieved from http://planning.gov.mv/en/images/stories/publications/strategic_action_plan/SAP-EN.pdf [accessed: 30th November 2012]

HDC (2011). Introduction. Housing Development Corporation (2011). Retrieved from http://www.hdc.com.mv/development/introduction.php [accessed: 15th November 2012]

Homer Energy (2012). Homepage. Retrieved from http://homerenergy.com/

Homer Energy (2004). Homer Help Menu: Annualized Costs. HOMER v. 2.81

Indexmundi (2013). Maldives Inflation Rate (Consumer Prices). Retrieved from http://www.indexmundi.com/maldives/inflation_rate_%28consumer_prices%29.html. Indexmundi (2013) [accessed: 10th January 2013]

Kesterton, L. (2010). An investigation into the policies, technologies and economics of achieving clean electricity in a small island in the Maldives (Master´s thesis, Oxford University, 2010)

Lambert T., Gilman, P., Lilienthal, P. (2006). Micropower System Modeling with HOMER. In Farret, F.A., Simões, M.G. (2006). Integration of Alternative Sources of Energy (pp. 379-416). New Jersery, Canada: John Wiley & Sons

Lau, K.Y., Yousof, S.N.M.A, Anwari, M., Yatim, A.H.M. (2010). Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions. *Energy 35* (2010), 3245-3255

Lilienthal, P. (2007). High Penetrations of Renewable Energy for Island Grids. *Power Engineering 111*(11). Retrieved from http://www.power-eng.com/articles/print/volume-111/issue-11/features/high-penetrations-of-renewable-energy-for-island-grids.html [accessed: 10th January 2013]

Maldives Energy Authority (MEA) (2011). Industries. Retrieved from http://www.mea.gov.mv/industries

Mayer, H. (2008). Physik für Studenten des Bakkalaureat UBRM an der Universität für Bodenkultur Wien. [Available from BOKU Vienna to enrolled students]

Merret, N. (2012 October 15). Maldives committed to carbon neutral aims despite political uncertainty. Minivan News. Retrieved from http://minivannews.com/society/maldives-committed-to-carbon-neutral-aims-despite-political-uncertainty-45440 [accessed: 10th January 2013]

Milford, L., Tyler, R., & Morey, J. (2011). Strategies to finance large-scale deployment of renewable energy projects: An economic development and infrastructure approach.

Montpelier, Vermont: Clean Energy Group. Prepared for the International Energy Agency's Implementing Agrement on Renewable Energy Technology Deployment.

Ministry of Economic Development, Republic of Maldives (2012). Economic Profile of the Maldives. Retrieved from http://www.trade.gov.mv/?lid=244 [accessed: 12th February 2013]

Ministry of Economic Development (n.d.). Invest Maldives: Investment opportunities development sector. Retrieved from http://www.investmaldives.org/mediacenter/documents/Utilities%20Booklet.pdf

Ministry of Environment and Energy (MEE), Republic of Maldives (2012). Scaling up Renewable Energy Program - Investment Plan. Male´, Maldives. Retrieved from http://co2.org/wp-content/uploads/2012/12/Maldives-SREP-last-version-from-MM.pdf

Ministry of Environment, Energy and Water (MEEW), Republic of Maldives (2007). Maldives Climate Change In-Depth Technology Needs Assessment: Energy Sector. Male´, Maldives. Retrieved from www.mhe.gov.mv/v1/download/158 [accessed: 10th January 2013]

Ministry of Home Affairs, Housing and Environment (MHAHE), Republic of Maldives (2001). First national communication of the Republic of Maldives to the United Nations Framework Convention on Climate Change. Male´, Maldives

Ministry of Housing and Environment (MHE) (2010). The Maldives´ 2009 Carbon Audit. Retrieved from: http://cbr.edmond-de-rothschild.ch/_common/medias/?uid=maldives-carbon-audit [accessed: 16th July 2012]

Ministry of Planning and National Development (2007). Seventh National Development Plan 2006-2010: Creating new opportunities. Ministry of Planning and National Development, Male´, Maldives

Mohamed, M. (2012). Energy Constraint and Adaptability: Focus on Renewable Energy on Small Islands (Doctoral thesis, University of Canterbury, 2012). Retrieved from http://ir.canterbury.ac.nz/handle/10092/6433

NASA (2012). Surface Solar Energy Data Set. Retrieved from http://eosweb.larc.nas.gov/sse/ [accessed: 08th July 2013]

N.N (2011). Scaling-up Renewable Energy program for low income countries (SREP): scoping mission, January 24-27, 2011. Retrieved from http://www.climateinvestmentfunds.org/cif/sites/climateinvestmentfunds.org/files/AM_Maldives_SREP_Scoping_Mission%20_Jan%202011.pdf [accessed: 10th October 2012]

NREL (2003). Wind Energy Resource Atlas of Sri Lanka and the Maldives. Colorado, USA: National Renewable Energy Laboratory. Available from http://www.nrel.gov/docs/fy03osti/34594.pdf [accessed: 10th January 2013]

Phuangpornpitak, N., Kumar, S. (2007). PV hybrid systems for rural electrification in Thailand. *Renewable & sustainable energy reviews, 11*(2007), 1530-1543

REEEP (2012). Policy Database: Maldives (2012). Retrieved from http://www.reegle.info/policy-and-regulatory-overviews/MV. Renewable Energy and Energy Efficiency Partnership [accessed: 10th January 2013]

Rehman, S., Al-Hadhrami, L.M. (2010). Study of a solar PV-diesel-battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. *Energy, 35*(2010), 4986-4995 [accessed: 28th January 2013]

Republic of Maldives (2012). SREP Investment Plan: Draft 4. Retrieved from http://www.trade.gov.mv/downloads/4f0bbff868388_SREP%20Investment%20Plan%20%28v2.3%29%20Pages%2001%20-10.pdf [accessed: 07th June 2013]

Robinson, JJ. (2011, October 9). Data matches rhetoric as Maldives turns to solar revolution. Minivan News. Retrieved from http://minivannews.com/politics/data-matches-rhetoric-as-maldives-turns-to-solar-revolution-26734 [accessed: 10th June 2013]

Solarserver (2010). Photovoltaik: Solarstrom und Solarzellen in Theorie und Praxis. Retrieved from: http://www.solarserver.de/wissen/basiswissen/photovoltaik.html

STELCO (2009). History. Retrieved from http://www.stelco.com.mv/history.php [accessed: 12th January 2013]

United Nations Development Programme (UNDP) (n.d): Maldives: Renewable Energy Technology Development and Application Project (RETDAP). MDV/03/G35/A/1G/99 (GEF) PIMS 2131. Retrieved from http://www.undp.org/content/dam/undp/documents/projects/MDV/00033954/Prodoc%20RETDAP%20Final-signed.pdf [accessed: 14th January 2013]

Swimsol GmbH (2010). Unpublished presentation on solar energy and the Swimsol platform

UNDP (2011). UNDP/GEF Project: Maldives – Renewable Energy Technology Development and Application Project (RETDAP): Final Evaluation Report. United

Nations Development Programme, Ministry of Housing and Environment (2011). Retrieved from http://erc.undp.org/evaluationadmin/manageevaluation/viewevaluationdetail.html;jsessionid=4DBCBFA006936AE4F5F903E24794796A?evalid=5872# [accessed: 28th January 2013]

UNDP (2012). Low Emission Climate-Resilient Development (LECReD). Retrieved from http://www.undp.org.mv/v2/downloads/4f75fdd09fcb0_LECReD%20Initiation%20Plan%202012.pdf [accessed: 28th January 2013]

Van Alphen, K. (2004). The Implementation Potential of Renewable Energy Technologies in the Maldives. Utrecht, Netherlands: Department of Science Technology and Society, Department of Innovation Studies, Utrecht University

Van Alphen, K., Kunz, H.S., Hekkert, M.P. (2008). Policy measures to promote the widespread utilization of renewable energy technologies for electricity generation in the Maldives. *Renewable and Sustainable Energy Reviews* 12(2008), 1959-1973

Van Alphen, K., van Sark, W.G.J.H.M., Hekkert, M.P. (2007). Renewable energy technologies in the Maldives: determining the potential. *Renewable & Sustainable Energy Reviews 11*(2007), 1650-1674

Van Sark, W.G.J.H.M., Lysen, E.H., Cocard, D., Beutin, P., Merlo, G.F., Mohanty, B. …Wajeeh, A. (n.d.). The first PV-Diesel hybrid system in the Maldives installed at Mandhoo Island. Available from http://www.researchgate.net/publication/46691530_The_First_PV-Diesel_Hybrid_System_in_the_Maldives_Installed_at_Mandhoo_Island

Weisser, D. (2004). On the economics of electricity consumption in small island developing states: a role for renewable energy technologies?. *Energy Policy, 32*(2004), 127-140 [accessed: 18th July 2012]

WeizSolar (2010). Powerpoint Presentation presented at a workshop in Weiz, Austria

Welt-Blick.de (2013). Bevölkerungsdichte Tokio. Retrieved from http://www.welt-blick.de/hauptstadt/tokio.html [accessed: 25th July 2012]

Wikimedia (2013). Retrieved from http://upload.wikimedia.org/wikipedia/commons/b/b4/Male-total.jpg

World Bank (2011). Maldives Economic Update. Retrieved from http://siteresources.worldbank.org/MALDIVESEXTN/Resources/306312-1302208101269/MaldivesEconomicUpdate2011.pdf [accessed: 10th August 2012]

10 Appendices

10.1 Map of North Central Province

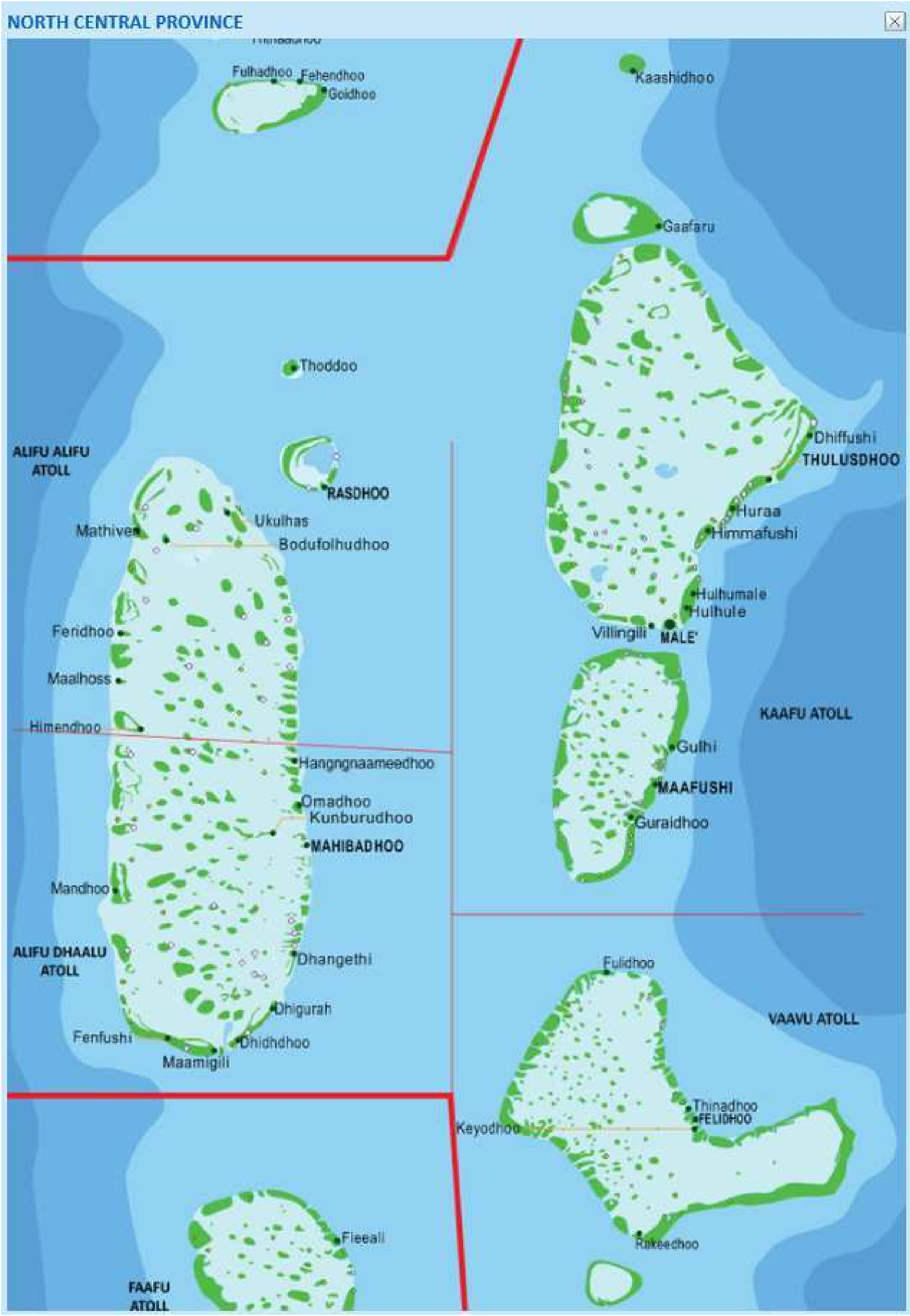
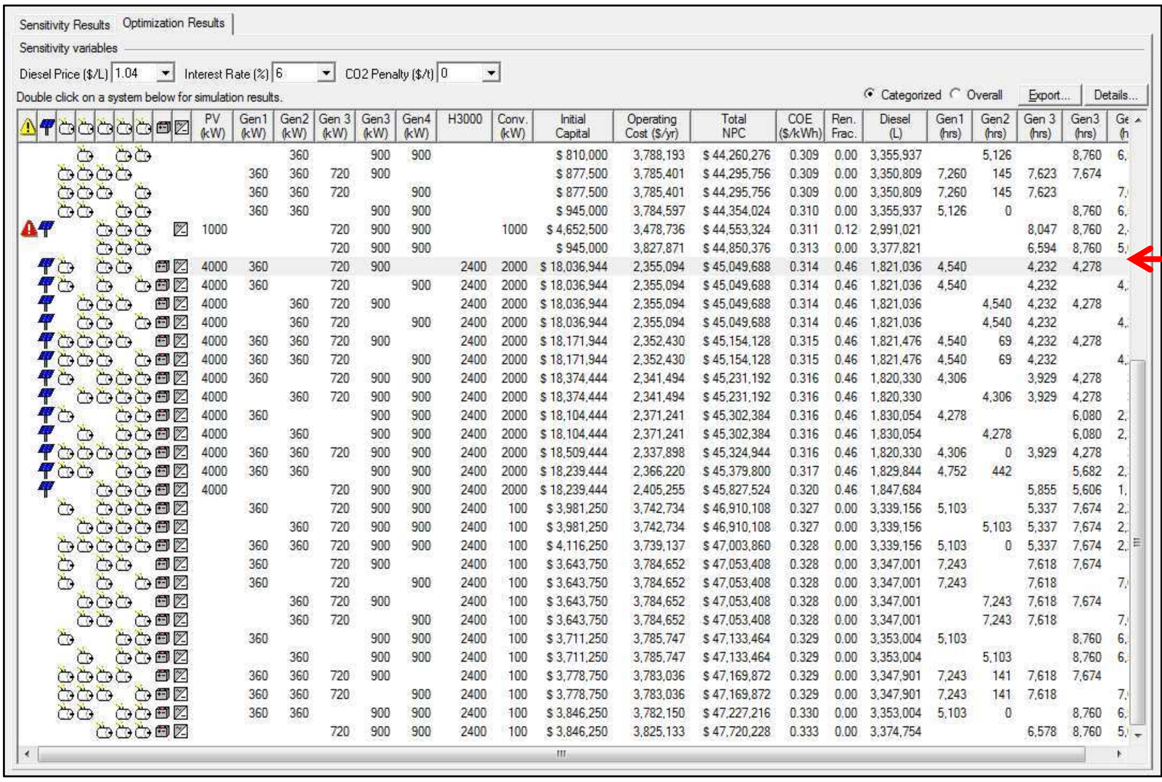


Figure 10.1: Map of the North Central Province (GoM, 2013b)

10.2 HOMER – System Report


Sensitivity Results | Optimization Results

Sensitivity variables

Diesel Price ($/L) 1.04 Interest Rate (%) 6 CO2 Penalty ($/t) 0

Double click on a system below for simulation results. Categorized Overall Export... Details...

PV (kW)	Gen1 (kW)	Gen2 (kW)	Gen 3 (kW)	Gen3 (kW)	Gen4 (kW)	H3000	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen1 (hrs)	Gen2 (hrs)	Gen 3 (hrs)	Gen3 (hrs)	Ge (h
		360		900	900			$ 810,000	3,788,193	$ 44,260,276	0.309	0.00	3,355,937		5,126		8,760	6,
	360	360	720	900				$ 877,500	3,785,401	$ 44,295,756	0.309	0.00	3,350,809	7,260	145	7,623	7,674	
	360	360	720		900			$ 877,500	3,785,401	$ 44,295,756	0.309	0.00	3,350,809	7,260	145	7,623		7,
	360	360		900	900			$ 945,000	3,784,597	$ 44,354,024	0.310	0.00	3,355,937	5,126	0		8,760	6,
1000			720	900	900		1000	$ 4,652,500	3,478,736	$ 44,553,324	0.311	0.12	2,991,021			8,047	8,760	2,
			720	900	900			$ 945,000	3,827,871	$ 44,850,376	0.313	0.00	3,377,821			6,594	8,760	5,
4000	360		720	900		2400	2000	$ 18,036,944	2,355,094	$ 45,049,688	0.314	0.46	1,821,036	4,540		4,232	4,278	
4000	360		720		900	2400	2000	$ 18,036,944	2,355,094	$ 45,049,688	0.314	0.46	1,821,036	4,540		4,232		4,
4000		360	720	900		2400	2000	$ 18,036,944	2,355,094	$ 45,049,688	0.314	0.46	1,821,036		4,540	4,232	4,278	
4000		360	720		900	2400	2000	$ 18,036,944	2,355,094	$ 45,049,688	0.314	0.46	1,821,036		4,540	4,232		4,
4000	360	360	720	900		2400	2000	$ 18,171,944	2,352,430	$ 45,154,128	0.315	0.46	1,821,476	4,540	69	4,232	4,278	
4000	360	360	720		900	2400	2000	$ 18,171,944	2,352,430	$ 45,154,128	0.315	0.46	1,821,476	4,540	69	4,232		4,
4000	360		720	900	900	2400	2000	$ 18,374,444	2,341,494	$ 45,231,192	0.316	0.46	1,820,330	4,306		3,929	4,278	
4000		360	720	900	900	2400	2000	$ 18,374,444	2,341,494	$ 45,231,192	0.316	0.46	1,820,330		4,306	3,929	4,278	
4000	360			900	900	2400	2000	$ 18,104,444	2,371,241	$ 45,302,384	0.316	0.46	1,830,054	4,278			6,080	2,
4000		360		900	900	2400	2000	$ 18,104,444	2,371,241	$ 45,302,384	0.316	0.46	1,830,054		4,278		6,080	2,
4000	360	360	720	900	900	2400	2000	$ 18,509,444	2,337,898	$ 45,324,944	0.316	0.46	1,820,330	4,306	0	3,929	4,278	
4000	360	360		900	900	2400	2000	$ 18,239,444	2,366,220	$ 45,379,800	0.317	0.46	1,829,844	4,752	442		5,682	2,
4000			720	900	900	2400	2000	$ 18,239,444	2,405,255	$ 45,827,524	0.320	0.46	1,847,684			5,855	5,606	1,
	360		720	900	900	2400	100	$ 3,981,250	3,742,734	$ 46,910,108	0.327	0.00	3,339,156	5,103		5,337	7,674	2,
		360	720	900	900	2400	100	$ 3,981,250	3,742,734	$ 46,910,108	0.327	0.00	3,339,156		5,103	5,337	7,674	2,
	360	360	720	900	900	2400	100	$ 4,116,250	3,739,137	$ 47,003,860	0.328	0.00	3,339,156	5,103	0	5,337	7,674	2,
	360		720	900		2400	100	$ 3,643,750	3,784,652	$ 47,053,408	0.328	0.00	3,347,001	7,243		7,618	7,674	
	360		720		900	2400	100	$ 3,643,750	3,784,652	$ 47,053,408	0.328	0.00	3,347,001	7,243		7,618		7,
		360	720	900		2400	100	$ 3,643,750	3,784,652	$ 47,053,408	0.328	0.00	3,347,001		7,243	7,618	7,674	
		360	720		900	2400	100	$ 3,643,750	3,784,652	$ 47,053,408	0.328	0.00	3,347,001		7,243	7,618		7,
	360			900	900	2400	100	$ 3,711,250	3,785,747	$ 47,133,464	0.329	0.00	3,353,004	5,103			8,760	6,
		360		900	900	2400	100	$ 3,711,250	3,785,747	$ 47,133,464	0.329	0.00	3,353,004		5,103		8,760	6,
	360	360	720	900		2400	100	$ 3,778,750	3,783,036	$ 47,169,872	0.329	0.00	3,347,901	7,243	141	7,618	7,674	
	360	360	720		900	2400	100	$ 3,778,750	3,783,036	$ 47,169,872	0.329	0.00	3,347,901	7,243	141	7,618		7,
	360	360		900	900	2400	100	$ 3,846,250	3,782,150	$ 47,227,216	0.330	0.00	3,353,004	5,103	0		8,760	6,
			720	900	900	2400	100	$ 3,846,250	3,825,133	$ 47,720,228	0.333	0.00	3,374,754			6,578	8,760	5,

Figure 10.2: HOMER – Simulation results window

10.3 System Report – Meeru Island Resort

Sensitivity case

	Value	metric
Diesel Price:	1.04	$/L
Annual Real Interest Rate:	6	%
CO2 Emissions Penalty:	0	$/t

Table 10.1: Sensitivity case

System architecture

	Value	metric
PV Array	4,000	kW
450kW	360	kW
900 kW	720	kW
1125 kW	900	kW
Battery	2,400	pcs
Inverter	2,000	kW
Rectifier	2,000	kW

Table 10.2: System architecture

Cost summary

	value	metric
Total net present cost	45,049,688	$
Levelized cost of energy	0.314	$/kWh
Operating cost	2,355,094r	$/yr

Table 10.3: Cost summary

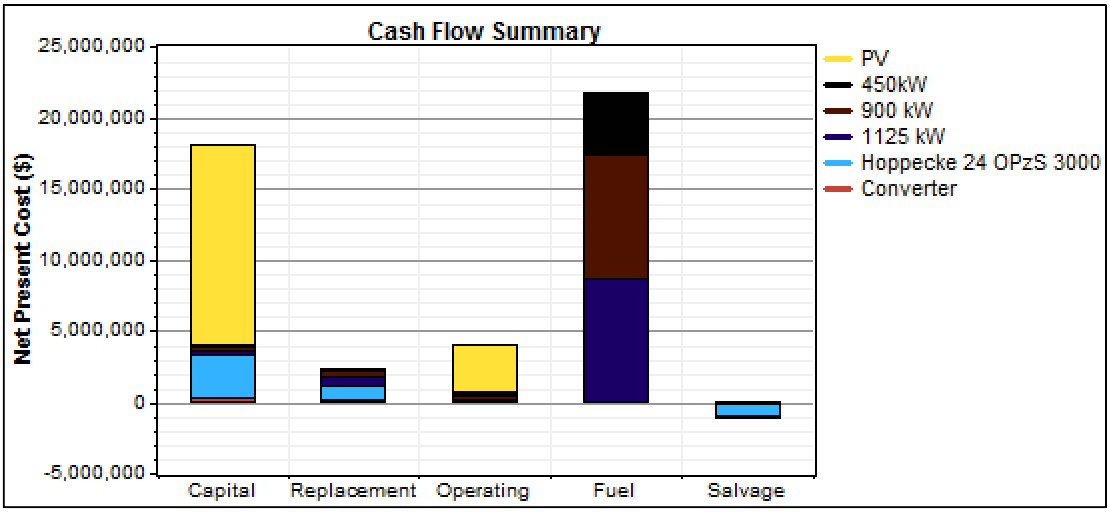


Figure 10.3: Cash flow summary by components

Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	14,000,000	0	3,211,579	0	0	17,211,580
450kW	135,000	220,564	260,367	4,306,245	-15,490	4,906,687
900 kW	270,000	423,145	242,704	8,786,220	-51,725	9,670,345
1125 kW	337,500	532,419	245,342	8,630,165	-60,783	9,684,644
Hoppecke 24 OPzS 3000	2,880,000	935,159	0	0	-865,627	2,949,532
Converter	414,444	224,779	0	0	-12,307	626,916
System	18,036,944	2,336,066	3,959,992	21,722,630	-1,005,933	45,049,696

Table 10.4: Net present cost Summary

Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	1,220,584	0	280,000	0	0	1,500,584
450kW	11,770	19,230	22,700	375,438	-1,351	427,787
900 kW	23,540	36,892	21,160	766,023	-4,510	843,105
1125 kW	29,425	46,419	21,390	752,417	-5,299	844,351
Hoppecke 24 OPzS 3000	251,092	81,531	0	0	-75,469	257,154
Converter	36,133	19,597	0	0	-1,073	54,657
System	1,572,543	203,669	345,250	1,893,878	-87,702	3,927,638

Table 10.5: Annualized cost summary

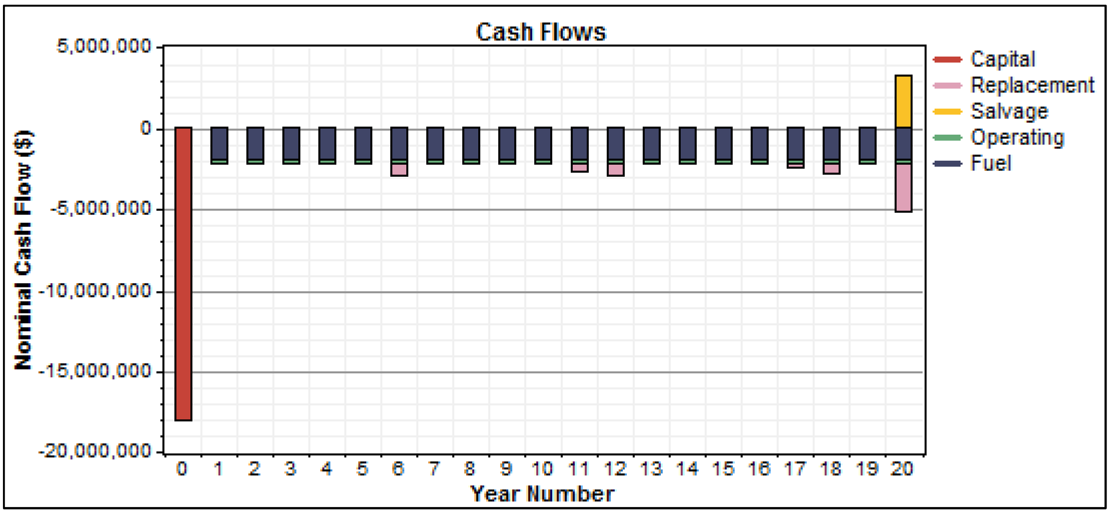


Figure 10.4: Cash flow summary by cost type

Electrical

Component	Production (kWh/yr)	Fraction
PV array	6,022,891	47%
450kW	1,333,977	10%
900 kW	2,765,813	22%
1125 kW	2,666,932	21%
Total	12,789,612	100%

Table 10.6: Electrical summary

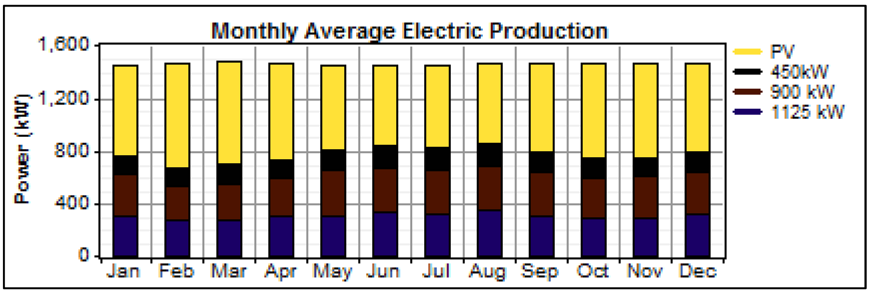


Figure 10.5: Monthly average electric production

Load	Consumption (kWh/yr)	Fraction
AC primary load	12,494,274	100%
Total	12,494,274	100%

Table 10.7: Load summary

Quantity	Value	metric
Excess electricity	0.0232	kWh/yr
Unmet load	0.0256	kWh/yr
Capacity shortage	1,132	kWh/yr
Renewable fraction	0.458	

Table 10.8: Load summary 2

PV

Quantity	Value	metric
Rated capacity	4,000	kW
Mean output	688	kW
Mean output	16,501	kWh/d
Capacity factor	17.2	%
Total production	6,022,891	kWh/yr

Table 10.9: PV Summary 1

Quantity	Value	metric
Minimum output	0.00	kW
Maximum output	3,553	kW
PV penetration	48.2	%
Hours of operation	4,380	hr/yr
Levelized cost	0.249	$/kWh

Table 10.10: PV Summary 2

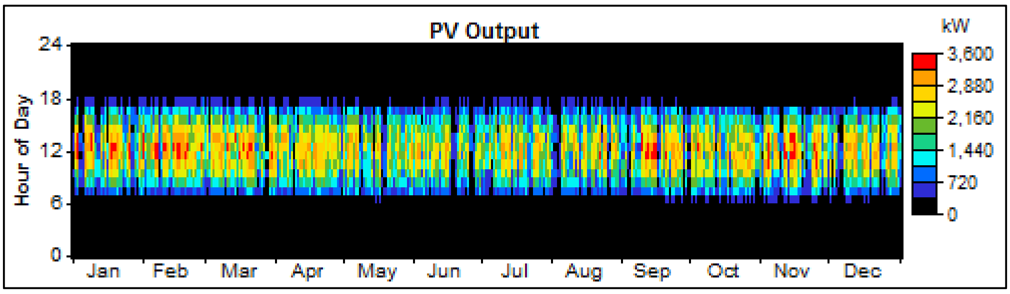


Figure 10.6: PV output

450kW Generator

Quantity	Value	metric
Hours of operation	4,540	hr/yr
Number of starts	1,098	starts/yr
Operational life	5.51	yr
Capacity factor	42.3	%
Fixed generation cost	17.1	$/hr
Marginal generation cost	0.259	$/kWh
Electrical production	1,333,977	kWh/yr
Mean electrical output	294	kW
Min. electrical output	180	kW
Max. electrical output	360	kW

Table 10.11: 450 kW Generator Summary 1

Quantity	Value	metric
Fuel consumption	360,998	L/yr
Specific fuel consumption	0.271	L/kWh
Fuel energy input	3,552,221	kWh/yr
Mean electrical efficiency	37.6	%

Table 10.12: 450 kW Generator Summary 2

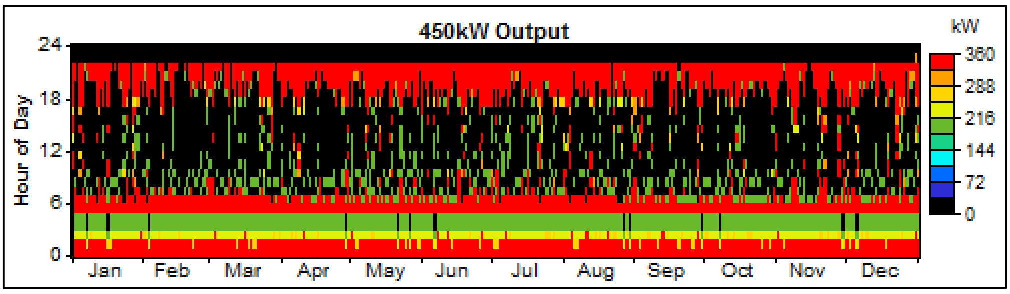


Figure 10.7: 450 kW Generator output

900 kW Generator

Quantity	Value	metric
Hours of operation	4,232	hr/yr
Number of starts	1,161	starts/yr
Operational life	5.91	yr
Capacity factor	43.9	%
Fixed generation cost	27.8	$/hr
Marginal generation cost	0.259	$/kWh

Table 10.13: 900 kW Generator Summary 1

Quantity	Value	metric
Electrical production	2,765,813	kWh/yr
Mean electrical output	654	kW
Min. electrical output	360	kW
Max. electrical output	720	kW

Table 10.14: 900 kW Generator Summary 2

Quantity	Value	metric
Fuel consumption	736,560	L/yr
Specific fuel consumption	0.266	L/kWh
Fuel energy input	7,247,751	kWh/yr
Mean electrical efficiency	38.2	%

Table 10.15: 900 kW Generator Summary 3

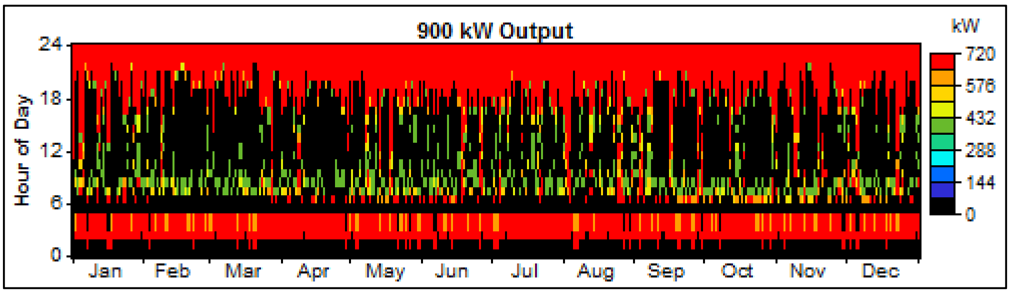


Figure 10.8: 900 kW Generator output

1125 kW Generator

Quantity	Value	metric
Hours of operation	4,278	hr/yr
Number of starts	820	starts/yr
Operational life	5.84	yr
Capacity factor	33.8	%
Fixed generation cost	33.0	$/hr
Marginal generation cost	0.259	$/kWh

Table 10.16: 1125 kW Generator Summary 1

Quantity	Value	metric
Electrical production	2,666,932	kWh/yr
Mean electrical output	623	kW
Min. electrical output	450	kW
Max. electrical output	817	kW

Table 10.17: 1125 kW Generator Summary 2

Quantity	Value	metric
Fuel consumption	723,478	L/yr
Specific fuel consumption	0.271	L/kWh
Fuel energy input	7,119,021	kWh/yr
Mean electrical efficiency	37.5	%

Table 10.18: 1125 kW Generator Summary 3

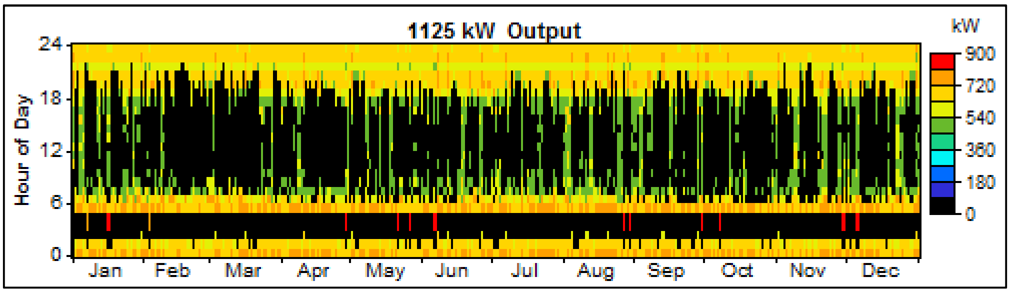


Figure 10.9: 1125 kW Generator output

Battery

Quantity	Value
String size	120
Strings in parallel	20
Batteries	2,400
Bus voltage (V)	240

Table 10.19: Battery summary 1

Quantity	Value	metric
Nominal capacity	14,400	kWh
Usable nominal capacity	10,080	kWh
Autonomy	7.07	hr
Lifetime throughput	24,470,400	kWh
Battery wear cost	0.127	$/kWh
Average energy cost	0.000	$/kWh

Table 10.20: Battery summary 2

Quantity	Value	metric
Energy in	1,353,964	kWh/yr
Energy out	1,175,548	kWh/yr
Storage depletion	9,253	kWh/yr
Losses	169,163	kWh/yr
Annual throughput	1,267,626	kWh/yr
Expected life	19.3	yr

Table 10.21: Battery summary 3

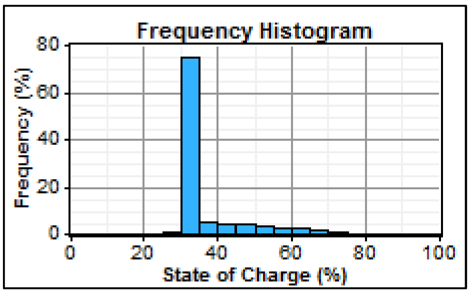


Figure 10.10: Battery state of charge

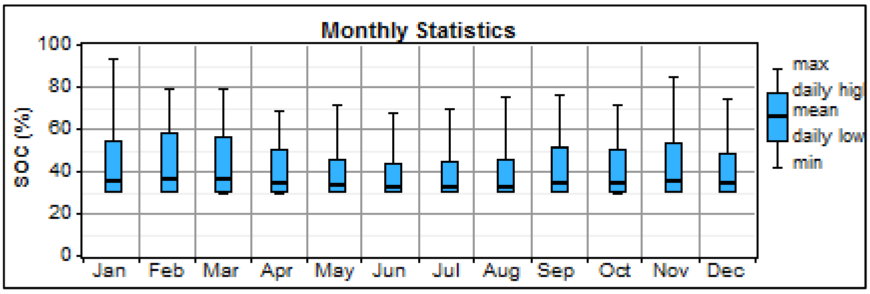


Figure 10.11: Battery state of charge monthly

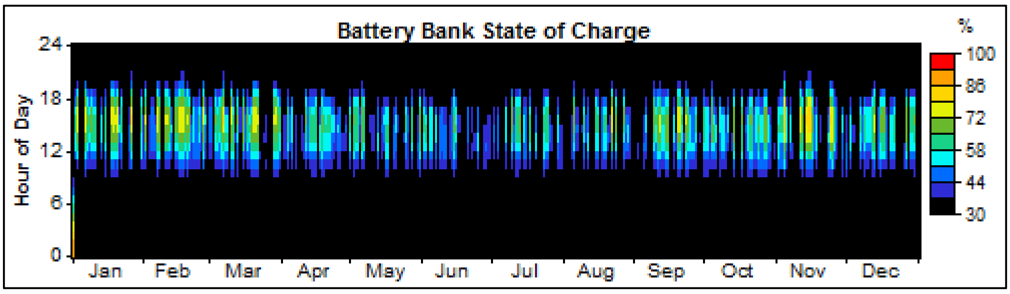


Figure 10.12: Battery state of charge - graphical

Converter

Quantity	Inverter	Rectifier	metric
Capacity	2,000	2,000	kW
Mean output	654	0	kW
Minimum output	0	0	kW
Maximum output	1,818	0	kW
Capacity factor	32.7	0.0	%

Table 10.22: Converter Summary 1

Quantity	Inverter	Rectifier	Units
Hours of operation	4,870	0	hrs/yr
Energy in	5,844,477	0	kWh/yr
Energy out	5,727,583	0	kWh/yr
Losses	116,894	0	kWh/yr

Table 10.23: Converter Summary 2

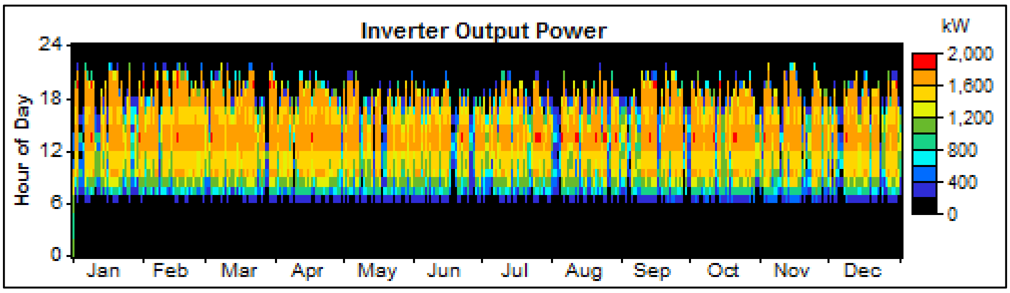


Figure 10.13: Inverter output power

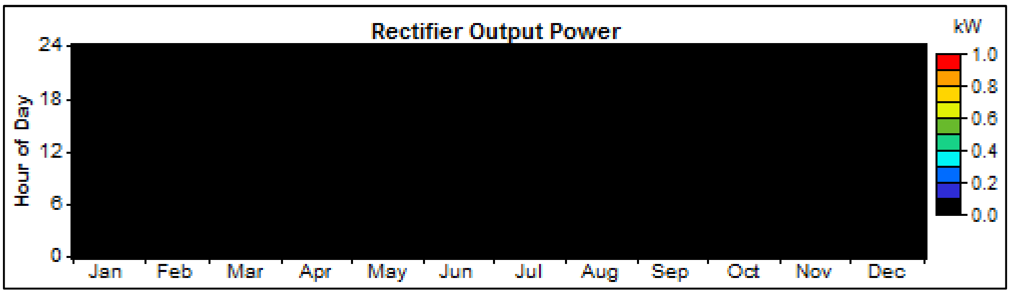


Figure 10.14: Rectifier output power

Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	4,795,387
Carbon monoxide	11,837
Unburned hydrocarbons	1,311
Particulate matter	892
Sulfur dioxide	9,630
Nitrogen oxides	105,620

Table 10.24: Emissions Summary